Genesis of Garnet-Bearing Rocks at the Berezitovoe Deposit, Upper Amur Region, Russia

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Abstract—The geological position, composition of mineral assemblages, and typomorphism of major minerals from garnet-bearing rocks at the Berezitovoe gold—base-metal deposit in the Upper Amur Region have been studied in detail. These are ore-bearing metasomatic rocks and metamorphosed porphyritic dikes. The garnet-bearing metasomatic rocks reveal zoning, which is caused by various degrees of metasomatic transformation of the Paleozoic porphyritic granodiorite that hosts the ore zone. The metasomatic replacement of granodiorite was accompanied by loss of Na, Ca, Ba, Sr and gain of K, Mn, and Rb. Garnet-bearing metasomatic and estimated at 3.9 kbar and 500°C from various mineral equilibria. The results of physicochemical simulation of garnet-bearing mineral assemblages carried out by minimizing the Gibbs free energy and the geological data show that garnet-bearing mineral assemblages arose at the Berezitovoe deposit as a result of local high-temperature thermal metamorphism of previously formed low-temperature metasomatic rocks close in composition to classic beresite. In this connection, we propose considering garnet-bearing metasomatic rocks as high-temperature metamorphosed beresites.

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INTRODUCTION

The Berezitovoe gold deposit is situated in the northwestern Amur oblast in the basin of the lower reaches of the Khaikta River, the large right tributary of the Greater Ol'doi River (Fig. 1). The deposit represents a special type of gold mineralization localized in the hydrothermal explosion structure and has no close analogs in morphology and composition of host rocks among known gold deposits in the Transbaikal and Far East regions. A distinguishing feature of orebearing rocks at this deposit is widespread garnetbearing mineral assemblages, in particular, garnetbiotite-anorthite-muscovite-quartz assemblages. This unusual mineralogical feature hampered typification and genetic interpretation of ore-bearing rocks at the Berezitovoe deposit, which were previously

regarded as beresite¹ (Kalinkin, 1971), greisen (Belyaeva and Zalishchak, 1989), or a new type of high-temperature potassic Au-bearing garnet-tourmaline-quartz-muscovite metasomatic rock (Buryak et al., 1978). We suggest that the unusual phase composition of metasomatic rocks is caused by the final thermal metamorphism superposed on the previously formed sulfide—silicate mineral assemblages (Avchenko et al., 2010). Recently obtained new factual evidence allows us to substantiate this viewpoint more comprehensively and to consider the genesis of garnet-bearing mineral assemblages in terms of physicochemical simulation of mineral systems.

GEOLOGY OF THE BEREZITOVOE DEPOSIT

The deposit is localized in the Selenga–Stanovoi Terrane situated in the southern framework of the North Asian Craton in the zone of its junction with the northern framework of the Mongolia–Okhotsk Foldbelt. This territory is characterized by a block structure and widespread Mesozoic magmatic activity. The deposit is hosted in an uplifted block of ancient metamorphic rocks surrounded in the east, north, and west by Triassic volcanic and volcanosedimentary rocks of 1 the Desovsky Complex and by large Late Jurassic– Early Cretaceous plutons of porphyritic granitoids combined into the Khaikta intrusive complex (Strikha et al., 2000).

The deposit consists of sulfide-bearing metasomatic rocks localized in the Late Paleozoic pluton of porphyritic granodiorite (Vakh et al., 2011) in the form 2

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The Russian term *berezite* (after Berezovskoe gold deposit in the Urals) is commonly spelled *beresite* in English. Translator's comment.



Fig. 1. Geological plan of ore zone at Berezitovoe deposit, level 676 m. (1) Paleozoic porphyritic biotite-hornblende granodiorite; (2–5) types of ore-bearing metasomatic rocks: (2) garnet-orthoclase-biotite-anorthite-muscovite-quartz with pyrite mineralization, (3) tourmaline-garnet-orthoclase-muscovite-quartz with mainly pyrite mineralization, (4) tourmaline-garnet-muscovite-quartz with gold-pyrite-galena-sphalerite mineralization; (5) tourmaline-garnet-quartz-muscovite with gold-pyrite-pyrrhotite-sphalerite mineralization; (6) xenolith of partly altered granodiorite; (7) metamorphosed porphyritic dike gar-

net-muscovite-biotite-quartz-anorthite in composition; (8) postmineral spessartite and porphyritic diorite dikes; (9) master fault; (10) zone of cataclastic and altered granodiorite with veinlets of base-metal mineralization; (11) underground mining work-

ings. Location of Berezitovoe deposit in index map (inset) is indicated by star.

of two combined overturned cones following one another; the southern cone is 1.5-2.0 times larger than the northern counterpart. These steeply dipping cones formed as a result of fluid explosions (Tugovik, 1983). In plan view, the orebody has a complex lenticular shape (Fig. 1); it reaches 950 m in length at the surface and 10-15 to 110 m in thickness.

The light gray to greenish gray massive, and less frequently fissile metasomatic quartz-muscovite host rocks are impregnated by almandine-spessartine garnet and tourmaline. Orthoclase, chlorite, biotite, anorthite, Zn-spinel (Fe-rich gahnite), titanite, zircon, epidote, allanite, prehnite, fluorapatite, fluorite, graphite, grothite (Vakh et al., 2009), and cervandonite-(Ce) (Vakh et al., 2010) are less abundant and occur in variable amounts. The metasomatic rocks are strongly brecciated; lithic fragments are cemented by sulfide minerals filling a complex fracture system and thus indicating that mineralization is superposed on metasomatic rocks. The major ore minerals are sphalerite, galena, pyrite, pyrrhotite, and magnetite; subordinate and rare minerals are marcasite, chalcopyrite, arsenopyrite, ilmenite, As-bearing pyrite, native gold, petzite, calaverite, argentite, hessite, altaite. aleksite, tetradymite, tellurobismuthite. aikinite, jordanite, tennantite, boulangerite, jamesonite, Bi-meneghinite, Sb-bursaite-cosalite, native bismuth, and scheelite.

The two types of Au-bearing ores markedly differ in structural position, mineralogy, and Au grade (Vakh,

1983). The main ore type localized as a complex stockwork in the main part of metasomatic zone is represented by Au-bearing base-metal mineralization with an average Au grade of 1-4 gpt. The second veinlet type of ore is insignificant and mostly related to near-latitudinal faults that crosscut the main ore zone. These are thin veins and veinlets consisting of sulfides and tourmaline; tourmaline-quartz, quartz-sulfide, quartz-garnet, and quartz-garnet-sulfide aggregates, which are hosted in the metasomatic ore zone and in granodiorite beyond this zone. The veinlets are 2 frequently distinguished by a high Au grade varying from tens to a few hundreds of gpt and characterized by widespread mineral aggregates composed of visible native gold, arsenopyrite, and complex sulfosalts enriched in Ag, Bi, Sb, As, and Te.

The metasomatic zone is crosscut by intramineral garnet-bearing metamorphosed porphyritic dikes and sporadic postmineral spessartite and porphyritic diorite dikes.

Thus, the Berezitovoe gold-base-metal deposit occupies a special position among other gold deposits in the northern framework of the Mongolia-Okhotsk Belt and represents a new geological and economic type of large-volume gold-sulfide mineralization, the formation of which was caused by multiple fluid activity within local pipes of explosion breccia filled with fragmented Late Paleozoic granitoids. It is suggested that, as compared with other gold deposits in the studied territory, the Berezitovoe deposit can be consid-

ered a root part of the common fluid—hydrothermal system and a transport conduit for ore-bearing solutions to form hydrothermal lode gold deposits at higher levels. It should be noted that the large-volume bodies of Au-bearing explosion breccia are characteristic of the adjacent territory of the eastern Transbaikal region (Abramov, 2011), including the Darasun deposit, where such bodies formed at the early stage of ore deposition and predated the formation of quartz veins with high-grade mineralization (Prokof'ev et al., 2008).

RESEARCH METHODS

Microscopic study of thin and polished sections of rocks and ores from the deposit was carried out at the Analytical Center of the Far East Geological Institute (FEGI), Far East Branch, Russian Academy of Sciences, which is equipped with modern high-precision microscopes: Axioplan 2 and Axiostar plus (Carl Zeiss, Germany) and Polam R-213 (LOMO, Russia). Chemical analysis of minerals was carried out at the Analytical Center using a JXA 8100 four-channel electron probe X-ray microanalyzer and VRA-30 and S4 Pioneer X-ray fluorescence spectrometers. The detection limit of elements from Na to U (VRA-30) and from F to U (S4 Pioneer) is 0.0005%.

MINERAL ASSEMBLAGES, ZONING, CHEMICAL COMPOSITION OF MINERALS, AND *PT* PARAMETERS OF THE GARNET-BEARING ROCK FORMATION

Various ore-bearing metasomatic rocks containing garnet and garnet-bearing metamorphosed porphyritic dikes are known at the deposit.

