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GEOLOGY

Thermal Metamorphism of Au–Ag Ores of the Nyavlenga Deposit (Northeast Russia)

N. E. Savva[a], **A. V. Volkov**[b], **and** **Corresponding Member of the RAS A. A. Sidorov**[b]

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The formation of several epithermal Au–Ag deposits in the Okhotsk–Chukot volcanogenic belt (OCVB) is closely associated with the recurrent activation of hydrothermal systems over a long period extending from the Late Jurassic to the Paleogene. Ores of the Dukat, Nyavlenga, and other deposits, which formed at early stages of volcanism, were rejuvenated in the course of plutonic magmatism that promoted the redistribution of mineral matter. Thus, orebodies of epithermal deposits formed in the course of sequential increase in temperature (“progressive” mineralization, according to Sidorov and Goncharov [1]) rather than the conventional hydrothermal scenario of a decrease in temperature from the early to late stages.

In contrast to the Dukat deposit located in the adjacent Ag–Sn ore district, the Nyavlenga deposit, a proxy of volcanic-hosted deposits with progressive ore formation, is characterized by an abundance of Cu–Mo mineralization.

The Nyavlenga ore field (northern Okhotsk region) is confined to a volcanic dome located in the central part of the NE-oriented volcanotectonic depression. The depression is considered a reference volcanic structure with intrusive framing in the OCVB [2]. The central sector of the depression is filled with volcanic sediments of the Askol’da Complex, while the periphery is surrounded by granitoid intrusions of the Nyavlenga and Magadan complexes.

Based on Rb–Sr isochron data, the Askol’da, Nyavlenga, and Magadan complexes are estimated at 125 ± 1, 112 ± 2, and 107 ± 3 Ma, respectively [3]. Igneous rocks and epithermal Au–Ag veins were intruded by subalkaline basalt dikes in the Late Cretaceous–Paleogene (68–59 Ma [3]).

Petrochemical diagrams emphasize the comagmatic nature of volcanic and intrusive rocks in the Nyavlenga Depression (Fig. 1a) and their calc-subalkaline composition (Fig. 1b). The prominent trend (Fig. 1b) indicates that the rocks are products of a single magma chamber, the sequential activation of which reflected the ongoing tectonic movements along the subduction zone.

Volcanic rocks of the ore field underwent intense metasomatic alterations that smoothed away their primary petrographic features. The total area of metasomatic alterations is approximately 15 km^2. The table presents the sequence of metasomatic transformations and their brief characteristics. In terms of pH and temperature characteristics, the formation of ore mineralization fits the metasomatic process [4].

Geostructural, mineralogical, and geochemical features of the Nyavlenga deposit are scrutinized in [5, 6]. The present paper is devoted to new data on the thermal metamorphism of ores of this deposit.

The subalkaline granite porphyry stock (Magadan Complex) was recovered by boreholes at a depth of 100–150 m beneath orebodies (OB) at the western flank of the Nyavlenga deposit (Fig. 2). The emplacement of this stock provided a stable thermal field, which, in turn, fostered the rejuvenation of hydrothermal-metasomatic activity. Mineralization of the new (second) stage of ore formation consists of the Ag–Cu–Mo assemblage and drastically differs from that of the previous (Au–Ag) epithermal stage [7]. Since fluid inclusions are lacking in recrystallized quartz, the temperature of ore metamorphism can be estimated based on mineralogical thermometers. Chalcopyrite of the early stage contains stellate sphalerite segregations (specific exsolution texture). According to Firsov [8], sphalerite homogenizes gradually at 500–350°C. In addition, sphalerite of the early stage includes emulsion dissemination of chalcopyrite, pyrrhotite, cubanite, and mackinawite. According to Ramdohr [9], cubanite and mackinawite are typical of ores formed at very high temperatures. According to Schidlowski and Ottemann [10], mackinawite usually occurs in association with recrystallized sulfides formed in the course ore metamorphism. Hence, the temperature could exceed 500°C

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[a] *Northeastern Complex Research Institute,
Far East Division, Russian Academy of Sciences,
ul. Verkhneportovaya 16, Magadan, 685000 Russia*

