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GEOCHEMISTRY

Nanogold in the Noni Deposit

V. I. Palazhchenko and Academician of the RAS V. G. Moiseenko

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The abundance and diversity of genetic types of gold concentrations have stimulated constant interest in the comprehensive investigation of gold, gold–silver, and complex (multicomponent) deposits. The bulk contents of noble metals used in geochemistry do not provide information concerning their natural paragenetic associations, occurrence modes, relationships with host minerals, and genesis. As is known, the latter is governed by specific conditions of natural systems. In the majority of well-known large and unique deposits, native and mineral forms of gold are found mainly as submicroscopic segregations. Therefore, elucidation and study of geochemical criteria of the origin of specific natural phenomena is an essential issue [1].

Ontogenetic information based on the study of gold species is governed by processes of their origin and consequent spatiotemporal evolution. Information concerning the occurrence mode, morphological and microtextural characteristics, paragenetic associations, interrelations, and compositions of coexisting minerals is also essential for elaboration of optimal technological schemes of gold extraction.

The Noni gold–silver deposit is located in the East Bureya auriferous zone (Khabarovsk region). The deposit is confined to the central-type East Bureya volcanoplutonic structure of the Cretaceous age [2]. According to V.A. Buryak and A.V. Perestoronin (1989), the gold mineralization is developed in a steep tectonic zone. In terms of genesis and ore formation, the Noni deposit is classed as a Au-bearing massive sulfide base metal (hereafter, MSBM) deposit with superimposed gold–quartz mineralization. The Au-bearing MSBM stage is divided into two substages with early (Au-bearing arsenopyrite–pyrrhotite–pyrite) and late (gold–quartz–base metal) associations. According to V.A. Buryak (1989), quartz–vein and quartz–stringer mineralizations formed at the final stage mineralization, i.e., after the precipitation of the bulk of sulfides. Thus, they represent the latest products of the auriferous ore fluid. Ore material was fractionated due to its evolution under conditions of long-term tectonic activity and high permeability of enclosing rocks. The fractionation fostered the differentiation of ores after each stage of their precipitation.

The superposition of quartz–vein mineralization promoted the dissolution and redeposition of some portions of gold located in the paragenetic association with sulfides of the first generation or inside the sulfides as fine dissemination, resulting in the coarsening of gold particles. Gold grains typically make up intergrowths with vein quartz or occur in interstices between quartz crystals. Unaltered Au-bearing massive sulfide ores contain fine-dispersed gold ($<10n$ μm). Macroscopic gold was found in the Noni deposit only once by geologists of Prospecting Team 192 in 1987. Hypogene gold was recorded in rocks with chlorite–sulfide mineralization sampled from a depth of 94 m in borehole 2.

The fineness of gold particles commonly varies from 650 to 900 and increases to 950 in the oxidation zone. The metal is mainly associated with silver, arsenic, copper, antimony, and bismuth. Gold shows positive correlation with sulfides and negative correlation with quartz.

The complete development of an oxidation zone is fostered by the abundance of sulfide (primarily, chalcopyrite–pyrite) mineralization and the presence of water-permeable tectonic zones. We studied semioxidized gold- and quartz-bearing MSBM ores. These ores represent a transitional type between oxidized and primary ores. Therefore, they occupy an intermediate position in the section. The semioxidized ores are characterized by the presence of secondary minerals of Cu, Pb, Zn, and Sb (chalcocite, cuprite, tenorite, covellite, native copper, cerussite, anglesite, and bindheimite). The Au content is slightly higher than that in primary ores. The average fineness of gold varies from 850–900 in the oxidation zone to 800–850 in primary ores. In some places, the hypogene gold includes low-grade species matching electrum. Based on compositional data reported by V.A. Buryak (1989), gold from the oxidation zone actually represents a hypogene species that was not subjected to appreciable supergene alterations. Native gold from the Noni deposit virtually always con-

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*Institute of Geology and Nature Management,
Amur Research Institute, Far East Division,
Russian Academy of Sciences, per. Relochnyi 1,
Blagoveshchensk, Amur oblast, 675000 Russia;
e-mail: veronica@ascnet.ru*