The metasomatic rocks reveal distinct zoning. The following mineralogical zones are distinguished from 2 more or less fresh granodiorite toward the center of the metasomatic lode:

- 2 (1) Slightly altered granodiorite (Q + Pl (An₂₅₋₃₂) +
- 2 Kfs + Bi + Hb). The alteration of granodiorite is expressed as the development of secondary biotite replacing hornblende and as small amounts of newly formed muscovite, quartz, chlorite, and epidote. The structure of rocks is granitic, porphyritic, and medium-grained. Individual oligoclase grains reach a centimeter in size. K-feldspar is represented by latticed microcline. Accessory minerals are apatite, zircon, magnetite, allanite, and titanite. The chemical 2 compositions of granodiorite are given in Table 1
- (nos. 1–5).
 (2) Heavily altered granodiorite (Q + Pl (An_{25–32}) + Kfs + Bi + Hb). The alteration is expressed as the appearance of tiny tabular Ca-plagioclase crystals (up to anorthite in composition), abundant muscovite and quartz, epidote, chlorite, and sulfides (mainly pyrite). Tourmaline and andradite–grossular garnet are noted locally. The initial granitic hypidiomorphic-granular

structure is well retained. The zone of heavily altered granodiorite measures a few meters in thickness. The 2 chemical compositions of the rocks are given in Table 1 (nos. 6-15).

(3) Dark gray fine-grained metasomatic rock substantially differs in outer appearance from heavily altered granodiorite. This is a compact dark gray rock 2 with abundant euhedral pink garnet crystals. The mineral assemblage is $Q + Ms + Gr + Kfs + Bi + Pl (An_{90-95})$. The chemical compositions of the rock are given in Table 1 (nos. 16–18), and chemical compositions of minerals, in Table 2 (samples 8-1, 8-1A, 8/6). The peculiarity of this type of rocks is emphasized by a significant amount of newly formed plagioclase close in composition to anorthite. Tourmaline, pyrite, pyrrhotite, magnetite, ilmenite, sphalerite, and galena have been noted in small amounts. This zone varies in thickness from a few decimeters to 10 m and rims a pipelike metasomatic lode at its contact with granodiorite (Fig. 1).

(4) Light gray ore-bearing metasomatic rock occupies the main portion of the metasomatic lode. This is a light gray fine-grained rock with pinkish brown small garnet aggregates locally associated with gahnite (Znspinel) (Vakh and Sapin, 1982). The mineral assemblage is Q + Ms + Gr + Kfs + Bi. No anorthite is identified in this rock, and biotite occurs in minor amounts. Sporadic small aggregates of dark brown tourmaline are characteristic overall. The chemical compositions of the rock are given in Table 1 (nos. 19, 20), and chemical compositions of minerals, in Table 2 (samples 8-2, B-1).

(5) The sites with Q + Ms + Gr + Kfs and $Q + Ms \pm$ Gr mineral assemblages occur locally among light gray metasomatic rocks. These very fine-grained rocks, which do not form distinct zones, are more frequently located close to the center of the metasomatic body, as well as at the northwestern flank of the metasomatic lode (Fig. 1). Quartz–garnet veinlets and monomineralic garnet segregations a few centimeters across occur in metasomatic rocks composed of Q + Ms + Gr + Kfsand $Q + Ms \pm Gr$ mineral assemblages. The chemical compositions of the rocks are given in Table 1 (nos. 21, 23), and chemical compositions of minerals, in Table 2 (sample 40).

Metamorphosed porphyritic dikes are a special type of garnet-bearing rocks with distinctly expressed indications of thermal metamorphism, which are significant for genetic interpretation of the deposit. Metamorphosed porphyritic dikes occur in central part of the ore zone as a network of thin dikes having sharp contacts with metasomatic rocks (Fig. 1). These are dark gray fine-grained rocks with numerous euhedral garnet porphyroblasts up to 5–6 mm in size. The groundmass consists of plagioclase, biotite, magnetite, ilmenite, and quartz. Plagioclase occurs in form of small phenocrysts up to 1 mm long and as tiny shapeless grains hundredths and tenth fractions of a millimeter in size. Both plagioclase varieties do not reveal substantial difference in chemical composition. Mag-

2 Table 1. Major c	oxide (wt %)) and minor	element (r	pm) conter	nts in grano	diorite, met	asomatic re	ocks, and m	letamorpho	sed porphy	ritic dikes a	t Berezitovo	e deposit
Sample	Vk-1	Vk-2	Vk-3	1-B	1-B-A	2-B	3-B	7	5	5-A	5-B	5-C	200*
No.	1	2	3	4	5	9	7	8	6	10	11	12	13
SiO ₂	68.71	68.32	69.57	62.68	63.20	67.27	66.27	67.29	66.23	65.29	63.24	63.41	66.42
TiO ₂	0.34	0.31	0.27	0.47	0.44	0.31	0.30	0.52	0.36	0.39	0.37	0.48	0.43
AI_2O_3	15.80	16.28	15.73	17.07	17.82	16.48	15.13	14.93	16.51	16.99	16.96	17.56	14.91
$\mathrm{Fe}_2\mathrm{O}_3$	3.34	3.00	2.58	5.18	4.69	3.27	4.85	3.66	4.39	4.52	5.39	4.43	1.66
FeO	n.d.	n.d.	n.d.	n.d.	n.d.	.p.u	n.d.	n.d.	.p.u	n.d.	n.d.	n.d.	3.14
MnO	0.088	0.088	0.055	0.09	0.08	0.22	0.22	0.07	90'0	0.19	0.39	0.26	1.35
MgO	0.94	0.83	0.73	1.19	1.18	0.64	0.96	1.60	0.98	1.02	1.26	1.01	0.89
CaO	3.14	3.23	2.02	4.49	3.80	2.55	4.50	2.91	2.21	3.42	4.74	3.89	3.33
Na_2O	4.56	4.66	4.23	4.67	5.01	3.49	1.99	4.16	4.04	1.99	0.92	1.20	0.33
K_2O	2.78	3.01	4.5	2.41	2.47	4.07	4.19	3.82	3.63	4.35	4.47	5.38	5.73
P_2O_5	0.14	0.12	0.1	0.20	0.19	0.12	0.13	0.18	0.15	0.16	0.15	0.19	0.20
IOI	0.88	0.93	1.01	0.69	0.47	0.70	0.53	0.10	0.49	0.80	1.10	1.00	1.47
Total	100.71	100.77	100.80	99.15	99.34	99.13	99.07	99.24	90.06	99.13	98.98	98.82	99.47
S	0.031	0.02	0.00	0.002	0.002	0.018	0.177	0.005	0.003	0.007	0.062	0.024	I
V, ppm	40	32	26	40	38	27	29	46	29	34	32	40	Ι
Cr	164	91	110	52	13	11	10	47	Ĺ	12	11	12	I
Rb	93	95	104	99	99	136	164	128	138	216	246	260	Ι
Ba	804	931	1127	1043	1241	1141	1111	934	1264	814	611	751	Ι
Sr	296	310	480	757	772	421	302	806	463	374	322	373	I
Cu	8	9	12	21	19	18	28	11	25	76	139	64	Ι
Zn	89	62	50	75	72	276	460	65	315	385	872	521	I
Ga	21	21	16	19	19	16	15	19	18	19	17	19	Ι
As	2	2	2	7	5	4	28	7	42	54	147	128	I
Pb	21	22	23	18	18	14	15	28	19	31	20	37	I
Th	6	6	11	13	11	8	8	23	10	10	6	13	I
U	3	3	1	3	2	2	3	5	1	2	2	3	I
Ni	6	7	9	11	8	Ĺ	10	14	8	6	6	6	Ι