[b] *Institute of Geology of Ore Deposits, Petrography,
Mineralogy, and Geochemistry, Russian Academy of Sciences,
Staromonetnyi per. 35, Moscow, 119017 Russia;
e-mail: alexandr@igem.ru*

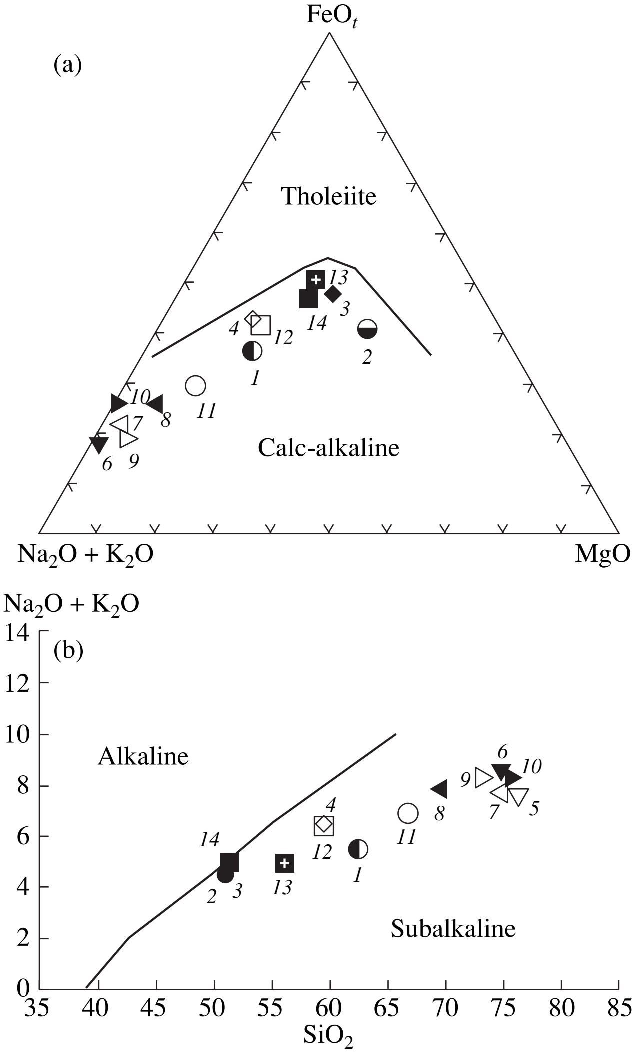

Fig. 1. Petrochemical diagrams of magmatic rocks in the Nyavlenga volcanotectonic depression (silicate analyses adopted from [2]). (*1, 2*) Lower sequence: (*1*) andesite dacites, (*2*) basalt; (*3, 4*) intrusions comagmatic with the lower sequence: (*3*) meladiorites, (*4*) diorites; (*5*) subalkaline rhyolites of the middle sequence; (*6*) ignimbrites of rhyolites of the upper sequence; (*7*) leucocratic subalkaline biotite garnets of the Polimetallicheskii Massif; (*8*) automagmatic breccia; (*9*) subalkaline micropegmatitic granites of the Nochnoi Massif; (*10*) alkaline micropegmatitic arfvedsonite–aegirine garnets of the Verkhnyaya Buyunda Massif; (*11*) hornfels–biotite granodiorites of the Tsirkovoi Massif; (*12–14*) intermediate and basic intrusions in acid effusives and granites: (*12*) diorites, (*13*) gabbro diorites, (14) gabbro.

