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GEOLOGY

# New Data on Invisible Gold in Disseminated Sulfide Ores of the Natalka Deposit

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The issue of invisible gold in deposits has a great scientific and applied significance. The study of the nature and occurrence mode of gold makes it possible to elucidate ore formation conditions. The majority of large and superlarge deposits belong to the disseminated gold–sulfide ore type with refractory properties that hamper gold extraction by the commonly used method (e.g., cyanidation). Therefore, the study of disseminated sulfide ores fosters the elaboration of scientific principles of the technology of their processing. The invisible gold is widespread in sulfides of gold ore, massive sulfide, porphyry copper, and copper–nickel deposits. The invisible gold prevails in many mesothermal stringer–disseminated gold–sulfide deposits with minor quartz veins.

The Natalka deposit is a large (in terms of gold reserves) object represented by disseminated, stringer–disseminated, and less common vein ores. In [1], details of the geological setting and structure of this deposit are sufficiently well presented. The mineral composition of ores is also considered. However, occurrence modes of gold and the state of gold in Au-bearing sulfides, in particular, are not discussed.

It is well known that deposits of the gold–quartz formation, which allegedly includes the Natalka deposit, are characterized by sulfide-poor quartz veins that fill up shear and tensile fractures. The sulfide content in ores of this formation does not exceed 2–3%. However, in contrast to many deposits of the gold–quartz formation, some ore zones of the Natalka deposit contain a significant content of Au-bearing sulfide dissemination (acicular arsenopyrite and minor pyrite) that impregnate the schistosed, folded, and boudined rocks in dynamometamorphosed zones.

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Figure 1 shows two ore types in the Natalka deposit: the major stringer gold–quartz type (Figs. 1a, 1b) and the disseminated gold–sulfide type (Fig. 1c). The scale of the disseminated gold-sulfide mineralization is uncertain. High contents of the invisible gold are typical of disseminated ores represented by black shales with arsenopyrite and pyrite impregnation and local quartz veinlets (Fig. 1c). In stringer ores, arsenopyrite and pyrite are developed as relatively large grains in selvages and quartz veinlets (Fig. 2a). The disseminated ore is characterized by the distribution of arsenopyrite and pyrite along schistosity planes. This is particularly typical of the finer-grained varieties of these sulfides (Fig. 2b). According to our data, the content of disseminated sulfides in the stringer–disseminated ore is usually 3–3.5% and as much as 6.1% in some places (Figs. 1b, 1c, 2b).

In the Natalka deposit, the major ore minerals are as follows: arsenopyrite, pyrite, native gold, galena, and pyrrhotite. Scheelite, cassiterite, ilmenite, rutile, sphalerite, chalcopyrite, antimonite, and electrum are sporadic minerals. Gold is associated with quartz and sulfides. The size of gold segregations varies from 0.2 to 0.5 mm (up to 2 mm in some places). They have interstitial, spongy, and lumpy structures. The fineness ranges from 620 to 800 (average 750). Quartz is the major gangue mineral. Albite, orthoclase, adular (at upper horizons of the deposit), calcite, ankerite, and dolomite are subordinate minerals. Sericite and chlorite are widespread.

Thus, the mineral composition of ores in the Natalka deposit indicates the occurrence of gold as native segregations and Au-bearing sulfides (mainly, arsenopyrite).

The composition of arsenopyrite and the Au content in this mineral were determined by the microprobe method. In addition, the Au content in arsenopyrite monofractions was determined by the atomic absorption and ICP-MS methods. The INAA method was used to determine the Au content in separate crystals.

