

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/323552560>

Gahnite in Rare-Metal Metasomatic Rocks of the Verkhneurmiysky Ore Cluster, Amur River Region

Article in *Geology of Ore Deposits* · December 2017

DOI: 10.1134/S1075701517080025

CITATIONS

0

READS

205

3 authors, including:



Viktor I. Alekseev

Empress Catherine II Saint Petersburg Mining University

45 PUBLICATIONS 158 CITATIONS

[SEE PROFILE](#)



Yu. B. Marin

76 PUBLICATIONS 490 CITATIONS

[SEE PROFILE](#)

MINERALS AND MINERAL PARAGENESES

Gahnite in Rare-Metal Metasomatic Rocks of the Verkhneurmisky Ore Cluster, Amur River Region

V. I. Alekseev*, Yu. B. Marin, and I. M. Gembitskaya

St. Petersburg Mining University, St. Petersburg, 199106 Russia

**e-mail: via@spmi.ru*

Received October 10, 2016

Abstract—A new finding of Zn-spinel (gahnite) in biotite metasomatic rock of the Verkhneurmisky copper–tungsten–tin ore cluster is described in this paper, including the chemical composition of gahnite, its paragenesis, and place in the regional evolution history of hydrothermal processes. Gahnite is commonly localized in biotite–microcline metasomatic rocks at the lower subore stage of the greisen metasomatic column in proximity to the exocontact of the rare-metal granite massif. Gahnite from rare-metal ore occurrences belongs to the hercynite–gahnite–franklinite isomorphic series and contains significant isomorphic admixtures of iron (24.3%) and manganese (0.65%). Based on our results and earlier published data, it is suggested that gahnite can be a mineral-indicator of rare-metal metasomatism.

Keywords: gahnite, Zn-rich hercynite, siderophyllite, lithium–fluoric granite, greisen, zwitter, tungsten–tin deposit, Far East, Amur River Region

DOI: 10.1134/S1075701517080025

INTRODUCTION

Lithium–fluoric granite intrusions revealed in recent decades in the immediate proximity to the largest tungsten–tin deposits of the Pacific ore belt suggest that the complex mineralization of these deposits arose as a result of hydrothermal processes accompanying the intrusion and crystallization of lithium–fluoric rare-metal granites (Finashin, 1986; Nedosekin, 1988; Marin et al., 1990; Gavrilenko and Panova, 2001; Gonevchuk et al., 2008; *Geodynamics ...*, 2006; Rub and Rub, 2006; Trunilina et al., 2008; Efremov, 2012; Alekseev, 2014). These data have found confirmation in results of evolutionary analysis of magmatic accessory and hydrothermal mineralization in tungsten–tin ore clusters (Alekseev and Marin, 2014a). In the magmatic stage of their formation, the evolution is traced from early magmatic accessory minerals of lithophile elements—W, Nb, Ta, Hf, REE (tungsten tantaloniobates, niobic ferberite, cyrtolite, monazite-(Ce))—to late and postmagmatic minerals of chalcophile elements—Sn, As, Bi, Pb (cassiterite, Sn-bearing rutile, bismutopyrochlore, chernovite-(Y), etc.). This tendency was retained at the postmagmatic stage: multistage zwitter–tourmalinite with lithophile–chalcophile (Sn, W, Cu, Nb, Bi, As, In, REE) mineralization formed in association with Li–F granites (Alekseev and Marin, 2014b). This paper, which continues a study of the evolution of mineral forms of ore elements in ore–magmatic systems of the Far East, describes a Zn-spinel (gahnite) find in high-tempera-

ture rare-metal metasomatic rocks of the Badzhal ore district and considers its genetic significance. The high crystallization temperature of Zn-spinel in combination with the insignificant geochemical role of zinc in magmatic and high-temperature metasomatic petrogenesis makes Zn-spinel indicators of the ore formation settings.

Zinc in the Evolutionary Series of Minerals at Greisen Deposits

As is known, rare-metal (Sn, W, Be, Ta, Li, Cs, F) and copper–base-metal (Cu, As, Zn, Pb) deposits can be related to “ilmenite granitoids” (Marin, 2004). The evolutionary trend of mineral forms—rare-metal granite → zwitter → tourmalinite → beresite—is traced for most ore elements in ore clusters of the Pacific belt (Alekseev, 1989; Marin et al., 1990; Gavrilenko and Panova, 2001; Gonevchuk, 2002; *Geodynamics ...*, 2006). Meanwhile, there is also the mineralogical–geochemical evolution of economic chalcophile elements, e.g., Cu, Zn, Ag, which are not detected in accessory minerals of rare-metal granites. In particular, the mineralogy of zinc remains inadequately explored in Far Eastern greisen deposits. This chemical element is not an economic component of ore and is not commonly mentioned as an admixture in rare-metal granites. The only occurrence of genethelvitite is known in rocks of granitoid series in molybdenum provinces (Marin, 2004).