Chemical composition of native gold, wt %

Ord. no.	Au	Ag	Fe	Ti	Cu	Bi	Pb	Total
1	64.34	35.95	0.16		0.01			100.55
2	65.22	34.51	0.20	0.01	0.02			99.96
3	64.54	35.51	0.15	0.01	0.01			100.22
4	80.0	20.00			0.1			100.1
5	82.2	17.80			0.1			100.1
6	83.7	16.30			0.1			100.1
7	79.6	20.40	1.0	0.01	0.02	1.0		102.3
8	86.8	13.20	2.0		0.05	1.0		103.5
9	96.4	3.60	1.0		0.1	1.0		102.1
10	96.0	3.40	1.0		0.1	1.0		101.5
11	95.8	4.17	1.0	0.003	0.03	1.0		102.003
12	92.6	7.24	1.0	0.005	0.05	1.0		101.895
13	94.68	2.90	1.31	0.01	0.03		0.08	99.01
14	94.71	2.88	1.75	0.01	0.04		0.45	99.84
15	95.85	2.94	1.33	0.01	0.03		0.25	100.41
16	96.02	2.43	1.28		0.01		0.08	99.82
17	97.24	1.55	0.89		0.01		0.05	99.74

Note: (4–12) Data of V.A. Buryak (1989): (4–6) chemical composition of hypogene gold, (7–12) gold from the oxidation zone.

tains a significant amount of Ag, Cu, Fe, and Ti as the typical trace elements (table). This fact is consistent with the more basic composition of host rocks (diorite porphyries) that are usually enriched in the elements mentioned above.

We studied thin sections with microscopic gold segregations taken from the semioxidized gold- and quartz-bearing MSBM zone. The paragenesis of minerals, their interrelations, occurrence mode, and chemical composition were studied by the high-resolution scanning electron probe and X-ray microspectral analysis methods (LEO-1420 scanning electron microscope equipped with RONTEC energy-dispersive spectrometer; JSM-35C JEOL scanning electron microscope equipped with SDS-35 wave-dispersive spectrometer). In order to examine morphological features of the submicroscopic gold and its interrelations with host minerals, we first wiped the polished sections using a wad wetted with diluted nitric acid and then washed them in alcohol.

Native gold from the semioxidized zone can be divided into two distinct genetic varieties (Fig. 1). This fact is supported by their morphological and compositional features (table). Xenomorphous native gold of the first generation is characterized by a lower grade with nearly equal concentrations of Au and Ag atoms corresponding to their proportions in electrum (table, analyses 1–3). As was mentioned above, this type of gold occurs in the hypogene ore. Gold grains ranging in size from *n* to 10*n* μm are primarily confined to sulfide–quartz conjugation zones. The detrital quartz (from 10*n* μm to *n* mm in size) in fissured and crushed inequigranular aggregates contains Fe (up to 0.68 wt %). Sulfides (mainly, pyrite) and oxidized minerals of iron (primarily, magnetite) are juxtaposed in the ore. Primary grains contain regeneration rims confined to the periphery of sulfides (in some places, the process of regeneration is developed in deep zones of sulfides). Regeneration rims fill up the intergranular space and isolate the native gold from quartz grains. Tiny gold particles of the first generation are often confined to voids and cracks in pyrite grains that are isolated from quartz grains.

Gold of the second generation is closely associated with terminal phases of the high-temperature hydrothermal stage characterized by the mobilization and input of elements associated with the Au-bearing massive sulfide mineralization (primarily, chalcophile elements, such as Pb, Zn, Cu, As, Ag, and others). High-temperature hydrothermal solutions could transport Au. However, this metal could also be released from the solutions and concentrated in the sulfide matrix. The neogenic gold is characterized by a high grade (Ag up

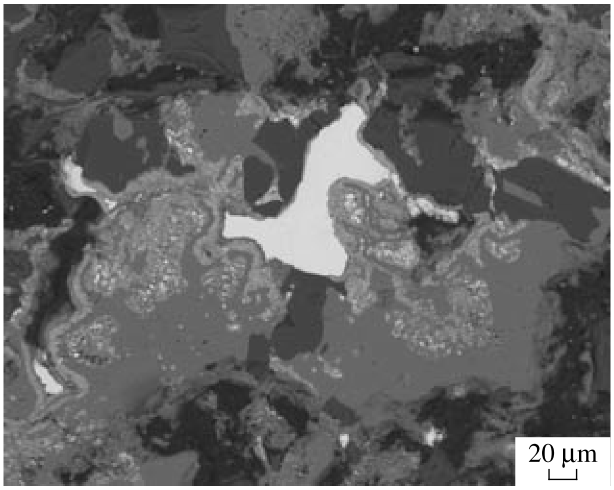

Fig. 1. Paragenetic association of early and late gold generations with host rocks.

to 3 wt %, Fe up to 1–2 wt %). Traces of Cu, Pb, and Ti are ubiquitous (table, analyses 13–17). The trace elements mentioned above can be related to the presence of microphases of their minerals in the intergranular space of dispersed gold particles.