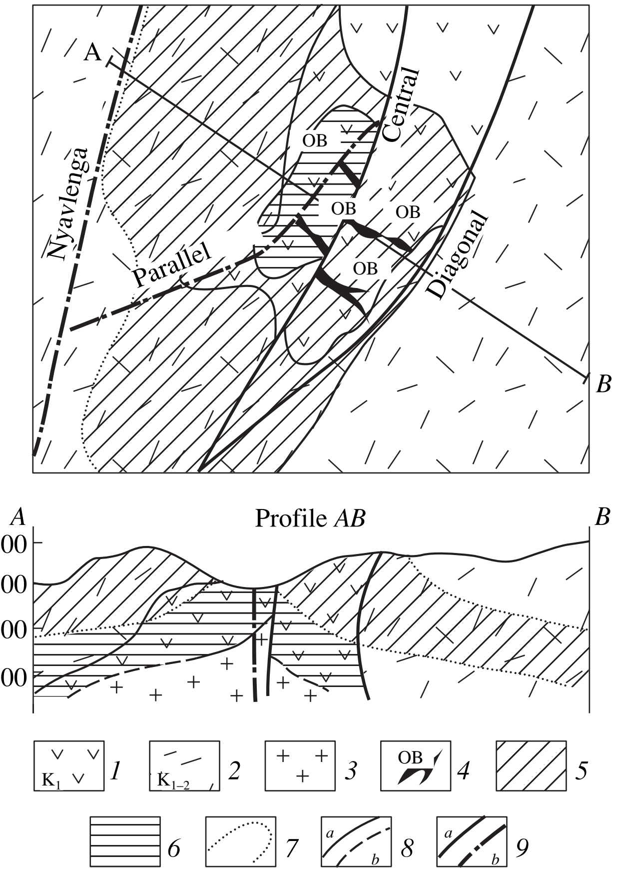

Fig. 2. Metasomatic aureoles at the Nyavlenga deposit. (*1*) Andesites; (*2*) sheets of rhyolites, rhyodacites, and ignimbrites of the analogous composition; (*3*) subalkaline garnets; (*4*) orebodies and their numbers; (*5, 6*) aureoles of the development of thermal metamorphism: (*5*) outer (pyrophyllite–chlorite and corundum–diaspore), (*6*) inner (magnetite–hematite–epidote aureole with garnet, actinolite, and wollastonite); (*7*) contours of aureoles of thermal metamorphism; (*8*) geological boundaries: (*a*) proven, (*b*) inferred; (*9*) fractures: (*a*) proven, (*b*) inferred. (OB) Orebody.

during the metamorphism of ores at the Nyavlenga deposit.

Mechanisms of the metamorphic redistribution of materials in Au–Ag ores of the Nyavlenga deposit are discussed below (Fig. 3).

Indicators of solid phase diffusion. Primary fine-dispersed Au–Ag polysulfide ores of the volcanogenic-hydrothermal stage formed from colloidal solutions. This is supported by the presence of chalcedony, colloform structures, and other features. Relicts of the primary substrate are observed at horizon +950 m in OB 2. Fine-grained mineral blends are characterized by the coarsening of phases as the result of weak differentiation that reflects the general succession of the evolution of many Au–Ag deposits.

For example, the upper and middle horizons of orebodies contain hypidiomorphic and allotriomorphic segregations of the spongy pyrite (first productive mineral assemblage) with submicroscopic inclusions of native silver (up to 1.5 wt %). In the course of metamorphism, the inclusions became larger and free from Ag and other nonstructural admixtures (Cu up to 0.5 wt %; As up to 1.3 wt %; Pb, Zn, and Sb up to 0.1 wt %). These elements abandoned the pyrite segregations and formed their own mineral species (chalcopyrite, sphalerite, galena, acanthite, native silver, and electrum) that precipitated near the pyrite segregations. The