The mineralogical study of the Verkhneurmiskiy copper–tungsten–tin cluster in the Badzhal district of the Amur River region has shown that the main mass of zinc is incorporated into ferroan sphalerite associated with galena in postore beresite and chlorite veins at the supraore level. An insignificant part of sphalerite crystallized at the stage of tourmalinite formation superimposed on tin-bearing greisen. Sphalerite from tourmalinite contains a substantial admixture of iron (up to 11.66 wt %) and is associated with sulfides and sulfostannates at the upper level, as well as with stannoidite, mawsonite, and roquesite at the medium levels. Zn sulfostannates—kesterite and sakuraiite—were identified in tourmalinite of the Pravourmiskoe deposit in association with chalcopyrite and sphalerite. It is noteworthy that such a rare mineral as sakuraiite was also detected in tourmalinite, which surrounds the Kulyuveem stock of Li–F granite in Chukotka (Alekseev, 2014). As it approaches the rare-metal granites in Chukotka and Amur River region, sphalerite disappears from typical metasomatic mineral parageneses. Thus, syngenetic zinc minerals have not been established in early rare-metal metasomatic rocks—greisen and zwitter—related to Li–F granites of the Far East. According to our data, zinc is recorded (0.62–1.67 wt %) only in accessory ilmenite from rare-metal biotite metasomatic rocks of the Severny ore cluster in Chukotka (Alekseev, 2014). Therefore, the finding of Zn-spinel (gahnite ZnAl_2O_4) in early dark-mica metasomatic rock of the Verkhneurmiskiy ore cluster is noteworthy.

Findings of Gahnite in Igneous and Metamorphic Rocks

Gahnite was discovered in 1807 by I.G. Gahn in talc schist of the Falun District, Sweden. In Russia it was found for the first time also in talc schist in the Shishimsky Mountains of the Urals (Bukanov, 2008). Gahnite is known from metamorphic schists and gneisses in Kola Peninsula, Transbaikalia, the Polar Urals, Kazakhstan, Scotland, and Australia (Sumin, 1950; Gandhi, 1971; Beach, 1973; Kochetkova, 1979; Zhdanov et al., 1983; Kozyreva and Shvetsova, 2007). A part of the gahnite findings is confined to fields of copper and base-metal mineralization hosted in skarn and other contact-metasomatic rocks (Vokes, 1962; Gandhi, 1971; Lisitsin and Yurkina, 1974; Spry, 1987; Ivanyuk et al., 2006; Bukanov, 2008), including the Beresitovoe Deposit in the Far East (Vakh and Sapin, 1982). In all cases, gahnite, as a rule, is hydrothermal metasomatic in origin and crystallizes in late veinlets and segregations (Sumin, 1950; Vokes, 1962; Gandhi, 1971; Beach, 1973; Lisitsin and Yurkina, 1974; Zhdanov et al., 1983). In metamorphic rocks, gahnite may be xenogenic, inherited from a hydrothermally altered protolith (Kozyreva and Shvetsova, 2007).

In 1931, gahnite was established from pegmatites of Kyzyl Kumy by A.F. Sosedko (1961). Later, this mineral was identified in rare-metal granitic pegmatites

and leucogranite on the Kola Peninsula (Kolmozero–Voron'ya), in Karelia (Alakurti), the Urals (Ilmeny, Adui), Buryatia (Solongo), the Eastern Sayan (Gol'tsovskoe), Madagascar (Betrok), Scotland (South Harris), Argentina (Pampean), California (Pala), and Finland (Rosendal), see Pehrman, 1948; Labuntsov, 1950; Bazhenova, 1955; Von Knorring and Dearnley, 1960; Sosedko, 1961; Lisitsin and Yurkina, 1974; Tarnovsky and Shiryaeva, 1977; Spry, 1987; Kobayashv, 2006; Bukanov, 2008; Popova and Kotlyarov, 2010; Kolisnichenko et al., 2013; Voloshin, 2014; Heimann et al., 2015, 2016). Here gahnite, like in metamorphic rocks, is related to areas of secondary quartz–albite–muscovite alteration (Von Knorring and Dearnley, 1960; Lisitsin and Yurkina, 1974; Tarnovsky and Shiryaeva, 1977; Voloshin, 2014; Heimann et al., 2016). Thus, a significant part of gahnite findings are related to altered rare-metal pegmatites and granites. This implies that zinc occurs in early postmagmatic solutions of rare-metal ore–magmatic systems.

GAHNITE FROM THE VERKHNEURMIISKY ORE CLUSTER

Gahnite was found in the Verkhneurmiskiy cluster at the Vysokoe and Grustnoe ore occurrences near the area of rare-metal granites of the Pravourmiskiy Complex (Alekseev, 2014). The **Vysokoe ore** occurrence is located in the south of the Verkhneurmiskiy ore cluster and enters the Synchuga ore field. The occurrence is a series of nearly parallel, steeply dipping zones of quartz–muscovite and quartz–biotite metasomatic rocks oriented NNW (330° – 350°) with total power from 3 to 20 m. Micaceous metasomatic rocks are classified as greisens replacing rhyolitic crystalline ignimbrites in the exocontact zone of the Verkhneurmiskiy granitic massif. The distance from surface to the roof of granitic massif is estimated at 100–200 m. Metasomatic rocks are gray, green, and brown in color; they are locally ocherous and cavernous. Fine-grained lepidogranoblastic and blastoporphyritic structures are typical. The texture is massive or mottled with segregations of biotite, muscovite, tourmaline, sulfides, and microveinlets. Thin, a few millimeters in thickness, quartz veinlets with disseminations of brown and green biotites, purple fluorite, black tourmaline, and less abundant cassiterite, arsenopyrite, chalcopyrite, and sphalerite are typical of greisen. Zones of wall-rock biotitization are 0.5–1.5 cm thick. The predominant greisen zones are combined with radial veins of tourmalinites with cassiterite–quartz clusters.