Percolation of high-temperature Pb- and Cu-rich hydrothermal solutions in cracks and intergranular spaces promoted significant alterations at the periphery of primary sulfide grains. The consequent exothermal reaction between the primary sulfides and high-temperature hydrothermal solutions produced a new mineral paragenesis in some places. The composition of the newly formed thin-prismatic microcrystals is similar to that of betekhtivite $Pb_2(Fe, Cu)_{21}S_{15}$ with traces of K (Fig. 2). The reaction was probably accompanied by the release of a significant volume of gas, the formation of microcavities, and the simultaneous development of numerous microcrystals. The irregular composition of microcrystals is evident in the transverse plane of polished sections. Their reflected electron images show a dark core (up to 0.1 μm in size) with a composition similar to that of the primary sulfide. In some places, the microcrystals grow along different directions. However, low-magnification images show that the growth of microcrystals follows the pathway of hydrothermal solutions along grain boundaries. Recrystallization of grains is occasionally oriented from their periphery to the core. Oxidized minerals of iron are unaltered in such cases.

The irregular growth of gold grains is related to processes described above. Gold particles released in the course of the interaction between hydrothermal solutions and primary sulfides could serve as catalysts of the subsequent reactions. The morphological features of particles and aggregates of the secondary gold, as well as specific features of its interaction with primary minerals, suggest that the hydrothermal solutions transported Au. Submicroscopic gold particles formed during the relative rise of temperature owing to the input of a new portion of mineral-forming solutions. This process was stimulated by microchemical reactions between the hydrothermal solutions and primary minerals. Heterocatalytic interaction with the surface of neogenic microcrystals fostered the release and precipitation of nanometric gold (hereafter, nanogold) particles. All submicroscopic gold particles are aggregated into the following hierarchical system.

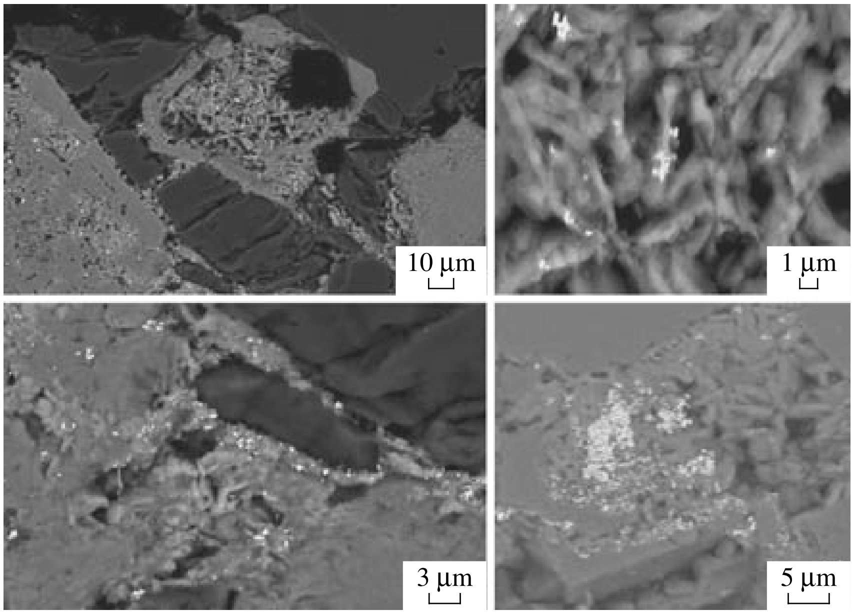

Fig. 2. Recrystallization of primary sulfides and heterocatalytic origin of nanogold particles.

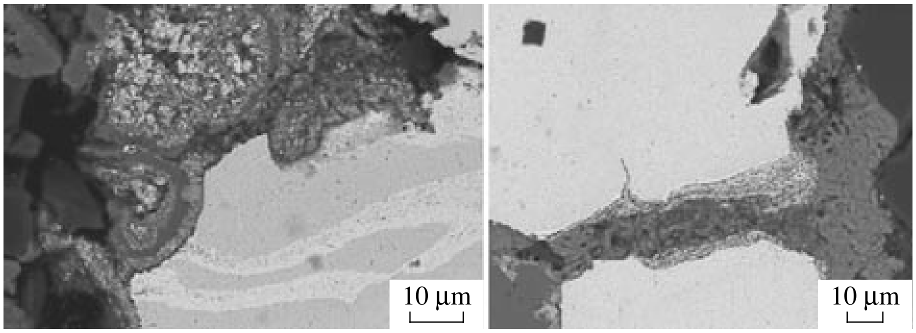

Fig. 3. Filling of cracks and intergranular spaces of primary grains with high-grade gold.

