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GEOCHEMISTRY

High-Fe Garnet Paraamphibolites at the Base of the Khabarny Ophiolitic Allochthon in the Southern Urals

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Ophiolitic allochthons are often accompanied by metamorphic rocks, which bear additional information on the tectonic setting and formation conditions of allochthons. Metamorphic aureoles are most frequently composed of greenschist- and amphibolite-facies metabasic rocks [2, 7, 9, 12]. In some cases, the peak of metamorphism is marked by garnet amphibolites or eclogites. Well-studied metamorphic complexes are known at the base of the Voikar–Syn'ya and Kempirsai ophiolitic massifs in the Polar and southern Urals, respectively. According to Efimov et al. [2, 3], garnet amphibolites were formed in these massifs as a result of high-pressure metamorphism characterized by a counterclockwise *PT* trend. The maximum *PT* parameters were 750–500°C at 10–13 kbar. Various gabbroic rocks and less abundant basic volcanics served as protoliths. We found garnet amphibolites at the base of the Khabarny ophiolitic allochthon. The unusual phase and chemical compositions of these rocks testify, in our opinion, to the sedimentary nature of the protolith.

The Khabarny and Kempirsai ophiolitic massifs are constituents of the upper tectonic sheet of the Sakmara allochthonous zone in the southern Urals [4, 7] (Fig. 1). Deep drilling data have shown that the thickness of the Khabarny mafic–ultramafic tectonic sheet is not greater than 1.5–2.0 km, and this sheet is underlain almost everywhere by metamorphic rocks. Kheraskov [12] suggested that the metamorphic rocks were also involved in thrusting and compose the base of the allochthon. The thickness of metamorphic rocks does not exceed 1 km. These rocks crop out along the western, northwestern, and eastern contacts of the mafic–ultramafic body. Amphibolites of the northwestern segment were studied by Paneyakh and Sobolev [9], who showed that these rocks correspond to the epidote–amphibolite metamorphic facies (T = 400–450°C and P = 3–4 kbar). Subalkali oceanic basalts served as a protolith, and metamorphism was related to the obduction of ophiolitic sheet on this protolith. No garnet amphibolites were reported.

All revealed outcrops of garnet amphibolites are located in the eastern tract of metamorphic rocks, which appreciably differs in geology and protolith lithology from the northwestern tract. At a first approximation, the metamorphosed sequence consists of two units (Fig. 1). Uniform and foliated epidote amphibolites, 600–800 m in apparent thickness, make up large open folds in the eastern footwall and come into tectonic contact with an autochthon composed of almost unmetamorphosed sandstone and conglomerate of the Lower Ordovician Kidryasy Formation. To the west, the foliated amphibolites abruptly give way to thin-banded amphibolites intercalated with quartzite, quartzitic gneiss, and metapelitic crystalline schists. These rocks are deformed into small-amplitude, often recumbent, disharmonic isoclinal folds with nearly horizontal axial planes. Zones of high-temperature blastomylonites are frequent. The thickness of this unit is 100–200 m. These rocks underlie gabbronorite of the East Khabarny Complex (Fig. 1). At the contact with gabbronorite, amphibolites are transformed into pyroxene hornfels.

We found garnet amphibolites in the hanging wall of the metamorphic sequence, approximately at a distance of 20–50 m from contact with gabbronorite, where garnet amphibolites are intercalated with beds a few meters thick composed of garnet-free amphibolite, quartzite, quartzitic gneiss, and cummingtonite–garnet microgneiss. The narrow transitional zone between gneiss and garnet amphibolite is composed of a fine alternation of these rocks and may be interpreted as a stratigraphic contact. Particular bodies and lenses of garnet amphibolites reach 0.5 m in thickness. Outcrops of garnet amphibolites are traced a few kilometers from north to south along the strike of the metamorphic zone. Amphibolites are severely deformed into small recum-