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1356	26	54.27	1.36	17.88	11.16	n.d.	0.54	3.88	4.86	2.03	3.39	0.43	0.36	100.16	0.053	158	65	242	424	221	35	235	21	142	317	5	1	46	of ore zone; out on a S4 ot analyzed.
1326	25	50.51	1.25	16.87	14.02	n.d.	0.84	5.25	5.19	1.02	3.41	0.34	0.21	98.92	0.099	175	245	283	286	230	37	407	21	164	131	3	0	120	urginal parts were carried cted; dash, n
1325	24	54.64	1.36	17.73	10.96	n.d.	0.59	3.86	5.35	1.79	3.04	0.44	0.09	99.84	0.065	165	81	201	452	259	47	231	22	126	318	5	0	53	c rock in ma ce. Analyses
664*	23	68.58	0.45	16.77	2.02	1.95	0.10	0.72	0.17	0.18	5.08	0.23	3.18	99.43	I	I	I	I	I	I	Ι	I	I	I	I	I	I	I	metasomati rphyritic dik al. (1984). r
659*	22	68.70	0.40	15.64	4.29	0.58	0.40	0.44	0.17	0.18	4.91	0.21	3.6	99.65	Ι	I	I	Ι	I	I	Ι	I	I	Ι	I	Ι	Ι	I	rnet-bearing orphosed po strachenko et
182*	21	65.46	0.37	14.59	5.73	1.45	0.1	0.75	0.35	0.28	5.23	0.16	4.76	99.20	I	Ι	I	I	I	I	Ι	Ι	I	I	I	I	I	I	dark gray ga -26) metam aken from Pe
9	20	67.63	0.32	18.14	3.46	n.d.	1.47	0.42	0.26	0.18	5.27	0.02	2.17	99.32	0.079	31	4	274	217	13	7	454	21	37	159	4	1	5	nt; (16–18) lization; (24- *Analyses ta
8-2	19	69.42	0.36	17.87	2.31	n.d.	0.10	0.48	0.22	0.15	5.93	0.14	2.27	99.26	0.017	26	1	292	387	35	10	75	19	271	40	20	4	5	certain exte lfide minera Nozdrachev
8-1	18	65.47	0.40	16.94	4.41	n.d.	0.96	1.04	2.76	0.26	5.06	0.14	1.59	99.03	0.232	30	9	266	341	117	29	1339	18	188	261	22	9	8	/ altered to a u-bearing su analyst E.A.
4-C	17	64.89	0.36	15.93	5.34	n.d.	0.39	0.95	2.88	0.84	5.71	0.15	1.52	98.95	0.741	37	20	341	978	349	29	510	18	6	167	10	2	11	tasomatically rock with A ut the FEGI,
4-A	16	69.15	0.28	15.98	4.37	n.d.	0.47	0.91	2.12	0.30	4.03	0.11	1.50	99.22	0.078	27	9	223	489	81	25	943	18	Í.î.	1182	17	1	7	nodiorite me metasomatic ruker AXS) a
199*	15	63.30	0.47	16.42	1.58	3.35	1.35	1.14	3.85	0.38	5.84	0.24	1.8	99.72	I	I	Ι	I	I	I	Ι	I	I	I	I	Ι	I	I	nblende grai vite-quartz j ctrometer (B
233*	14	67.60	0.48	15.70	0.77	3.08	0.83	0.80	4.37	1.62	3.70	0.24	0.98	100.17	I	I	I	I	I	I	I	I	I	I	I	I	I	I	c biotite-hor aring musco rescence spec
Sample	No.	SiO ₂	TiO ₂	Al_2O_3	$\mathrm{Fe}_2\mathrm{O}_3$	FeO	MnO	MgO	CaO	Na_2O	K ₂ O	P_2O_5	LOI	Total	S	V, ppm	Cr	Rb	Ba	Sr	Cu	Zn	Ga	As	Pb	Th	U	Ni	2 (1–15) porphyritic (19–23) garnet-be Pioneer X-ray fluo

Table 1. (Contd.)

GENESIS OF GARNET-BEARING ROCKS

Table 2. at Berezi	Chemic tovoe de	al compo posit	sition (w	1 %) and	l crystal e	chemical	formula	coefficie	nts (apfi	1) of min	erals fro	m metas	omatic re	ocks and	metamo	rphosed J	porphyrit	ic dikes
Sample			8-	-					8-1A				-8	2			ZG-96	
Mineral	gr-c	gr-r	gr-c	bi	plag	snu	gr-c	gr-r	bi	plag	snu	gr-c	gr-c	bi	snus	gr-c	gr-r	chl-1
No.	1	2	3	4	5	9	7	8	6	10	11	12	13	14	15	16	17	18
SiO_2	37.36	38.21	37.51	36.54	44.96	46.27	37.53	38.20	35.75	45.65	46.16	37.03	36.64	35.76	45.45	36.90	37.52	25.86
TiO_2	0.0	0.0	0.0	1.79	0.0	0.5	0.0	0.0	1.77	0.00	0.46	0.0	0.0	2.74	0.36	0.0	0.0	0.0
Al_2O_3	21.07	21.36	21.06	18.23	36.66	33.28	20.7	21.11	18.04	36.93	32.92	20.35	20.92	17.79	32.82	20.14	20.18	19.09
FeO	15.3	17.1	16.97	20.94	0.0	4.04	17.34	17.84	21.70	0.0	4.03	12.91	14.89	22.88	3.61	8.82	11.87	23.29
MnO	20.98	17.97	19.94	0.65	0.0	0.0	21.42	19.79	0.73	0.0	0.00	26.38	25.68	0.48	0.0	30.24	22.16	3.19
MgO	0.54	0.99	1.27	8.88	0.0	0.96	0.98	0.85	8.72	0.0	0.89	0.54	0.57	8.55	0.73	0.39	0.42	13.46
CaO	5.51	6.16	4.39	0.0	18.83	0.0	2.86	3.52	0.0	19.15	0.0	2.97	2.38	0.0	0.0	2.71	8.24	0.0
Na_2O	0.0	0.0	0.0	0.0	0.61	0.0	0.0	0.0	0.0	0.64	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
K_2O	0.0	0.0	0.0	10.32	0.0	11.99	0.0	0.0	10.08	0.0	11.51	0.0	0.0	10.52	11.86	0.0	0.0	0.0
Total	100.76	101.8	101.14	97.35	101.06	97.04	100.83	101.31	96.78	102.37	95.97	100.18	101.08	98.70	94.83	99.20	100.39	84.89
Si	3.004	3.021	3.001	2.755	2.050	3.092	3.026	3.047	2.726	2.055	3.110	3.018	2.964	2.693	3.103	3.035	3.018	2.835
Τi	Ι	I	I	0.101	I	0.025	Ι	I	0.102	Ι	0.023	I	Ι	0.155	0.018	1	1	I
AI	1.997	1.990	1.985	1.620	1.970	2.621	1.967	1.985	1.621	1.959	2.614	1.955	1.994	1.579	2.641	1.953	1.913	2.466
$\mathrm{F}\!\mathrm{e}^{+2}$	1.029	1.131	1.122	1.320	I	0.226	1.169	1.190	1.384	I	0.227	0.872	0.929	1.441	0.206	0.607	0.748	2.135
Fe^{+3}	1	I	0.013	I	I	I	I	I	I	I	I	0.008	0.078	I	I	I	0.051	I
Mn	1.429	1.203	1.351	0.042	I	I	1.463	1.337	0.047	Ι	I	1.821	1.759	0.031	I	2.107	1.510	0.296
Mg	0.065	0.117	0.151	0.998		0.096	0.118	0.101	0.991	Ι	0.089	0.066	0.069	0.960	0.074	0.048	0.050	2.200
Са	0.475	0.522	0.376	I	0.920	I	0.247	0.301	Ι	0.924	Ι	0.259	0.206	I		0.239	0.710	I
Na	0.00	I		I	0.054	I		I	Ι	0.056	Ι	I				I	I	Ι
K	0.00	I		0.993	Ι	1.022	I	I	0.981	Ι	0.989	0.0	Ι	1.011	1.033	I	Ι	Ι
$X_{\mathrm{Fe}}^{\mathrm{Gr}}$	0.94	0.91	0.88				0.91	0.92				0.93	0.93			0.93	0.94	
$X_{ m Ca}^{ m Gr}$	0.16	0.17	0.13				0.082	0.10				0.08	0.07			0.08	0.23	
$X_{ m An}^{ m Pl}$					0.94					0.94								
$X_{\mathrm{Fe}}^{\mathrm{Bi}}$				0.57					0.58					09.0				

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Table 2. (Contd.)

(1)	snu	35	45.52	0.46	31.76	4.11	0.0	0.73	0.0	0.42	11.58	94.59	3.134	0.024	2.577	0.237	Ι	Ι	0.075	Ι	Ι	1.017			
B-1	gr-r	34	37.65	0.0	20.46	18.54	18.81	1.07	3.81	0.0	0.0	100.34	3.041	I	1.947	1.252	Ι	1.287	0.129	0.330	Ι	Ι	06.0	0.11	
	gr-c	33	37.28	0.0	20.56	16.52	19.56	0.85	5.88	0.0	0.0	100.64	2.999	I	1.949	1.057	0.054	1.333	0.102	0.507	Ι	I	0.91	0.17	
	snm	32	43.95	0.92	30.78	3.23	0.0	1.06	0.0	0.0	11.13	91.06	3.117	0.049	2.573	0.192	I	I	0.112	I	I	1.007			
	snm	31	46.78	0.3	31.60	3.35	0.0	1.51	0.0	0.0	11.48	95.03	3.172	0.015	2.525	0.190	I	Ι	0.153	I	Ι	0.993			
	plag	30	43.84	0.0	34.37	0.0	0.0	0.0	18.35	0.97	0.0	97.53	2.075	I	1.917	I	I	Ι	Ι	0.930	0.089	I			0.91
	plag	29	45.79	0.0	35.71	0.0	0.0	0.0	18.59	0.95	0.0	101.05	2.087	I	1.918	I	I	Ι	Ι	0.908	0.084	I			0.91
8/6	bi	28	35.43	2.47	17.83	19.67	0.79	9.94	0.0	0.0	10.15	96.28	2.697	0.141	1.600	1.252	I	0.051	1.128	I	I	0.986			
	bi	27	35.23	2.48	16.89	18.78	0.87	8.97	0.0	0.0	10.11	93.34	2.762	0.146	1.561	1.231	I	0.058	1.048	I	I	1.011			
	kfs	26	64.42	0.0	18.12	0.0	0.0	0.0	0.0	0.73	16.30	99.56	2.997	I	0.993	I	I	Ι	Ι	I	0.066	0.967			
	gr-r	25	37.25	0.0	20.97	16.47	21.66	1.25	2.84	0.0	0.0	100.44	3.008	I	1.996	1.112	I	1.482	0.150	0.246	Ι	I	0.88	0.08	
	gr-c	24	37.72	0.0	20.30	15.34	19.29	0.89	7.05	0.0	0.0	100.58	3.027	Ι	1.920	1.003	0.026	1.311	0.106	0.606	Ι	Ι	06.0	0.20	
	kfs	23	63.36	0.0	18.65	0.0	0.0	0.0	0.0	0.82	15.72	99.25	2.973	I	1.031	I	I	I	I	I	0.075	0.941			
40	snu	22	46.3	0.0	34.14	1.87	0.0	1.01	0.0	0.0	11.17	94.49	3.122	I	2.713	0.105	I	I	0.102	I	Ι	0.961			
	gr-c	21	35.53	0.0	19.72	6.84	31.17	0.64	2.32	0.0	0.0	96.22	3.013	I	1.971	0.482	0.003	2.239	0.081	0.211	0.0	0.0	0.85	0.07	
-96	chl -3	20	28.21	0.0	19.78	22.74	1.85	16.34	0.0	0.0	0.0	88.92	2.897	I	2.394	1.953	I	0.161	2.501	I	Ι	I			
ZG	chl -2	19	26.91	0.0	19.22	23.00	2.68	15.33	0.0	0.0	0.0	87.14	2.851	I	2.400	2.038	I	0.240	2.421	Ι	I	Ι			
Sample	Mineral	No.	SiO ₂	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K ₂ 0	Total	Si	Τi	AI	Fe^{+2}	Fe ⁺³	Mn	Mg	Ca	Na	K	$X_{ m Fe}^{ m Gr}$	$X_{ m Ca}^{ m Gr}$	$X_{ m An}^{ m Pl}$

