

Native Minerals and Intermetallides of Noble and Nonferrous Metals in Sediments of the Markov Deep, Mid-Atlantic Ridge

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The study of modern mineralization in spreading zones of the World Ocean is mainly focused on the precipitation of minerals from hydrothermal fluids and the consequent formation of sulfide edifices [1]. However, the study of ore minerals formed in the course of the alteration of magmatic rocks is no less essential. The present paper reports the first findings of native minerals of noble metals in sediments of the Markov Deep, Mid-Atlantic Ridge.

The bottom morphology, tectonics and neotectonic movements, oceanic lithosphere composition, and bottom sediments were investigated at the Sierra Leone site in the axial Mid-Atlantic Ridge (5–7° N) in 2001–2003 [5] (cruise 10 of the R/V *Akademik Ioffe* [2, 3] and cruise 22 of the R/V *Professor Logatchev* [4]). New occurrences of massive sulfide copper mineralization were discovered among metasomatites formed in the course of hydrothermal alteration of apogabbro cataclastites on the eastern wall of the Markov rift deep [2, 4]. The panning of loose bottom sediments (total volume 1.87 m³) taken with the help of drag corers (15 samples) and box corers (17 samples) yielded 32 concentrates of heavy fraction minerals. The panned samples were processed under laboratory conditions and then investigated with the following standard methods: sieve analysis (fractions +1, 0.5–1, 0.25–0.5, and 0.1–0.25, and –0.1 mm); gravitational, magnetic, and electric fractionations; and complete mineralogical analysis of fractions and separation of native elements [8]. In addition,

V.V. Knauf extracted native metals and intermetallides from fraction –0.25 mm of panned samples I1032 and L1147 using the gravitational separator of an original construction (AOZT NATI Patent, 1996, Russia). Table 1 shows that 13 panned samples yielded the following native minerals and intermetallides of noble and nonferrous metals that can concentrate in placers (grain size >0.1 mm): native gold (Au, Ag), isoferroplatinum (Pt₃Fe), tetraferroplatinum (PtFe), native lead (Pb), native tin (Sn), native copper (Cu), and Zn-bearing copper (Cu, Zn). Samples L1093 and L1104 yielded moissanite (SiC).

Bottom sediments used for the panning are mainly composed of carbonate sediments and foraminiferal oozes with a minor admixture of the sandy fraction coupled with fragments of magmatic rocks (basalt, volcanic glass, and basic and ultrabasic rocks) and gastropods. The sandy fraction is mainly composed of foraminifers, chloritized green rock fragments, volcanic glass, quartz, calcite, and serpentine. The content of heavy fraction minerals in sediments varies from 0.1 to 100 g. The heavy fraction is dominated by pyroxenes (primarily, clinopyroxene), magnetite, minerals of the epidote–zoisite group, and occasional chrome spinels (Table 2). The panned samples also contain indicator-minerals of hydrothermal activity, such as iron sulfides (pyrite, marcasite, pyrrhotite, and troilite); copper sulfides (chalcopyrite, chalcocite, and bornite); sphalerite, hematite, pyrolusite, atacamite, barite, aragonite, apatite, and so on; unidentified hydroxides of Fe, Mn, and subordinate Ta and Nb; and native minerals and intermetallides of noble metals. These minerals are universally found as separate grains at the Sierra Leone site. They can tentatively be united into the following mineral assemblages (Table 2): (1) pyroxene–epidote and massive sulfide assemblages (sample I1032); (2) chrome spinel–pyroxene assemblage (sample I1064); (3) magnetite–pyroxene and barite–hematite assemblages (sample I1061); and (4) magnetite–amphibole–pyroxene assemblage with a minor content of the heavy fraction (sample I1054 and others).

