

Mineralogical and Geochemical Features of Graphitized Rocks in the Chernorudka–Barakchin Tectonic Zone

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Abstract—The morphological and structural characteristics of graphite from the deep Chernorudka–Barakchin Fault Zone, Western Baikal region, are described. A complex of mineralogical investigations shows that graphite varieties of the Baikal region are characterized by a perfect structure. The most crystallographically regular samples are composed only of sp^2 -carbon, whereas the virtually amorphous varieties are formed by sp^2 - and sp^3 -carbons as well. The characteristic features of the graphite varieties distinguish them from carbonaceous matter of metamorphic rocks. High concentrations of Co, Ni, Cr, Cu, Ti, Zn, Sc, V, S, Nb, Zr, Sr, Ba, Y, Nd, and La were detected while analyzing the microcomponent composition of the graphitized rocks. The majority of these elements are contained in microinclusions hosted in graphite. The elevated noble metal contents were established in graphitized metasomatic rocks, granitoids, and particularly, in graphite concentrates extracted from these rocks. Sulfides, native metals, and intermetallic compounds were detected in microinclusions. It is suggested that the inflow of reduced high-carbonaceous fluids was responsible for the transfer of chemical elements.

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INTRODUCTION

In spite of the long-standing study of the composition of metamorphic and igneous complexes in the Baikal region (Eskin et al., 1969, 1979; Kuklei, 1983; Petrova et al., 1984, 1995; Makrygina et al., 1992, 1996), many questions still remain unanswered. One of the problems pertains to the geochemistry of carbonaceous rocks characterized by unusually high contents of many incompatible elements.

GEOLOGY OF THE DEEP CHERNORUDKA–BARAKCHIN FAULT ZONE

The graphitized rocks of the Ol'khon region were considered to be a separate group of graphite deposits (Solonenko, 1951). We paid special attention to the linear tectonic zone, which is a fragment of the junction of the fold framework of the Siberian Platform and the platform basement in the Ol'khon region (Fig. 1). This NE-trending zone extends for a distance of 50 km along the Lake Baikal coast from the Anga River valley toward the Khadarta Peninsula, closely adjoining the Primorsky Fault. Then, the zone changes its direction and is traced along the Barakchin and Zamugoi Islands, in the Maloe Sea and the northern Ol'khon Island. The deep Chernorudka–Barakchin Fault Zone was studied in detail by Letnikov et al. (1990, 1995). The Chernorudka–Barakchin Zone is composed of metasomatically altered high-grade metavolcanic rocks of the Ol'khon

Group that adjoins the Ol'khon Island in the southwest. The metavolcanic rocks comprise diopside, two-pyroxene–hornblende, hornblende–diopside–plagioclase (often with garnet) crystalline schists, and plagiogneisses intercalated with quartzite and marble. The schists, carbonate, and volcanic rocks underwent high-temperature metasomatic alteration; ultramafic and granitoid rocks are altered to a lesser extent (Petrova et al., 1984; Savel'eva, 1998b).

The highest metamorphic grade in the Chernorudka–Barakchin Zone corresponds to P - T conditions of granulite facies of a moderate pressure (7–8 kbar) and a high temperature (700–850°C) (Petrova et al., 1984). According to E.V. Bibikova et al. (1990), granulite-facies metamorphism in the Barakchin Tectonic Zone is Early Paleozoic in age (485 ± 5 Ma). According to Letnikov et al. (1995), the age of the endogenic processes in this zone is estimated at 500–445 Ma.

The graphite mineralization, which was detected in all rocks of the Chernorudka–Barakchin Zone, is a distinguishing feature that distinguishes this zone from other metamorphic rocks of the Ol'khon region. No graphite was revealed in the deep Primorsky Fault Zone (Letnikov et al., 1995, 1996; Savel'eva, 1998). The Chernorudka–Barakchin Zone is readily traced by near-field transient electromagnetic sounding and the natural electrical field method, which are sensitive to the graphite occurrence in rocks (Kozhevnikov, 1998).