Arsenopyrite was analyzed in three samples taken from the Uchastkovaya zone (horizon 650 m). Samples N-1 and N-3 represent the typical low-grade stringer ores, in which black shales intersect the rare (nearly parallel) quartz veinlets up to 0.3–1.0 cm thick. Based

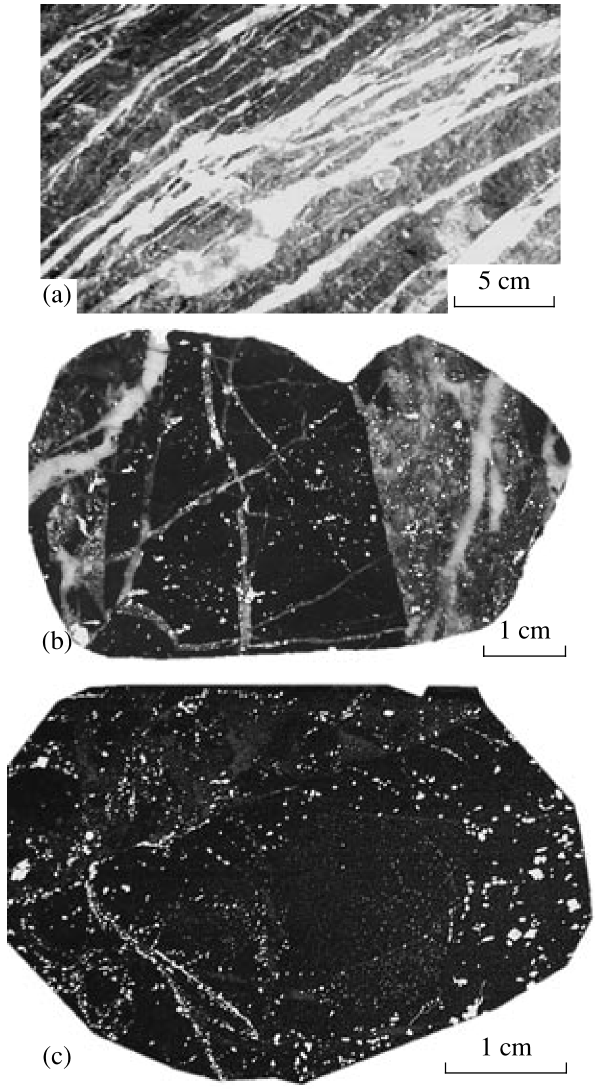


**Fig. 1.** Ore types in the Natalka deposit. (a) High-grade gold–quartz ore, ore piece fragment, museum of the North-eastern Complex Research Institute, Far East Division, Russian Academy of Sciences, Magadan, Russia; (b) common stringer ores, sample N-2, reflected light image of polished section; (c) disseminated gold–sulfide ore, sample N-3, reflected light image of polished section.

on the examination of polished sections, the content of acicular and short-prismatic arsenopyrite in veinlet selvages of such zones is 2.6 and 1.7%, respectively. Sample N-3 is virtually devoid of quartz veinlets. However, scanning of two polished samples showed that the content of acicular arsenopyrite dissemination in them varies from 4.3 to 6.15% (Fig. 1b).

The microprobe analysis of arsenopyrite in samples N-1 (20 analyses), N-2 (19 analyses), and N-3 (37 analyses) showed that Au is present in six arsenopyrite grains from sample N-1 (140–220 g/t), eight grains from sample N-2 (110–310 g/t), and fourteen grains from sample N-3 (150–470 g/t). In three arsenopyrite grains of sample N-3 (14 analyses), the Au content was as high as 400, 440, and 470 g/t (Table 1). The table shows that arsenopyrite from the disseminated ore sample N-3 has a nonstoichiometric composition (prevalence of S over As). Based on the INAA data, the Au content in arsenopyrite ranges from 18.75 g/t (sample N-1) to 94.65 g/t (sample N-2) and 482.6 g/t (sample N-3). In the arsenopyrite from sample N-3, the Au content varies from 470 g/t (AAS method) to 460 g/t (ICP-MS method).

Thus, microprobe data on high Au contents in arsenopyrites from disseminated ores of the Natalka deposit were confirmed by the INAA, AAS, and ICP-MS methods.

Microprobe and INAA analyses of arsenopyrites (Table 1) revealed high S/As values (1.28–1.35), high Au content (140–470 g/t), and significant Sb admixture (0.01–0.07%). Based on microprobe data, the arsenopyrite is characterized by nonstoichiometric proportions of the major components Fe, As, and S (Table 1). The S content (up to 23.22%) in the Natalka arsenopyrite is higher than the stoichiometric content (19.7%).

