

Accepted Manuscript

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PII: S0169-1368(16)30248-7

DOI: <https://doi.org/10.1016/j.oregeorev.2018.03.024>

Reference: OREGEO 2540

To appear in: *Ore Geology Reviews*

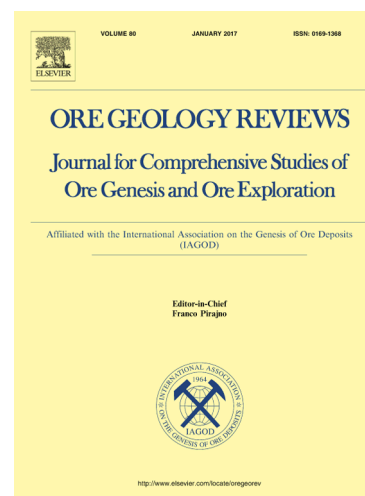
Received Date: 7 May 2016

Revised Date: 21 March 2018

Accepted Date: 27 March 2018

Please cite this article as: N.A. Goryachev, V.I. Shpikerman, S.E. Church, V.I. Gvozdev, Calcic Skarn Ore Deposits of the North-East Russia, *Ore Geology Reviews* (2018), doi: <https://doi.org/10.1016/j.oregeorev.2018.03.024>

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CALCIC SKARN ORE DEPOSITS OF THE NORTH-EAST RUSSIA

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Abstract

In this paper, we summarize characteristics of calcic skarn ore deposits in Northeast Asia. The study area includes a wide variety of terranes, which experienced both subduction and collisional granite magmatism, and contains a skarn deposits of various types, mostly of sub-economic. This provides an opportunity to examine the relationships among skarn metal types, host rocks, and plutons, within various tectonic settings. The paper is based on the authors' observations (at 17 deposits and prospects) as well as on a review of published data on these and other skarn deposits. Major skarn mineralization in Northeast Asia was formed in the Late Mesozoic accretionary and post-accretionary periods. Skarn deposits of Fe, W, Mo, Pb-Zn, and Au (Co) show the same type of skarn mineralogy. The type of host rocks, more rarely granitoid, and the type of mineralization control the composition of garnet and pyroxene, formed in the skarn deposits. Garnet and vesuvianite, associated with tin skarn deposits, have high Sn concentrations. The garnet, associated with skarn deposits in terrigenous terranes, has higher TiO₂ concentrations than those in the garnet in skarn deposits from carbonate platform terranes. During skarn deposit formation, the Fe content of the main skarn minerals (garnet and pyroxene) increases. Ore mineralization, which accompanied skarns, exposes isotopic compositions of crustal Pb. Island arc granitoids have primitive ⁸⁷Sr/⁸⁶Sr values, while collision granitoids show more elevated crustal ⁸⁷Sr/⁸⁶Sr signatures.

Key words: Northeast Asia, skarn ore deposits, garnet, diopside-hedenbergite, S- and Pb- isotopes.

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1. Introduction

Skarn deposits are widespread all over the world and represent a most important source of Fe, W, Pb-Zn, Au, Cu, and other metals (Smirnov 1976, Einaudi et al. 1981, Meinert 2005). Some skarn deposits in Northeast Russia have long been known along the northeastern margin of the Asian continent. Geological studies of this territory have documented the existence of skarn deposits of Fe (Fadeev 1974), W (Dorofeev 1961, Gvozdev, 2010), Sn (Flerov 1976), Au (Volkov et al. 2008) and Pb-Zn (Shpikerman 1987, 1998) here. At the present, we know of more than 50 deposits and prospects of the skarn type in the area (Khanchuk, 2006). The information on them is dispersed in a few publications that usually summarize the characteristics of this or that metal or the group of metals (Nekrasov 1962, 1966; Flerov 1976; Bakharev et al. 1988; Shpikerman 1987, 1998; Volkov et al. 2008; Gvozdev 2010), or generalized mineralogical reports (Yakovlev et al. 1979, Polovinkin & Goryachev 1981, Belinsky 1988). The authors published data on geological conditions at skarn deposit locations, their mineral composition, genesis, and mineral potential. Most are calcic skarn deposits. Magnesia skarns rarely play an important role in boron-rich deposits, and magnesium-rich zones are sometimes observed in the early stages of Sn-skarn deposits in dolomitic strata. In general, comprehensive information on calcic skarn mineralization in this region has never been published. The present paper aims to summarize the characteristics of calcic skarn ore deposits in Northeast Russia. The area includes a wide variety of terranes, has experienced both subduction and collisional granitoid magmatism, and contains various skarn types, although mostly non-commercial. Northeast Russia is a valuable ground to examine relationships among skarn mineralization, host rocks, pluton types, and tectonic settings. These studies are based on the authors' field observations (at 17 deposits and prospects) as well as published materials and other skarn deposits.

2. General description of skarn ore deposits

2.1. Classification and general features.

Based on the ore mineralization character, we distinguish the following six types of skarn ore deposits in Northeast Russia: Fe, W (locally containing Cu and Bi), Mo, Pb-Zn, Au (occasionally with Co), and Sn skarns (**Table 1**). These deposits distribution is presented in **Fig. 1**. In each deposit type, either sulfide or oxide ore minerals dominate. Thus, magnetite mineralization is typical for Fe skarn deposits, scheelite or scheelite-sulfide mineralization for W deposits, cassiterite for Sn ore deposits, and sulfo-arsenide and sulfide mineralization for Au-Co and Pb-Zn deposits, respectively. In all cases, according to Einaudi et al. (1981) and Meinert (2005), the skarn deposit type is determined by ore

mineralization. As suggested by Zharikov (1968, 1985), skarn mineralization resulted from the fluid magmatic-ore system evolution. Skarn is formed at an early stage followed by ore mineralization at a later stage.

The size and extent of many skarn deposits in the area have not been studied comprehensively enough to calculate tonnage. Only a few deposits have been explored. Thus, at Fe skarn lode deposits ore resources reach 110-300 Mt of ore (Cherninsoye, Khrustalnoye); the Sn Kanyon deposit is characterized by the 800 000 t of ore with the Sn grade about 1%; and the resources of W ore of the Agylky deposit are about 8 Mt of ore with 0.9% of WO_3 . The deposits of major types are briefly presented in **Table 2**.

2.1.1. Iron ore skarns.

Iron skarns are represented by small magnetite deposits located in the Omulevka and Prekolyma terranes and the Omolon microcontinent. The largest Fe skarn deposits are found in the Omolon microcontinent. Host rocks are Paleozoic and Neoproterozoic carbonate strata intruded by Late Jurassic and Early Cretaceous granitoids. To exemplify those, we will describe characteristics of two deposits.

The Cherninskoye deposit is located at the northern contact of the Kanyon granite pluton (**Fig. 2**), in Upper Permian carbonate rocks of the Turinskaya suite. They comprise the limbs of a synclinal fold of sub-latitudinal strike with angles of incidence of 30-60°N. The limestone bed thickness is less than 250 m. The deposit is underlain and overlapped by terrigenous rocks. Magmatic rocks are represented by granites of the Late Jurassic Bolshoy Kanyon pluton, the roof of which gently dips northward with small dome-like prominences accompanied by aplite dikes. All sections of ore-bearing skarns are confined to marble outcrops of the Permian Turinskaya suite. Ore-bearing skarns are lense-like bodies along the hornfels-marble contact, and rarely in the granite-marble contact with. Skarn bodies are several meters thick, rarely reaching 20-30 m in thickness. They extend along strike for a distance of 60 to 400 m. Silicate minerals are essentially pyroxene (hedenbergite), garnet, and epidote, with magnetite- and magnetite-ilvaite lenses and veins observed. Skarns are distinctly zoned (**Table 3**).

Sometimes later axinite is observed in this skarn (in the Verkhny-Sphalerite section). In general, the Cherninskoe skarns are composed of fine-grained pyroxene aggregates with clots of isotropic garnet later rimmed by anisotropic garnet. Spherulite aggregates are typical for epidote. Ilvaite and magnetite are directly associated with epidote. Magnetite $[(Fe_{0,995}Mn_{0,005})Fe_{1,999}O_4]$ was formed during the decomposition of hedenbergite and garnet, formed earlier. Skarn minerals were replaced by actinolite and chlorite with quartz, calcite, and associated sulfides (pyrrhotite, galena, and sphalerite; Ruchkin et al., 1984). Two types of ore bodies are known at the deposit: skarn-magnetite and skarn-sulfide (base-metal). Magnetite

ore bodies are usually separated from sulfide ores; however, later generation chalcopyrite, pyrrhotite, and Co-minerals (cobaltite and glaucodot) are often associated with magnetite ores.