Graphite mineralization in high-grade metamorphic sequences is not a rare phenomenon. The $\delta^{13}\text{C}$ values of

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graphite from metamorphic rocks of the Ol'khon region vary from -1.3 to -3.1% in marble and from -16.1 to -18.2% in quartzite (Letnikov et al., 1997). The high $\delta^{13}\text{C}$ of graphite from quartzite fits the carbon isotopic composition of the subaerial organic remains (Galimov, 1973; Faure, 1986). The $\delta^{13}\text{C}$ values of graphite from plagioclase schists, calciphyre, granitized crystalline schists, metagranitoid rocks, cataclastic, and mylonitized metasomatic rocks vary from -14.7 to -7.2% (Letnikov et al., 1997). These values are in line with the isotopic composition of the mantle-derived carbon (Galimov, 1973; Faure, 1986). Thus, graphite of metamorphic rocks in the Ol'khon region may be considered a common component of the metasedimentary sequence, whereas within the Chernorudka–Barakchin Fault Zone, graphite might be a product of carbonaceous metasomatism related to the activity of reduced-fluid systems (Ivankin et al., 1984; Novgorodova, 1986; Thompson et al., 1989, 1993, 1995; Letnikov et al., 1996a, 1997). This process could be expressed in the deposition of native carbon as graphite, anthraxolite, kerite, and other species.

CARBONACEOUS MATTER OF THE CHERNORUDKA–BARAKCHIN TECTONIC ZONE

In the Chernorudka–Barakchin Tectonic Zone, the amount of graphite varies from sporadic disseminations or a finely dispersed admixture in the mylonitic zones to large (up to 20 cm in diameter) nodules at the contact of quartzite boudins with marble or to virtually monomineralic veins and interbeds that contain up to 90 wt % graphite.

The studied samples are dominated by rounded, irregular, hexagonal, and distorted hexagonal grains of a pinacoidal habit. The thickness of the plates in the graphite concentrate varies by ten times within a sample. The edges of the plates are often limited by swells; furthermore, they may be strongly bent up to the formation of small saucers. Distinct striation systems crossed at an angle of 60° are observed on the $\{002\}$ surface of many graphite plates. Striated rays on the smooth surface of the plates were formed due to the bending of graphite plates moving to meet one another (Shumilova et al., 2003a). This effect may be caused by the lateral growth and counter movement of surficial crystallization fronts or by the bending of a just-condensed surface of graphite layers poorly attached to the growing crystal. This interpretation is confirmed by the fact that only a surface of the plate is subjected to the bending, whereas a cavity is formed inside a plate. The mechanical deformation of the plates cannot be ruled out as well.

As was established by the Debye–Scherrer method, the carbonaceous matter from the Chernorudka–Barakchin Tectonic Zone is characterized by a structure typical of crystalline hexagonal graphite with characteristic reflections $d_{002} = 3.35\text{--}3.36$ Å, $d_{101} = 2.03$ Å, $d_{004} = 1.678$ Å, $d_{112} = 1.154$ Å, $d_{110} = 1.230$ Å, and