Thus, the Natalka arsenopyrite shows a distinct prevalence of S over As. The maximum As content is observed in arsenopyrites with the highest S/As values. Similar S-rich arsenopyrites were recorded previously in the Maisk, Nezhdanin, Olimpiada, and Veduga deposits (Table 2).

Table 2 shows that arsenopyrites from ore veins and veinlets in gold–quartz and gold–rare metal deposits have a nearly stoichiometric composition (S/As = 0.9–1.14). In contrast, Au-rich arsenopyrites from disseminated ores of gold–sulfide deposits have a nonstoichiometric composition (S/As = 1.21–1.35). Arsenopyrites from various ore types of the Natalka and Nezhdanin deposits are characterized by different compositions and S/As ratios (Table 2). These variations testify to different formation conditions of vein and disseminated ores in these deposits.

It is worth mentioning that some gold deposits in the world contain arsenopyrite with a significantly higher Au content [3]. The highest Au contents have been recorded in the Le Chantelle and Vallerange deposits, France (12 000–13 000 g/t) and the Congress deposit, Canada (13 000 g/t). However, these deposits are characterized by a high As/S ratio [3] that can suggest the metamorphism of ores.

Based on the Mössbauer spectroscopy data, arsenopyrites from the majority of disseminated gold–sulfide ore deposits contain gold in the chemically bonded or metallic form up to 2 nm in size [3].

In gold deposits of Russia, like in other deposits with the invisible gold, this element is mainly contained in the Au-bearing arsenopyrite. Based on the ICP-MS data, the Au content in arsenopyrites is 4700 g/t in the Olimpiada deposit, 1140 g/t in the Veduga deposit, and 1400 g/t in the Nezhdanin deposit [3].

Following Petrovskaya [5], many researchers believe that the preferential Au concentration in early sulfides is related to the selective precipitation of this

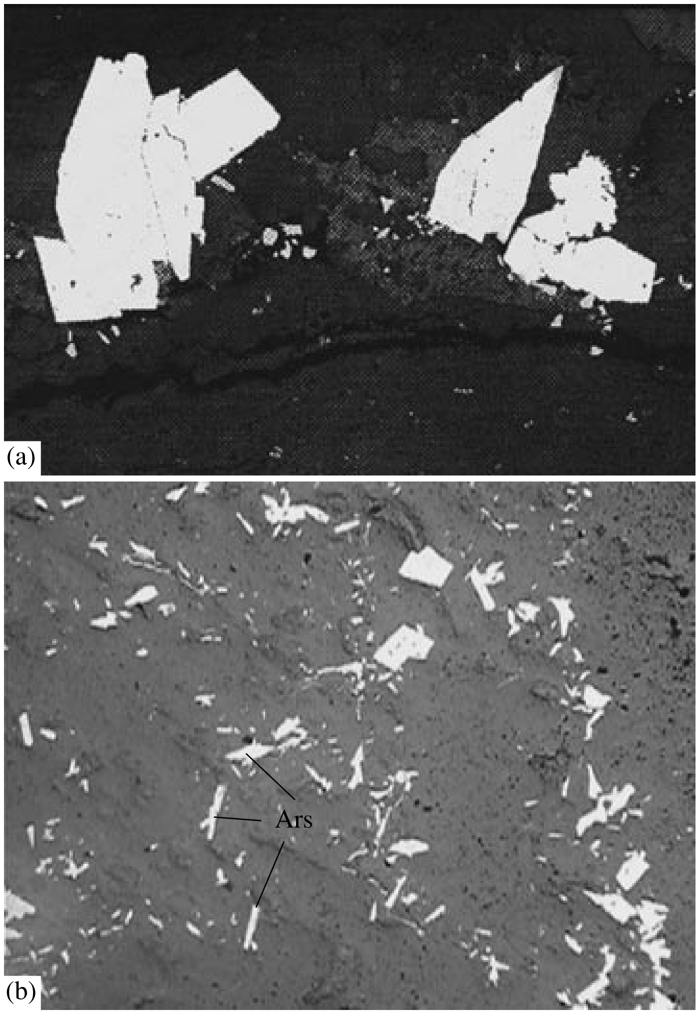


**Fig. 2.** Arsenopyrite in ores of the Natalka deposit. (a) Coarse-grained arsenopyrite in quartz veinlet, sample N-2, polished section, magn. 40; (b) dissemination of acicular Au-rich arsenopyrite, sample N-3, polished section, magn. 40.

element in sulfides during the impact of late Au-bearing solutions. This mechanism was recorded at gold–quartz deposits. Our data support an alternative concept [6], according to which the major portion of gold in arsenopyrites is related to the joint crystallization of these minerals at the early stage of ore formation. These data also confirm the concept [7], according to which gold is transferred as complex S–As compounds.