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Table 1. Minerals of the heavy fraction in sediments of the Markov Deep, Mid-Atlantic Ridge (wt %)

Mineral	Sample											
	I1032				I1064				I1061			
	Grain size fraction (mm)											
	+0.5	0.5–0.25	–0.25	X	+0.5	0.5–0.25	–0.25	X	+0.5	0.5–0.25	–0.25	X
Magnetite	0.9	1.5	2.4	2.2	5.1	15.5	13.0	11.5	s.p.	12.7	35.1	20.0
Magnetite and rock intergrowths	n.d.	2.2	2.3	0.6	15.2	n.d.	n.d.	3.8	n.d.	0.7	0.7	0.7
Magnetite nodules	n.d.	n.d.	s.p.	s.p.	n.d.	n.d.	n.d.	n.d.	s.p.	3.3	1.5	2.8
Pyroxene group	5.0	11.8	20.0	12.3	13.5	46.5	57.4	38.9	n.d.	51.7	21.9	24.7
Epidote–zoisite group	33.1	51.1	53.2	45.9	n.d.	n.d.	n.d.	n.d.	15.0	n.d.	0.6	4.0
Olivine	n.d.	n.d.	n.d.	n.d.	s.p.	n.d.	n.d.	s.p.	n.d.	n.d.	n.d.	n.d.
Garnet	n.d.	n.d.	s.p.	s.p.	n.d.	n.d.	s.p.	s.p.	n.d.	n.d.	s.p.	s.p.
Amphibole	n.d.	1.4	n.d.	0.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	2.2	0.9
Chlorite group	n.d.	1.1	n.d.	0.3	6.4	n.d.	n.d.	2.3	21.0	n.d.	n.d.	5.4
Chrome spinels	0.5	1.5	s.p.	0.7	32.6	16.1	17.4	22.6	n.d.	n.d.	n.d.	n.d.
Ilmenite	n.d.	n.d.	n.d.	s.p.	n.d.	n.d.	n.d.	n.d.	n.d.	5.0	21.9	10.5
Iron sulfides	9.9	4.4	2.9	5.6	n.d.	0.8	s.p.	0.3	n.d.	n.d.	n.d.	n.d.
Copper sulfides	21.8	13.8	6.7	13.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Hematite	24.8	12.3	6.2	14.3	n.d.	11.1	n.d.	3.4	20.0	20.8	6.3	14.0
Pyrolusite	n.d.	n.d.	n.d.	n.d.	n.d.	s.p.	n.d.	s.p.	n.d.	n.d.	n.d.	n.d.
Atacamite	n.d.	1.0	3.8	1.6	n.d.	n.d.	s.p.	s.p.	n.d.	s.p.	s.p.	s.p.
Rock fragments	4.0	s.p.	2.4	2.1	27.1	11.0	10.4	16.7	44.0	4.9	0.9	13.1
Zircon	n.d.	s.p.	s.p.	s.p.	n.d.	s.p.	n.d.	s.p.	n.d.	n.d.	0.7	0.2
Apatite	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.9	0.3	n.d.	n.d.	n.d.	n.d.
Barite	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	s.p.	8.1	3.3
Sphene	n.d.	n.d.	s.p.	s.p.	n.d.	n.d.	s.p.	s.p.	n.d.	n.d.	n.d.	n.d.
Aragonite	n.d.	n.d.	n.d.	n.d.	n.d.	s.p.	0.8	0.2	n.d.	0.8	n.d.	0.2
Gold	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	s.p.	n.d.	s.p.
Magnetic and electromagnetic fractions (g)												
Magnetic	0.03	0.11	0.30	0.44	0.52	1.63	0.74	2.89	<0.01	0.02	0.06	0.08
Electromagnetic	3.09	6.21	5.83	15.13	2.04	8.91	4.60	15.55	0.06	0.10	0.08	0.24
Nonelectric	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.36	0.36	<0.01	<0.01	0.02	0.02
Heavy fraction in general	3.12	6.32	6.13	15.57	2.56	10.54	5.70	18.80	0.06	0.12	0.16	0.34

Note: The complete mineralogical analysis was carried out by M.V. Kosolapova. (X) Mean value; (n.d.) not detected; (s.p.) single points.