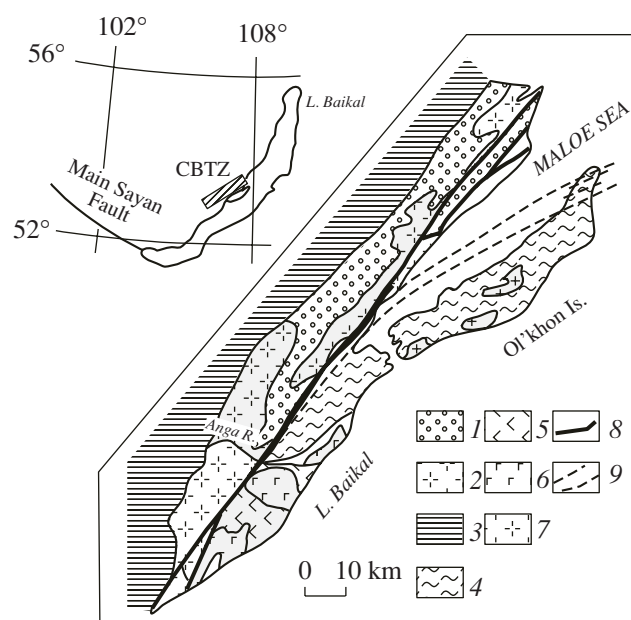


Fig. 1. Geological sketch map of the western Baikal region. (1, 2) Paleoproterozoic rocks of the platform basement: (1) Sarma Group, (2) granites of the Primorsky Complex; (3) platform sedimentary cover; (4–7) Caledonian fold system: (4) Ol'khon Group, (5) the Anga Group, (6) gabbro, (7) granite; (8, 9) fault zones: (8) Primorsky Fault, (9) Chernorudka–Barakchin Tectonic Zone (CBTZ), after V.B. Savel'eva.

$d_{114} = 0.992$ Å (Table 1). The samples with a cryptocrystalline or virtually disordered structure are rare and characterized by d_{002} equal to 3.32 and 3.39 Å that is typical of graphite.

Raman spectroscopy is a high-efficiency method for the determination of the structural ordering of graphite. The Raman spectra were obtained on a T-64000 spectrometer of the Jobin Yvon Company, France, equipped with an Olympus microscope and an ultrasensitive ionization detector. Here, a Spectra Physics 2020 ionized argon laser ($\lambda = 514.5$ nm) was used as an exciting line (analyst L.A. Mikhalsyn). The uncertainty of the position of the line maximums is ± 1 cm^{-1} . The scheme of the spectra recording with an ultrasensitive ionization detector admitted the accumulation of the signal and the improvement of signal/noise ratio by ten times that which corresponded to the exposition of one spectrum during a few hours. We have obtained two spectra of graphite, which are almost identical in terms of the set of lines with the wave numbers (Fig. 2).

According to these results, the Raman spectra consist of intense lines. Line 1582 cm^{-1} corresponds to the major E_{2g} -type vibration of graphite (that is, corresponds to graphite proper). A wide line in the region of 2727 cm^{-1} is considered to be a superposition of several lines and the Raman line of the second order. The origin of the lines 842 and 852 cm^{-1} with a main intensity of 10–15% is unknown to date. The same pertains to other

Table 1. Results of X-ray diffraction analysis of graphite from the Chernorudka–Barakchin Zone using the Debye–Scherrer method

1		2		3		4		5		6	
<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å	<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å	<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å	<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å	<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å	<i>I</i> , cond. unit	<i>d</i> / <i>n</i> , Å
10	3.36	10	3.32	10	3.35	10	3.35	10	3.36	10	3.39
8	2.03	1	1.185	2	2.02	8	2.02	1	2.12	1	3.05
3	1.675	1	1.124	3	1.674	2	1.678	6	2.03		
4	1.23			1	1.542	2	1.541	6	1.678		
8	1.156			5	1.23	6	1.232	4	1.541		
1	0.992			5	1.154	8	1.156	6	1.232		
				2	0.992	2	0.992	8	1.156		
								6	0.991		

Note: (1) diopside–plagioclase metasomatic rock, (2) diopside–amphibole–plagioclase metasomatic rock, (3) quartzite, (4) clinopyroxene granite, (5) calcite marble, (6) scapolite–hedenbergite metasomatic rock. Analytical conditions: AROS program of automated analysis, $\text{CuK}\alpha$, ball is 0.3 mm, 20 kV, 10 mA, exposure time is 6 h; analyst T.N. Popova, Institute of Geology, Komi Scientific Center, Ural Division, Russian Academy of Sciences.

low-intensity lines. Since the spectra of this type are devoid of the line 1350 cm^{-1} , which is frequently detected in natural graphite, corresponding to the D-band of graphite, and traditionally interpreted as evidence for finely dispersed and disordered carbonaceous matter, the analyzed samples may be classified as well-ordered in terms of Raman spectroscopy.