Formation sequence and characteristics of metasomatites in the Nyavlenga deposit

Facies	Rock	Characteristics of metasomatites		
		Major minerals	input elements	output elements
Preore stage (regional)				
Greenstone	Greenstone rocks	Albite, tremolite, epidote, chlorite	–	–
Epidote–chlorite	Propylites	Epidote, calcite, chlorite, sericite, quartz, pyrite	K, Pb, Ag, Rb, Zn, Ba, Sn, Mo, Cl	Na, Sr, Mg, Cr, Cu
Sericite	Secondary quartzites	Quartz, sericite	Al_2O_3, Cr	Na, K, Pb, Sr
Pyrophyllite	The same	Pyrophyllite, corundum, paragonite, dickite, rutile, pyrite, muscovite	Ni, H_2O	Ag, Pb, Zn, Cu, SiO_2, V, B
Ore stage (volcanogenic ore formation)				
Quartz–adular–sericite	Apopropylites	Quartz, orthoclase, sericite, chlorite, pyrophyllite, calcite	K, Rb, Ag, Pb, Zn, Ba	Cl, Mg, Cu, V, Ca, Co, Cr, Sn
Tectonomagmatic activation (emplacement of granitoids)				
Thermal metamorphic	Hornfelses	Staurolite, biotite, andalusite, cordierite	Al_2O_3, Mg (K)	OH, CO_2, F, Ca
Impact of fluid				
Albite–amphibole–fluorite	Greisenized rocks	Fluorite, actinolite, tremolite, albite, biotite	F, OH (K)	K, Ca, Mg, Fe
Epidote–vesuvian–garnet	Skarn-type rocks	Epidote, garnet (grossular–andradite), vesuvian, pyroxene, spinel, magnetite	Ca, Mg, Fe, Si (Al)	K, F, OH, Na
Carbonate–chlorite–sericite	Beresitized rocks	Sericite, carbonate, chlorite, quartz	OH, CO_2	
Postore stage				
Zeolite–carbonate	Zeolitized and carbonatized rocks	Zeolites, carbonate, gypsum	CO_2, H_2O, SO_2	

newly formed minerals are observed as drop-shaped inclusions in (or around) pyrite grains and as growth rims and interstitial segregations in the vein matrix (Fig. 4).

The solid phase diffusion promoted the rearrangement of chalcopyrite emulsion in sphalerite. The chalcopyrite emulsion in unaltered sphalerite is random and strongly variable in size. In mineral clusters subjected to heating, the chalcopyrite emulsion is coarser and concentrated along twin sutures, growth zones, and cataclasis sectors. The Cu content is as much as 9.1 wt % in sphalerite saturated with the chalcopyrite emulsion and only 0.1–0.3 wt % in the metamorphosed mineral.

The solid phase diffusion is also responsible for concentration variations in different galena generations. The Ag content in galena varies from 1 to 3 wt % (maximum 5.2 wt %) in unmetamorphosed mineral assemblages. Thermal impact upon the mineral provokes its recrystallization and the sequential migration of trace elements to the periphery of crystals and along intergranular boundaries beyond the mineral. Consequently, galena becomes virtually sterile relative to Ag (maximum 0.1 wt %).

Owing to different rates of the solid phase diffusion of Au and Ag, natural Au–Ag alloys retain traces of heating that can be revealed by the structural etching of grains. Inhomogeneity of the thermal field is reflected in the following features: the replacement of the obscure-zonal pattern by the distinct zonal pattern at the transition from the upper sections of vein zones to the lower sections; the development of granulation and variation in the volume of Au–Ag phases in sectors subjected to the maximal heating; and drastic increase in the dispersion of gold fineness. This conclusion is confirmed by results of the analysis of furrow samples (data of the Karamken Geological Exploration Expedition) taken along the pitch and crosscuts of the intensely metamorphosed OB 1. Here, the highest Ag concentrations are confined to selvages of orebodies, while the highest Au concentrations are recorded in the central sectors. Microprobe analyses showed that OB 1 contains virtually pure native silver and electrum, whereas ore relicts of the first stage are mainly composed of küstelite and a small amount of native silver.

Chemical dissolution, corrosion, and redeposition. In contrast to the structure of the Dukat deposit, the tectonic fabric of the Nyavlenga deposit did not change during the emplacement of subalkaline granites. Therefore, material inside orebodies was mainly redistributed by metasomatic processes. Minerals were corroded and dissolved not only in the course of decrease in temperature, but also with variation of the chemical parameters.