Two grains of rounded equant grains of *isoferroplatinum* (size 0.1–0.15 mm) were found in sample I1032. Isoferroplatinum makes up the intergrowth with tetraferroplatinum (Fig. 1a) or platinum oxide. Traces of other elements of the platinum group are absent in both isoferroplatinum (Table 3, analyses 1–3) and tetraferroplatinum (analysis 4). Such isoferroplatinum and tetraferroplatinum are commonly found in cumulates of polyphase zonal dunite–pyroxenite–gabbro massifs (in particular, gabbro [7–9]) and placers of the platinum mineralogical–geochemical type [10].

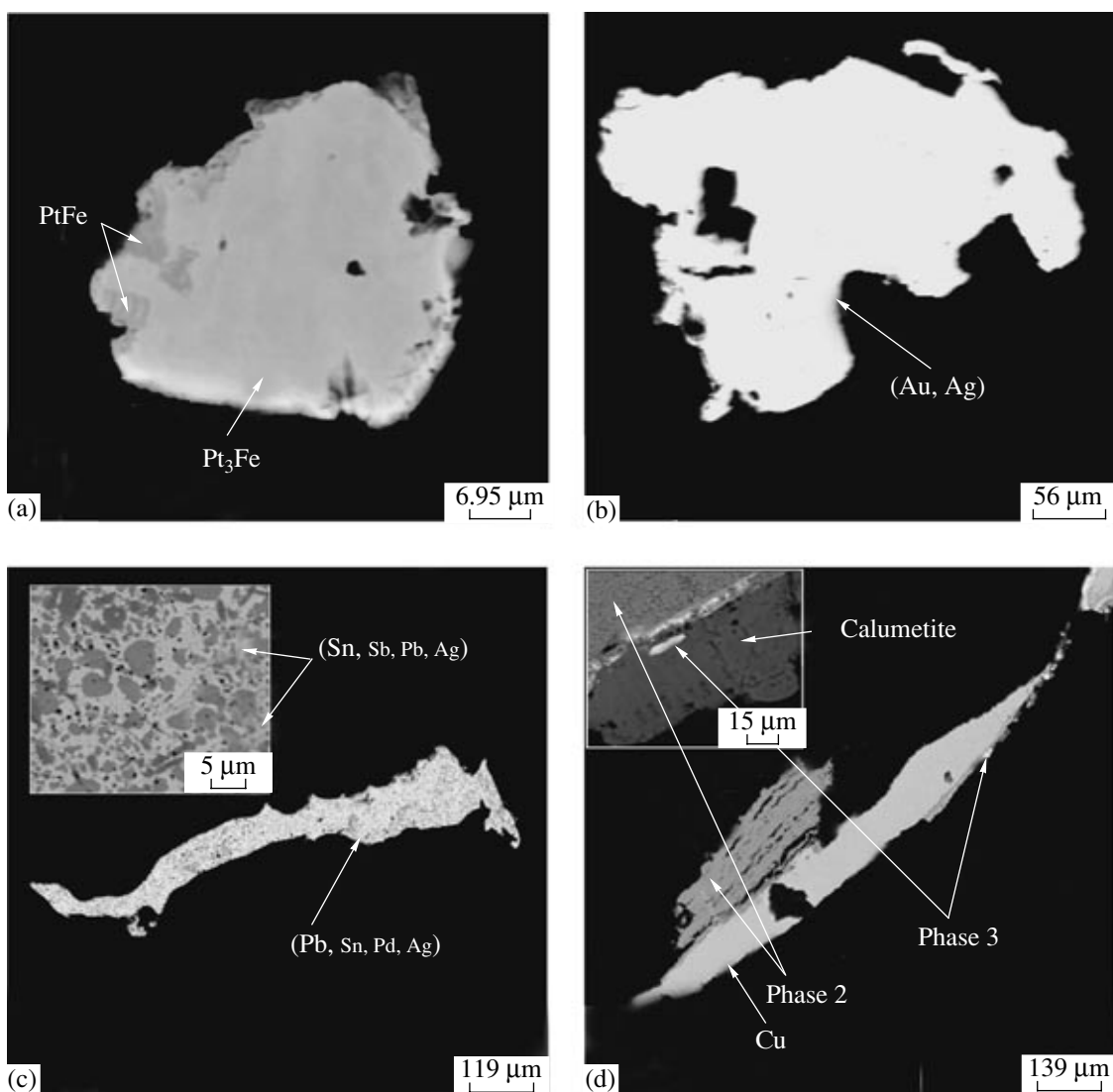
Native gold was found as slightly rounded lumps in fraction 0.25–0.5 mm of sample I1061 (Fig. 1b). Intergrowths with hematite were also found. Native gold has a fineness of ~750 (Table 3, analyses 5–8). Intergrowth of the native gold with hematite and their close association with barite in panned samples (Table 2) suggest that primary ores include the gold–hematite–barite assemblage that is commonly formed at the latest stage of the deposition of massive sulfide ores [1].