Another example of iron skarn deposit is the Khrustalnoye deposit (Fadeev 1974, Nokleberg et al. 2005), located in the southern part of the Omolon microcontinent. Here, ore bodies are localized along the contact between the Cretaceous granite pluton and Neoproterozoic limestone strata. Near the deposit, outcrops of Precambrian magnetite-bearing quartzite are found. Neoproterozoic limestone at the contact of intrusive is transformed into garnet, garnet-pyroxene, and pyroxene-clinohumite skarns. They form a wide (to 600 m) margin along the contact and near the intrusive contact. Skarn mineralogy changes to tremolite-wollastonite marble. Magnetite ore bodies, 800 m long and 100 m thick, form an ore zone exceeding 2 km in length. These ore zones are confined along faults and are lens-like bodies of continuous magnetite ore surrounded by the aureole of magnetite disseminated in skarn. The ore contains 51 to 58 % Fe, with low (to 0.2-0.3 g/t) Au grades (Fadeev 1974, Khanchuk, 2006). Disseminated scheelite is rarely observed in skarn. Ore resources reach 130 Mt.

2.1.2. Tungsten skarn deposits.

The W skarn deposits are located in the Verkhoyansk passive continent margin (Agylky deposit), in the Kular-Nera shelf terrane (O'Keiskoye prospect), and in the Omulevka passive continent margin terrane (Lenkovoye prospect).

The largest is the Agylky deposit (Nokleberg et al. 2005, Gvozdev 2010), described in detail in Naiborodin 1958, Dorofeev 1961, Flerov et al. 1974, and Gvozdev 2010. The deposit is represented by scheelite-sulfide bodies in pyroxene, pyroxene-epidote, and pyroxene-garnet skarns. Skarns replace single thin (3-10 m) beds of Triassic limestone (**Fig. 3**), localized among argillite. Sedimentary rocks form a small anticline fold within the thermal aureole of a granite pluton that is not exposed. Sedimentary rocks are cut by granodiorite-porphry dikes. Primary skarn minerals are intensively replaced by later actinolite, biotite, and sulfide minerals. Ore bodies are composed of three gradually deposited mineral groups: scheelite-quartz, sulfide, and carbonate. Tungsten in the ore is present mostly as scheelite. The principal sulfide minerals are pyrrhotite and chalcopyrite with minor pyrite, arsenopyrite, stannite, sphalerite, galena, bismuthinite, and native bismuth (Naiborodin, 1958; Flerov et al., 1974; Gvozdev, 2010). Banded ores, formed during the selective replacement of carbonate interbeds by skarn and ore minerals, are common.

The Lenkovoye and O'Keiskoye prospects represent this skarn type. The Lenkovoye prospect is localized within the Omulevka passive continental margin terrane. It is the sub-meridionally oriented skarn body, 100 m long and 10 m thick, located along the contact of terrigenous and carbonate Middle Paleozoic rocks. A granitic intrusive (Late Mesozoic?) is presumably found at depths. Skarns are represented by primary

grossular-epidote minerals that have been intensively replaced by later actinolite and chlorite (**Fig. 4**). Scheelite, containing to 4.71 % MoO₃, forms ore disseminated in the grossular-epidote aggregate. There are very few sulfide minerals in these skarn deposits. Low concentrations of Sn were observed in the ore.

The O'Keiskoye prospect is located in southern part of the Yana-Kolyma folded belt, and like the Agylki deposit, it is confined to a thin bed of Triassic limestone. Skarn minerals have replaced the bed in the contact aureole of small granitic stock of the Late Mesozoic age. The main skarn minerals are grossular and epidote; rarely occurs pyroxene. Post-skarn minerals are represented by chlorite and actinolite. Scheelite is associated with epidote.

2.1.3. Molybdenum skarn–deposits

Molybdenum skarn deposits are rare and located in microcontinents associated with ancient carbonate strata. The Med'gorskoye deposit is situated in the northern part of the Omolon microcontinent. Skarns are localized along the contacts between of the Medgorsky Cretaceous granitoid pluton (3 km²) and the Lower Carboniferous marble (Litvin 1959). The major pluton phase is granodiorite and quartz monzonite, whereas the marginal phase is porphyritic diorite. The main skarn bodies are located along the southern contact of pluton (about 1.2 km²). The principal skarn minerals are garnet, pyroxene, scapolite, actinolite, epidote, chlorite, calcite, and quartz. Magnetite, hematite, pyrite, chalcopyrite, molybdenite, pyrrhotite, and sphalerite are the widest-spread among the skarn, as well. Molybdenite is irregularly distributed in the ore. Large accumulations of molybdenite ore are confined to the later actinolite-chlorite alteration phase. Four ore bodies, 100-150 m long and 2-28 m thick, are known. The Mo average grade is 0.13 to 0.4 % (Litvin 1959).

The Murometz deposit is located on the southern flank of the Okhotsk microcontinent. Skarn bodies occur in Middle Cambrian dolomite beds along the contact with the Early Cretaceous quartz monzodiorite pluton. Skarn mineralization extends for 1000 m and gently (20-40°) dips beneath the pluton. Early skarn mineralogy is magnesium rich (spinel, forsterite, diopside, tremolite, phlogopite), whereas later it is more calcic (pyroxene-salite and diopside; garnet-grossular and andradite; scapolite) (Nikitin & Rasskazov 1979, Krasny & Rasskazov 1975). Calcic skarn mineralogy is predominant.

The latest ore stage is represented by magnetite, chalcopyrite, molybdenite, scheelite, pyrrhotite, bornite, pyrite, galena and sphalerite. These minerals compose several bodies 6-12 m thick, consisting of stockwork veinlets, disseminated ore, and, rarely, massive ore. Disseminated Cu mineralization (chalcopyrite) is also observed in altered quartz monzodiorite (Nikitin & Rasskazov 1979, Krasny & Rasskazov 1975). The Cu grade

is up to 10 %; Mo, to 0.3 %; and occasional WO₃, up to 0.92 %.

2.1.4. *Pb-Zn skarn deposits.*

The Pb-Zn skarn deposits are widespread in the Omulevka passive continental margin terrane (e.g., Verkhny-Taskan and Kunarevo ore districts). Pb-Zn skarn deposits of Verkhny-Taskan district, (Vera, Nadezhda, and Terrassnoye) were formed along the contact with the apical part of the Khiulchan granite pluton (**Fig. 5**). Two types of Pb-Zn skarns are distinguished on the basis of their distance from the contact with granite: the Vera skarn, in the upper part of intrusion zone, and the Nadezhda and Terrassnoe skarns, formed in the periphery zone of the intrusion.

Skarn bodies of the Vera ore deposit are localized along the contacts of granite- porphyry and granite with the Middle Devonian limestone. These pyroxene-garnet and often garnet-magnetite skarn deposits form lens-like bodies, to 15-20 m thick and to 100 m long. Zonation is rarely observed: granite-porphyry – garnet-magnetite skarns – garnet-epidote skarn – pyroxene skarn – limestone.