A different degree of crystallinity of individual graphite particles is clearly recorded in the Laue patterns obtained with the single-crystal X-ray diffraction analysis. The presence, partial occurrence, and complete absence of Debye rings in the Lauegrams testify to the polycrystalline structure of the carbonaceous matter (Fig. 3). The dimensions of the studied graphite particles and the conditions of the XRD analysis were identical. The Laue patterns were obtained with an RKOP-A X-ray camera produced at Moscow State University, Russia; the distance from crystal to the film is 31 mm, and a BSV-29 X-ray tube with an iron anode served as the source of irradiation. Smooth, thin, and flat graphite particles 1 mm in size were selected for the analysis (analyst G.N. Kablis).

Low-energy spectroscopy revealed that the graphite varieties from the Baikal region are characterized by a perfect structure. Moreover, the most crystallographically regular samples are composed only of sp^2 -carbon, whereas the virtually amorphous samples comprise both sp^2 - and sp^3 -carbons with only $d_{002} = 3.35\text{--}3.37\text{ Å}$. This means that some kinds of graphite are characterized by the disordered structure of turbostatic graphite.

The morphology and structure of graphite that occurs in the deep Chernorudka–Barakchin Fault Zone allow us to suggest that the origin of the graphite is unrelated to metamorphism. In our opinion, the most plausible mechanism of such graphitization might be related to graphite precipitation from the evolving car-

bon–hydrocarbon fluid that circulated through a deep fault zone (Letnikov et al., 1997; Savel'eva, 1998; Danilova et al., 2001; Shumilova et al., 2003b).

The unusual forms of the surface relief of many graphite plates indicate the participation of a fluid phase in the crystallization of native carbon (Fig. 4). The illustrations display a surface covered by numerous newly formed microparticles of a smoothed pyramidal hexagonal habit with blunt edges. The microparticles of different dimensions are uniformly oriented. Occasionally, microparticles contact with one another, while, in other cases, they are isolated but retain the same orientation. Microparticles reveal small pits largely located on the inferred lateral sides of the smoothed pyramids. Similar pits were observed in experiments as a result of the thermal impact on bitumen under the conditions of a deficiency of oxygen (Cherevko et al., 2002).

GEOCHEMISTRY OF GRAPHITIZED ROCKS FROM THE CHERNORUDKA–BARAKCHIN TECTONIC ZONE

The graphitized rocks from the Chernorudka–Barakchin Tectonic Zone and the graphite varieties therein contain Co, Ni, Cr, Cu, Ti, Zn, Au, Pt, Pd, Sc, V, S, F, as well as Ba, Sr, Nb, Zr, Nd, Ce, Y, and La (Savel'eva, 1998; Danilova, 2003). The Co, Ni, Cr, Cu, Zn, Sc, V, and S contents are appreciably higher in the carbonized metasomatic rocks than in the materials devoid of carbon. The highest contents were established in graphitized rocks with fassaite, amphibole, and scapolite; the elevated concentrations are characteristic of graphitized pyroxene–plagioclase metasomatic rocks. Thus, the elevated contents of the above-listed elements are correlated, to some degree, with the occurrence of native carbon in the rocks.