Very small dimensions of the Au-bearing sulfides testify to high rates of their crystallization. Taking into consideration the facts mentioned above, we can assume that gold and S–As complexes were transported by high-temperature gaseous fluids. This mechanism is suggested by data on the modern ore-forming system of Kudryavyi Volcano [8] and fluid inclusions [9].

Sulfur isotope data on the Au-bearing arsenopyrites (from –7.61 to –3.05‰) in disseminated ores of the Natalka deposit indicate the possibility of a crustal source of sulfur.

Scanning electron microscopic and microprobe investigations carried out by A.M. Gavrilov and A.P. Pleshakov revealed that arsenopyrites in disseminated ores from the Maisk deposit contain irregular dissemination and clusters of round gold grains (0.04–0.3 μm across) that represent the major (probably unique) occurrence mode of the invisible gold in sulfides [10]. However, investigations of arsenopyrites with the invisible gold in the chemically bonded form (Olimpiada, Veduga, and other deposits) demonstrated a sufficiently uniform distribution of Au [2–4].

Thus, the inhomogeneous Au distribution detected by microprobe analyses in arsenopyrites from the Natalka deposit can indicate the metallic occurrence mode of this element.

In conclusion, it should be emphasized that the Au-rich arsenopyrite has been recorded for the first time in the Natalka deposit. We have also established that the sulfide content can be as much as 4–6% (average 2.5–3%) at deep levels of this deposit. These facts are essential for the

**Table 1.** The composition of arsenopyrite from the Natalka deposit (based on microprobe analyses)

| Ord. no. | Fe | As | S | Co | Sb | Ag | Au | S/As | Total |
|---|---|---|---|---|---|---|---|---|---|
| | at % | | | | | wt % | | | |
| 1 | 38.57 | 27.62 | 33.79 | 0.03 | 0.01 | 0.008 | 0.047 | 1.22 | 100.02 |
| 2 | 37.94 | 27.20 | 34.86 | 0.00 | 0.00 | 0.005 | 0.023 | 1.28 | 100.00 |
| 3 | 36.82 | 27.23 | 35.95 | 0.00 | 0.00 | 0.004 | 0.040 | 1.32 | 100.00 |
| 4 | 37.22 | 27.53 | 35.25 | 0.00 | 0.00 | 0.010 | 0.014 | 1.28 | 100.00 |
| 5 | 36.66 | 27.82 | 35.52 | 0.01 | 0.00 | 0.000 | 0.044 | 1.28 | 100.01 |
| 6 | 35.14 | 27.57 | 37.25 | 0.00 | 0.03 | 0.000 | 0.019 | 1.35 | 100.00 |
| 7 | 32.85 | 32.63 | 34.52 | 0.00 | 0.00 | 0.008 | 0.026 | 1.06 | 100.00 |
| 8 | 32.82 | 32.62 | 34.55 | 0.00 | 0.00 | 0.001 | 0.031 | 1.06 | 100.00 |
| 9 | 32.76 | 32.64 | 34.60 | 0.01 | 0.00 | 0.006 | 0.022 | 1.06 | 100.00 |