The Nadezhda and Terrassnoye skarn deposits in the periphery zone are located 1.5-2 km from the granitoid pluton contact. The Nadezhda ore deposit is located along the contact between a dike of diorite porphyry and Middle Devonian limestone. The Terrassnoye ore deposit (Kontaktovoye ore body) is localized along the tectonic contact with the Upper Devonian limestone and Carboniferous-Permian cherty-carbonate terrigenous rocks (Shpikerman, & Sotnikov 1983). Pyroxene-garnet and epidote-pyroxene-garnet facies compose the skarn silicate mineralogy. The ore bodies extend for several hundred meters. Zonation is not characteristic for the deposit. Sulfide mineralization is superimposed on the skarns. The earliest mineral association in skarn is represented either by pyroxene or pyroxene and garnet. Pyroxene usually forms radial aggregates (**Fig. 6**). Ore samples, observed in thin-sections, show a thin zone of fine-grained pyroxene, laid at the base of the sphalerite zone. Layers of later quartz-calcite with chlorite, epidote, and redeposited garnet are often developed along them. Usually there are 2-3, at most 5 of such layers; each layer to 10 cm thick. For the Dalnegorsk skarn deposit in the south of the Russian Far East, such bedding was interpreted as a result of a gradual increase in different pyroxene generations (Khetchikov 1960). However, the pyroxene composition in different layers is identical, and their composition within single crystal is regular. There are not distinctly expressed inner skarn tectonic. All of the above mentioned indicates that they were formed as simultaneous metasomatic replacement of thin layers of the bedded substratum. Such interbedding is possible, in particular, along the contacts of limestones and siltstones. Within the Verkhny-Taskan skarn district, regular changes in composition of pyroxene from salite (Vera and Nadezhda) to hedenbergite (Terrassnoye) are observed. The Mn content of pyroxenes also increases. It should be noted that, in the Nadezhda skarn deposit, two generations of pyroxene are found: 1) earlier salite and 2) later hedenbergite. In pyroxenes of the Terrassnoye skarn deposit, the early generation of garnet, contains to 40% grossular molecule. Garnet forms fine-grained isotropic aggregates in pyroxene, and sometimes composes

the nucleus of anisotropic recrystallized andradite. The later association of post-skarn alteration is represented by chlorite, epidote, quartz, and calcite. Epidote in the Nadezhda deposit skarn probably belongs to the skarn mineral assemblage and replaces garnet. By composition, epidote is a ferruginous variety that may have been formed during the later stage alteration. Layers of quartz with calcite cut the skarn, and replace anisotropic andradite with a large percentage of spessartine molecules (up to 7.3%). Andradite often composes string margins overgrown by thin spines and plates of hematite. Usually, a later alteration mineral assemblage replaces skarn minerals along grain boundaries or in small crystalline masses. Actinolite is not found. Chlorite compositions are magnesia-ferruginous with manganese admixtures.

Skarn of the Kunarevo ore deposit. The Kunarevo Pb-Zn (Ag) deposit (Shpikerman 1987, Shpikerman & Sotnikov 1983) is located in the Omulevka passive continental margin terrane. The deeply eroded Late Jurassic - Early Cretaceous volcanic structure of the Uyandino-Yasachny volcanogenic belt (island arc) forms the basement of the ore district. Rocks beneath the volcanic belt include Paleozoic terrigenous-carbonate strata. The volcanic structure itself is composed of gently dipping Middle- to Upper Jurassic volcanoclastic-sedimentary strata. This volcanic-sedimentary assemblage is underlain by a single conglomerate bed. In the central part of the structure, a volcanic-tectonic depression, 4-5 km in diameter, is traced in the Paleozoic basement rocks, intensively altered into skarn and propylitic mineral assemblages. Small plutonic bodies, consisting of diorite and granodiorite, dacite-porphyry and granite-porphyry, intrude Mesozoic volcanoclastic-sedimentary sequences and Paleozoic basement rocks. . At the NEISRI Laboratory, a Rb-Sr isochron was obtained from the rhyolite using standard methods, which resulted in the age of 141.5 ± 6.5 m.y. with $Sr_0 = 0.7090 \pm 0.0003$ (**Table 4**). Skarn mineralization is intensively developed at two locations (Skarnovy and Kohglomeratovy) in the southern and western flanks of the structure. Copper-porphyry mineralization is observed in the central part of the volcanic structure (Shpikerman, 1998).

The Skarnovy skarn is located in the contact zone of the quartz diorite stock. Ore bodies are represented by numerous (about 30) skarn and sulfide ore veins and lenses. They occur as either vertical or steeply dipping veins, ranging from 0.3 to 3.5 m in thickness and from 40 to 400 m in length. These veins cut contact-metamorphosed Mid-Upper Jurassic siltstone and diorite of the stock. The major vein minerals are hedenbergite, garnet, and quartz; galena and sphalerite are dominant sulfide minerals.

The Konglomeratovy skarn, located to the south of Skarnovy, is represented by a gently dipping skarn body with sulfide mineralization localized in calcareous conglomerates. Ores are low-grade and disseminated. The ore body is 10-25 m thick and is localized under the shale. Mineralization is traced by drill holes to the depth of 300 m. The main ore body (No. 1) is a skarn vein deposited in fractures and cutting the contact metamorphosed siltstone and diorite. The vein is exposed in a steep vertical section for 100 m: it has a complex composition and is composed

predominantly of aggregates of epidote, pyroxene (hedenbergite and ferrosalite - up to 20% of diopside molecule), actinolite, ferrous chlorite, and quartz with lenses and bands of fine-grained sulfides (sphalerite, pyrite, pyrrhotite, and galena). Locally this vein appears as breccia-like. In the vein, vertical zonation is observed with – pyroxene (hedenbergite)-ilvaite skarns in the upper part, pyroxene (hedenbergite)-epidote skarns with the ilvaite admixture and abundant sulfide at middle horizons, and the lower part composed of pyroxene-epidote skarns and epidote-chlorite alteration. In some sections of the lower part of the vein, relict crosscut zonation (diorite - epidote hornblende alteration – pyroxene skarn – quartz - chlorite breccia – epidote-quartz-sulfide vein – hornblende alteration – diorite) is observed. Epidote-pyroxene skarns compose the base of skarn bodies of the Konglomeratovy section, where later epidote-chlorite alteration is intensively developed within them. Major ore minerals are sphalerite and pyrite; galena, chalcopyrite, and pyrrhotite also occur. Ore body No. 1, contains 1.05% Pb, 10.5% Zn, 0.97% Cu, 170 g/t Ag, 38 g/t Sb, and 538 g/t Bi. Total resources of the deposit are estimated as 80 Mt of Pb-Zn ore.

Skarns of the Arman district. The district is located in the outer part of the Okhotsk-Chukotka volcanogenic belt (Umitbayev 1986). It is confined to the domed Upper Permian and Triassic terrigenous rocks in the Viliga shelf terrane. These sedimentary rocks are cut by small stocks of Late Cretaceous granite, granodiorite, and syenite-diorite. Skarn formed along the shelly stratum of the Norian (Upper Triassic) limestones at the exocontact of the Bonsalchan leucocratic granite stock. The skarn mineralization area is not large (2×5 km), but a large pluton, based on a vast hornfels and a large geophysical anomaly over the deposit, is inferred at depth. Skarn Pb-Zn deposits, associated with those of the Sn ore, are attached to the intrusive zone above the pluton. Skarn mineralization is confined to a 5-20 m thick marble stratum within the hornfels. Skarn mineralization consists of pyroxene-epidote, garnet-pyroxene, rarely garnet facies; no zonation is exposed. Skarn minerals are intensively replaced by later actinolite-chlorite and quartz alteration. The alteration zone is associated with intensive sulfide mineralization (pyrrhotite, galena, and sphalerite). Sulfide mineralization composes lenticular ore bodies, to 200-300 m long and 1-5 m thick, that are often attached to faults. Ores are disseminated, but the main ore body is represented by massive aggregates of pyrrhotite and sphalerite with galena and sometimes arsenopyrite and chalcopyrite. Later quartz-calcite-fluorite veins and veinlets are widespread in them.

2.1.5. Gold-(cobalt) skarn deposits.

Au (Co) skarn deposits of the Tuguchak area. Kandidatskoye, Arbatskoye, Zeiskoye, Khospokchan, and other skarn ore deposits (Nekrasov 1962, Goryachev & Polovinkin 1980, Polovinkin & Goryachev 1981, Bakharev et al. 1988) are located along the southern contact of the large granodiorite-granite Ulakhan-Tass pluton with limestones and terrigenous rocks of the Ulakhan-Tas section of the Omulevka passive continental

margin terrane. The Kandidatskoye deposit is typical and the largest (**Fig. 7**), represented by a skarn zone of garnet-pyroxene, pyroxene, wollastonite-pyroxene, and epidote-pyroxene compositions. The skarn bodies, containing occasional axinite, formed along the contact of Permian terrigenous and limestone strata above the Early Cretaceous granodiorite pluton. The ore body is steeply dipping and funnel-shaped in cross section; it is 150 m long and 20 m wide and contains both massive and disseminated sulfide-arsenide ore. At a depth of 50 m, the ore body decreases to 10 m in thickness. The skarn is characterized by fine-grained mineralogy. Cross-section zonation is as follows: biotite hornfels, a thick zone of pyroxene-plagioclase, sometimes scapolite-pyroxene around the skarn rock (2-3 times thicker than the skarn), fine-grained garnet (grossular)-pyroxene (salite) skarn (often this zone is absent), fine-grained-pyroxene skarn, a thin zone (0-2 m) of wollastonite-pyroxene skarn, and marble or pyroxene hornfels.