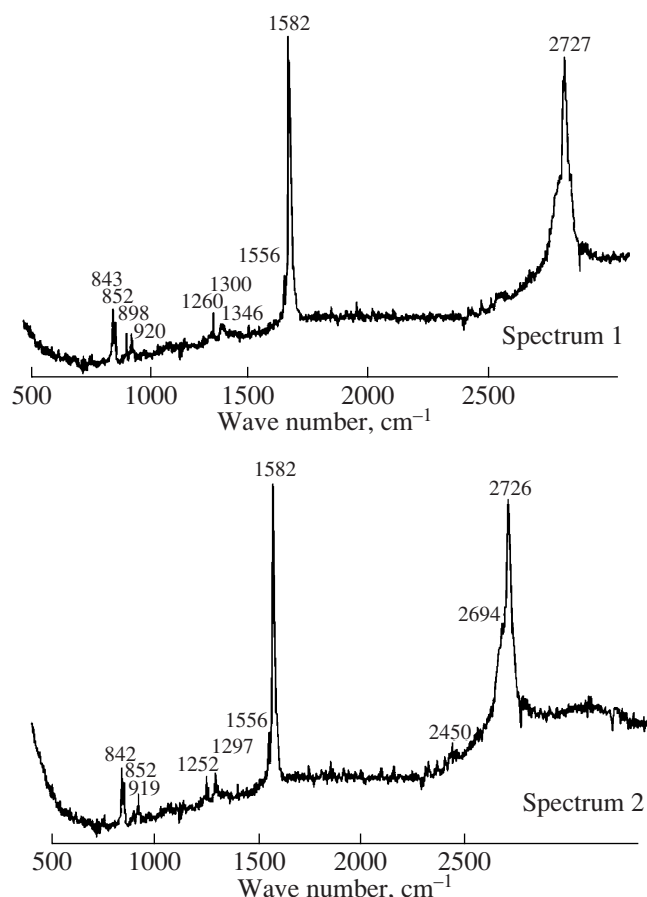


Fig. 2. Raman spectra of graphite from the clinopyroxene-plagioclase metasomatic rock.

The granitized rocks of the tectonic zone enriched in graphite stand out by elevated Nb contents, whereas Sr, Ba, and Zr, conversely, are removed from the intensely graphitized areas. In general, it may be noted that the alteration of mafic crystalline schists was accompanied by the removal of lithophile elements and their precipitation in spatially associated granitoid and carbonate rocks. In contrast to the graphite-free counterparts, the graphitized metasomatic rocks, granitoid, quartzite, and marble are enriched in Nd, La, Ce, and Y.

An outlook for the discovery of noble metals in the high-carbonaceous metasomatic rocks that occur within the deep fault zones (Ivankin et al., 1984; Buslaeva et al., 1989; Thompson et al., 1993; Letnikov et al., 1996a) stimulated the study of the Au, Pt, and Pd distribution in the graphite-bearing rocks of the Chernorudka-Barakchin Tectonic Zone. Gold was determined by the extraction atomic absorption spectroscopy (Instruction of Research Counsel on Analytic Requirements no. 237-S, 1987), whereas Pt and Pd were analyzed with AAS by means of sorption on a PSTM-3T sorbent.

It was established that highly graphitized crystalline schists are enriched in Au. The detected Au content of

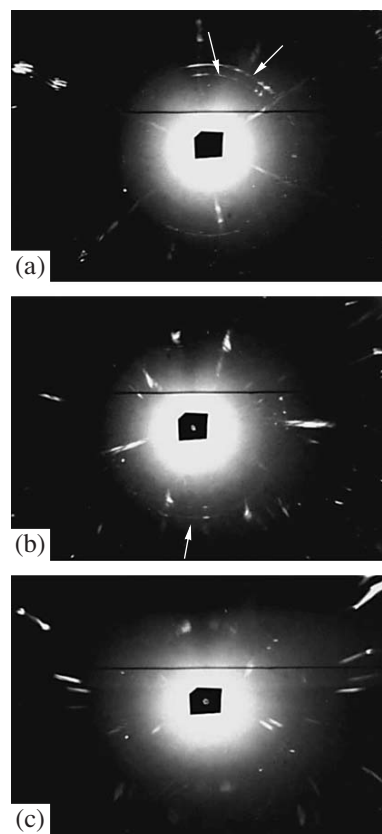


Fig. 3. Lauegram of graphite samples with different degrees of crystallinity: (a) with distinct Debye rings (indicated with arrows), (b) with partially expressed Debye rings, and (c) without Debye rings.