GENESIS OF GARNET-BEARING ROCKS

0.0 11.83 95.87

0.0

mus 36 46.18 0.56 32.55 3.9 0.0 0.0 3.120 0.028 2.592 0.220

0.085

Ι

1 1

Ι

1.020

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0.53

0.54

 $X_{
m Fe}^{
m Bi}$

	plag1 plag2 plag 3	52 53 54	1 51.65 54.83 55.60	0.0 0.0 0.0	1 28.61 29.47 28.87	3 0.0 0.0 0.66	0.0 0.0 0.0	0.0 0.0 0.0	10.94 10.51 10.57	4.72 5.11 5.64	0.41 0.0 0.31	96.33 99.92 101.65	2.424 2.465 2.471		1.583 1.561 1.512			- 0.022	0.022	- - 0.022 - - - - - - - -	- - 0.022 - - - 0.023 - - - - - - - - 0.55 0.506 0.503	- - 0.022 - - - 0.022 - - - - - - - - 0.55 0.506 0.503 0.43 0.445 0.486	- - 0.022 - - - 0.022 - - - - - - - - 0.55 0.506 0.503 0.43 0.445 0.486 7 0.025 - 0.018	- - 0.022 - - - 0.023 - - - - - - - - 0.55 0.506 0.503 0.43 0.445 0.486 0.025 - 0.018	- - 0.022 - - - 0.022 - - - - - - - - 0.55 0.506 0.503 0.43 0.445 0.486 0.025 - 0.018	$\begin{array}{ c c c c c c c c c c c c c c c c c c c$
1356	bi	51	35.64	2.27	17.64	17.58	0.5	11.37	0.0	0.0	9.84	94.84	2.718	0.13	1.586	1 1 1 1 1			- 0.032	0.032		0.032 1.293 	0.032 0.032 1.293 - - 0.957	0.032 0.032 1.293 	0.032 0.032 1.293 0.957	0.032 0.032 1.293 - 0.957
	gr-c	50	36.13	0.0	19.6	17.65	20.09	1.39	3.46	0.0	0.0	98.32	2.986	I	1.909	1 102	701.1	0.118	0.118	0.118 0.118 1.407 0.171	0.118 0.118 1.407 0.171 0.306	0.118 0.118 0.171 0.306 -	0.118 0.118 0.171 0.306 -	0.118 0.118 0.171 0.171 0.306 - -	$\begin{array}{c} 1.102 \\ 0.118 \\ 1.407 \\ 1.407 \\ 0.171 \\ 0.306 \\ - \\ - \\ 0.87 \\ 0.87 \\ 0.10 \end{array}$	0.118 0.118 0.171 0.171 0.306 0.306 0.306 0.306 0.306 0.306 0.10
	gr-r	49	36.59	0.0	20.49	20.1	17.24	1.7	2.91	0.0	0.0	99.03	2.993	Ι	1.975	1 22	000.1	0.039	0.039 0.039 1.194	0.039 0.039 1.194 0.207	0.039 0.039 1.194 0.207 0.255	0.039 0.039 1.194 0.207 0.255 -	0.255 0.255 0.255 0.255 0.255 0.255	0.039 0.039 0.207 0.207 0.255 0.255 0.255 0.267 0.267 0.87	0.039 0.039 1.194 0.207 0.255 0.255 0.255 0.255 0.255 0.255 0.87 0.87	0.039 0.039 1.194 0.207 0.255 0.255 0.255 0.255 0.255 0.87 0.87
	gr-ñ	48	36.2	0.0	19.17	17.97	20.12	1.23	3.73	0.0	0.0	98.42	2.995	Ι	1.869		1.103	0.141	1.103 0.141 1.41	1.103 0.141 1.41 0.152	1.103 0.141 1.41 0.152 0.331	1.103 0.141 1.41 0.152 0.331 -	1.103 0.141 1.41 0.152 0.331 -	1.103 0.141 1.41 0.152 0.331 - - 0.88	1.103 0.141 1.41 0.152 0.152 0.331 - - 0.88 0.88 0.11	1.103 0.141 1.41 0.152 0.331 - - 0.88 0.88
	ilm	47	0.0	48.73	0.0	41.22	7.05	0.0	0.0	0.0	0.0	97.00	I	0.951	Ι		0./96	0.099	0.796 0.099 0.155	0.796 0.099 0.155 -	0.796 0.099 	0.796 0.099 0.155	0.796 0.099 0.155	0.796 0.099 0.155	0.796 0.099 0.155	0.796 0.099 0.155 0.155
	plag	46	51.59	0.0	29.20	0.0	0.0	0.0	12.82	4.23	0.0	97.83	2.391	Ι	1.595		I				- - - 0.637		- - - 0.637 0.380			
	plag	45	49.55	0.0	30.48	0.0	0.0	0.0	13.27	3.56	0.0	96.85	2.323	I	1.684						- - - 0.667					
	plag	44	47.55	0.0	31.79	0.0	0.0	0.0	14.89	2.62	0.0	96.86	2.240	Ι	1.765		I									
26	bi	43	36.42	1.83	15.40	15.25	0.5	13.6	0.0	0.0	9.46	92.46	2.831	0.107	1.411	0 001	1//.0		- 0.033	0.033	$\begin{array}{c} - \\ - \\ 0.033 \\ 1.514 \\ 0 \end{array}$	0.033 0	0.033 0.033 0.033 0 0 0.938	0.033 0.033 0 0 0.938 0.938	0.033 0.033 0.033 0.033 0.033 0.033 0.938	0.033 0.033 0.033 0.033 0.033 0.033 0.033 0.033 0.033 0.033 0.038 0
13	bi	42	36.22	2.01	16.19	15.73	0.42	13.37	0.0	0.0	9.73	93.67	2.772	0.116	1.460	1.007		I	0.027			0.027 0.027 1.525 0		$\begin{array}{c c} - & - \\ \hline & 0.027 \\ \hline 1.525 \\ \hline 0 \\ - \\ 0.950 \\ \hline \end{array}$	$\begin{array}{c c} - & - \\ \hline 0.027 & 0.027 \\ \hline 1.525 & 0 \\ - & - \\ \hline 0.950 & 0.950 \end{array}$	$ \begin{array}{c ccccccccccccccccccccccccccccccccccc$
	gr-r	41	36.45	0.0	19.91	17.67	18.10	1.65	4.29	0.0	0.0	98.07	3.004	Ι	1.934	1.159		0.059	0.059 1.236	0.059 1.236 0.203	0.059 1.236 0.203 0.379	0.059 1.236 0.203 0.379	0.059 1.236 0.203 0.379 -	0.059 0.203 0.203 0.379 - - 0.85	0.059 0.236 0.203 0.203 0.379 - - 0.85 0.13	0.059 0.203 0.203 0.203 0.379 - - 0.85 0.85 0.13
	gr-r	40	35.59	0.0	20.44	18.52	17.68	1.86	3.79	0.0	0.0	97.89	2.936	I	1.987	1.137	-	0.141	0.141 1.235	0.141 1.235 0.229	0.141 1.235 0.229 0.335	0.141 1.235 0.229 0.335	0.141 1.235 0.229 0.335 -	0.141 1.235 0.229 0.335 - - 0.83	0.141 1.235 0.229 0.335 - - 0.83 0.83	0.141 1.235 0.229 0.335 0.335 0.83 0.83
	gr-c	39	36.20	0.0	19.53	14.94	19.84	1.11	6.09	0.0	0.0	97.71	2.995	Ι	1.904	0.928		0.106	0.106 1.390	0.106 1.390 0.137	0.106 1.390 0.137 0.540	0.106 1.390 0.137 0.540	0.106 1.390 0.137 0.540 -	0.106 1.390 0.137 0.540 0.87	0.106 1.390 0.137 0.540 - - 0.87 0.87 0.18	0.106 1.390 0.137 0.137 0.137 0.540 - - 0.87 0.87 0.18
	gr-c	38	36.68	0.0	20.03	14.21	20.25	0.89	6.33	0.0	0.0	98.39	3.012	1	1.938	0.938		0.038	0.038 1.408	0.038 1.408 0.109	0.038 1.408 0.109 0.557	0.038 1.408 0.109 0.557	0.038 1.408 0.109 0.557 -	0.038 1.408 0.109 0.557 	0.038 1.408 0.109 0.557 - - 0.89 0.18	0.038 1.408 0.109 0.557 - 0.89 0.89 0.18
B-1(1)	bi	37	35.81	2.31	17.41	21.06	0.82	9.0	0.0	0.0	9.86	96.27	2.738	0.133	1.569		1.340	1.340	1.346 - 0.053	1.340 - 0.053 1.026	1.346 - 0.053 1.026 -	1.346 - 0.053 1.026 -	1.340 0.053 1.026 - - 0.962	1.340 - 0.053 1.026 - 0.962	1.340 - 0.053 1.026 - 0.962	1.340 - 0.053 1.026 - 0.962
Sample	Mineral	No.	SiO ₂	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	Total	Si	Ξ	Al	ŝ	Fe^{+2}	Fe ⁺² Fe ⁺³	Fe ⁺² Fe ⁺³ Mn	Fe ⁺² Fe ⁺³ Mn Mg	Fe ⁺² Fe ⁺³ Mn Mg Ca	Fe ⁺² Fe ⁺³ Mn Mg Ca Na	Fe ⁺² Fe ⁺³ Mn Mg Ca Na K	$\begin{array}{c c} Fe^{+2} \\ Fe^{+3} \\ Fe^{+3} \\ Mn \\ Mg \\ Mg \\ Na \\ K \\ K \\ K \\ K \\ K \\ K \end{array}$	$\begin{array}{c c} Fe^{+2} \\ Fe^{+3} \\ Fe^{+3} \\ Mn \\ Mn \\ Mg \\ Mg \\ Na \\ K \\ K \\ X_{ef}^{Gr} \\ X_{Ca}^{Gr} \\ X_{Ca}^{Gr} \\ R \\ Ca \\ X_{Ca}^{Gr} \\ X_{Ca$	$\begin{array}{c c} Fe^{+2} \\ Fe^{+3} \\ \hline \\ Fe^{+3} \\ \hline \\ Mn \\ Mg \\ Ma \\ \hline \\ K \\ K \\ K \\ Ca \\ X_{Ca}^{Gr} \\ X_{Ca}^{Gr} \\ \hline \\ X_{Ca}^{Gr} \\ \hline \\ X_{Ca}^{Pl} \\ \hline \end{array}$