Lollingite and arsenopyrite mineralization (**Fig. 8**), often accompanied by later minerals containing Bi and Au, is superimposed on the skarn body. Ore mineralization is irregularly distributed, from the disseminated sulfide-skarn ore to the massive sulfo-arsenide ore. Three post-skarn mineral assemblages are distinguished by their composition: lollingite-arsenopyrite with the minerals of Co (Co-arsenopyrite, lollingite, cobaltite, nicelite, glaucodot, safflorite), pyrrhotite-polymetallic (pyrrhotite, chalcopyrite, sphalerite, galena), and Au-Bi (bismuthinite, joseite A and joseite B, hedleyite, maldonite, native Bi and Au) (Bakharev et al. 1988, Gamyagin et al. 1998). Ore grades range to 55 g/t gold (average 7- 10 g/t), to 3-5% As, Co and Zn, and to 0.5% Bi and Ni. Gold is very fine-grained, less than 0.1 mm, and its fineness ranges between 600-1000 (Bakharev et al., 1988).

In the Tuguchak area, large (to 1-2 km²) skarn bodies are often found. These deposits consist of series of lenses, veins, and veinlets of coarse-grained garnet with the axinite. Sometimes, axinite, axinite-pyroxene with calcite veined rocks completely replace the garnet skarn. Occasionally, skarns are cut by aplite veins and by quartz-tourmaline veinlets. Skarn garnets of the Tuguchak area are grossular, but pyroxene composition is salite.

By characterizing the gold skarn type, we feel obliged to comment on the possible prospects of gold-skarn mineralization (Teutejak and others) in the Northern Priokhotye (Volkov et al., 2008). These are the outer zones of the Uda-Murgal and Okhotsk-Chukchi active magmatic arcs. According to Volkov et al., they are typical gold skarn deposits. But we have to say that, according to our data (Goryachev et al., 2006) and the data presented on Fig. 2 (Volkov et al. 2008), the skarns of the Teutejak deposit are overlapped by the later gold-bearing quartz stockwork with gold-bismuth mineralization, accompanied by quartz-tourmaline-sericite alteration. This means that the Teutejak deposit is not genetically gold-skarn, unlike, e.g, the Hedley gold skarn deposit in British Columbia, Canada (Ray & Dawson 1994, 1998). This is a typical intrusion-related stockwork-

type deposit (Goryachev et al., 2006). In Teutedjak skarns, only pyrrhotite-base metallic ores of the same type as the Armansky skarn field are genetically related, and gold mineralization was superimposed on the skarns about 15 million years later. Therefore, we do not characterize this as a gold-skarn deposit and cannot assess the prospects of this area for gold-skarn mineralization.

2.1.6 Tin skarn ore deposits.

Sn skarn deposits are associated with carbonate strata of the Omulevka passive continental margin terrane, where they were intruded by collisional granites of the Main Kolyma batholite belt. The Kanyon deposit (Vladimirov 1958, Politov 1983, Politov & Partsevsky 1983) and the Chibagalakh deposit (Flerov 1976, Flerov et al. 1974) are typical examples.

The Kanyon deposit is located at the south-western contact of the Kanyon pluton with Permian limestones of the Turinskaya suite. Skarn ore bodies lie along the contact of marble beds with the roof of the Kanyon pluton, leucocratic biotite granite. Flat and lensoid skarn bodies are steeply (45-85°) dipping to the west or north-east, depending on the attitude of the bedding at the intrusive contact. Skarn bodies are typically 200-300 m or longer, irregular (0.5 to 20 m) in thickness. Occasionally, some ore bodies converge at depth into a single body more than 30 m thick (**Fig. 9**). The skarn of the Kanyon deposit has variable composition: pyroxene-wollastonite, pyroxene, pyroxene-garnet, garnet, garnet-vesuvianite, and pyroxene-axinite. Datolite and danburite are present (Vladimirov 1958), as well as a rare Sn silicate - malayaite (Politov & Partsevsky 1983). Later minerals are calcite, fluorite and quartz. The specific feature of the skarn is the huge crystalline aggregates of hedenbergite (to 50 cm), datolite, danburite, axinite, and andradite with arsenopyrite and arseno-sulfosalts. Recrystallized andradite contains about 1% Sn. Sometimes, recrystallized andradite veins cut the earlier skarn (**Fig. 10**), but more often they form large aggregates. Greisen of quartz-muscovite composition with tourmaline, cassiterite, arsenopyrite, sphalerite, and calcite is superimposed on the skarns. Cassiterite crystals are coarse grained and reach 1.5-3 cm on the long axis.

In mineral deposit formation, we distinguish three events: (1) skarn, (2) post-skarn (recrystallization and boron mineralization), and (3) greisen ore. The last event may be subdivided into three stages: cassiterite-muscovite, polysulfide, and quartz-calcite-fluorite. Ar-Ar data from the last stage muscovite has a plateau age of 145.2 ± 0.6 Ma (Newberry et al. 2000), same as granites. A Rb-Sr isochron from granite gave the age of 151 ± 11 Ma with $Sr_0=0.7108 \pm 0.0007$; and SHRIMP zircon data, 148 ± 2.2 , 150 ± 2.1 , 150 ± 2.2 , 156 ± 2.4 , 163 ± 3 , and 153.1 ± 2.4 Ma (Kuznetsov et al. 2008) (See Table 4). More than 60 skarn bodies are known at this deposit; only 16 are Sn-bearing. The Sn grade ranges from 0.01 to 14%. The deposit is explored by adits and trenches; the resources comprise about 800 000 t of ore with an average Sn grade of 1%.

Likewise, Sn mineralization in the Chibgylykhsy skarn deposit is located on the Selenyakh Ridge (Flerov 1976). A few dozens of skarn ore bodies, 0.2-20 m thick and up to 260 m long, are localized at the contact of the Early Cretaceous granite pluton with the Early Paleozoic limestone and dolomite of the Omulyovka passive continental margin terrane. Unlike the Kanyon deposit, magnesia skarn with the ludwigite mineralization formed here in dolomite at the early stage. The skarns are preserved as relicts among the later calcic skarn mineralization represented by pyroxene-wollastonite, pyroxene-garnet, garnet, and garnet-vesuvianite facies. Subsequently, epidote-chlorite alteration was superimposed on the skarns. Similar to the Kanyon deposit, high-grade Sn ore (to 0.6%) is present in andradite and vesuvianite (Flerov 1976, Flerov et al. 1974, Belinsky 1989). Cassiterite, deposited at the latest greisen stage, is associated with muscovite, quartz, tourmaline, accessory beryl and fluorite. In this stage, sulfide phases are characterized by pyrrhotite-sphalerite with smaller amounts of arsenopyrite, iliolingite, stannite, and chalcopyrite (Flerov, 1976, Flerov et al. 1974).

2.2. Host rocks and terranes.

2.2.1. Tectonic history.

Northeast Russia is a complex mosaic of terranes accreted to the passive margin of the Siberian craton in Late Mesozoic time (Parfenov & Kuzmin 2001, Nokleberg et al. 2005, Khanchuk 2006). These terranes are mostly fragments of the passive Siberian continental margin that rifted from it in the Early Paleozoic (Shpikerman 1998). The rifting events of the passive continental margin essentially resulted from accretionary tectonic processes at the end of the Middle Jurassic time, caused by the increase in the Kula plate spreading rate, the opening of the Canadian basin in the Arctic, and the change in the movement of the North-American plate (Parfenov 1984, 1995; Zonenshain & Natapov 1987). Uyandina-Yasachnaya, Svetonosko-Oloyskaya, and Uda-Murgal subduction-related magmatic arcs could not compensate tectonic processes in the Arctic and the Pacific, and the convergence of these moving plates at that time. As a result, compression led to complex folding of the strata and to the emplacement of magmatic belts in the area (Parfenov & Kuzmin 2001, Khanchuk 2006). In Middle Cretaceous, the Okhotsk-Chukotka volcanogenic belt formed along the new continental margin (Belyi 1994, Khanchuk 2006), which was accompanied by intrusion of post-accretionary granitoid plutons (90-70 m.y.).

2.2.2. General description of host rocks.

This huge territory of North East Russia (over 2 million km²) is characterized by a miogeoclinal that folded and deformed strata; it was these tectonic zones that hosted gold-quartz mineralization. Another characteristic of the area is Late Mesozoic orogenic events (Goldfarb et al. 2014). Tectonic zones include the largest sialic province of Mesozoides, the Verkhoyansk-Kolyma folded district. Skarn ore deposits and prospects formed (**Fig. 11**) at the locations where Late Mesozoic granitoid plutons intrude limestone and marble in various tectonic settings.