**Table 2.** Average composition of arsenopyrite in different types of gold deposits (based on microprobe analyses)

| Ord. no. | Deposit | Ore type | *N* | Fe | As | S | S/As |
|---|---|---|---|---|---|---|---|
| | | | | at % | | | |
| | | | Gold–sulfide deposits of disseminated ores | | | | |
| 1 | Natalka | Stringer | 12 | 32.87 | 33.99 | 33.25 | 0.98 |
| 2 | Natalka | Disseminated | 37 | 36.74 | 27.37 | 35.89 | 1.31 |
| 3 | Natalka | Stringer | 19 | 32.73 | 32.75 | 34.51 | 1.05 |
| 4 | Natalka | The same | 19 | 32.48 | 32.27 | 35.24 | 1.09 |
| 5 | Maisk | Disseminated | 10 | 31.82 | 29.89 | 38.17 | 1.28 |
| 6 | Nezhdanin | The same | 161 | 36.19 | 40.41 | 23.27 | 1.35 |
| 7 | Nezhdanin | Vein | 43 | 35.40 | 43.93 | 20.64 | 1.09 |
| 8 | Olimpiada | Disseminated | 14 | 33.12 | 29.69 | 37.17 | 1.25 |
| 9 | Veduga | The same | 13 | 33.27 | 30.23 | 36.44 | 1.21 |
| | | | Gold–rare metal (Au–As–Bi–Te) occurrences | | | | |
| 11 | Chistoe | Stringer | 3 | 33.29 | 34.57 | 32.14 | 0.86 |
| 12 | Teutedzhak | The same | 2 | 31.77 | 34.3 | 33.46 | 0.98 |
| 13 | Maltan | The same | 2 | 34.28 | 34.56 | 31.16 | 0.9 |
| 14 | Gai | The same | 6 | 33.55 | 32.57 | 33.49 | 1.02 |
| | | | Gold–quartz deposits | | | | |
| 15 | Svetloe | Vein | 4 | 33.34 | 30.84 | 35.82 | 1.14 |
| 16 | Karal'veem | The same | 3 | 34.17 | 32.88 | 32.95 | 1.0 |
| 17 | Igumenov | The same | 11 | 33.47 | 35.07 | 31.46 | 0.9 |

Note: Sources of analyses: (1) [1]; (2–5) IGEM (A.I. Tsepin, analyst); (6, 7) V.V. Alpatov; (8, 9) [2]; (11–14) N.E. Savva; (15) N.A. Gorychev; (16) [11]; (17) [12].

development of ore processing technology for the Natalka deposit. Specific features of ore formation in this deposit make it possible to recognize the gold–sulfide–quartz type in the group of disseminated gold–sulfide deposits.


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## REFERENCES


1. V. I. Goncharov, S. V. Voroshin, and V. A. Sidorov, *The Natalka Gold Ore Deposit in Magadan* (SVKNII DVO RAN, 2002) [in Russian].
2. A. D. Genkin, F. E. Wagner, T. L. Krylova, et al., Geol. Ore Deposits **44** (1), 52 (2002) [Geol. Rudn. Mestorozhd. **44** (1), 59 (2002)].

3. A. D. Genkin, N. S. Bortnicov, L. Cabry, et al., Econ. Geol. **93**, 463 (1998).
4. E. E. Wagner, P. Marion, J. R. Regward, et al., in *Gold* (South Afr. Inst. Min. Metal., Johannesburg, 1986), pp. 435–443.
5. N. V. Petrovskaya, *Native Gold* (Nauka, Moscow, 1973) [in Russian].
6. A. M. Gavrilov, Tr. TsNIGRI, Issue 178, 33 (1983).
7. V. N. Sorokin, Geokhimiya **12**, 1892 (1973).
8. M. A. Yudovskaya, V. V. Distler, I. V. Chaplygin, et al., Dokl. Earth Sci. **391**, 874 (2003) [Dokl. Akad. Nauk **391**, 535 (2003)].
9. A. V. Volkov and A. A. Sidorov, Dokl. Earth Sci. **403**, 700 (2005) [Dokl. Akad. Nauk **403**, 220 (2005)].
10. *Prospecting–Evaluation Criteria of Gold Deposits in Perivolcanic Zones: Methodical Recommendations* (SVKNII DVO RAN, 1982) [in Russian].
11. N. M. Davidenko, *Mineral Assemblages and Formation Conditions of Au-bearing Quartz Veins in the Malo-Anyusik Region of Western Chukotka* (Nauka, Novosibirsk, 1975) [in Russian].
12. E. E. Tyukova, *Problems of Metallogeny in Ore Districts of Northeast Russia* (SVKNII DVO RAN, 2005), pp. 125–156 [in Russian].