Gahnite was identified in a zone of grayish green quartz–muscovite–biotite metasomatic rock (Fig. 1a) 20 cm in thickness. The zone is enriched in metasomatic veinlets of white, glassed quartz, along which fine disseminations of Zn-spinel are localized. The veinlets are accompanied by zonal haloes consisting of the inner microcline–biotite–quartz zone with apatite

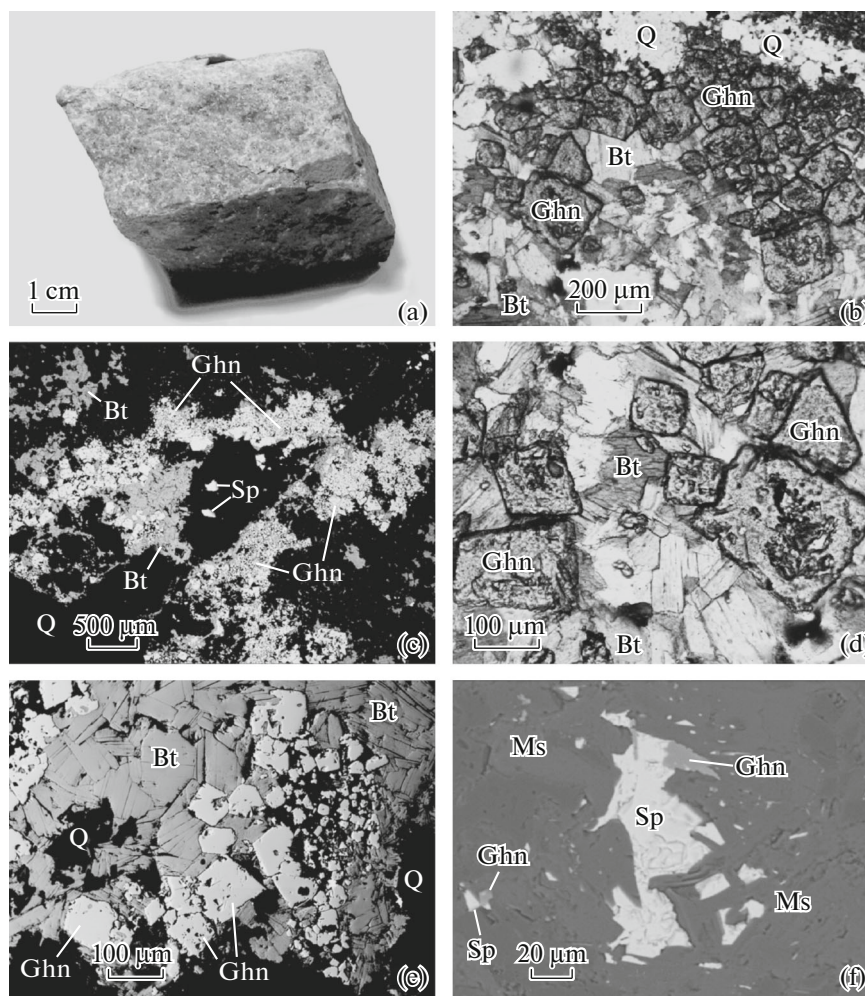


Fig. 1. Gahnite from biotite metasomatic rocks at Vysokoe ore occurrence in Verkhneurmitsky ore cluster, Amur River region: (a) microcline–siderophyllite–quartz metasomatic rock with gahnite, (b, d) gahnite segregations in siderophyllite–quartz aggregate, (d, e) gahnite crystals in siderophyllite segregations, (f) gahnite and sphalerite intergrowths in quartz–muscovite greisen. Bt, biotite; Ghn, gahnite; Ms, muscovite; Sp, sphalerite; Q, quartz. (a) hand specimen; (b, d) thin section, plane light; (c, e, f) BSE images (regime COMPO on a JSM-6460LV (c, f) and a JXA-8230 (e) electron microscopes.

grains, precisely where spinel concentrates, and the outer quartz–muscovite zone with fine (10–150 μm) disseminations of sulfides and cassiterite. Quartz, accessory zircon, and manganese ilmenite (3.85 wt % MnO) are relict minerals of rhyolite. Biotite is represented by ferrous siderophyllite with $I = 100\text{Al}/(\text{Al} + \text{Si} + \text{Mg} + \text{Fe}) = 19.68$ and $f = 100\text{Fe}/(\text{Fe} + \text{Mg}) = 94.57$; muscovite is also ferric (2.76 wt % Fe_2O_3). Sulfides are ferroan sphalerite (16.63 wt %), pyrrhotite, galena, and pyrite.

Gahnite occurs as lenticular segregations 0.1–1.0 mm across in microcline–biotite–quartz aggregates near selvages of quartz veinlets, as well as rare single crystals in biotite segregations. It frequently grows together with biotite and is surrounded by a buffer mica fringe at contacts with quartz. The spinel clusters at contact with quartz are composed of fine-grained (<10 μm) aggregates of xenomorphic gahnite and of relatively

coarse (10–150 μm) euhedral grains at contacts with biotite segregations (Figs. 1b, 1c). Gahnite has a slight greenish hue in transmitted light; the specimen is a grass-green color. The largest octahedral crystals make up intergrowths according to spinel law and are overcrowded with biotite inclusions (Figs. 1d, 1e). Single xenomorphic gahnite grains 10–20 μm in size grow together with sphalerite in quartz–muscovite aggregates enriched in sulfides (Fig. 2f).