Most skarn mineralization is found in the Paleozoic carbonate rocks of the Omulevka passive continental margin terrane (Omulevka, Selennyakh, and Ulakhan-Tas districts). In this terrane, deformed rocks were intruded by diorite and granite plutons of the Late Jurassic – Early Cretaceous age and formed Pb-Zn, Sn, and Fe skarn ore deposits. Skarn deposits (Fe, Mo, and Cu) are also found in Proterozoic and Lower Paleozoic carbonate suites of the Omolon, Okhotsk, and Seward microcontinents (cratonic terranes), where they are associated with the post-accretionary granitoid intrusives. Skarn mineralization rarely occurs among the Mesozoic deformed sedimentary rocks of the Verkhoyansk passive continental margin, and the Svyatonosky and Viliga shelf terranes. There skarns form singular deposits or groups of ore occurrences confined to the occasional thin bands of Permian or Triassic limestone along the contacts with accretionary and post-accretionary granitic plutons of the Early (W and Au-Co deposits) and Late (Pb-Zn deposits) Cretaceous time.

There three events resulted in the development of skarn ore deposits : (1) typically, they were formed along the contact of granite plutons with marble or limestone, (Med’Gora, Chibagalakh, Kanyon skarn fields, etc.); (2) skarn ore bodies were formed locally along the contact of hornfels and marble or limestone, (Kandidatskoye, Kunarevskoye, etc.); and (3) skarn mineralization replaced a single bed of limestone in the contact aureoles of granitoid plutons (Agylki, O’Keiskoye, Teutedjak, and skarn deposits in the Verkhne-Armansky district). These three kinds of skarn mineralization are typical for different skarn ore deposits, irrespective of their age.

Besides, single skarn deposits, such as the Kunarevskoye deposit (Shpikerman 1998), occur very rarely. These ore bodies crosscut Jurassic sedimentary and intrusive rocks, e.g., chlorite-polysulfide veins at the Orlinoye deposit. Similar veins are known within the neighboring volcanic structures of the Uyandino-Yasachny volcanogenic belt (Shpikerman 1987, 1998).

2.2.3. Skarn-forming plutons: composition, age, and tectonic settings.

Magmatic skarn occurrences are represented by the Uyandino-Yasachnaya and Uda volcanic belts conjugated to sedimentary basin, isolated volcanic structures, and numerous plutonic granitoid belts. The belts are developed along the boundaries of the major terranes and

within the Verkhoyansk miogeocline belt (Parfenov, 1995). They form skarn deposits in the Main Kolyma, North- and South-Verkhoyansk granitoid belts with plutons of collision and subduction signatures (Fig. 11, 12). Post-accretionary magmatism of the Okhotsk-Chukotka active continental margin magmatic belt is of great importance here. Plutonic and volcanic belts control the setting of many Mo and Pb-Zn skarn ore deposits. Using geological and geochronological data, we distinguish three series of Late Mesozoic granitoids for Northeast Russia: (1) collisional - Late Jurassic-Early Cretaceous; (2) accretionary - Early Cretaceous; and (3) post-accretionary - Late Cretaceous (Goryachev & Goncharov 1995). Among those, diorite-granodiorite, granodiorite-granite, alkaline granite and granite-leucogranite associations are distinguished. SHRIMP U-Pb, Rb-Sr, and Ar-Ar age data (Table 4) show the synchronism of the formation of granitoids in some associations with that of other rocks only at particular stages of the regional history (Goncharov 1995, Goryachev 1998, Newberry et al. 2000, Kuzmin & Parfenov, 2001, Khanchuk, 2006, Akinin et al. 2009). Irrespective of the host rocks character, localization of skarn deposits is mostly determined by the fact that granitoid plutons are located either near the contact with skarn bodies or at the depth beneath them. The composition of magmatic rocks associated with various skarn types differs (**Table 5**).

Most of the intrusive rocks are hypabyssal granodiorites and granites with signatures of granitoids of I- and S-types of the ilmenite series (Trunilina 1992, Goryachev & Goncharov 1995, Parfenov & Kuzmin 2001, Khanchuk 2006). Some of them are included in volcanic-plutonic associations (e.g, plutons of the Kunarevo and Khiulchan fields in the Late Jurassic Uyandino-Yasachny island-arc volcanic belt and the Arman field in the Okhotsk-Chukotka magmatic belt). According to geochemical data, they predominantly belong to the subduction-related pluton type. The Kanyon and Ulakhan-Tass plutons have the geochemical signature closer to S-type collision granites than I- and A-type (**Fig.12**). The skarn mineralization age is determined mainly by that of the associated granites (**Table 4**).

2.3. Data for skarn mineral assemblages and compositions.

Mineral composition and skarn mineral zonation are typically observed in skarn bodies along intrusive and marble contacts. In skarn bodies developed along the contact of hornfels with marbles, scapolite and pyroxene-plagioclase zones occur. We distinguish three mineral assemblages in skarn bodies: (1) skarn assemblage containing wollastonite-pyroxene, pyroxene, pyroxene-garnet, vesuvianite-garnet, epidote-garnet, and garnet facies, (2) later skarn assemblage with epidote, epidote-magnetite, axinite, magnetite-ilvaite facies, and (3) post-skarn assemblage with actinolite, chlorite, chlorite-calcite, axinite-quartz, and calcite.

2.3.1. Description of the main skarn minerals.

Garnets. The study of garnets from skarn deposits of different types has shown that the earlier garnet is characterized by its essentially grossular composition, but the later garnet composition is andradite. The later anisotropic garnet is of practically pure andradite composition. As a rule, in the center of garnet crystals are enriched with the grossular molecule (**Fig. 13**). As shown on the diagram (**Fig. 14**), garnets from the skarn-polymetallic ore deposits of the Omulevka composite terrane occur essentially in the field of garnets with the predominance of the andradite molecule. Thus, they are close to composition of the garnet from Pb-Zn deposits in Primorye (Far East of Russia). Simultaneously, the garnet from skarn deposits in island arc terranes, such as in the Arman field, has more grossular composition. Fields of grossular garnets in composition are close to garnets from W deposits (Lenkovoye, O'keiskoye) and the Au-skarn Kandidatskoye deposit (See Fig. 14).

Pyroxenes. Pyroxenes expose similar differences in composition. Pyroxenes from skarn deposits of the Omulevka composed terrane are close in composition to those from skarn Pb-Zn deposits in the Far East Russia (**Fig. 15**). An exception is pyroxenes (salites) of the Verkhny-Taskan area their composition similar to that of salites from Au-skarn deposits of the Ulakhan-Tass Ridge. Pyroxenes of the Arman Pb-Zn skarn area are close to them in composition, differing only in Mn enrichment. For both garnets and pyroxenes from different deposits, the Fe content from earlier to later generations and from the center to the rims of crystals is consistently increasing.

Chlorite. The composition of post-skarn chlorite depends mainly on the composition of the initial skarn minerals. In cases of pyroxenes with a relatively higher MgO content, Mg-chlorites are observed (Lenkovoye, Nadezhda); with ferrous pyroxenes (Kanyon, Kunarevo), chlorite has a very high Fe content.

2.3.2. Compositions typical of skarns hosting different mineralization types.

Skarn ore deposits with W mineralization belong to the garnet-epidote and pyroxene facies, unlike the garnet-pyroxene skarns with Sn, Au and Pb-Zn mineralization. Sn-bearing skarn deposits have increased Sn grade in later garnet generations (**Fig. 16**), reaching 1.34 % SnO₂ with accompanying later boron-silicate mineralization. Our data on the skarn bodies of the Tuguchak ore district attest to the fact that the geochemical speciation of skarn minerals depends on the type of ore mineralization that accompanied them. Thus, non-mineralized skarn from Au-skarn deposits has the larger concentrations of Au and Co than hornfels, whereas skarn bodies containing only Co or Pb-Zn (**Fig. 17**) have lower Au grade than hornfels and granitoids. Sn-bearing polymetallic skarns contain very small Au and Co concentrations.