Native lead is the most abundant mineral (Table 3). This mineral is found as lumpy, oblate, and oblong

Table 2. Results of the analysis of native minerals and intermetallides (wt %) from sediments of the Markov Deep, Mid-Atlantic Ridge

Element	I1032 2.1.1.	I1032 2.1.2.	I1032 2.2.1.	I1032 2.2.2.	I1061 1.1.1.	I1061 1.1.2.	I1061 1.1.3.	I1061 1.1.4.
	1	2	3	4	5	6	7	8
Au	n.d.	n.d.	n.d.	n.d.	78.2	75.3	74.1	76.9
Pt	90.3	90.4	90.3	76.5	n.d.	n.d.	n.d.	n.d.
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ag	n.d.	n.d.	n.d.	n.d.	22.0	22.7	24.9	22.6
Cu	n.d.	n.d.	n.d.	1.5	n.d.	n.d.	n.d.	n.d.
Fe	9.2	9.3	9.6	21.7	n.d.	n.d.	n.d.	n.d.
Total	99.50	99.70	99.90	99.70	100.20	98.02	98.99	99.48
Element	I1054 1.1.1.	L1092 2.5.1.	L1116 3.3.1.	L1116 3.3.2.	L1127 3.2.1.	L1129 3.4.1.	L1130 4.1.1.	L1130 4.2.1.
	9	10	11	12	13	14	15	16
Pb	96.8	95.3	97.6	97.6	97.5	98.1	96.4	96.8
Sb	n.d.	4.38	n.d.	n.d.	n.d.	0.68	0.59	0.66
Sn	2.12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ag	0.63	n.d.	n.d.	n.d.	n.d.	n.d.	0.63	0.82
Pd	0.70	n.d.	0.83	0.87	n.d.	n.d.	0.78	0.67
Total	100.26	99.69	98.46	98.43	97.46	98.81	98.40	98.91
Element	L1157 3.4.1.	I1054 1.1.2.	I1054 1.1.3.	L1147 2.6.1.	L1092 2.1.1.	L1092 2.2.1.	L1093 1.1.1.	L1105 3.1.1.
	17	18	19	20	21	22	23	24
Pb	97.0	2.73	3.38	n.d.	98.7	98.0	96.4	100.8
Sb	n.d.	3.96	3.75	n.d.	n.d.	n.d.	n.d.	n.d.
Sn	n.d.	92.7	92.0	99.7	n.d.	n.d.	n.d.	n.d.
Ag	n.d.	n.d.	0.42	n.d.	n.d.	n.d.	n.d.	n.d.
Pd	0.76	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	n.d.	n.d.	n.d.	1.41	1.48	1.38	1.40
Total	97.78	99.36	99.51	99.70	100.09	99.51	97.74	102.20
Element	L1127 3.3.1.	L1127 3.1.1.	L1130 2.2.1.	L1130 2.2.2.	L1130 2.2.5.	L1147 5.2.1.	L1147 3.2.1.	L1147 7.4.1.
	25	26	27	28	29	30	31	32
Pb	98.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	35.3	36.5
Cu	n.d.	98.2	97.1	98.6	98.4	99.5	62.5	62.4
Fe	n.d.	n.d.	n.d.	n.d.	n.d.	0.30	1.80	0.40
S	1.51	n.d.	n.d.	n.d.	0.15	n.d.	n.d.	n.d.
Total	100.43	98.22	97.05	98.63	98.52	99.80	99.60	99.30