The composition of spinel was subject to scrutiny at the Shared-Use Center of the St. Petersburg Mining University. The petrochemical features of spinel-bearing metasomatic rocks have been assessed, and admixtures of trace elements were examined with X-ray fluorescence spectroscopy (XRF-1800). Based on the obtained geochemical information, we searched for accessory minerals on JSM-6460LV and JSM-7001F electron microscopes. The revealed spinel grains were

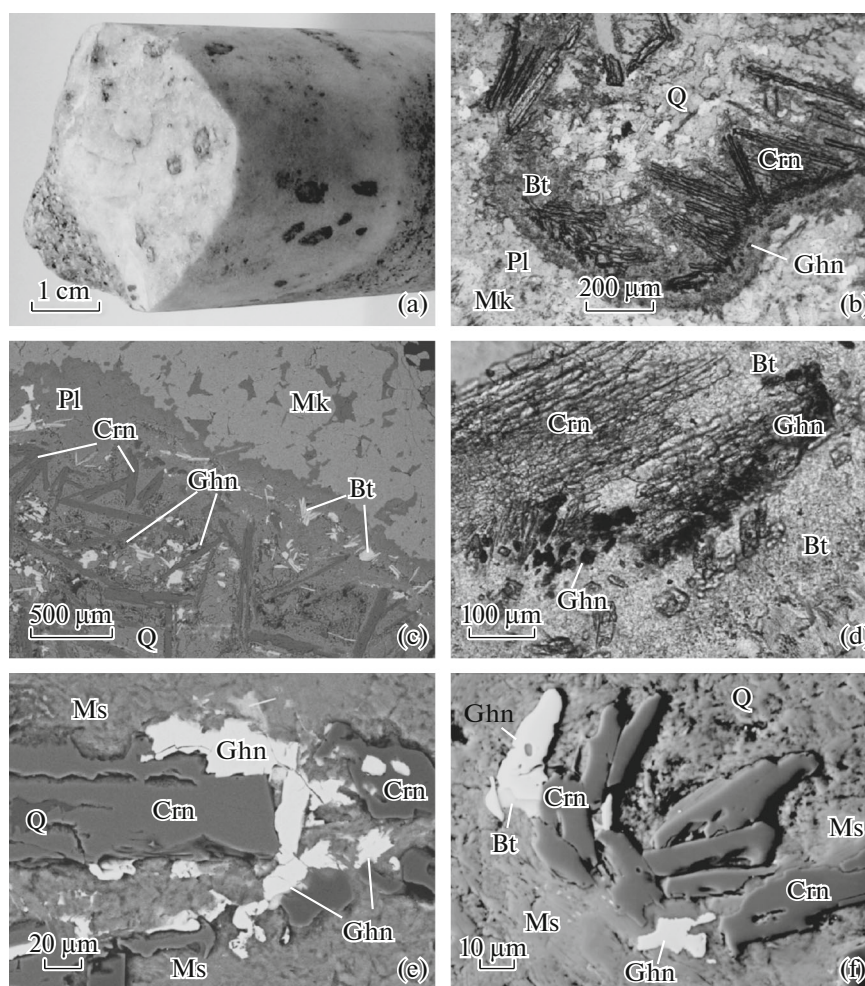


Fig. 2. Zn-rich hercynite in biotite metasomatic rocks at Grustnoe ore occurrence of Verkhneurmisky ore cluster, Amur River region: (a) biotitic microcline after rhyolite: biotite–corundum–quartz clusters with Zn-rich hercynite are seen; (b, c) zonal biotite–corundum–quartz pseudomorphs after plagioclase phenocrysts with inclusions of Zn-rich hercynite; (d, e, f) Zn-rich hercynite crystals in paragenesis with corundum, biotite (siderophyllite), and muscovite. Mk, microcline; Pl, plagioclase; see Fig. 1 for or symbols. (a) core sample; (b, d) thin section, plane light; (c, e, f) BSE images (regime COMPO on a 6460LV (c, e) and a JXA-8230 (f) electron microscopes).

studied on an electron probe microanalyzer. All admixtures were within the detection limits (0.01 wt %) of the wave spectrometer attached to JXA-8230 electron probe analyzer. The results of X-ray microanalysis are given in the table.

The chemical composition of spinel from biotite metasomatic rock at the Vysokoe ore occurrence is characterized by stability within the studied area (wt %): 55.54 Al_2O_3 , 25.77 ZnO , 21.17 ($\text{Fe}_2\text{O}_3 + \text{FeO}$), 0.06 MnO , and 0.05 MgO (see Table 1). The mineral corresponds to ferrihercynite in the gahnite–franklinite series: $(\text{Zn}_{0.58}\text{Fe}_{0.42}\text{Mn}_{0.002}\text{Mg}_{0.002})(\text{Al}_{1.99}\text{Fe}_{0.01})\text{O}_4$.

As is known, the crystal lattice of spinel is characterized by variable dimensions of the cells occupied by cations and by a wide isomorphic capacity. By calculation based on stoichiometry, it has been established that the most important are zinc (Zn^{IV} 0.58 f.c.), iron

of variable valency (Fe^{VI} 0.42, Fe^{IV} 0.01), and manganese (Mn^{IV} 0.002). This is a typomorphic attribute of gahnite from the Verkhneurmisky ore cluster. Fluctuations of the main admixtures are 10.01–21.17% ($\text{Fe}_2\text{O}_3 + \text{FeO}$) and 0.00–0.28% MnO . The presence of iron in two crystal chemical positions reflects partial inversion of the found spinel. If this suggestion is valid, then in accordance with experiments performed by O'Neill and Dollase (1994), a very high ($>900^\circ\text{C}$) crystallization temperature of gahnite from the Verkhneurmisky cluster is suggested.