2.3.3. Mineralization in skarns.

Scheelite commonly occurs as a typical mineral associated with epidote in W skarns and often occurs in Pb-Zn skarn deposits. However, two very different types of occurrences of scheelite are distinguished: one is the epidote-grossular-scheelite assemblage without sulfides in the Lenkovoye skarn deposit (Omulyovka terrane); another, the epidote-quartz-scheelite assemblage in the Pb-Zn skarn deposits in the Kunarevo district. Scheelite in these assemblages differs in composition and luminescence. Scheelite in the first assemblage has yellow luminescence and contains to 4.71 % MoO₃, whereas scheelite in the second assemblage has blue luminescence and contains less than 0.57 % MoO₃. We assume that scheelite with higher Mo concentrations was formed in the high calcic epidote-garnet scheelite skarn paragenesis, i.e. garnet with more than 50 % of grossular molecule is primary and earlier, while scheelite from sulfide skarn deposits is later and probably secondary, i.e. it was recrystallized.

Polysulfide mineralization is localized either among the pyroxene skarn minerals or in close association with post-skarn silicate minerals. It is represented by deposit-specific mineral assemblages. Thus, Mo, Au, and Co deposits have high concentrations of arsenopyrite and lollingite and are characterized by the presence of Co and Bi minerals (in Au deposits). Pyrrhotite, galena, and sphalerite are typomorphic for Pb-Zn deposits. Typical for Sn deposits are arsenopyrite, cassiterite, and sphalerite; and indicative for W deposits are mainly scheelite, minor pyrrhotite, chalcopyrite, bismuthine, and sulfo-tellurides of Bi (Agyłki). These mineral suites from the polysulfide assemblage appear typical of the final stages in formation of various skarn deposits.

2.3.4. Sulfur isotope data.

The sulfur isotopes in sulfides from various metal skarn deposits are relatively light (**Table 6**). But the sulfur isotopic composition of sulfides from Pb-Zn skarn deposits differs from that in Paleozoic stratiform and stratabound Pb-Zn deposits of the Omulevka terrane, though they are spatially associated. Sulfides of these skarns contain relatively lighter sulfur isotopes ($\delta^{34}\text{S}$ up +0.6 to -10.8‰) (**Fig. 18**), which is close to the $\delta^{34}\text{S}$ sulfide composition in Sn skarn (Flerov et.al. 1981, Ishihara et.al. 1995) and in granitoid-related Au ore and orogenic Au deposits (Goryachev 2003, Goryachev & Pirajno 2014). It is plausible to argue for a juvenile origin for the light sulfur. It should be noted that sulfides from the Paleozoic Pb-Zn stratiform deposits of the Omulevka terrane contain heavy sulfur, probably derived from sea water ($\delta^{34}\text{S}$ from

Permian sea water was +12 to +15‰; Chang et al. 2008).

2.3.5. Lead isotope data.

A study of Pb isotopes in arsenopyrites, pyrrhotites, and galena from skarn ore deposits (**Table 7**), conducted by the US Geological Survey (Church et al. 2013) has shown that sulfides from various skarn ore deposits (Au, Pb-Zn, Mo, and Sn) have a range of Pb isotopic values. Deposit types cannot be distinguished by their Pb-isotope compositions. Pb in the skarn deposits has apparently been derived from the low crust (**Fig. 19**). The Pb- isotopic signature, in general, reflects the age of the tectono-stratigraphic terrane of the host rocks at depth. Model Pb-Pb ages become younger, as the accreted terranes age is getting young to the east of the Siberian craton.

2.3.6. Sr isotopic data in granitoids.

Data on Sr isotopes in several skarn-producing granitoids (**Table 4**) show the possible participation of mantle and crustal sources in their formation. While being formed, subduction-related granitoids acquired an essentially primitive or mantle signature, but collision granitoids (Kanyon pluton) have crustal signatures, i.e. higher $^{87}\text{Sr}/^{86}\text{Sr}$ values.

2.3.7. Temperature conditions of skarn formation.

Mineral assemblages and compositions of co-existing pyroxenes and garnets make it possible to estimate formation temperatures for skarn deposits belonging to the wollastonite-pyroxene, pyroxene-garnet, and pyroxene-garnet-epidote facies. According to V.A. Zharikov (1968, 1985), these skarn deposits were formed at 700-500°C. The presence of epidote and axinite as well as the increased values of the Fe distribution coefficients in the coexisting pyroxenes and garnets ($K_p=0.13-2.5$) indicate that the skarns were formed under conditions of normal to decreased acidity. Pyroxene-scapolite paragenesis of some deposits (e.g., Kandidatskoye, Med'Gora) was formed under the same conditions. Basing on the paragenesis of garnet-epidote facies in W-bearing skarns, they crystallized in the environment of increased alkalinity at relatively lower temperatures (400-500°C), according to the classification by V.A.Zharikov (1968). Judging by the experimental data (Kurshakova 1968), axinite crystallized at temperatures of 400-350°C due to the increase of acidity of the hydrothermal fluid and boron activity. The study of the homogenization

temperatures of the primary skarn minerals from the Kanyon exposed the maximum homogenization temperatures of 640-665°C that garnet and vesuvianite, while pyroxenes have lower temperatures, ranging from 550-630°C (V.K.Politov et al. 1981 - written com.). Recrystallized skarn minerals have homogenization temperatures of 425-450°C; cassiterite, between 450-328°C. These data are close to the maximum temperatures for minerals from calcic Sn-skarn of the Chubagalakhsky deposit (Belinsky 1988).

3 Discussion

Major factors that influenced skarn mineralization types are magmatism and the tectonic setting (Einaudi et.al. 1981). Examples from Canadian Cordillera have shown that Fe, Cu, and Au skarn deposits are mostly localized in the island-arc terranes, while W skarn deposits are found in passive continental margin terranes of the North-American craton (Ray & Dawson 1998). This implies correlation between the skarn composition and type of mineralization, and the type of the host terrane. Data from this study as well as from other investigators show that skarn ore deposits in Northeast Russia are genetically related to I-type granitoids predominantly of the ilmenite series. They were formed in active continent margin magmatic arcs, island arcs, and collisional tectonic settings. Locations of skarn deposits of different types are probably influenced by the rocks composition in the host terranes: e.g., Sn skarn deposits (Kanyon, Chybygalakh), major Pb- Zn skarn deposits (Kunarevo, Terrassnoe, Mikhailovskoye), and Fe skarn deposits (Cherninsoye) are located in predominantly limestone terranes of the passive continental margin. However, W-Cu (Agylky, O'Keiskoye) and Au-Co (Kandidat, Arbat, and Khospokchan) skarn deposits are hosted mostly in the Verkhoyansk passive continent margin, with predominantly terrigenous shelf suites and island arc terranes with terrigenous shelf sedimentary rocks. Both Fe and Mo skarn deposits (Khrustalny, Med'Gora) are known in the Omolon and Okhotsk microcontinents, but these skarn types are also found in the Cretaceous active continental margin magmatic belt. In all these cases, the granitic bodies are I-type granitoids of differing ages (See Table 4) within different host terranes.

The data on $\delta^{34}\text{S}$ and Pb isotope composition make it possible to assume the magmatic source of the skarn deposits. It follows from the practically identical composition of Pb isotopes of the skarn ore deposits localized in different terranes, as well as from their characteristics similar to those of granitoid-related Sn and Au deposits in the area (see Fig. 19). However, it should be mentioned that the $\delta^{34}\text{S}$ isotope composition of skarn deposits in the Omulevka terrane differs from that of Permian Pb-Zn stratabound and stratiform deposits (See Fig. 16). This fact argues for a magmatic source of Late Mesozoic skarns. However, the $\delta^{34}\text{S}$ data from Pb-Zn stratabound deposits probably comes from seawater. The Pb

isotope data generally indicate a low crustal origin for Pb, which we suggest to interpret as derived by fluid circulation within underlying crustal levels.

Likewise Northeast Russia's skarn deposits associated with similar granitoid types indicate that differences in skarn minerals composition depends on the type of host rocks. These differences are not associated with the character of ore mineralization. Thus, the garnet from Pb-Zn and W skarn deposits in terrigenous terranes has a higher TiO₂ grade than that in the garnets of the same types of skarn deposits in terranes with limestones dominating among sedimentary rocks (**Fig. 20**), and these compositional data permit to demonstrate the host rocks influence on the garnet composition. Normally, garnets of Au-Co, Sn, and Pb-Zn skarn deposits localized in shelf terrigenous terranes have a composition with more grossular molecules than garnets of Pb-Zn and W skarns in carbonate terranes (see Fig. 14). We have shown that pyroxenes in Au-Co and Pb-Zn(Ag) skarn deposits localized in terrigenous and island arc terranes are salites, while pyroxenes in skarn deposits in carbonate terranes are hedenbergites (see Fig. 15). However, the latter may represent reduced skarn facies. Despite the magmatic granite source of skarn deposits, we trace the impact of the host rock composition on the type of ore mineralization and on the composition of skarn minerals.