Note: Analyses were carried out with a LINK-1000 energy-dispersive spectrometer at the Institute of Precambrian Geology and Geochronology, St. Petersburg (M.D. Tolokachev, analyst). Analytical conditions: accelerating voltage 25 kV, current 1–3 nA, probe diameter 2–3 μm, counting time 100 s; standards: pure metals (Pt, Os, Ir, Ru, Rh, Pd, Au, Ag, Fe, Ni, Cu, Pb, and Zn) and synthetic compounds (PbS, Cu₂S, FeAs₃, and PtAs₃); (n.d.) not detected.



Native minerals and intermetallics of noble and nonferrous metals from sediments of the Markov Deep, Mid-Atlantic Ridge. Photomicrographs were taken by M.D. Tolkachev with an AVT-55 scanning electron microscope at the Institute of Precambrian Geology and Geochronology, St. Petersburg. (a) Aggregate of isoferroplatinum (Pt_3Fe) and tetraferroplatinum ($PtFe$); (b) native gold (Au, Ag) and hematite intergrowth; (c) aggregation of native lead (with traces of $Sn, Pd,$ and Ag) and native tin (with traces of $Sb, Pb,$ and Ag) (the native lead is light-colored); (d) intergrowth of native copper with oxychlorides of Cu and Pb : (Phase 2) $Cu_{16}Cl(OH)_{15} \cdot nH_2O$, (phase 3) $Pb_9Cu_5Cl_2(OH)_{26}$, (calumetite) $Cu(OH,Cl)_2 \cdot 2H_2O$.

grains (0.1–2 mm) with traces of $Pd, Sb,$ and Ag (Table 3, analyses 10–17). In one sample, we found a subgraphic aggregate of native lead and tin (Fig. 1c). The native lead contains traces of $Sn, Pd,$ and Ag (Table 3, analysis 9), while the native tin contains traces of $Sb, Pb,$ and Ag (analyses 18, 19). Unusual lamellar segregations (0.15–1.5 mm) with ~1.42 wt % S (analyses 21–25) can be referred to as new phase 1 ($Pb_{11-X}S$). They are probably cryptocrystalline native lead–galena aggregates with an ideal constant composition ($166Pb \cdot 17PbS$). One grain showed the intergrowth of phase 1 ($Pb_{11-X}S$) with augite and its composition corresponds to $Ca_{1.00}(Mg_{0.77}Fe_{0.28}Ti_{0.02})_{1.07}[(Si_{1.79}Al_{0.15})_{1.94}O_6]$ (Table 3, analysis 21).

Native tin also occurs as homogeneous lumps 0.2 mm across (Table 3, analysis 9).

Native copper is widespread as lamellar and extended interstitial segregations (0.1–2 mm). Native copper is generally represented by the pure variety (Table 3, analyses 26–30). Analyses 31 and 32 correspond to the $Fe-$ and $Zn-$ bearing copper ($Cu_{0.63}Zn_{0.35}Fe_{0.02}$). X-ray images of such $Zn-$ bearing copper from ultramafic rocks of the Koryak Highland [11] and hydrothermal deposits of the Urals [1] indicated that this mineral is an analogue of $\alpha-Cu$ or synthetic $\alpha-brass$. The rim of native copper often makes up intergrowths with oxychlorides of Cu and Pb (Fig. 1d). They include calumetite ($Cu(OH,Cl)_2 \cdot 2H_2O$), atacamite ($Cu_2Cl(OH)_3$), and

Table 3. Compositions of minerals of native elements from sediments of the Markov Deep, Mid-Atlantic Ridge (wt %)