The **Grustnoe ore** occurrence is situated in the north of the Verkhneurmisky ore cluster in the axial part of the Badzhal Ridge and enters the Axis-Badzhal ore field. The ore occurrence is represented by near-latitudinal (70° – 75°) steeply dipping zones of metasomatic bodies, from 1 to 100 m in total thickness, in a sequence of rhyolites with interbeds of rhyodacitic

Table 1. Chemical composition of gahnite and Zn-rich hercynite of Verkhneurmisky ore cluster, wt %

Component	Gahnite (Vysokoe)				Zn-rich hercynite (Grustnoe)			
	1	2	3	4	5	6	7	8
MgO	—	—	0.23	0.05	—	—	—	0.27
Al ₂ O ₃	54.19	55.61	55.59	55.54	55.12	54.92	55.66	55.72
MnO	—	—	0.26	0.06	1.36	1.07	1.18	1.23
Fe ₂ O ₃ *	19.07	18.84	21.17	18.57	31.45	31.33	26.62	30.57
ZnO	26.60	25.54	22.74	25.77	11.61	12.40	16.49	11.84
Total	99.86	99.99	99.98	100.00	99.54	99.71	99.94	99.62
Formula coefficients of cations								
Mg	—	—	0.01	0.002	—	—	—	0.01
Al	1.96	1.99	1.99	1.99	1.98	1.97	1.99	1.99
Mn	—	—	0.01	0.002	0.04	0.03	0.03	0.03
Fe ²⁺	0.40	0.43	0.47	0.42	0.70	0.69	0.60	0.69
Fe ³⁺	0.04	0.01	0.01	0.01	0.02	0.03	0.01	0.01
Zn	0.60	0.57	0.51	0.58	0.26	0.28	0.37	0.27

(1–3, 5–7) representative X-ray spectral microanalyses (JXA-8230) of gahnite and Zn-rich hercynite respectively from rare-metal metasomatic rocks of Verkhneurmisky ore cluster; (4, 8) mean compositions of gahnite and Zn-rich hercynite (17 and 28 analyses respectively). Dash denotes that element was not detected; Fe₂O₃* is total FeO + Fe₂O₃. Formulas were calculated on basis of three cations with subsequent calculation of Fe²⁺ and Fe³⁺ coefficients.

lavas and tuffs. The zone is localized in the exocontact of the Verkhneurmisky granitic massif and composed of muscovite–topaz–quartz greisen with biotite and admixtures of fluorite, tourmaline, wolframite, cassiterite, arsenopyrite, and halcopyrite. Sericite, chlorite, and albite are widespread in the outer parts of the greisen zone. The structures of greisen are microlepidogranoblastic and blastoporphyratic. In the southern part of the ore occurrence, steeply dipping greisen bodies are splayed by low-angle (azimuth 152°–165° SE, angle 13°–30°) wolframite–topaz and quartz metasomatic veins similar in composition and attitude to veins of the nearby located Pravourmiskoe deposit. In the eastern part of ore occurrence, where the erosion level is shallower, the topaz–muscovite greisen bodies give way to thick (5–20 m) zones of muscovite greisen with tourmaline, cassiterite, and sulfides. At the lower hypsometric levels, light-micaceous greisen gives way to quartz–biotite and K-feldspar–biotite metasomatic rocks with garnet, apatite, allanite, halcopyrite, and pyrrhotite disseminations. The metasomatic biotite-bearing rocks are characterized by thin biotite–quartz and K-feldspar veinlets with sulfides. The structure of biotite is microheteroblastic, and the texture is banded, spotty, or massive.

In exploration borehole 2/20 at a depth of 139.5 m and 30 m above granite roof in the Verkhneurmisky massif, rhyolitic ignimbrite was discovered, which has a zone of biotitic microcline more than 3 cm in thickness with relatively large (3–7 mm) biotite–corundum–quartz clusters, where spinel close in composition to gahnite has been identified (Fig. 2a). Micro-

cline contains quartz (5%), biotite (5%), monazite and apatite phenocrysts. The structure of microcline is fine-grained (0.1–0.5 mm), hypidioblastic, and blastoporphyratic. Relics of magmatic K-feldspar phenocrysts are observable. The aforementioned clusters with spinel are pseudomorphs after plagioclase (oligoclase, andesine) phenocrysts with characteristic zonal structure. Cores of pseudomorphs mainly consist of microgranoblastic quartz, whereas margins are occupied by zones of packet aggregates of finely tabular corundum 0.2–1.0 mm along the pinacoid (0001). The corundum zone is framed by a rim of twisted tabular siderophyllite ($l = 24.38; f = 90.09$). The outer rim is composed of secondary tabular oligoclase (Figs. 2b, 2c). The multitude xenomorphic microsegregations (20–50 μm) of Zn-spinel (Figs. 2d–2f) are recorded at the contact between corundum and mica. A weak calcite–chlorite–sericite beresitic alteration is superimposed on microcline. Because of this, corundum and biotite in clusters with spinel are partly replaced by ferric muscovite (0.55 wt % Fe₂O₃).

Spinel in biotite–microcline aggregates at the Grustnoe ore occurrence is distinguished, like gahnite at the Vysokoe ore occurrence, by elevated ferri-ferrous contents (14% Fe^{VI}, 39% Fe^{IV}) and a substantial share of zinc (Zn^{IV} 0.27 f.c.) and Mn (Mn^{IV} 0.03). In its composition (wt %)—55.72 Al₂O₃, 30.57 (Fe₂O₃ + FeO), 11.84 ZnO, 1.23 MnO, 0.27 MgO (see Table 1)—spinel is related to Zn-rich hercynite of the hercynite–gahnite–franklinite series: (Fe_{0.69}Zn_{0.27}Mn_{0.03}Mg_{0.01})(Al_{1.99}Fe_{0.01})O₄. Fluctuations of the main components

are as follows: 20.07–39.24% ($\text{Fe}_2\text{O}_3 + \text{FeO}$), 0.72–1.70% MnO. According to single observations on crystals of gahnite, the Zn/Fe ratio increases toward the margins of grains already described by Spry (1987).