4 Conclusions

The major skarn mineralization in Northeast Russia was formed during the Late Mesozoic in the accretionary and post-accretionary periods of the regional tectonic history. Skarn deposits of different metals have discrete sets of skarn mineral assemblages. The character of host rocks, more rarely the granitoid type or the type of accompanied mineralization, is strongly correlated with the composition of the principal skarn mineral assemblage: e.g., high concentrations of tin are typical in garnet and vesuvianite from Sn skarn deposits. The Fe grade in the main skarn minerals increases during the skarn deposit formation. Ore mineralization that accompanied the skarn formation has crustal Pb isotope signatures. Subduction-related granitoids have primitive ⁸⁷Sr/⁸⁶Sr values, but collision granitoids ⁸⁷Sr/⁸⁶Sr crustal signatures are higher. Skarn ore specifics vary depending on the geodynamic setting of their formation. Accretionary skarn deposits in collision settings are represented by deposits of iron, tin, and tungsten; to a smaller extent, by base metals and gold skarn deposits. Accretionary and post-accretionary deposits in subduction settings are represented by deposits of molybdenum, base metals, and, possibly, gold. The scale of deposits depends on local geological conditions: the scale of granitoid magmatism and the distribution and thickness of limestone ore-hosting strata. Therefore, skarn deposits of base metals within the Omulevka terrane of the passive continental margin have great prospects.

5. Acknowledgments

The authors are extremely grateful to Professor Rainer Newberry for help and useful discussions. We thank Elena Burak for translating the first version of the manuscript. We are grateful to F. Pirajno, T.Slobodina, and a n two anonymous reviewers for significant improvements to the manuscript.

Part of the research, presented in this report, was sponsored by the Far East Branch of the Russian Academy of Sciences (Project 15-I-2-073).

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Summary of ore-bearing calcic skarn in Northeast Asia

Characteristics	Fe skarn	W skarn	Mo (Cu) skarn	Pb-Zn skarn	Au (Co) skarn	Sn skarn
Relative distribution	Minor (6)	Rare (4)	Very rare (2)	Typical (21)	Rare (4)	Typical (10)
Size	Medium	Medium-to-small	Small	Large-to-medium	Small	Medium
Metal association	Mn	Cu, Bi	As, Cu	Ag	As, Bi, Te, Mo	As
Host terranes	Microcontinents and passive continental margin	Passive continental margin	Microcontinents	Passive continental margin	Passive continental margin	Passive continental margin
Intrusive rocks	Granites of I type, rarely collision granites of S type, and inner plate granites of A type	Collision granodiorites of I type	Magmatic arc (?)	Subduction related diorites and granodiorites of I type and collision granites of S type	Monzonites and granites of magmatic subduction arcs of I type and probable collision (?)	Collision granites of S type
Age of plutons, Ma	Late Cretaceous	145-143	Cretaceous	154-141, and 85-80	140-124	163-146
Volcanic rocks	-	-	-	Andesites and dacites	-	-
Pluton morphology	Large linear plutons and small stocks	Large isometric plutons	Large isometric plutons	Small fractured plutons and dikes, rarely large isometric plutons	Large linear plutons and small stocks	Large isometric plutons
Localization of skarns bodies	At the contact of granites and marbles	Replacement of limestone bands in the supra-intrusion zone	Contact of limestones with granites	Contacts of limestones with hornfels, contacts with granites and diorites	Contacts of marbles with hornfels, contacts with granites	Contacts of marbles with granites
Early skarn associations	Pyroxene, garnet	Pyroxene, garnet, epidote	Pyroxene, garnet	Pyroxene, garnet	Pyroxene, garnet, wollastonite	Pyroxene, garnet, wollastonite
Late skarn associations	Ilvaite, epidote, magnetite	Epidote	Pyroxene	Epidote, ilvaite, magnetite	Axinite, datolite	Axinite, vesuvianite, danburite, datolite

Post skarn associations	Chlorite, calcite, quartz	Biotite(?), actinolite, chlorite, quartz	Chlorite	Chlorite, calcite, quartz	Axinite, quartz	Muscovite, quartz, tourmaline, fluorite, calcite
Ore mineralization (major ore minerals)	Magnetite	Scheelite, pyrrhotite, chalcopyrite, bismuthinite, native Bi	Molybdenite, arsenopyrite, chalcopyrite	Galena, sphalerite, pyrrhotite, sulfosalts	Co-arsenopyrite, lollingite, molybdenite, Bi-sulfotellurides native Au and Bi	Cassiterite, arsenopyrite, sphalerite
Examples of deposits	Khrustalnoye, Arangasskoye	Agylki, Lenkovoye, O'Keiskoye	Med' Gora, Promezhutochnoe, Muromets	Terrasnoye, Kunaryovskoye, Armanskoye, Mikhailovskoye	Kandidatskoye, Arbatskoye, Khospokchan, Teutedzhak	Kanyon, Chybygalakh
References	Fadeev, 1974; Ruchkin et al. 1984 writt.comm.; present research	Naiborodin 1958; Dorofeyev 1961; Flyorov et al. 1974; Gvozdev, 2010, present research	Litvin 1959, present research	Shpikerman 1987, present research	Bakharev et al. 1988, present research	Vladimirov 1958; Flerov et al. 1974; present research

Table 2

The brief description of the several studied skarn lode deposits

Skarn deposit	Host terrane	Host rocks	Igneous rocks	Major metals	Minor metals	Major skarn facies	Major ore minerals	Grade-tonnage
Kandidat	Omulevka passive continental margin	Permian terrigenous with single limestone beds	Early Cretaceous granodiorite of I type, ilmenite series	Au, Co, As	Bi, Te, Mo	Garnet-pyroxene, pyroxene, wollastonite-pyroxene	Arsenopyrite, cobaltite, pyrrothite, lollingite, Bi-tellurides	5-7 g/t, estimated 20-30 t Au
Khospokchan	Omulevka passive continental margin	Permian terrigenous with single limestone beds	Early Cretaceous granodiorite of I type, ilmenite series	Au, Co, As	Bi	Garnet-pyroxene	Arsenopyrite, cobaltite, pyrrothite, lollingite	no data
Mikhailovskoye	Omulevka passive continental margin	Devonian limestone, marble	Early Cretaceous granodiorite of I type, ilmenite series	Pb, Zn	Ag, Sn	Garnet-pyroxene	Galena, sphalerite, stannite	no data
Chebagalak	Omulevka passive continental margin	Ordovician limestone, dolomite	Early Cretaceous granite of S type	Sn	B, Be	Garnet-pyroxene, pyroxene	Cassiterite	no data
Terrasnoye	Omulevka passive continental margin	Devonian limestone	Late Jurassic-Early Cretaceous granodiorite of I type, ilmenite series	Pb, Zn	Ag	Pyroxene	Galena, sphalerite	
Nadezhda	Omulevka passive continental margin	Devonian limestone	Late Jurassic-Early Cretaceous granite of I type (?)	Pb, Zn		Pyroxene	Galena, sphalerite	

Skarn deposits	Host terrane	Host rocks	Igneous rocks	Major metals	Min or	Major skarn facies	Major ore minerals	Grade-tonnage
Kunarevo	Omulevka passive continental margin	Jurassic conglomerates , Late Jurassic-Early Cretaceous diorite	Late Jurassic-Early Cretaceous diorites of I-type	Pb, Zn, Ag	Bi	Pyroxene, epidote-pyroxene	Galena, sphalerite	70 mln t of ores with 3-5% of Pb and 10% of Zn
Kanyon	Omulevka passive continental margin	Permian limestone	Late Jurassic-Early Cretaceous S type granite	Sn	As, B	Garnet-pyroxene, wollastonite-pyroxene, axinite-pyroxene	Cassiterite, arsenopyrite, sphalerite,	7000 t of Sn and 0.8% Sn grade
Cherninskoye	Omulevka passive continental margin	Permian limestone	Late Yurassic-Early Cretaceous S type granite	Fe	Pb, Zn	Epidote-magnetite, garnet-epidote	Magnetite, sphalerite, galena	300 mln t of ores
Lenkovoye (Rossi'skoye)	Omulevka passive continental margin	Ordovician limestone	?	W		Garnet-epidote	Sheelite	no data
Agyli	Verkhoyansk passive continental margin	Triassic terrigenous rocks with single limestone beds	Early Cretaceous I-type granodiorite-porphry	W, Cu	Bi	Pyroxene	Sheelite, chalcopyrite, pyrotite, bismutinite	about 9 mln t of ores with 0.9% WO ₃ grade
O'Keyskoye	Kular-Nera shelf terrane	Permian terrigenous rocks with single limestone beds	Early Cretaceous I-type (?) granite	W	Mo	Garnet-epidote	Sheelite	no data