0.02–0.03 ppm is by almost an order of magnitude higher than the global mean Au content in mafic rocks (Vinogradov, 1962). In the graphitized melanosome of the high-temperature metasomatic rocks, the Au content increases to 0.08 ppm (Table 2). In leucosome, the Au content is also much higher than the global mean value, but is slightly lower than in the above-mentioned rocks. Pt and Pd accumulate in graphitized crystalline schists and metasomatic rocks as well. The most carbonized metasomatic rocks contain up to 0.57 ppm Pt (0.3 ppm, on average) and 0.09 ppm Pd (0.04 ppm, on average) against 0.10 and 0.019 ppm of the global mean contents in mafic rocks, respectively.

Graphitized granitoids are characterized by constant content of Pt (0.2 ppm, on average) and elevated Au and Pd contents in comparison with the global mean for felsic rocks. No Pt and Pd were detected in highly graphitized quartzite boudins from marbles; the Au content in quartzite is about 0.01 ppm. The host graphitized marble contains 0.025 ppm Pt and 0.01 ppm Pd, on average.

The noble metal contents in graphite concentrates extracted from the carbonized rocks are two times higher than in the rocks themselves. Au and Pd contents

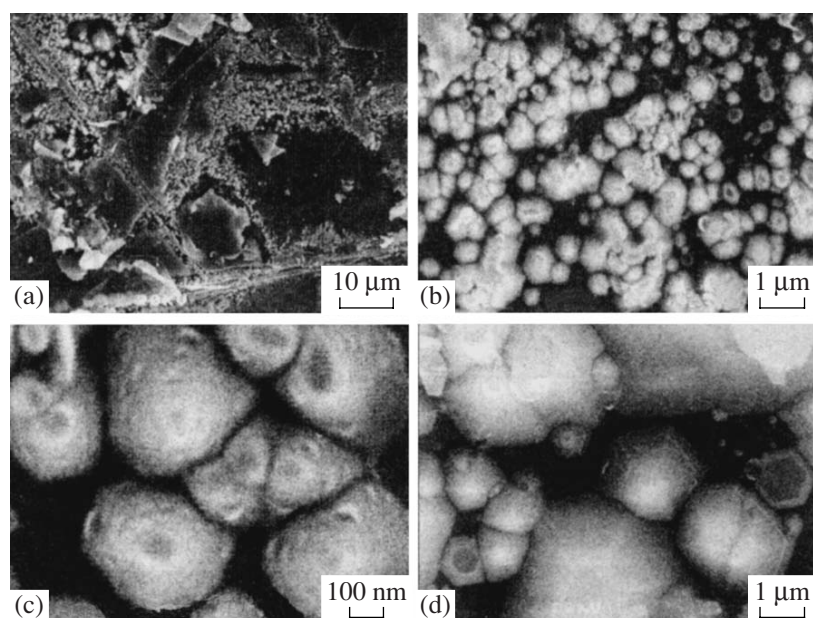


Fig. 4. Morphology of the graphite particle surface: (a) general view of the surface, (b) growth forms on the graphite surface, (c) pyramidal growth forms with rounded edges and pits on the lateral surfaces, and (d) various sized nuclei on the graphite surface.

attain 0.10 and 0.06 ppm, respectively. Pt has not been detected in graphite separations. In contrast to the investigation of graphitized rocks, we failed to achieve complete burning of graphite during the analysis of the graphite concentrates with extraction AAS, so that it cannot be ruled out that Pt contained precisely in the unburnt material and, thus, was not detectable. It is

quite possible that the depletion of graphite concentrates in Au and Pd is related to the same cause.