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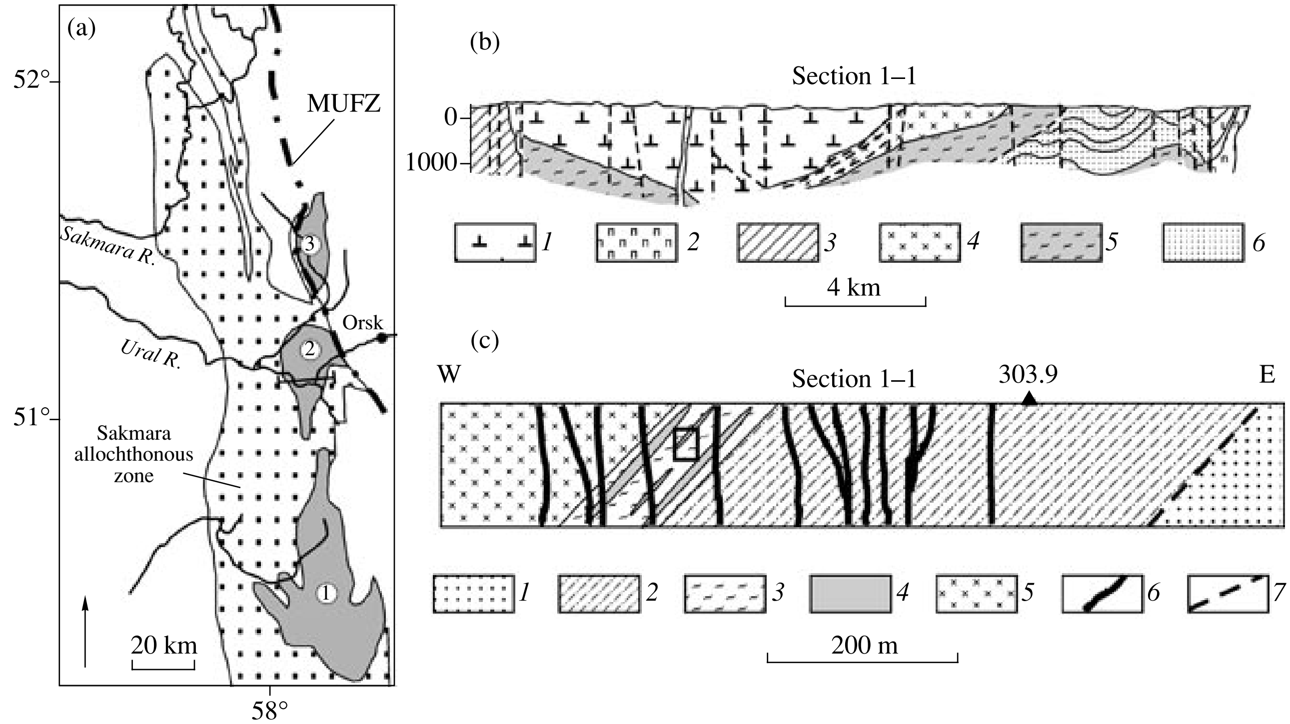

Fig. 1. (a) Ophiolitic allochthons in the Sakmara allochthonous zone of the southern Urals, after [4]: (1) Kempirsai, (2) Khabarny, and (3) Khalilovo allochthons in the Main Ural Fault Zone (MUFZ); (b) schematic latitudinal geological section across the Khabarny allochthon, after the data of the Orenburggeologiya Territorial Survey (profile is shown in panel (a)): (*1*) peridotite of the Khabarny massif, (*2*) pyroxenite, (*3*) gabbro, (*4*) East Khabarny dunite–clinopyroxenite–websterite–gabbronorite complex, (*5*) garnet-free amphibolite at the base of the allochthon, (*6*) Lower Paleozoic volcanosedimentary rocks; (c) geological section 1–1 near the elevation mark of 303.9 m: (*1*) arkose sandstone and conglomerate of the Lower Ordovician Kidryasy Formation (autochthon); (*2–4*) base of the allochthon: (*2*) foliated epidote amphibolite, (*3*) deformed thin-banded amphibolite and garnet amphibolite, (*4*) amphibole–garnet quartzite and quartzitic gneiss; (*5*) gabbronorite of the East Khabarny Complex, (*6*) gabbrodolerite dikes, (*7*) thrust fault; the box in Fig. 1c shows the position of garnet amphibolites.

bent folds with segregations of quartz–feldspathic (granitic) material in their hinges. Amphibolites are crosscut by sporadic veins of amphibole plagiogranite.

Garnet amphibolite is a dark, thin-banded, fine- to medium-grained rock. The banding is related to nonuniform distribution of light and dark minerals. The rock has a porphyroblastic microstructure with a nematogranoblastic matrix. Bluish green hastingsite (35–60%), plagioclase $An_{25–35}$ (10–30%), brownish red almandine (5–20%) with an elevated percentage of a grossular end member (up to 25 mol %), and quartz (5–15%) are the major minerals; relict ferroaugite is identified as inclusions in hastingsite; grunerite and ilmenite are second in abundance (up to 5%); while apatite and zircon are accessory minerals. The chemical compositions of minerals are presented in Table 1. All Fe–Mg minerals are distinguished by high Fe/(Fe + Mg) values ranging from 0.60–0.95.