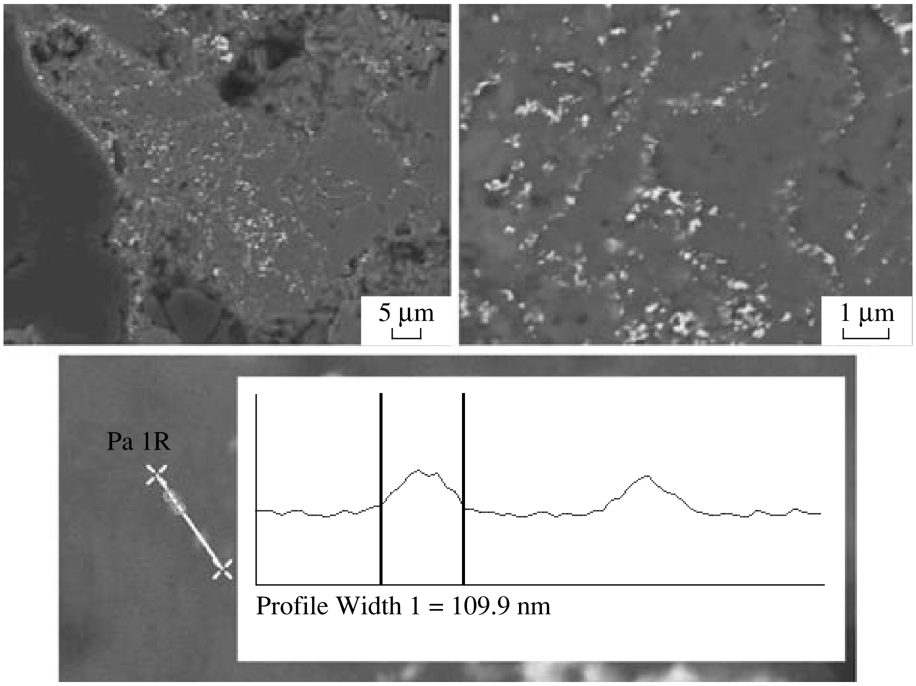

Fig. 4. Localization and dimension of secondary gold.

Well-crystallized fractal-type rims with abundant high-grade nanogold particles are developed around nearly all primary gold grains (Fig. 1). In some places, individual gold particles merge in the course of the precipitation of high-grade nanogold particles on primary gold grains and the filling of intergranular spaces (Fig. 3). The nanogold particles are oriented along grain boundaries as lamellar structures. Enlargement of the transverse dimension of particles and their compaction in the course of the precipitation of new portions promoted the gradual filling of the intergranular space with the neogenic minerals.

The well-crystallized zones are primarily confined to junctions of primary sulfides and quartz grains. As the solutions penetrate the deeper zones of grains, the degree of crystallization is deteriorated. Such places include structures related to the gradual solidification and periodic entrapment of nanogold with the formation of wavy bands of gold particles in the noncrystalline mass (Fig. 4). The gold-hosting noncrystalline phase is distinguished from the crystallized phase by depletion in Cu and enrichment in K. Particles of the secondary gold have a typical size of 100 nm. However, they are often divided into structures of smaller rank (Fig. 4).

Thus, the analytical results suggest that the major portion of gold in the Noni deposit is represented by submicroscopic and nanometric particles. The subordinate hypogene gold is not the main carrier of such gold particles. The gold particles were formed during the aggregation of individual nanogold particles in the course of microscale chemical reactions. Therefore, local settings played a crucial role in the formation of the unique Noni gold deposit. Recurrent tectonic pulses governed the major stages of ore formation and the subsequent evolution of ore-bearing solutions as a response to variations in the physicochemical environment of ore deposition. Local evolution of mineral paragenesis owing to superimposed processes fostered the differentiation of matter and the spatial juxtaposition of minerals of different stages. This conclusion is supported by the small-scale redistribution of chemical elements and the wide (microscopic and submicroscopic) range of local settings.

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REFERENCES

1. A. A. Sidorov and I. N. Tomson, Tikhookean. Geol., No. 6, 97 (1989).
2. V. G. Moiseenko and L. V. Eirish, *Gold Deposits of Eastern Russia* (Dal'nauka, Vladivostok, 1996) [in Russian].