DISCUSSION

As is seen from the above description, the Zn-spinel revealed in the Verkhneurmiysky ore cluster is confined to the fields of the earliest metasomatic rocks in the studied area: tungsten–tin greisens and zwitter (Alekseev, 1989). The spinel-bearing microcline–biotite–quartz and biotite–corundum–microcline metasomatic rocks occur at the lower (subore) levels of zwitter approaching the granite roof, where microcline appears in dark-micaceous metasomatic rock. Gahnite is formed at deep levels of the hydrothermal column and is related to the high-temperature stage of its evolution, which is characterized by alumina-rich fluids with a potassic alkaline component.

The occurrence of gahnite in peraluminous rare-metal metasomatic rocks indicates the presence of zinc in fluids at the early stage of evolution of the Verkhneurmiysky ore–magmatic system. It should be emphasized that the rare-metal granites of the Pravourmiysky Complex, to which the ore-forming and hydrothermal processes are spatially related, do not contain zinc-bearing minerals (Alekseev and Marin, 2014b). This allows us to suggest that zinc was incorporated into gahnite either by extraction of fluids from country rocks (Vokes, 1962; Gandhi, 1971; Beach, 1973; Lisitsin and Yurkina, 1974; Kochetkova et al., 1979; Vakh and Sapin, 1982; Zhdanov et al., 1983; Kozyreva and Shvetsova, 2007; Kolisnichenko et al., 2013) or is gained along with transmagmatic fluids (Alekseev, 2014). A subcrustal source of zinc is corroborated by a high zinc mineralization temperature. The enrichment of Cr-spinel in zinc as evidence for its mantle origin is considered in relation to diamond potential (Makeev and Makeev 2005; Silaev, 2008) and rare-metal mineralization in the Timan–Urals (Glukhov et al., 2015). The occurrence of Zn-bearing Cr-spinel as a sign of diamond potential has been discussed since 1970 (Meyer and Boyd, 1972).

The finding of Zn-spinel in metasomatic rocks of the Far East described in this paper is not the first. Spinel has been revealed in topaz greisens at the Oloyno deposit in the Lesser Khingan, where it is hosted in biotite–corundum–K-feldspar cluster identical to the cluster of the Grustnoe ore occurrence (Itsikson, 1956). A mineral from the franklinite–jacobsite series close to gahnite was identified in the opened fluid inclusion in quartz from rare-metal zwitter of the Severny (Northern) massif in the North Chukchi Peninsula (A.V. Kurguzova, oral communication). In the same area, green spinel was noted in xenoliths contained in granitic rocks (Zagruzina, 1965). Gahnite from rare-metal ore occurrences differs in elevated Fe and Mn contents (24.27 and 0.65 wt %, respectively)

and is a constituent of the hercynite–gahnite–franklinite series (Lisitsin and Yurkina, 1974; Tar-novsky and Shiryayeva, 1977; Kobayash, 2006; Kozyreva and Shvetsova, 2007; Popova and Kotlyarov, 2010; Kolisnichenko et al., 2013; Heimann et al., 2016).

Thus, gahnite can be regarded as a mineral indicator of rare-metal ore–magmatic systems. It should be noted that another hydrothermal zinc mineral—genthelvite $\text{Zn}_4\text{Be}_3(\text{SiO}_4)_3\text{S}$ —also containing Fe and Mn as admixtures (Raimbault and Bilal, 1993; Marin, 2004; Haapala and Lukkari, 2005) plays a similar indicative role in regions with evolved rare-metal granites and pegmatites.

CONCLUSIONS

(1) Gahnite and Zn-rich hercynite from tungsten–tin deposits in Amur River region are related to biotite–microcline metasomatic rocks of the lower (subore) stage of metasomatic column of zwitter localized in the near exocontact zone of ore-bearing rare-metal granites. Zn-spinel from rare-metal ore occurrences contains isomorphic admixtures of iron and manganese and enters into hercynite–gahnite–franklinite series.

(2) The setting of Zn-spinel formation is characterized by early hydrothermal metasomatic alteration of rare-metal pegmatites and granites, as well as country rocks and thus reflects the participation of zinc in formation of rare-metal ore–magmatic systems. Zinc sources can be mantle transmagmatic fluids, which predate the rare-metal granitic complexes and participate in their formation.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 18-05-00201) and the Ministry of Education and Science of Russia under basic and project parts of state program nos. 5.2115.2014/K in 2014–2016 and 5.9248.2017/6.7 in 2017–2019.