In addition to noble metals, the graphite concentrates are enriched in some other elements. For example, the Nb content in 95% of the graphite samples is 2–5 times higher than in the rocks. The Zr content is an order of magnitude higher in graphite as well. The Zn

Table 2. Au, Pt, and Pd contents in graphitized rocks and graphite from the Chernorudka–Barakchin Tectonic Zone, ppm

Rock	Au	Pt	Pd	Native C, wt %
Diopside–plagioclase schist (±amphibole, garnet, biotite)	$\frac{0.03(3)}{0.02-0.03}$	$\frac{0.2(3)}{0.2-0.26}$	$\frac{0.02(3)}{\text{n.d.}-0.03}$	$\frac{0.13(3)}{0.1-0.19}$
Fassaite–amphibole–plagioclase metasomatic rock (±diopside, spinel, garnet)	$\frac{0.06(7)}{0.03-0.08}$	$\frac{0.3(7)}{\text{n.d.}-0.56}$	$\frac{0.04(7)}{0.02-0.09}$	$\frac{1.5(7)}{0.5-3.25}$
Pyroxene–plagioclase metasomatic rock	$\frac{0.02(3)}{\text{n.d.}-0.04}$	$\frac{0.3(3)}{\text{n.d.}-0.56}$	$\frac{0.02(3)}{0.01-0.03}$	$\frac{5.7(3)}{0.8-15.54}$
Granitoid	$\frac{0.004(3)}{\text{n.d.}-0.01}$	$\frac{0.2(3)}{0.04-0.34}$	$\frac{0.01(3)}{\text{n.d.}-0.02}$	$\frac{6(3)}{1.7-8.6}$
Quartzite	$\frac{0.01(1)}{\text{n.d.}-0.01}$	$\frac{\text{n.d.}}{\text{n.d.}-0.059}$	$\frac{\text{n.d.}}{\text{n.d.}-0.02}$	$\frac{2.4(1)}{0.05-3.3}$
Marble	$\frac{0.005(3)}{0.0027-0.01}$	$\frac{0.025(3)}{\text{n.d.}-0.059}$	$\frac{0.01(3)}{\text{n.d.}-0.02}$	$\frac{1.6(3)}{0.05-3.3}$
Graphite concentrate	$\frac{0.1(4)}{0.03-0.24}$	$\frac{\text{n.d.}}{\text{n.d.}-0.059}$	$\frac{0.06(4)}{0.02-0.12}$	$\frac{53.2-82.3(4)}{0.05-3.3}$

Note: Numerals above the line are the average contents, numerals in parentheses are the numbers of the samples, and the numerals under the line are the ranges. The Au content was determined with extraction atomic absorption spectroscopy, and the uncertainty of measurements is about 0.2%. The Pt and Pd contents were determined with atomic absorption spectroscopy. Detection limits, ppm: 0.01 for Au, 0.2 for Pt, and 0.05 for Pd. Analyses were carried out at the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences, analyst M.M. Smagunova; n.d. denotes not detected.

Table 3. Composition of microinclusions of native metals in graphite, at %

Element	Ti			Cu		Fe	Pt	Sn	Pb	Zn
	1	2	3	1	2	1	1	1	1	1
Ti	98.75	98.36	98.58	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Fe	n.a.	n.a.	n.a.	"	"	96.92	4.63	"	"	"
Ni	"	"	"	"	"	3.08	n.a.	"	"	"
V	1.25	1.64	1.42	"	"	n.a.	"	"	"	"
Cu	n.a.	n.a.	n.a.	92.82	96.33	"	27.41	2.41	"	"
Zn	"	"	"	2.68	1.23	"	n.a.	n.a.	"	100
Pb	"	"	"	n.a.	2.44	"	"	"	100	n.a.
Sn	"	"	"	4.5	n.a.	"	"	97.59	n.a.	"
Pt	"	"	"	n.a.	"	"	64.86	n.a.	"	"
Rh	"	"	"	"	"	"	3.1	"	"	"
Total	100	100	100	100	100	100	100	100	100	100