Element	I1032 2.1.1.	I1032 2.1.2.	I1032 2.2.1.	I1032 2.2.2.	I1061 1.1.1.	I1061 1.1.2.	I1061 1.1.3.	I1061 1.1.4.
	1	2	3	4	5	6	7	8
Au	n.d.	n.d.	n.d.	n.d.	78.2	75.3	74.1	76.9
Pt	90.3	90.4	90.3	76.5	n.d.	n.d.	n.d.	n.d.
Sn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ag	n.d.	n.d.	n.d.	n.d.	22.0	22.7	24.9	22.6
Cu	n.d.	n.d.	n.d.	1.5	n.d.	n.d.	n.d.	n.d.
Fe	9.2	9.3	9.6	21.7	n.d.	n.d.	n.d.	n.d.
Total	99.50	99.70	99.90	99.70	100.20	98.02	98.99	99.48
Element	I1054 1.1.1.	L1092 2.5.1.	L1116 3.3.1.	L1116 3.3.2.	L1127 3.2.1.	L1129 3.4.1.	L1130 4.1.1.	L1130 4.2.1.
	9	10	11	12	13	14	15	16
Pb	96.8	95.3	97.6	97.6	97.5	98.1	96.4	96.8
Sb	n.d.	4.38	n.d.	n.d.	n.d.	0.68	0.59	0.66
Sn	2.12	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Ag	0.63	n.d.	n.d.	n.d.	n.d.	n.d.	0.63	0.82
Pd	0.70	n.d.	0.83	0.87	n.d.	n.d.	0.78	0.67
Total	100.26	99.69	98.46	98.43	97.46	98.81	98.40	98.91
Element	L1157 3.4.1.	I1054 1.1.2.	I1054 1.1.3.	L1147 2.6.1.	L1092 2.1.1.	L1092 2.2.1.	L1093 1.1.1.	L1105 3.1.1.
	17	18	19	20	21	22	23	24
Pb	97.0	2.73	3.38	n.d.	98.7	98.0	96.4	100.8
Sb	n.d.	3.96	3.75	n.d.	n.d.	n.d.	n.d.	n.d.
Sn	n.d.	92.7	92.0	99.7	n.d.	n.d.	n.d.	n.d.
Ag	n.d.	n.d.	0.42	n.d.	n.d.	n.d.	n.d.	n.d.
Pd	0.76	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	n.d.	n.d.	n.d.	1.41	1.48	1.38	1.40
Total	97.78	99.36	99.51	99.70	100.09	99.51	97.74	102.20
Element	L1127 3.3.1.	L1127 3.1.1.	L1130 2.2.1.	L1130 2.2.2.	L1130 2.2.5.	L1147 5.2.1.	L1147 3.2.1.	L1147 7.4.1.
	25	26	27	28	29	30	31	32
Pb	98.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Zn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	35.3	36.5
Cu	n.d.	98.2	97.1	98.6	98.4	99.5	62.5	62.4
Fe	n.d.	n.d.	n.d.	n.d.	n.d.	0.30	1.80	0.40
S	1.51	n.d.	n.d.	n.d.	0.15	n.d.	n.d.	n.d.
Total	100.43	98.22	97.05	98.63	98.52	99.80	99.60	99.30

Note: Analyses were carried out with a LINK-1000 energy-dispersive spectrometer at the Institute of Precambrian Geology and Geochronology, St. Petersburg (M.D. Tolkachev, analyst). Analytical conditions: accelerating voltage 25 kV, current 1–3 nA, probe diameter 2–3 μm , counting time 100 s; standards: pure metals (Pt, Os, Ir, Ru, Rh, Pd, Au, Ag, Fe, Ni, Cu, Pb, and Zn) and synthetic compounds (PbS, Cu₂S, FeAsS, and PtAs₂); (n.d.) not detected.

two new compounds that can probably be referred to as phase 2 ($\text{Cu}_{16}\text{Cl}(\text{OH})_{15} \cdot n\text{H}_2\text{O}$) and phase 3 ($\text{Pb}_9\text{Cu}_5\text{Cl}_2(\text{OH})_{26}$).