REFERENCES

- Alekseev, V.I., Metasomatic zoning of the Badzhalsky district ore fields (Amur River region), *Zap. Ross. Mineral. O-va*, 1989, no. 5, pp. 27–37.
- Alekseev, V.I., *Litii-floristye granity Dal'nego Vostoka* (Lithium-Fluorine Granites of the Far East), Saint Petersburg: St. Petersburg. Gornyi Univ., 2014.
- Alekseev, V.I. and Marin, Yu.B., Accessory mineralization of rocks from late cretaceous intrusive series with Li–F granites in the Far East, *Zap. Ross. Mineral. O-va*, 2014a, no. 3, pp. 1–23.
- Alekseev, V.I. and Marin, Yu.B., Composition and evolution of accessory mineralization of Li–F granites in the Far

- East as indicators of their ore potential, *Zap. Ross. Mineral. O-va*, 2014b, no. 6, pp. 1–16.
- Bazhenova, L.N., About gahnite from pegmatite of western Azov region, *Miner. Sb. L'vov Gos. Univ.*, 1955, no. 9.
- Beach, A., The mineralogy of high temperature shear zones at Scourie, N.W. Scotland, *J. Petrol.*, 1973, vol. 14, no. 2, pp. 231–248.
- Bukanov, V.V., *Tsvetnye kamni. Entsiklopediya (Gemstones: Encyclopedia)*, Saint Petersburg: Otava, 2008.
- Tarnovskiy G.N., Shiryayeva V.A. Gahnite from rare-metal pegmatite of Eastern Siberia, in *Mineraly i mineral'nye assotsiatsii Vostochnoi Sibiri* (Minerals and Mineral Associations of Eastern Siberia), Irkutsk: Vost. Sib. Kn. Izd., 1977.
- Efremov, S.V., Rare-Metal Granitoids of Chukchi Peninsula: Geochemistry, Sources of Matter and Formation Models, *Extended Abstract of Doctoral (Geol.-Min.) Dissertation*, Irkutsk, 2012.
- Finashin, V.K., *Olovorudnye mestorozhdeniya Primor'ya (geologiya i genesis)* (Tin-ore Deposits of Primorye Territory (Geology and Genesis), Vladivostok: FEB RAS, 1986.
- Gandhi, S.M., On the ferroan gahnite of Mamandur, Madras state, India, *Mineral. Mag.*, 1971, vol. 38, pp. 528–529.
- Gavrilenko, V.V. and Panova, E.G., *Geokhimiya, genesis i tipomorfizm mineralov mestorozhdenii olova i vol'frama* (Geochemistry, Genesis, and Typomorphism of Minerals from Tin and Tungsten Deposits), Saint Petersburg: Neva courier, 2001.
- Geodynamics, magmatizm and metalogeny of the Russian East: Books 1, 2*. Eds. A.I. Khanchuk. Vladivostok: Dal'nauka, 2006.
- Glukhov, Yu.V., Makeev, B.A., Varlamov, D.A., Shevchuk, S.S., and Isaenko, S.I., Chromespinelides with zinc-bearing epigenetic rims from Devonian conglobreccia horizons of Ichet'yu placer-like occurrence (Middle Timan), *Lithosfera*, 2015, no. 2, pp. 103–120.
- Gonevchuk, V.G., *Olovonosnye magmaticheskije sistemy Dal'nego Vostoka: magmatizm i rudogenez (Tin-Bearing Systems of the Far East: Magmatism and Ore Genesis)*, Vladivostok: Dal'nauka, 2002.
- Gonevchuk, V.G., Kokorin, A.M., Korostelev, P.G., et al., *About problems in the classification of tin deposits according to the formation basis, Tikhookeanskii rudnyi pojas: materialy novykh issledovaniy (k 100-letiyu E.A. radkevich)* The Pacific Ore Belt: Materials of New Researches (to the 100th anniversary E. A. Radkevich), Vladivostok: Dalnauka, 2008, pp. 70–88.
- Haapala, I. and Lukkari, S., Petrological and geochemical evolution of the Kymi stock, a topaz granite cupola within the Wyborg rapakivi batholith, Finland, *Lithos*, 2005, vol. 80, pp. 347–362.
- Heimann, A., Yonts, J.A., and Galliski, M.A., The composition of gahnite in granitic pegmatites from the Pampean pegmatite province, Argentina: implications for pegmatite fractionation, *Can. Mineral.*, 2015, vol. 53, pp. 1–26.
- Heimann, A., Yonts, J.A., and Wise Michael, A., Melt evolution in felsic dikes inferred from the composition of gahnite in two new occurrences, Pala Chief and Elizabeth R composite dikes, California, *Mineral. Petrol.*, 2016, vol. 110, no. 6, pp. 1–16.
- Itsikson, G.V., *Gidrottermal'nye izmeneniya vmeshchayushchikh porod olovorudnogo mestorozhdeniya na Malom Khingane* (Wall Rock Alteration of Tin Ores in the Lesser Khingan Mountains), Moscow: Gosgeoltekhizdat, 1956.
- Ivanyuk, G.Y., Pakhomovsky, Y.A., Konopleva, N.G., Yakovenchuk, V.N., Menshikov, Yu.P., and Mikhailova, Yu.A., Spinel-group minerals in rocks of the Khibiny alkaline pluton, Kola Peninsula, *Zap. Ross. Mineral. O-va* 2007, no. 5, pp. 64–75.
- Von Knorring, O. and Dearnley, R., The Lewisian pegmatites of South Harris, outer Hebrides, *Mineral. Mag.*, 1960, vol. 32, pp. 366–378.
- Kobyashev, Yu.S., The list of Urals mountains minerals (species and phase), *Ural'sk. Geol. Zh.*, 2006, no. 2.
- Kochetkova, K.V., Kovalev, K.R., and Kovaleva, L.T., About zinc-containing staurolite of the Holodninsky deposit (northern Baikal region), *Dokl. Akad. Nauk SSSR*, 1979, vol. 246, no. 2, pp. 452–455.
- Kolisnichenko, S.V., Popov, V.A., and Kissin, A.Yu., Chrysoberyl–beryl granite pegmatites from the Yeremkin massif, Southern Urals, *Lithosfera*, 2013, no. 2, pp. 135–144.
- Kozyreva, I.V. and Shvetsova, I. V., Find of a rare mineral gahnite in diaspore–pyrophyllite slates of Subpolar Urals Mountains, in *Geodinamika, magmatizm, sedimentogenez i minerageniya Severo-Zapada Rossii* (Geodynamics, Magmatism, Sedimentogenesis and Metallogeny of the Northwest Russia), Petrozavodsk: Inst. Geol. Karel'sk. Nauchn. Ts., 2007, pp. 176–178.
- Labuntsov, A.N., *About several new minerals from Ilmensky Mountains, Tr. Mineral. Muzeya An SSSR*, 1950, pp. 134–135.
- Lisitsin, A.E. and Yurkina, K.V., About a find of gahnite in leucocratic granites, *Zap. Ross. Mineral. O-va*, 1974, no. 5, pp. 641–643.
- Makeev, A.B. and Makeev, B.A., Zn-chromespinelides from the Middle Timan and nether-Polar Urals, *Dokl. Earth Sci.*, 2005, vol. 404, no. 2, pp. 235–240.
- Marin, Yu.B., Skublov, G.T., and Gulbin, Yu.L., Mineralogical–geochemical criteria of local predicting of rare-metal deposits, in *Mineralogicheskoe kartirovanie i indikator orudneniya* (Mineralogical Mapping and Indicators of Mineralization), Leningrad: Nauka, 1990, pp. 67–94.
- Marin, Yu.B., Accessory minerals of granitoid series in tin and molybdenum provinces, *Zap. Ross. Mineral. O-va*, 2004, no. 6, pp. 1–7.
- Meyer, H.O.A. and Boyd, F.R., Composition and origin of crystalline inclusions in natural diamonds, *Geochim. Cosmochim. Acta*, 1972, vol. 86, pp. 1255–1278.
- Nedosekin, Yu.D., *Redkometal'nye granity Severo-Vostoka SSSR* (Rare-Metal Granites of the Northeast USSR), Moscow: Nauka, 1988.
- O'Neill, H.St.C. and Dollase, W.A., Crystal structures and cation distribution in simple spinels from powder XRD structural refinements: MgCr_2O_4 , ZnCr_2O_4 , Fe_3O_4 and the temperature dependence of the cation distribution in ZnAl_2O_4 , *Phys. Chem. Miner.*, 1994, vol. 20, no. 8, pp. 541–555.
- Pehrman, G., Gahnit von Rosendal auf Kimito, SW Finland, *Bull. Geol. Inst. Univ. Upsala*, 1948, vol. 32, pp. 329–336.
- Popova, V.I. and Kotlyarov, V.A., New data on the accessory minerals of the Semeninskaya pit of the Aduy pegma-