The studied garnet amphibolites are unusual in chemical composition (Table 2), which differs from both apogabbroic garnet amphibolites described in other ophiolitic complexes of the Urals and from garnet-free amphibolites of the Khabarny ophiolitic allochthon (Fig. 2). The rocks are characterized by a wide range of SiO_2 content (46–63 wt %). Despite the high average silica content, the garnet amphibolites are characterized by notable contents of Fe (FeO up to 20 wt %) and Ti (TiO_2 up to 4.5 wt %). In low-silicic amphibolites that fit basalts in SiO_2 content (46–53 wt %), the Al_2O_3 and CaO contents are always lower than 10 wt %. This fact is inconsistent with the basaltic cotectic and comes into conflict with the orthomagmatic origin of the protolith. The Fe/(Fe + Mg) ratio (or *f* value) in garnet amphibolites (0.7–0.8, on average) is higher than that typical of most igneous rocks ($f < 0.7$). Garnet amphibolites are depleted in K and Sr. Moreover, the Rb contents are lower than the detection limit of the XRF method, i.e., 5 ppm (Table 2). At the same time, the REE contents are 70–80 times higher than the chondritic level (Fig. 3). Garnet amphibolites are characterized by elevated contents of Y (130–180 ppm), Zr (160 ppm), Nb (7–9 ppm), and Hf (4–5 ppm). The studied rocks are close in chemical composition to garnet paraamphibolites of the Precambrian Polmostundra Formation in the Kola Peninsula [8].

The normative composition of these rocks contains 3–20 wt % of quartz, 55–30 wt % of clinopyroxene and orthopyroxene (the latter is predominant), and 35–

Table 1. Major and trace element contents (wt % and ppm, respectively) in garnet amphibolites at the base of the Khabarny

Component	Khb-1819	Khb-1789	Khb-1790	Khb-1809	Khb-1813	Khb-1831	Khb-1844	Khb-1845
SiO_2	46.35	51.39	52.52	54.56	52.50	59.50	55.28	61.11
TiO_2	4.43	3.59	3.24	2.54	2.62	2.63	2.08	1.40
Al_2O_3	8.37	9.08	9.00	8.82	9.28	9.35	11.86	12.27
Fe_2O_3	8.70	5.54	7.29	7.21	5.27	7.81	3.52	7.84
FeO	13.50	14.30	12.80	13.80	15.20	8.50	10.40	5.80
MnO	0.39	0.31	0.33	0.33	0.32	0.37	0.25	0.32
MgO	3.73	2.99	2.92	2.07	2.06	2.42	3.14	1.76
CaO	8.76	8.57	7.86	7.58	7.41	5.87	7.45	6.14
Na_2O	1.80	2.50	2.20	2.50	3.20	1.70	3.70	2.70
K_2O	0.60	0.43	0.40	0.16	0.25	0.67	0.44	0.43
P_2O_5	0.55	0.61	0.62	0.88	0.71	0.60	0.32	0.49
L.O.I.	1.77	0.00	0.00	0.00	1.70	1.20	1.57	0.71
Total	98.95	99.30	99.17	100.46	100.53	100.62	99.99	100.97
Fe/(Fe + Mg)	0.76	0.78	0.79	0.84	0.84	0.78	0.70	0.80
Rb	<5	<5	<5	<5	<5	<5	<5	<5
Sr	35	91	58	88	350	104	156	168

Note: Major elements were determined with the XRF method on a VRA-30 analyzer; Rb and Sr were determined with the XRF method on a SRM-18 analyzer at the Institute of Geology and Geochemistry, Ural Division, Russian Academy of Sciences (G.M. Yatluk, V.P. Vlasov, and N.P. Gorbunova, analysts).

Table 2. Chemical composition of minerals from garnet amphibolites at the base of the Khabarny allochthon, wt %