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Table 2. (Contd.)

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Fig. 2. Almandine–spessartine garnet grains in (a) metasomatic rock and (b) metamorphosed porphyritic dike. (a) Zonal garnet consisting of light gray low-Ca core with quartz and orthoclase inclusions and Ca-enriched rim without inclusions is incorporated into quartz–orthoclase–chlorite groundmass. Zonal distributions of Fe, Mn, and Ca in garnet crystal are shown in Figs. 4 and 5. Sample ZG-96 (Table 2). (b) Euhedral garnet crystal with numerous magnetite inclusions is incorporated into quartz–plagioclase biotite groundmass. Sample 1356 (Table 2). Reflected electron image.

netite frequently occurs within garnet crystals. Tiny biotite flakes replace groundmass and plagioclase phenocrysts. Pyrite dominates among ore minerals; arsenopyrite, sporadic small aggregates of galena, scheelite, and gersdorffite are subordinate in abundance. The chemical compositions of rocks are given in Table 1 (nos. 24–26), and chemical compositions of minerals, in Table 2 (samples 1326, 1356).

The aforementioned descriptions of garnet-bearing rocks show that garnet, biotite, and muscovite are the most abundant minerals; plagioclase also occurs in some rock varieties. These minerals are briefly characterized below.

Garnet is widespread in dark and light gray metasomatic rocks of the Berezitovoe deposit and commonly occurs as euhedral crystals 0.5-2.0 mm in size, occasional large pockets up to 5-10 cm in size, veinlets, or rims of fine grains over larger porphyroblasts. Some garnet crystals reveal marginal resorption, and in this case, the crystal margins containing numerous quartz inclusions acquire a complex configuration. As a rule, garnet crystals exhibit chemical and optic zoning (Fig. 2a) and contain many inclusions of quartz, mica, and ore minerals: magnetite, ilmenite, pyrite, galena, sphalerite, and even native gold (Fig. 3). The chemical zoning of garnet clearly resembles the so-called direct zoning of growth described in metamorphic complexes of greenschist and amphibolite facies (Avchenko, 1982). This zoning is expressed as a significant decrease in Mn content from the crystal core toward its margins along with insignificant enrichment in Fe and Mg in the same direction (Fig. 4). The zonal arrangement of Ca is often more complex: a low-Ca core (Fig. 5) and Ca-rich rim are the most distinguished; in the outermost parts of

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Ca-rich rims, the Ca content again decreases (Fig. 4). In metamorphosed dikes, garnet occurs as rather large porphyroblasts frequently perfectly faced, up to 2 mm in size, and enriched in magnetite inclusions (Fig. 2b). All garnets in metasomatic rocks and dikes are Fe- and Mn-rich. The spessartine content is 50–70%. Garnet from metamorphosed dikes is more magnesian and enriched in Ca than from light gray metasomatic rocks



Fig. 3. Inclusion of native gold in aggregate of almandine– spessartine garnet grains. Sample ZG-1285. Reflected electron image.



Fig. 4. Microprobe profiles of Mn, Fe, and Ca distribution in a zonal garnet crystal from metasomatic garnet–biotite–muscovite–quartz rock. Enrichment in Fe and depletion in Mn from core toward margin of crystal is clearly seen. Ca distribution is more complex. Sample B-1 (Table 2).

(Table 2). The content of ferric component in garnet from metasomatic rocks and dikes is commonly very low (occasionally below the detection limit) and indicates that garnet crystallized under reductive conditions (Table 2).

Muscovite occurs in metasomatic rocks as elongated colorless flakes 0.1–0.4 mm in size. As follows from the plots, the chemical compositions of muscovite from the Berezitovoe deposit completely fall in the field of metamorphic micas of low and moderate pressures and deviate from typical compositions of sericite from beresite in the elevated total Fe, Mg, and Mn contents (Fig. 6) and higher concentration of tetrahedral alumina (Fig. 7). Thus, the chemistry of white micas from the deposit reflects the specific formation of metasomatic rocks.

Biotite is observed as a small flakes and crystals no more than 0.5 mm long. Biotite is characterized by a rather high Ti content (up to 2.0-2.5 wt %). The Fe/(Fe + Mg) ratio of biotite ranges from 40 to 60%.

Plagioclase is most abundant in dark gray metasomatic rocks, where it occurs as tiny shapeless and tabular crystals 0.02–0.05 mm in size close to anorthite in composition. This plagioclase is poorly identified under an optic microscope, because twins are commonly not observed in tiny crystals. This is probably why Buryak et al. (1978) did not mention anorthite in metasomatic rocks at the Berezitovoe deposit. Minute tabular crystals of calcic plagioclase started to grow already in the altered granodiorite adjoining dark gray 2 metasomatic rocks, where this mineral replaces primary plagioclase of granodiorite and occasionally 2 occurs as separate grains (Zalishak, 1978). In the dark gray metasomatic rocks proper, anorthite is sufficiently persistent in composition and varies in a narrow range of An_{90-94} (Table 2). Plagioclase in garnetbearing metamorphosed dikes corresponds to An₅₁₋₅₅ in composition (Table 2, sample 1356). The composition of plagioclase in metamorphosed garnet-bearing dikes is more heterogeneous than in metasomatic



Fig. 5. Microprobe profiles of Ca distribution in zonal garnet crystal: low-Ca core and Ca-enriched outer rim are clearly seen. Sample ZG-96.



Fig. 6. Chemical composition of sericite (muscovite) plotted in coordinates A (Al)–S (Si)–F (Mg + Fe + Mn), apfu. (I–V) fields of micas from (I) rocks underwent of argillic alteration and replaced with hydromica, (II) beresite, (III) micas in beresite from the Urals, (IV) epigenetic sedimentary micas, (V) sericite (muscovite) from low- and medium-pressure metamorphic rocks (*Metasomatizm ...*, 1998). (1) muscovite from metasomatic rocks of Berezitovoe deposit; (2) phengite (Ph) and muscovite (Ms). In addition to mica compositions listed in Table 2, micas from samples 20D, 148, 68, 75-4 and 81 from Berezitovoe deposit have been used.

Al_{IV}

1.0

0.8

0.6

0.4

0.2

0

1.0

1.2

□ Ms

ш

I

 Al_{VI}

1.8

Fig. 7. Chenical compositions of muscovites from Berezitovoe deposit plotted in diagram of Al distribution by tetraand octahedral sites (*Metasomatizm* ..., 1998). See Fig. 6 for fields and symbols.

1.4

Fg 🗔

IV

1.6

rocks. For example, plagioclase in sample 1326 varies in composition from An_{62} to An_{76} .