Note: (1–3) numbers of analyzed points. Analysis was carried out with a Link EDS at the Institute of Geology, Komi Scientific Center, Syktyvkar, analyst V.N. Filippov; n.a. denotes not analyzed.

and Ni contents in graphite is 2–10 times higher than in rocks. Graphite is also characterized by elevated contents of Ti (20–150 ppm), Mo (8–15 ppm), Cu (1.2–2.2 ppm), and S (80–150 ppm). Conversely, Sr was not detected in the graphite concentrate, while the Y content usually does not depend on the degree of carbonization (analyses have been carried out by the XRF method at the Analytical Center of the Institute of the Earth's Crust, Siberian Branch, Russian Academy of Sciences, analyst T.A. Yasnygina). V and Nd were almost permanently detected in a chemically refined flotation concentrate of graphite. In a few samples, the highest V and Nd contents were 0.282 and 8.891 wt %, respectively (analyses have been carried out by the XRF method at the Institute of Geology, Komi Scientific Center, Ural Division, Russian Academy of Sciences, analyst S.T. Neverov).

V, Nd, and other trace elements, including Nb, Zr, Rb, Y, Sr, Pb, Th, U, Ni, Zn, Cu, Ti, Mo, Ag, and S detected in graphite concentrates may be contained in mineral microinclusions. This suggestion has been confirmed by the microprobe analyses of graphite flakes and segregations separated from the most carbonized rocks, including diopside–plagioclase crystalline schists, metasomatic rocks, granitoids, quartzite, and marble. Segregations of ore minerals were found on the surface of graphite grains. The images were obtained with a JSM SEM (Geol. Japan). The chemical compositions of the microinclusions were determined with a Link EDS (Great Britain) at the Institute of Geology, Komi Scientific Center, Ural Division, Russian Academy of Sciences (analyst V.N. Filippov).

Microinclusions occur as irregular, isometric, or oblong grains up to 1–10 μm in size. Graphite contains inclusions of chalcopyrite, molybdenite, phosphate–yttrium, and intermetallic Cu–Zn–Pb–Al, Fe–Ni–Cr

compounds, zircon, barite, Fe, and Cr oxides often with V, Zn, Mn, and Al admixtures. Judging from the chemical composition (Table 3) and intensity of the luminescence of the objects in secondary electrons, the detected Ti, Fe, Zn, Cu, Pb, Sn, and Pt are present in the native form.

CONCLUSIONS

The specific mineralogical and geochemical features of the graphitized rocks that occur in the Chernorudka–Barakchin Tectonic Zone suggest that carbonization was accompanied by the migration and deposition of many chemical elements. Some of these elements may be mantle-derived and supplied to the host rocks along with CO, CH₄, and other components of reduced carbon–hydrocarbon fluids.

This suggestion is based not only on the results of our investigations; this topic was the subject of discussion in many recent publications (Slobodskoi, 1981; Novgorodova, 1983; Ivankin et al., 1984; Tomson et al., 1984, 1989, 1993, 1995; Buslaeva et al., 1989). Slobodskoi, Buslaev, and Novgorodova provided evidence for the occurrence of organometallic compounds in the carbonaceous matter of metasomatic rocks. The breakdown of organometallic compounds under the effect of many physicochemical factors gives rise to the formation of native metals and nonmetals, various intermetallic compounds, sulfides, oxides, hydroxides, etc.

It may be assumed from the aforesaid that precisely metallocarbonic compounds are a possible mode of the occurrence and migration of ore matter that participated in the formation of the intrafault complex of rocks in the Chernorudka–Barakchin Zone. A wide range of the detected elements testifies to a low degree of fractionation of the fluid system that concurrently

supplied Au, Pt, Pd, Co, Ni, Cr, Cu, Ti, Zn, Sc, V, S, as well as Nb, Zr, Sr, Ba, Y, Nd, and La. In other words, the mantle-derived fluid did not experience fractionation in the root portion of the graphite-forming system, having retained such a wide and unusual set of ore elements.

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