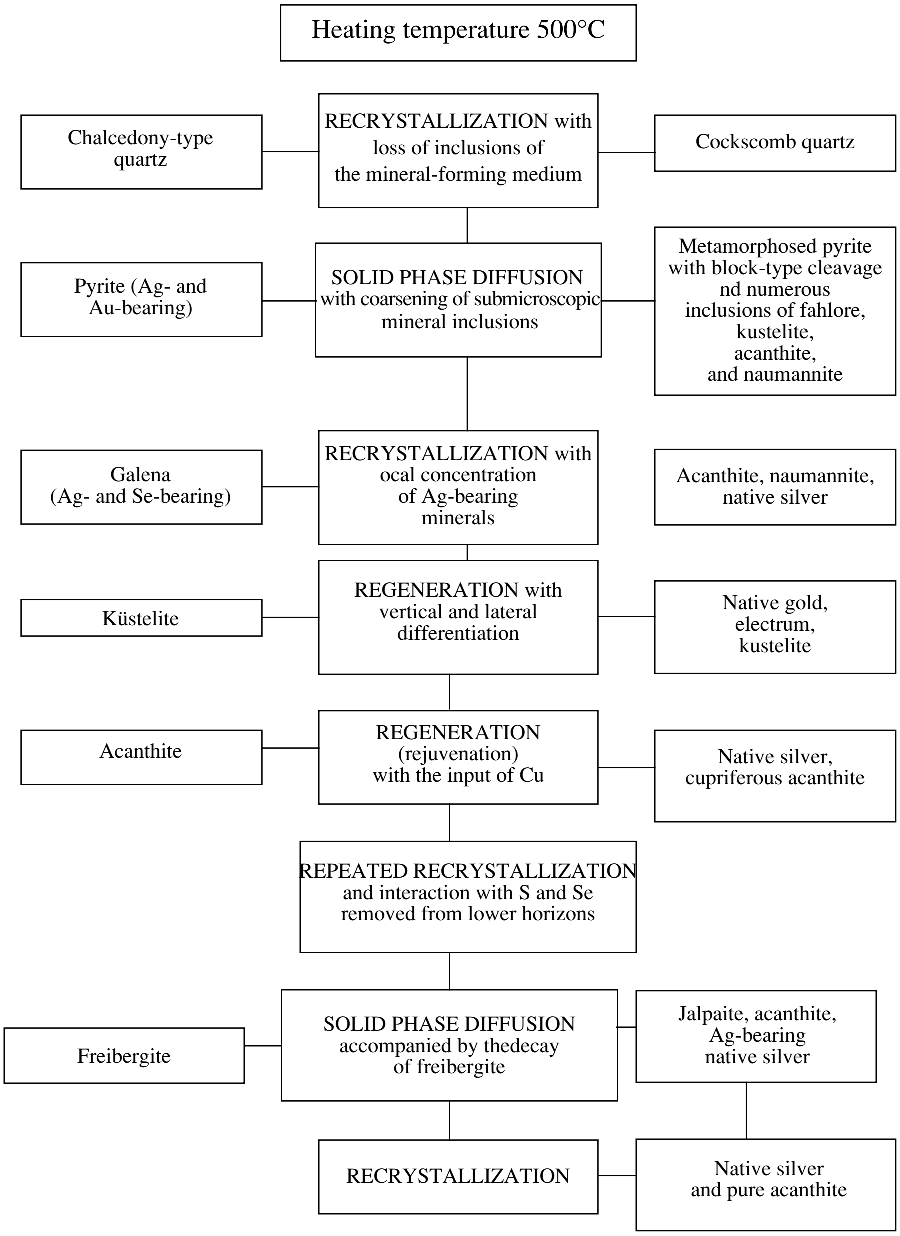

Fig. 3. Scheme of the metamorphic redistribution of mineral matter at the Nyavlenga deposit.