It should be noted that anorthite-bearing rocks is a special attribute of metasomatic rocks at the Berezitovoe deposit. As will be shown below, their formation is 2 caused by removal of Na from granodiorite and subse-

quent recrystallization of rocks for elevated *PT* parameters.

Our detailed mineralogical study of major minerals in metasomatic rocks and metamorphosed dikes allowed us to estimate the formation conditions of garnet-bearing mineral assemblages using modern geothermometers and geobarometers. The formation temperature and pressure of the Gr + Bi + Ms + Pl +Q assemblage were estimated from the PET program (Dachs, 1998), which uses a Gr-Bi thermometer calibrated by L. Perchuk and I. Lavrent'eva (Perchuk, 1993) along with Gr-Bi-Pl and Gr-Ms-Pl geobarometers. In addition, the temperature of the Gr-Ms equilibrium was determined with an empirical garnetmuscovite thermometer (Chun-Ming et al., 2002). The intersections of equilibrium lines of different geobarothermometers in PT plots make it possible to determine P and T synchronously in each sample with the Gr + Bi + Ms + Pl + Q mineral assemblage (Fig. 8). The *P* and *T* estimates are summarized in Tables 3 and 4. As seen from these tables, the temperatures of mineral equilibria fall into the interval of 580 to 450°C and the mean values are 507 (Table 3) and 496°C (Table 4). The pressure is estimated at 4.80-2.75 kbar, and the mean value, 3.9 kbar. The boundary (minimum and maximum) P and T estimates are not probable,



Fig. 8. Temperature and pressure of garnet-biotite-muscovite-anorthite metasomatic rock formation (sample 8-1-A). Mineral thermobarometers (numerals in circles): 1, garnet-biotite thermometer; 2, garnet-plagioclasesericite (muscovite) thermobarometer; (3) garnet-plagioclase biotite thermobarometer.

because only cores of zonal garnets were used in calculations. The mean P and T estimates should be more reliable. It is noteworthy that the PT formation conditions of metasomatic rocks and metamorphosed porphyritic dikes are almost the same (Table 3).

VARIATION OF GRANODIORITE CHEMICAL 2 COMPOSITIONS AND METAMORPHOSED DIKES AS A RESULT OF METASOMATIC ALTERATION

As the study of metasomatic rocks at the Berezitovoe deposit has shown, Na and Ca are removed from granodiorite, whereas K and Mn are gained (Petra-2 chenko and Belyaeva, 1984). The most persistent removal is noted for Na, while Mn reveals a significant gain (500-1500%). We have taken samples along the profile from relatively fresh granodiorite to light gray 2 metasomatic rock at the eastern flank of the deposit (level 780 m). The chemical compositions of these samples (Table 1) completely corroborate the data of Petrachenko et al. (1984) and additionally demonstrate the obvious loss of Ba and Sr and gain of Rb toward deeply altered rocks (Table 5; Fig. 9). The loss of Na, Ca, Ba, and Sr is easily explained by the breakdown and recrystallization of feldspars in metasomatic rocks with a decrease in the total content of plagioclase in rocks. Crystallization of muscovite in metasomatic rocks results in their enrichment in K and Rb as compared with granodiorite. Thus, this is evidence 2 that metasomatizing solutions contain Na, Ca, Mn, K, Ba, Sr, and Rb.

No.	Sample	Pressure, kbar	Temperature, °C	Analysis number in Table 2	Note
1	8-1	4.8	580	3, 4, 5, 6	Garnet core
2	8-1	3.5	450	1, 4, 5, 6	Garnet core
3	8-1	5.2	535	2, 4, 5, 6	Garnet rim
4	8-1-A	2.75	502	8, 9, 10, 11	Garnet rim
5	8/6	5.50	510	24, 30, 32, 28	Garnet core
6	8/6	3.50	540	25, 30, 32, 28	Garnet rim
7	1326	3.80	450	38, 43, 46	Garnet core and extremely sodic plagioclase
8	1326	4.10	505	40, 43, 44	Garnet rim and extremely sodic plagioclase
9	1326	3.90	450	38, 43, 44	Garnet core and extremely calcic plagioclase
10	1356	3.50	510	48, 51, 52	Garnet core and extremely calcic plagioclase
11	1356	3.20	525	49, 51, 52	Garnet core and extremely calcic plagioclase
12	1356	3.22	525	49, 51, 54	Garnet rim and extremely sodic plagioclase
13	1356	3.55	505	48, 51, 54	Garnet core and extremely sodic plagioclase
	Average P, T	3.9	507	—	_

 Table 3. Pressure and temperature of metasomatic rock and metamorphosed porphyritic dike formation at Berezitovoe deposit

(1-6) metasomatic rocks in ore zone; (7-13) metamorphosed porphyritic dikes. Temperature and pressure were calculated using PET program package (Dachs, 1998).

Table 4. Temperature of garnet-biotite and garnet-muscovite equilibria in metasomatic rocks at the Berezitovoe deposit

Sample	Geothermometer	Method's author	Analysis number in Table 2	Temperature, °C at 3.5 kbar pressure
8-2	Garne-biotite	Dachs (1998)	12, 14	500
8-2	Garnet-muscovite	Chun-Ming et al. (2002)	12, 15	480
B-1(1)	Garne-biotite	Dachs (1998)	33, 37	515
B-1(1)	Garne-biotite	Dachs (1998)	34, 37	525
B-1(1)	Garnet-muscovite	Chun-Ming et al. (2002)	33, 35	470
B-1(1)	Garnet-muscovite	Chun-Ming et al. (2002)	34, 36	486
Average	_	_		496

Temperature and pressure were calculated using PET program package (Dachs, 1998) and garnet--muscovite geothermometer (Chun-Ming et al., 2002).

² A sharp change in chemical composition of granodiorite as a result of its metasomatic alteration is illustrated by Fig. 10, where chemical compositions of rocks are plotted in the classification diagram proposed by De La Roche et al. (1980). The deeply reworked light gray metasomatic rocks make up a cluster in the right lower corner of the diagram, whereas the data points of dark gray rocks are located close to the field of altered granodiorite. The dark gray anorth- 2 ite-bearing metasomatites occupy an intermediate position between the altered granodiorite with the ini- 2 tial structure retained and deeply altered metasomatic rocks. As this plot illustrates, the garnet-bearing metamorphosed porphyritic dikes did not undergo metaso-

	No	Zone number	Composition	Sample number		Oxi	de, wt %	6 and ele	ement, p	pm	
	110.	in Fig. 12	of zone	in Table 1	Na ₂ O	CaO	MnO	K ₂ O	Rb	Ba	Sr
2	1	4	Slightly altered grano- diorite	4; 5	4.84	4.14	0.085	2.44	66	1142	764
2	2	3	Altered granodiorite	6	3.49	2.55	0.22	4.07	136	1141	421
2	3	3	Altered granodiorite	7	1.99	4.50	0.22	4.19	164	1111	302
2	4	3	Altered granodiorite	10-12	1.37	4.02	0.28	4.73	241	725	356
	5	2	Dark gray metasomat- ic rock	13-15	0.47	2.59	0.61	4.93	277	603	182
_	6	1	Light gray metasomat- ic rock	16; 17	0.16	0.24	0.78	5.60	283	302	24

2 Table 5. Variation of granodiorite composition caused by metasomatic alteration (Fig. 9): initial data

matic alteration; their data points fall into the field of diorite and do not reveal any shift toward metasomatic rocks (Fig. 10). This is crucial for substantiating the origin of garnet-bearing rock considered in the next section.

ORIGIN OF GARNET-BEARING METASOMATIC ROCKS AT THE DEPOSIT: MAIN HYPOTHESES

The origin of garnet-bearing metasomatic rocks at the Berezitovoe deposit is interpreted from two viewpoints. According to the first concept, these rocks were 2 formed as products of metasomatic alteration of granodiorite at a temperature of $\sim 500^{\circ}$ C and a pressure of 3–4 kbar. The elevated *PT* parameters and specific composition of metasomatic rocks enriched in Mn, Ca, and Al facilitated the formation of a mineral assemblage consisting of Mn-garnet, Ca-plagioclase, biotite, muscovite, and quartz. This simple hypothesis, however, does not explain the petrologic features of the rocks under consideration.

First, attention must be given to the fact that garnet-bearing metamorphosed dikes, which cross cut metasomatic zone, do not undergo metasomatism themselves. Moreover, porphyritic dikes, as a rule, do not contain Au-bearing base-metal mineralization, which is widespread in the adjacent metasomatic rocks. At the same time, the *PT* conditions estimated for postmetasomatic and postmineral dikes are the same as for metasomatic rocks (Tables 3, 4). It remains unexplained how the dikes, which were injected at a peak in metasomatism (judging from the *PT* conditions), remained untouched by this process yet nevertheless underwent recrystallization.

Second, the garnet crystals in metasomatic rocks and metamorphosed dikes reveal direct zoning, or growth zoning, with a decrease in Mn and increase in Mg concentrations from the crystal core to its margin. Such zoning is typical of metamorphic complexes, which underwent prograde metamorphism under conditions of greenschist and amphibolite facies (Avchenko, 1982). Moreover, some garnet crystals have a complex zonal distribution of calcium with low-Ca core and marginal zone enriched in Ca (Fig. 5). Since meta-somatism is characterized by a distinctly expressed gain of Mn and loss of Ca, the garnet crystals should be characterized by gradual enrichment in Mn and depletion in Ca from cores to the outer rims. To resolve these contradictions, we had stated alternative hypothesis providing insights into the origin of garnet-bearing metasomatic rocks of the Berezitovoe deposit.