Component	Sample Khb-1819						Sample Khb-1789					
	Grunerite		Hastingsite*		Ferroaugite		Hastingsite		Garnet		Ferroaugite	
SiO_2	48.19	47.92	40.73	41.73	48.16	48.09	40.97	40.26	36.25	37.11	49.84	47.82
TiO_2	0.07	0.14	1.98	1.64	0.16	0.19	2.12	1.25	0.15	0.09	0.28	0.59
Al_2O_3	0.69	1.23	10.82	11.42	1.02	1.00	11.51	12.76	20.18	21.51	1.22	1.08
FeO*	38.52	39.00	28.13	27.00	24.49	26.17	25.21	25.37	31.77	30.08	20.80	21.11
MnO	1.28	1.39	0.56	0.46	0.94	0.90	0.27	0.25	1.80	2.63	0.49	0.46
MgO	5.87	6.10	3.75	3.53	4.63	4.80	4.95	4.67	1.94	1.82	7.22	7.33
CaO	1.59	0.84	9.19	10.46	19.25	18.27	11.01	11.05	8.35	7.15	19.89	20.98
Na_2O	0.17	0.24	2.36	1.58	0.54	0.42	1.99	1.81	n.a.	n.a.	0.12	0.10
K_2O	0.0	0.02	0.18	0.62	0.02	0.02	0.64	0.81	″	″	0.03	0.02
Total	96.38	96.88	97.70	98.44	99.21	99.87	98.67	98.09	100.46	100.39	99.89	99.49
Fe/(Fe + Mg)	0.78	0.78	0.80	0.81	0.74	0.75	0.74	0.75	0.90	0.90	0.61	0.61

Component	Sample Khb-1790				Sample Khb-1844				Sample Khb-1831			
	Hastingsite		Garnet		Hastingsite		Garnet		Hasting-site	Garnet	Biotite	
SiO_2	42.39	42.87	37.19	37.69	46.74	46.67	37.14	36.78	43.02	37.33	33.28	33.28
TiO_2	1.87	1.48	0.09	0.07	1.02	1.18	0.07	0.14	2.17	0.17	2.59	2.29
Al_2O_3	9.86	10.64	21.36	20.82	9.45	9.43	21.82	21.52	10.58	19.83	15.7	16.51
FeO*	26.63	27.71	30.34	30.86	21.47	21.74	29.74	29.28	23.44	33.64	25.05	24.71
MnO	0.26	0.21	1.78	1.82	0.30	0.28	2.26	2.04	0.22	1.37	0.13	0.12
MgO	4.19	3.1	2.00	1.96	7.74	7.64	2.78	2.95	6.08	2.22	8.24	7.28
CaO	10.09	10.76	7.69	7.32	10.42	10.42	6.71	7.59	10.74	5.58	0.11	0.13
Na_2O	1.86	1.71	n.a.	n.a.	1.47	1.54	n.a.	n.a.	1.78	0.01	0.13	0.13
K_2O	0.35	0.78	″	″	0.54	0.49	″	″	1.06	0.04	7.75	8.94
Total	97.50	99.25	100.45	100.54	99.14	99.40	100.52	100.30	99.09	100.19	92.97	93.38
Fe/(Fe + Mg)	0.78	0.83	0.89	0.90	0.60	0.61	0.85	0.85	0.68	0.89	0.63	0.65

Note: Chemical compositions were determined on a JXA-5 microprobe at the Institute of Geology and Geochemistry, Ural Division, Russian Academy of Sciences (V.G. Gmyra, analyst). (FeO*) Total iron; (n.a.) not analyzed. Hastingsite* is a brown (bluish green) mineral in the case of enrichment (depletion) in TiO_2.