tite field (Urals), *Novye Dannye o Mineralakh*, 2010, vol. 45, pp. 28–32.

Raimbault, L. and Bilal, E., Trace-element contents of helvite-group minerals from metasomatic albitites and hydrothermal veins at Sucuri, Brazil, and Dajishan, China, *Can. Mineral.*, 1993, vol. 31, pp. 119–127.

Silaev, V.I., Shabalin, V.N., Golubeva, I.I., Chazov, A.F., and Belousova, E.A., About zinc-containing and zincian chromespinelides of the Timan–Ural region, *Bull. Inst. Geol. Komi SC UB RAS*, 2008, no. 164, pp. 6–16.

Sosedko, A.F., *Materialy po geologii i geokhimii granitnykh pegmatitov* (Materials on Geology and Geochemistry of Granite Pegmatites), Moscow: Gosgeoltekhizdat, 1961.

Spry, P.G., Compositional zoning in zincian spinel, *Can. Mineral.*, 1987, vol. 25, pp. 97–104.

Sumin, N.G., About minor components in spinels, *Tr. Mineral. Muzeya AN SSSR*, 1950, vol. 2, pp. 113–125.

Trunilina, V.A., Orlov, Yu.S., Roev, S.P., and Zaytsev, A.I., Composition and genetic aspects of formation A-type granites of the Verkhoyansk–Kolyma infolded area, *Otechestvennaya Geol.*, 2008, no. 5, pp. 99–109.

Vakh, A.S. and Sapin, V.I., The first find of ferrian gahnite in the Far East, *Dokl. Akad. Nauk SSSR*, 1982, vol. 264, no. 5, pp. 1199–1202.

Vokes, F.M., Gahnite in the Bleikvassli ore, *Norsk Geologisk Tidsskrift. Contrib. Miner. Norway*, 1962, vol. 42, no. 15, pp. 317–329.

Voloshin A.V. Sketches to history of mineralogical studying of rare-metal and amazonite granite pegmatite from Kola peninsula, in *Geologiya i strategicheskie poleznye iskopaemye Kol'skogo poluostrova* (Geology and Strategic Commercial Minerals of the Kola Region), Apatity: K & M, 2014, pp. 10–25.

Zagruzina, I.A., Late Mesozoic granitoids of the Chaun Bay east coast, *Tr. Severovost. Kompleks. Nauchn-Issled. Inst.*, 1965, vol. 12, 4–140.

Zhdanov, V.V., Matveychik, B.S., and Kuranova, V.N., Gahnite from Bol'shie Keivy schists, *Zap. Ross. Mineral. O-va*, 1983, no. 5, pp. 611–614.

Translated by V. Popov