This hypothesis assumes that metasomatism developed under PT conditions that ruled out garnet crystallization, i.e., out of the garnet stability field. Porphyritic dikes were injected after a peak in metasomatism, and subsequent mineral formation proceeded at elevated P and T. As a result, porphyritic dikes and previously formed metasomatic rocks underwent recrystallization with the formation of metamorphic mineral assemblages containing garnet. In other words, it is suggested that the garnet-bearing mineral assemblages were formed as products of the superposed high-temperature process. This hypothesis (evidence is adduced below) readily explains the appearance of garnet in dikes and chemical zoning of garnet crystals in both dikes and metasomatic rocks and allows us to understand all of the observed mineralogical and petrologic features of metasomatic rocks and metamorphosed dikes. Therefore, we take this model as the basis for interpreting the formation conditions of garnet-bearing mineral assemblages at the deposit. Thus, we probably have to call the metasomatic rocks under consideration allometasomatic, but this term is out of use in the geological literature.

PHYSICOCHEMICAL SIMULATION OF GARNET-BEARING MINERAL ASSEMBLAGES

The computer simulation of mineral assemblages based on minimization of the Gibbs free energy was

carried out to prove and illustrate the gradual transformation of garnet-free metasomatic rocks into garnetbearing mineral assemblages as a response to the changed *PT* conditions. Physicochemical simulation was conducted using the Selector program. The main principles of Selector's operation and its capabilities were considered by Avchenko et al. (2009) and Chudnenko (2010). In a new version of this program, simulation takes into account models of mineral solid solutions (Avchenko et al., 2011). This feature of the new version of Selector makes it possible to verify the simulated mineral assemblages by directly comparing them with real mineral assemblages observed in nature.

Three samples were selected for simulation. Two of them represent garnet-bearing rocks from the dark gray (sample 8-1) and the light gray (sample 8-2) metasomatic zones. The third sample, 1356, was taken from metamorphosed porphyritic dike. The chemical compositions of these samples (Table 1) are known, as well as the mineral assemblages, chemical compositions of minerals (Table 2), and approximate PT formation conditions (Tables 3, 4). The entire thermodynamic system consists of 97 components, which make up the major observed and possible minerals under the given PT conditions: quartz, plagioclase, K-feldspar, ortho- and clinopyroxene, garnet, cordierite, biotite, olivine, amphibole, muscovite, ilmenite, magnetite, hematite, native iron, corundum, graphite, sillimanite, kyanite, andalusite, epidote, zoisite, clinozoisite, rutile, spinel, titanite, staurolite, calcite, dolomite, wollastonite, talc, kaolinite, chlorite, and apatite. The simulation relies on an internally consistent thermodynamic data set (Holland and Powell, 1998) with allowance for models of solid solutions. The database of solid solution models has been substantially reworked as compared with that published by Avchenko and Chudnenko (2011) and involves new models of ortho- and clinoamphiboles, biotite, clinopyroxene, ilmenite, and spinel (White and Powell, 2002; White and Pomroy; Green and Holland, 2007; Diener and Powell, 2007; Tajcmanova and Connolly, 2009). This allowed us to significantly enhance the simulation precision with respect to convergence of model and real compositions of the phases in the mineral assemblages. To simulate a gas fluid, an ideal blend of real gases (H₂O, CO₂, CH₄, CO, H₂, O₂) was used. The variation of the thermodynamic parameters of gases as a function of pressure was calculated by the Benedict-Webb-Rubin equation modified by Lee and Kesler (1975).

The model consisted of two reservoirs. Certain amounts of excess H₂O, CO₂, and carbon were placed in the first reservoir to form a fluid in equilibrium with graphite. Therefore, the fluid formed in the first reservoir contained methane, hydrogen, and carbon monoxide in addition to H₂O and CO₂. The P_{H_2O}/P_{CO_2} ratio in this fluid was 2.8 and the logarithm of oxygen

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Fig. 9. Variation of granodiorite composition caused by metasomatic alteration. Metasomatic zones: (I) light gray ore-bearing tourmaline–garnet–muscovite–quartz metasomatic rock, (II) dark gray garnet–orthoclase–biotite–anorthite–muscovite–quartz metasomatic rock, (III) metasomatically altered granodiorite, (IV) slightly altered granodiorite. Numerals in circles indicate location of samples. No/Nz is ratio of the concentrations in sample from zone IV to those in zones (I–III) (curve of loss); Nz/No is ratio of the concentrations in sample from zone (I to those in zones (V) (curve of gain). Initial data shown in Table 5.

fugacity at P = 3000 bar and $T = 508^{\circ}$ C was -23.3. This reduced, substantially aqueous fluid entered the second reservoir, where the real compositions of metasomatic rocks and metamorphosed dikes had been placed in the form of corresponding molar quantities of SiO₂, TiO₂, Al₂O₃, Fe₂O₃, FeO, MnO, MgO, CaO, Na_2O , and K_2O calculated from the data in Table 1. In the course of simulation, the PT parameters, composition, and amount of fluid were to obtain the compositions of mineral assemblages and particular coexisting minerals that would be close to the real counterparts observed in the studied mineral assemblages. The simulation results, including composition of minerals, $P, T^{\circ}C, f_{CO_2}, P_{CO_2}, P_{H_2O}$, and fluid/rock ratio, are given in Table 6. Nearly complete coincidence of the real and model compositions of minerals has been achieved. Especially good convergence of the real mineral assemblage and its model was established for sample 8-1. It should be emphasized that even such fine parameters as the molar fraction of Mn in garnet

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2

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Fig. 10. Chemical compositions of granodiorites, metasomatic rocks, and metamorphosed porphyritic dikes plotted in R1–R2 classification diagram proposed by De La Roche et al. (1980). Rock types: (1) metamorphosed porphyritic dike, (2) porphyritic
2 granodiorite, (3) metasomatically altered granodiorite, (4) dark gray garnet–orthoclase–biotite–anorthite–muscovite–quartz metasomatic rock, (5) light gray tourmaline–garnet–muscovite–quartz metasomatic rocks. Initial data shown in Table 5.

or Ti molar fraction of biotite are close in the model and real minerals.

Verification of the simulation is also emphasized by the evidence shown in Table 7. In this table, we compare the results of quantitative calculation of mineral assemblage carried out using the MINSQ program (Hermann and Berry, 2002) with the amounts of minerals established by Selector. MINSQ performs calculations based on the chemical composition of rock itself and available compositions of observed minerals. In other words, this program does not contain any thermodynamic information and outputs only a modal composition of the mineral assemblage. Table 7 shows good convergence of modal compositions of sample 8-1 calculated using the two programs and thus verifies the simulation.

The almost complete analogy of model and natural mineral assemblages and compositions of minerals therein undoubtedly proves the equilibrium of garnetbearing metasomatic mineral parageneses with and without anorthite (samples 8-1, 8-2), as well as complete recrystallization of metamorphosed porphyritic dikes (sample 1356). An insignificant increase in oxygen fugacity and partial water pressure in the models leads to disappearance of garnet in the mineral assemblage of sample 8-2.

Figure 11 shows the evolution of mineral assemblages of garnet-bearing metasomatic rocks caused by variation in temperature and pressure, using the model of sample 8-1 as an example. As is seen from this figure, garnet disappears from the mineral assemblage of this sample at 450°C, while calcite, chlorite, and dolomite appear; however, biotite remains stable. At 300°C, biotite disappears as well, and garnet-biotite-muscovite assemblage with Ca-plagioclase (sample 8.1) is transformed into a calcite-chlorite-albite (garnet-free) assemblage with muscovite, quartz, and Mn-ilmenite. The evolution of plagioclase is noteworthy. At 500°C, high-Ca plagioclase (An₈₆) occurs both in model 8-1 and in reality, whereas pure albite is formed in the model at 300°C without any change in bulk

GENESIS OF GARNET-BEARING ROCKS

Sample	$X_{\rm Fe}^{ m Gr}$	X_{Ca}^{Gr}	X_{Mn}^{Gr}	$X_{\rm An}^{\rm Pl}$	$X_{\rm Fe}^{\rm Bi}$	Ti ^{Bi} apfu	P, kbar	T°C	f_{O_2}	P _{CO2} , kbar	P _{H2} O, kbar	W/R
8-1 (real assemblage)	0.91	0.17	0.45	0.94	0.57	0.10	_	_	_	_	_	_
8-1 (model assem- blage)	0.91	0.17	0.50	0.86	0.57	0.10	3	508	-19.8	0.9	2.1	0.3
8-2 (real assemblage)	0.93	0.07	0.58	No	0.60	0.16	—	_	-	-	-	-
8-2 (model assem- blage)	0.92	0.07	0.53	No	0.64	0.07	3	508	-20.4	1.0	1.9	0.25
1356 (real assem- blage)	0.87	0.08	0.40	0.51	0.46	0.13	_	_	_	_	Ι	_
1356 (model assemblage)	0.86	0.08	0.41	0.53	0.46	0.07	3	470	-21.8	1.6	1.4	0.25

Table 6. Chemical composition of minerals in real and model mineral assemblages at certain physicochemical formation parameters of metasomatic rocks and metamorphosed porphyritic dikes at the Berezitovoe deposit

 $X_{\text{Fe}}^{\text{Gr}} = \text{Fe}/(\text{Fe} + \text{Mg})$ of garnet; $X_{\text{Ca}}^{\text{Gr}} = \text{Ca}/(\text{Ca} + \text{Fe} + \text{Mg} + \text{Mn})$ of garnet; $X_{\text{Mn}}^{\text{Gr}} = \text{Mn}/(\text{Mn} + \text{Fe})$ of garnet; $X_{\text{An}}^{\text{Pl}} = \text{An}$, mol % in plagioclase; $X_{\text{Fe}}^{\text{Bi}} = \text{Fe}/(\text{Fe} + \text{Mg})$ of biotite; $\text{Ti}_{\text{apfu}}^{\text{Bi}} = \text{Ti}$ apfu of biotite; f_{O_2} , logarithm of oxygen fugacity; P_{CO_2} , CO₂ partial pressure of fluid; $P_{\text{H}_2\text{O}}$, H₂O partial pressure of fluid; W/R water/rock volume ratio.