At early stages of the second phase, aggressive hot fluid inclusions created extreme (significantly oxidative) conditions in root zones of OBs 1, 2, 6, and 11, resulting in the decomposition of the major portion of sulfide minerals. In these orebodies, porous pyrite aggregates are corroded or completely replaced by the newly formed hematite and magnetite (Fig. 4a). Traces of decomposition are clearly seen in the polycomponent mineral (freibergite). The skarnized ore always contains tiny relicts of fahlore in the metasomatic chalcopyrite and magnetite. The replacement of oxidative conditions in the solution by reductive ones fostered the precipitation of a new paragenesis of Ag–Cu massive sulfides (jalpaite, mckinstryite, and stromeyerite) and decrease in the general sulfide content in ores. This is evident from the virtual lack of pyrite; decrease in the content of chalcopyrite; and appearance of bornite, chalcocite, and valleriite in the ores. This process terminated after the precipitation of native gold and Cu-acanthite in the metasomatically altered selvages of orebodies. The interrelation of processes in different hypsometric levels of the thermal column is reflected well in the behavior of mobile components Se, Sb, and S. At the upper and middle levels of orebodies, the Se content is as much as 5.5 wt % in galena, 10 wt % in stephanite, 6.3 wt % in acanthite, and 0.8 wt % in freibergite. Elements like S and Sb are more typical of Au–Ag phases (Sb up to 3.6 wt %, S up to 1.9 wt %, and