The association of native forms of lead, tin, and copper with the Zn-bearing copper is probably a middle- and low-temperature product related to the metasomatism of ultrabasic and basic rocks. Intergrowths of augite with native lead, the presence of Pd in the native lead, and the admixture of Fe in the Zn-bearing copper [11] testify to the association of metasomatites with mafic rocks. This conclusion is supported by the findings of native forms of lead, tin, and copper in association with the Zn-bearing copper in massive sulfide copper deposits among metasomatites related to the hydrothermal alteration of apogabbro cataclasites on the eastern wall of the Markov Deep, Mid-Atlantic Ridge [5].

Thus, sediments of the Markov Deep contain rather large (>0.1 mm) grains of native minerals and intermetallides of noble and nonferrous metals that can be concentrated in placers. Intermetallides of Pt and Fe are likely to be derivatives of the gold-hematite-barite assemblage that forms at late (low-depth) stages of the formation of hydrothermal massive sulfide ores. The association of minerals of native forms of lead, tin, and copper with the Zn-bearing copper may be related to the hydrothermal transformation of ultrabasic and basic rocks accompanied by massive sulfide copper mineralization. The association of these minerals of native elements in sediments can also serve as a prospecting guide for sulfide mineralization at both the Sierra Leone site, in particular, and the seafloor, in general.

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REFERENCES

1. M. I. Novgorodova, *Native Metals in Hydrothermal Ores* (Nauka, Moscow, 1983) [in Russian].
2. Yu. M. Pushcharovsky, N. S. Bortnikov, S. G. Skolotnev, et al., *Dokl. Earth Sci.* **384**, 357 (2002) [*Dokl. Akad. Nauk* **384**, 83 (2002)].
3. S. G. Skolotnev, A. A. Peive, N. S. Bortnikov, et al., *Dokl. Earth Sci.* **391**, 679 (2003) [*Dokl. Akad. Nauk* **391**, 232 (2003)].
4. V. E. Bel'tenev, V. N. Ivanov, S. G. Skolotnev, et al., *Dokl. Earth Sci.* **395**, 187 (2004) [*Dokl. Akad. Nauk* **395**, 215 (2004)].
5. Yu. M. Pushcharovsky, S. G. Skolotnev, A. A. Peive, et al., in *Geology and Metallogeny of the Mid-Atlantic Ridge 5°–7° N* (GEOS, Moscow, 2004) [in Russian].
6. A. A. Kukharev, *Mineralogy of Placers* (Gosgeoltekhizdat, Moscow, 1961) [in Russian].
7. G. G. Dmitrenko, A. G. Mochalov, S. A. Palandzhyan, and E. M. Goryacheva, *Chemical Compositions of Rock-Forming and Accessory Minerals in Alpine-Type Ultramafic Rocks of the Koryak Highland* (SVKNII Dal'nevost. Nauch.-Issled. Tsentr Akad. Nauk SSSR, Magadan, 1985) [in Russian].
8. A. G. Mochalov, V. P. Zaitsev, Yu. V. Nazimova, et al., *Geol. Ore Deposits* **44**, 515 (2002) [*Geol. Rudn. Mestorozhd.* **44**, 556 (2002)].
9. Yu. V. Nazimova, V. P. Zaitsev, and A. G. Mochalov, *Geol. Ore Deposits* **45**, 515 (2003) [*Geol. Rudn. Mestorozhd.* **45**, 547 (2003)].
10. A. G. Mochalov, *Placers of Platinum Metals*, in *Placer Deposits in Russia and Other Countries of the CIS* (Nauchnyi Mir, Moscow, 1997), pp. 127–165 [in Russian].
11. N. V. Petrovskaya, *Native Gold* (Nauka, Moscow, 1973) [in Russian].
12. N. S. Rudashevsky, A. G. Mochalov, G. G. Dmitrenko, and Yu. P. Men'shikov, *Mineral. Zh.* **9** (4), 71 (1987).
13. M. Hansen and K. Anderko, *Structures of Double Alloys* (Metallurgizdat, Moscow, 1962) [in Russian].