Table 7. Modal composition of sample 8-1, wt % calculated from MINSQ and Selector program packages

Mineral	Q	Kfs	Plag	Ms	Gr	Bi	Mgt	Ilm	Ap
MINSQ	38.8	6.5	12.3	25.9	5	8.4	0.2	0.2	0.3
Selector	38.9	9.8	13.7	21.2	3.9	10.2	0.4	1.3	0.3

Q, quartz; Kfs, K-feldspar, Plag, plagioclase; Ms, muscovite; Gr, garnet; Bi, biotite; Mgt, magnetite; Ilm, ilmenite; Ap, apatite.

composition of rock or fluid. This implies that all Ca is removed from plagioclase and garnet to the newly formed calcite, Na is bonded in albite, and Mn from garnet is redistributed into ilmenite. With an increase in temperature above 500°C, cordierite, andalusite, and sillimanite appear along with garnet in the mineral assemblage (Fig. 11).

This model easily explains the formation of zonal Ca distribution in garnet crystals. Let us assume, for example, that new P and T conditions are superposed on mineral assemblages formed at 1 kbar and 300°C along the dashed path shown in Fig. 11. At point A at 2 kbar, garnet with a low-Ca core should appear in these rocks. If the lithostatic pressure sharply increases along the 500°C geotherm to 3 kbar (point B), then according to the model, low-Ca garnet cores must be overgrown by a shell enriched in Ca, because higher-Ca garnet reaches equilibrium with plagioclase due to the growth in pressure under approximately isothermal conditions. If during the retrograde stage at an approximately constant temperature, pressure somewhat releases, the high-Ca rim of garnet can, in turn, be overgrown by the outermost low-Ca zone. Thus, the changeable behavior of Ca in garnet crystals (Figs. 4, 5) is explained by the superposition of elevated *PT* parameters on the already formed metasomatic rocks.

Thus, physicochemical simulation of mineral assemblages yields an extremely simple explanation for the appearance of garnet-bearing rocks with anorthite. Granodiorite, which underwent low-tempera- 2 ture metasomatism with loss of Na and Ca and gain of Mn, was then involved in subsequent recrystallization at 500°C and 3 kbar.

SPECIFICITY OF METAMORPHISM RESULTED IN FORMATION OF GARNET-BEARING ROCKS

The specificity of high-temperature metamorphism superposed on low-temperature metasomatic rocks consists in its local manifestation only within the pipelike lode, whereas the adjacent granodiorite 2 remains unmetamorphosed. Most likely, local development of metamorphism was caused by two factors: first, by passage of a new fluid and thermal pulse through the previously formed ore-bearing metasomatic rocks during the final stage of ore formation and, second, by the morphology of the pipelike lode owing to which migration of fluid and passage of heat



Fig. 11. Fields of mineral assemblages calculated from model for sample 8-1 and inferred evolution trend of *PT* conditions for metasomatic rocks of Berezitovoe deposit. (1–6) mineral assemblages: (1) Gr + Bi + Kfs + Pl + Q + Sill + Ilm, (2) Gr + Bi + Kfs + Pl + Q + And + Ilm, (3) Gr + Bi + Kfs + Pl + Q + And + Cord + Ilm, (4) Gr + Bi + Ms + Kfs + Pl + Q ± TiMt, (5) Cc + Bi + Chl + Ms + Q + Dol + Ilm ± Kfs, (6) Cc + Chl + Ab + Ms + Q + Dol + Ilm + Kfs ± Kaol; (7) evolution trend of *PT* conditions for metasomatic rocks. Filled ovals designated by A and B correspond to *PT* conditions of low-Ca cores (A) and rims (B) of garnet crystals from sample 8-1. Numerals along right ordinate are values of $X_{Ca}^{Gr} = \frac{Ca}{Ca + Fe + Mg + Mn}$) of garnet in Gr + Bi + Ms + Kfs + Pl + Q ± TiMt mineral assemblage on isotherm of 510°C for sample 8-1.

through such a pipe encountered fewer obstacles than beyond its limits. No obvious correlation of the final stage of metasomatic rock transformation with a certain tectonomagmatic event in this region has been established. Most likely, the multistage formation of metasomatic rocks was controlled by the geodynamic regime of northern framework of the Mongolia– Okhotsk Foldbelt (Parfenov et al., 2003) and reflects the polycyclic evolution of ancient metamorphic domains in the Aldan–Stanovoi Shield, which underwent multiple structural and magmatic reworking in the Late Paleozoic and Mesozoic.

TYPIFICATION OF GARNET-BEARING METASOMATIC ROCKS OF THE BEREZITOVOE DEPOSIT

The compositionally original garnet-bearing rocks at the Berezovoe deposit cannot be referred to as greisen or classic beresite. Indeed, a determinant attribute of greisen is elevated fluorine activity in fluid (Metasomatizm ..., 1998) expressed as an abundance of F-bearing topaz and fluorite. Fluorite and F-bearing titanite (grothite) occasionally occur at the deposit, but they appeared only at the final stage of its evolution and in small amounts as veinlets and pockets frequently associated with chlorite (Vakh et al., 2009). Thus, topaz, fluorite, and beryl as typical greisen minerals and related mineralization (Sn-W-Mo-Be) are not characteristic of the Berezitovoe deposit. On the contrary, such unusual, for greisen, minerals as anorthite and Fe-Mn garnet occur here in mineral assemblages. Moreover, the ore hosted in metasomatic rocks

is composed of sphalerite, galena, pyrite, and pyrrhotite, which are not inherent to greisen. Thus, the mineralogy of the ore and metasomatic rocks of the studied deposit belie their belonging to the greisen family.

On the other hand, it is well known that beresites are characterized by a mineral assemblage consisting of carbonate, chlorite, muscovite, quartz, and pyrite. Beresitization commonly develops at a temperature no higher than 380°C, which is determined by the thermal stability of Fe-carbonates. The occurrence of garnet-bearing mineral assemblages with anorthite in metasomatic rocks of the Berezitovoe deposit, which are devoid of carbonates, as well as the rather high temperature of garnet—biotite and garnet—muscovite equilibria, does not allow us to consider them as classic beresites.

The physicochemical model of metasomatic rock formation (see above) clearly shows that common beresites could have been a low-temperature chemical equivalent of garnet-bearing metasomatic rocks. This statement is emphasized not only by the composition of model mineral assemblages under low *PT* conditions but also by gain of K and loss of Na typical of beresitization of granitic rocks (*Metasomatizm* ..., 1998).

Thus, the ore-bearing garnet-muscovite-quartz and garnet-biotite-muscovite-anorthite mineral assemblages at the studied deposit were most likely formed owing to recrystallization or thermal metamorphism of previously formed low-temperature beresitic mineral assemblages. In this connection, it is expedient to consider garnet-bearing metasomatic rocks of the beresite deposit as a special type of hightemperature *metamorphosed beresites*.

CONCLUSIONS

(1) The mineral assemblages and chemical composition of particular minerals of garnet-bearing metasomatic rocks and metamorphosed porphyritic dikes at the Berezitovoe deposit are the objects of this study. It has been established that they were formed at temperatures of $450-580^{\circ}C$ (~ $500^{\circ}C$, on average). The pressure is estimated at 2.75–4.8 kbar (3.9 kbar, on average).

(2) The formation of metasomatic rocks at this deposit was accompanied by the removal of Na, Ca,2 Ba, and Sr from granodiorite and gain of K, Rb, and

Mn. The metasomatic rocks are typical products of 2 acid leaching of granodiorite. The subsequent recrystallization of previously formed metasomatic rocks at elevated *PT* parameters gave rise to the formation of garnet-bearing mineral assemblages.

(3) In geological position, mineralogy, character of mineralization, and formation of *PT* conditions, the metasomatic rocks at the Berezitovoe deposit do not fit typical greisen or classic beresite. Based on the new data, the garnet-bearing rocks of the Berezitovoe deposit are considered a special type of high-temperature *metamorphosed beresites*.

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SPELL: 1. volcanosedimentary, 2. granodiorite