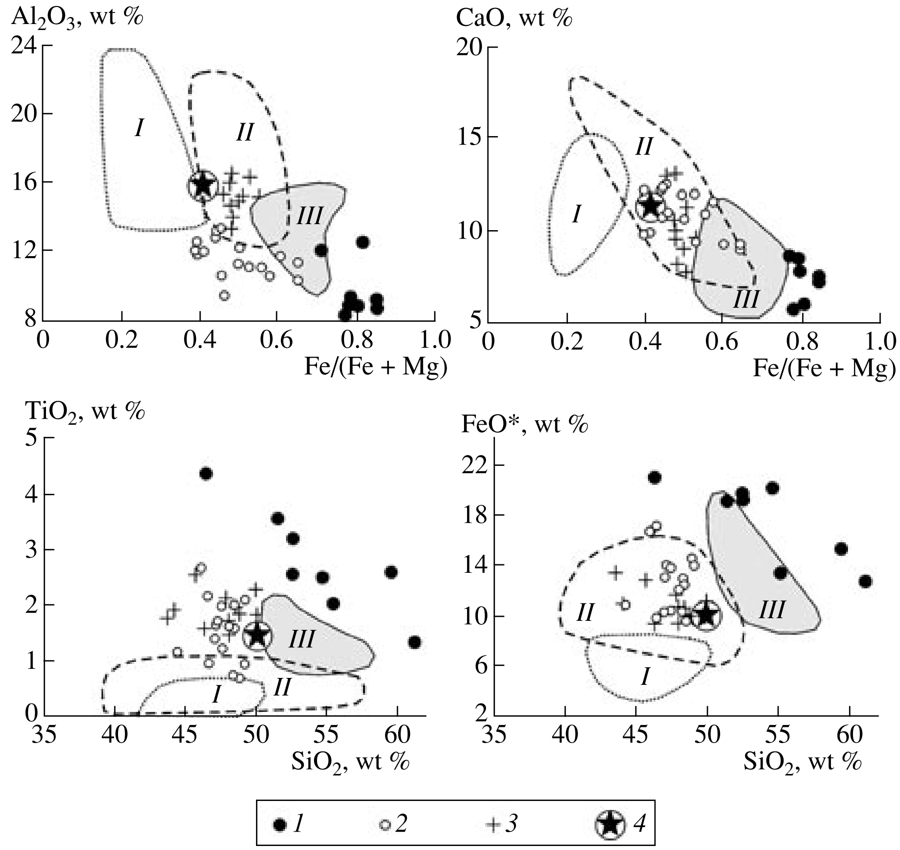

Fig. 2. Petrochemical characteristics of amphibolites at the base of the Khabarny allochthon. (*1, 2*) Eastern block: (*1*) garnet amphibolite, (*2*) normal amphibolite; (*3*) western block, after [9]; (*4*) average MORB composition. Fields in plots: (*I*) garnet amphibolites at the base of the Kempirsai ophiolitic massif [2], (*II*) garnet amphibolites of the Khord'yu Complex, the Voikar–Syn'ya ophiolitic massif, the Polar Urals [3]; (*III*) Precambrian garnet paraamphibolites from Kola Peninsula [8].

45 wt % of feldspars. This composition corresponds to two-pyroxene crystalline schists [10]. The occurrence of relict ferroaugite and grunerite, which could have replaced orthopyroxene, indicates that high-Fe two-pyroxene crystalline schists of the above normative composition could have served as a protolith for amphibolites. To reconstruct the composition of the protolith of garnet amphibolite, we used Predovsky's petrochemical method [6]. Based on the relative amounts of major chemical components, garnet amphibolites correspond to melanowackes or mixed products of the deep weathering of mafic and ultramafic rocks and Fe-rich sandstones.

The *PT* conditions of the main dynamometamorphic stage, when the hastingsite–garnet–plagioclase mineral assemblage was formed, were estimated based on amphibole–garnet geothermometers [5, 13] and an empirical amphibole–plagioclase geobarometer [11]. These *PT* conditions correspond to amphibolite facies: $T = 650–750°C$ and $P = 5–7$ kbar [10]. It may be suggested that higher temperature transformations predated the amphibolite-facies metamorphism marked by the formation of ferroaugite (relicts in hastingsite) and presumably orthopyroxene, which was subsequently replaced by grunerite.

The sedimentary origin of the amphibolite protolith is indicated by intercalation of garnet amphibolites with metaterrigenous sedimentary rocks, such as quartzite, cummingtonite–garnet gneiss (metagraywacke), and

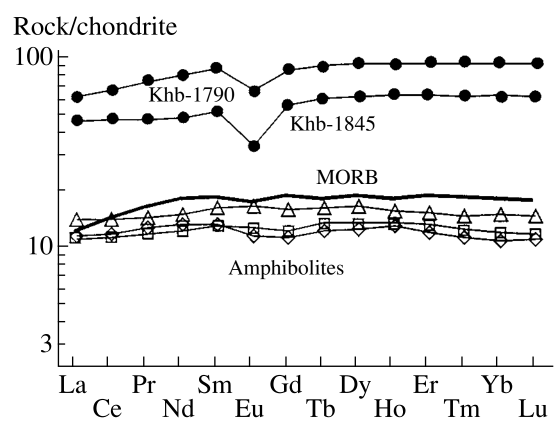

Fig. 3. Chondrite (C1)-normalized REE patterns of amphibolites at the base of the Khabarny massif. Samples Khb-1790 and Khb-1845 are garnet amphibolites. Analyses were performed with the ICP-MS method at the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements, Moscow (D.Z. Zhuravlev, analyst).

metapelites, as well as the chemical composition of garnet amphibolites. Thus, we furnish the first evidence for the occurrence of high-grade metasedimentary rocks at the base of ophiolitic allochthons in the Urals [1]. This composite sequence could be formed in an accretionary wedge of an island arc [7]. The amphibolite-facies dynamometamorphism of volcanosedimentary rocks was related to the obduction of ophiolites [7, 9] and probably to the emplacement of mafic and ultramafic rocks of the East Khabarny Complex.

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