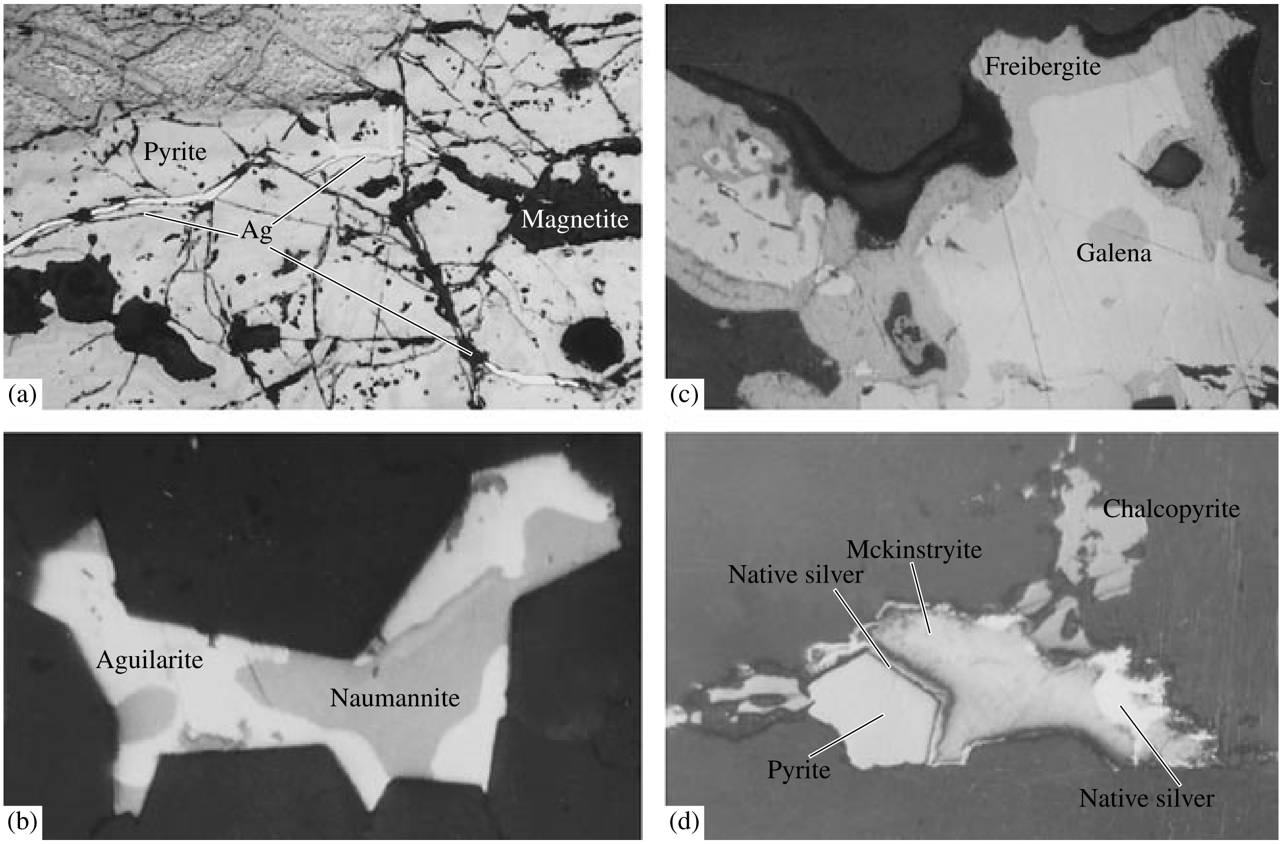

Fig. 4. Examples of reaction interrelations of ore minerals during the thermal metamorphism of Ag-bearing ores of the Nyavlenga deposit. Magn. 240. (a) Development of native silver along cataclasis cracks in early pyrite and replacement of pyrite by magnetite; (b) interstitial development of native silver and naumannite; (c) freibergite rim around galena segregations; (d) native silver rim around mackinstryite segregations.

Se up to 0.3 wt %). The appearance of such concentrations is related to the secondary enrichment of upper horizons in these elements that migrated in convective fluxes ascending from the contact with the abyssal pluton. The maximal rise of temperature in root zones of orebodies promoted the sublimation of Se, S, and Sb to subsurface horizons and the appearance of new minerals in late assemblages. These minerals make up isomorphic series (acanthite–aguilarite, galena–clausthalite) with the participation of S and Se.

Thus, study of the Nyavlenga deposit has revealed that the mineral matter of ores is differentiated in the course of redistribution due to thermal metamorphism. The differentiation is accompanied by widening of the spectrum of mineral species and local concentration of metals that can be considered a natural process of ore concentration. Thus, the process of differentiation governs the mineral type of ore deposit. The weakly differentiated Au–Ag ores are characterized by the freibergite and miargyrite mineral types; the moderately differentiated ores, by the pyrargyrite, polybasite, and stephanite mineral types; and the highly differentiated ores, by the silver–acanthite mineral types. The proportions of the epithermal Au–Ag and the conjugated porphyry Cu–Mo mineralization types suggest the probability of various sources of ore matter. The presence of porphyry Cu–Mo mineralization is assumed in alkaline granitoids at the dome basement. The juxtaposition of epithermal and porphyry mineralizations is probably typical of ore districts in the OCVB.

Thermal metamorphism promoted the thickening of orebodies in the Nyavlenga deposit, the concentration of Au and Ag in ore shoots, the release of these elements from sulfides, the formation of electrum, and the coarsening of segregations of native elements and their alloys. These processes undoubtedly made it possible to upgrade the technology of ore dressing.

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REFERENCES

1. A. A. Sidorov and V. I. Goncharov, Geol. Rudn. Mestorozhd. **21** (3), 19 (1979).

2. I. N. Kotlyar, *The Gold–Silver Potential of Volcanic Structures in the Okhotsk–Chukot Belt* (Nauka, Moscow, 1986) [in Russian].
3. I. N. Kotlyar, T. B. Rusakova, and A. M. Gagieva, Tikhookean. Geol. **23** (1), 3 (2004).
4. A. V. Volkov, L. N. Shishakova, and A. G. Demin, Dokl. Akad. Nauk SSSR **320**, 934 (1991).
5. A. G. Demin, in *Ore Formations of the Northeast Soviet Union* (SVKNII Dal'nevoctoch. Otd. Akad. Nauk SSSR, Magadan, 1990), pp. 202–214 [in Russian].
6. A. G. Demin, Kolyma, No. 4, 13 (1992).
7. N. E. Savva and S. F. Petrov, in *Mineralogy and Genetic Features of Gold and Silver Deposits* (SVKNI DVO RAN, Magadan, 1996), pp. 7–25 [in Russian].
8. L. V. Firsov, Dokl. Akad. Nauk SSSR **140**, 941 (1961).
9. P. Ramdohr, *Die Erzmineralien und Ihre Verwachsungen* (Acad. Verl., Berlin, 1960; Inostrannaya Literatura, Moscow, 1962).
10. M. Schidlowski and J. Ottemann, Am. Mineral. **51**, 1535 (1966).