Skarn deposits	Host terrane	Host rocks	Igneous rocks	Major metals	Min or	Major skarn facies	Major ore minerals	Grade-tonnage
Med'Gora	Omolon microcontinent	Carboniferous limestone	Cretaceous I-type (?) granoliorite	Mo	Cu, As	Garnet-pyroxene, pyroxene	Molybdenite, chalcopyrite, arsenopyrite	no data
Khrustal'ny	Omolon microcontinent	Neoproterozoic marbles	Cretaceous I- type (?) granite	Fe	Au	Garnet-pyroxene, pyroxene	Magnetite	130 mln t of Fe ores with 40-55% of Fe
Arman	Viliga shelf terrane	Triassic terrigenous rocks with single limestone beds	Late Cretaceous I-type granite	Pb, Zn, Ag	Sn	Pyroxene, amphibole-pyroxene, garnet-pyroxene	Galena, sphalerite, pyrotite	no data

Table 3

Skarn zonation of different sections of the Cherninskoye deposit.

Tikhiy cross-section	Khrustalny cross-section	Verkhe-Sphalerite cross-section
<i>Siltstone</i>	<i>Siltstone</i>	<i>Siltstone</i>
Epidote-garnet skarn with ilvaite	Magnetite-ilvaite lens	Epidote-magnetite skarn
Pyroxene skarn	Garnet-epidote skarn	Garnet-magnetite skarn
Epidote-garnet skarn	Garnet skarn	Pyroxene skarn
Epidote skarn (sometimes n/a)	Garnet-pyroxene skarn Pyroxene skarn	Actinolite-tremolite near-skarn rock
<i>Limestone</i>	<i>Limestone</i>	<i>Limestone</i>

Table 4

Dating of some skarn associated plutons (m.y).

Plutons	Skarn type	Rock	K/Ar	Ar/Ar	U/Pb SHRIMP	Rb/Sr
Kanyon	Sn	Granite		146 ⁶	148±2.2 - 163±3 ⁸	151±11 Sr ₀ =0.7110
Kunarev	Pb-Zn	Rhyolites				141±6.5 ¹ Sr ₀ =0.7090
Syachan	Sn	Granite	154-109 ²			
Ulakhan-Tass	Au-Co	Granodiorite Granite	140-124 ³ 129-118 ³	124 ⁶		127±1 Sr ₀ =0.7035 ⁴
Burgagy	Au?	Diorite Granodiorite	154 149		150.5±1.2 ⁹	145
Bonsalchan	Pb-Zn	Granite	73 ⁵			
O'Keiskoye	W	Granite			120.4±0.78 ¹⁰	135±2 Sr ₀ =0.7035 ⁴
Agylky	W	Granodiorite-porphry	145-143 ⁷			

Notes: ¹E.F.Dylevsky - write communication, ²Trunilina & Royev, 1988, ³Bakharev et al. 1988, Layer et al. 2000, ⁴Kotlyar & Zhylanova, 1997, ⁵Zagruzina, 1977, ⁶Newberry et al. 2000, ⁷Flerov et al. 1974; ⁸Shpikerman 2008; ⁹Akinin et al. 2009, ¹⁰Shpikerman et al. 2016.

Table 5

Granitoid chemical composition in some skarn-associated plutons.

Oxides	Burgagy (15)	Kanyon (4)	Ulakhan- Tas* (20)	Khiulchan ** (4)	Kunarev ** (5)	Syachan *** (33)	Agylki **** (5)
SiO ₂	68.37	71.62	69.79	75.99	63.85	72.35	68.01
TiO ₂	0.33	0.47	0.37	0.16	0.68	0.22	0.48
Al ₂ O ₃	15.57	14.12	14.61	12.34	16.21	14.16	14.63
Fe ₂ O ₃	4.21	0.76	0.19	1.33	5.90	0.56	0.8
FeO	n.d.	1.93	3.31	n.d.	n.d.	2.14	3.17
MnO	0.05	0.04	0.05	0.09	0.10	0.07	0.01
MgO	0.81	0.99	0.81	0.13	1.98	0.46	1.07
CaO	3.01	2.71	2.38	0.56	4.11	1.74	2.94
Na ₂ O	3.69	2.74	3.30	3.07	2.62	3.35	3.44
K ₂ O	3.27	4.03	4.48	5.33	4.43	4.25	3.17
P ₂ O ₅	0.10	0.13	0.19	0.01	0.12	0.05	0.14
p.p.p.	0.61	0.55	0.40	-	-	0.90	1.87
Total	100.02	100.08	99.90	100.01	100.00	100.25	99.41

Notes: Numbers in brackets show numerous analysis, n.d. – no detected; *Bakharev et al. 1988; **E.F.Dylevsky 1991 writt.com.; ***Trunilina 1992; **** Flerov et al. 1974 and Gvozdev 2010.

Table 6

Sulfur isotope data on ore minerals from skarn lode deposits.

Deposits	Major metals	Mineral	del ³⁴ S	References
Kanyon	Sn	Arsenopyrite	-6.0	Ishihara et.al. 1995
Agylky	W	Arsenopyrite	-2.9; -2.6	Gvozdev 2010
		Pyrrhotite	-2.9; -2.8	
		Chalcopyrite	-0.9; - 1.2	
Terrasnoye	Pb-Zn	Pyrite	+0.6	Shpikerman 1987
		Galena	-10.8	
Skarnovoye (Arman)	Pb-Zn	Pyrrhotite	-4.3	Ishihara et.al. 1995
Med Gora	Mo (Cu)	Molybdenite	-1.8	Present research
Mikhailovskoye	Pb-Zn	Arsenopyrite	-6.6; -8.1	
		Galena	-11.7	
Arbat	Au-Co	Cobaltite	-10.7	
Chospokchan	Au-Co	Arsenopyrite	-7.6; -7.3	
Kandidat	Au	Arsenopyrite	-8.2; -7.4; -8.5; -8.1; -8.2;	
			-7.4; -8.4; -8.2; -7.5	

Table 7

Lead isotope data on ore minerals from skarn lode deposits in North East Asia

Name of deposit	Host terranes	Major metals	Mineral	Pb-206/204	Pb-207/204	Pb-208/204
Cherninskoye	Omulevka passive continental margin	Fe	Galena	18.427	15.589	38.445
Kunarevo	Omulevka passive continental margin (mostly terrigenous)	Pb-Zn	Galena	18.513	15.573	38.511
Terrasnoye	Omulevka passive continental margin (mostly limestones)	Pb-Zn	Galena	18.583	15.589	38.441
Kanyon	Omulevka passive continental margin	Sn	Arsenopyrite	18.363	15.553	38.317
Kandidatskoye	Omulevka passive continental margin (mostly terrigenous shelf)	Au (Co)	Arsenopyrite	18.440	15.500	38.250
Med'gora	Omolon cratonal	Mo	Arsenopyrite	18.317	15.517	38.203
Armanskoye	Viliga terrigenous shelf	Pb-Zn	Pyrrhotite	18.383	15.545	38.363

Highlights

The specific of this paper are summary geological, mineralogical and isotope characteristics of calcic skarn ore deposits (at 17 deposits and prospects) of the Northeast Asia. Major skarn mineralization formed during the Late Mesozoic time. The type of host rocks, more rarely granitoid type, and the type of ore mineralization control the composition of garnet and pyroxene formed in the skarn deposits. Garnet from Sn skarn deposits have high concentrations of Sn. Garnet from skarn deposits in terrigenous terranes have higher TiO_2 content than one from carbonate terranes. During skarn formation, the Fe content of garnet and pyroxene increases. Ore mineralization that accompanied skarn has crustal Pb isotopic compositions, and relatively light isotope composition of sulfur in sulfides.

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