# NATIVE GOLD FROM MUTNOVSKOE ORE OCCURRENCE, SOUTH–EASTERN KAMCHATKA, RUSSIA

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Native gold from hydrothermal ore veins from the South-Eastern Kamchatka region is described. Silver content in the mineral measured by microprobe varies from 14.4 up to 32 wt.%. There are also Bi, Te and Se in the mineral composition. The heterogeneous structure of the gold grains observed gives their low microhardness. The conclusion on the correlation between physical properties, composition and conditions of mineral formation is made. 3 tables, 5 figures, 14 references.

Keywords: native gold, hydrothermal gold deposit, Mutnovskoe ore occurrence, South-Eastern Kamchatka.

## Brief geological overview of the region

Mutnovskoe ore occurrence is located in erosion-tectonic caldera of the Miocene-Pleistocene volcano in the south-east of Kamchatka (Aprelkov, Sheimovich, 1964; Aprelkov, Kharchenko, 1968). In terms of geology this area represents two structural levels (Lonshakov, 1979). The lower level consists of Oligocene-Miocene volcanic rocks and volcanic sediments crossed with intrusive bodies. The rocks of the lower level host the ore. Volcanic rocks are represented by fine fragmentary clastic tuffs of acidic and intermediate composition interbedded with andesite and andesite-basalt lava flows. They are present in the central part of the caldera. Intrusive massif with complex structure and composition that varies from quartz diorite to gabbro-diabase, is located in the same part of caldera. The massif is saturated with dacitic and quartz porphyry dikes. Volcanoclastic tuffs and tuffaceous sandstone are localized in the north-eastern part of the caldera. The upper structural level on the margins of the caldera consists of Upper Miocene-Pliocene and Lower Pleistocene volcanics covering underlying level with angular and azimuthal unconformity. Basaltic, andesite-basaltic lavas and rhyolite tuffs represent the upper volcanic rocks.

All ore hosting rocks are altered. Chemical analyses of rock samples taken across the ore body cross-section, show that propylitic alteration is characteristic for gabbro-diorite rocks. The comparison between altered and "fresh" rocks reveals that alteration resulted from potassium metasomatism with supply of $K_2O$ and $SiO_2$ and removal of $Na_2O$ and CaO (Table 1, an. 1 – 7). Argillic alteration is more developed in tuffs and andesite, which got depleted in $K_2O$, $Na_2O$ and CaO, but enriched in silica (Table 1, an. 8 – 13).

The ore bodies are represented by hydrothermal veins and veinlets which alternate with completely altered and strongly silicified rocks. They usually extend submeridionally or to the north-west and north-east. The veins dip is steep and subvertical; the thickness varies from some centimeters to several meters. The biggest ore body reaches 2 – 3 meters in some places and widens up to 10 – 15 m (in the north upper part) splitting into multiple veins and veinlets. Vein clusters change to one or two veins at depth, which is typical for low depth gold deposits according to some authors (Nekrasov, 1976).

The veins vary in mineral composition: there are quartz, quartz-sulfide and quartz-carbonate veins. Quartz-sulfide veins dominate in the southern part of the area while quartz and quartz-carbonate ones are more abundant in the north. Pyrite, sphalerite and galena are the most common sulfide minerals in quartz-sulfide veins (Borisova *et al.*, 1983). Minor ore minerals include chalcopyrite, fahlore; the less abundant are luzonite, hessite, altaite, sylvanite, proustite, pyrargyrite, selenium bearing berryite and cupropavonite (Borisova *et al.*, 1986, Borisova, Meshalkin, 1991).

## Characteristics of native gold

Native gold was observed in the crushed ore samples of the biggest ore body. It is represented by very small (0.01 mm) films, clumpy and interstitial particles in quartz. More rarely native gold was found as separated free grains of 0.01 – 0.1 mm in size. Such

*Table 1.* **Chemical composition of hydrothermally altered rocks of Mutnovskoe ore occurrence, wt.%**

| № an. | d, m | $SiO_2$ | $TiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | FeO | MnO | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | $H_2O$ | $S_{total}$ | LOI | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Profile 1 | | | | | | | | | | | | | | | | |
| 1 | 550 | 51.00 | 0.68 | 23.10 | 3.79 | 3.52 | 0.14 | 2.23 | 10.21 | 3.18 | 0.77 | 0.14 | 1.17 | 0.07 | – | 100.00 |
| 2 | 5.5 | 51.96 | 1.03 | 17.10 | 4.27 | 4.69 | 0.33 | 5.17 | 8.94 | 3.17 | 1.38 | 0.22 | – | n.d. | 1.64 | 99.90 |
| 3 | 4.5 | 49.16 | 1.13 | 16.36 | 3.93 | 4.90 | 0.62 | 0.88 | 16.30 | 2.30 | 1.38 | 0.26 | – | n.d. | 2.80 | 100.03 |
| 4 | 2.5 | 53.36 | 1.55 | 12.70 | 7.69 | 2.43 | 1.95 | 6.51 | 1.41 | 0.61 | 2.58 | 0.26 | – | n.d. | 8.26 | 99.31 |
| 5 | 1.5 | 51.25 | 1.74 | 17.19 | 1.78 | 8.15 | 0.68 | 1.76 | 7.36 | 2.30 | 2.40 | 0.21 | – | n.d. | 4.60 | 99.42 |
| 6 | 0.5 | 63.51 | 0.83 | 12.02 | 7.87 | 0.07 | 0.86 | 2.29 | 1.78 | 0.74 | 2.28 | 0.26 | – | n.d. | 6.85 | 99.36 |
| 7 | 0.05 | 57.94 | 0.94 | 15.93 | 4.93 | 0.74 | 1.49 | 4.81 | 1.34 | 1.08 | 4.74 | 0.30 | – | n.d. | 6.53 | 100.77 |
| Profile 2 | | | | | | | | | | | | | | | | |
| 8 | 5.3 | 74.80 | 0.65 | 13.60 | 0.54 | 0.23 | 0.042 | 0.40 | 0.05 | 0.12 | 6.69 | 0.036 | 1.98 | 0.08 | – | 99.22 |
| 9 | 4.3 | 72.60 | 0.41 | 14.90 | 0.44 | 0.26 | 0.078 | 0.43 | 0.05 | 0.10 | 7.78 | 0.052 | 1.92 | 0.05 | – | 99.07 |
| 10 | 3.3 | 75.80 | 0.78 | 10.40 | 3.80 | 0.18 | 0.080 | 0.65 | 0.09 | 0.05 | 3.70 | 0.140 | 3.12 | 0.34 | – | 99.13 |
| 11 | 2.3 | 84.20 | 0.80 | 8.60 | 0.31 | 0.15 | 0.091 | 0.53 | 0.05 | 0.025 | 2.11 | 0.060 | 2.24 | 0.03 | – | 99.20 |
| 12 | 1.3 | 89.60 | 1.04 | 5.70 | 0.02 | 0.17 | 0.068 | 0.31 | 0.05 | 0.016 | 1.35 | 0.026 | 1.52 | 0.02 | – | 99.89 |
| 13 | 0.4 | 94.60 | 1.15 | 1.30 | 0.13 | 0.06 | 0.017 | 0.06 | 0.05 | 0.029 | 0.22 | 0.028 | 1.49 | 0.02 | – | 99.15 |

*Note: d – distance from the sample location to the ore body, n.d. – not determined, Analyses 1–7 are slightly altered gabbro-diorite and propylitic rocks; analyses were done at spectral-chemical laboratory of Lomonosov Moscow State University, analyst V.N. Zhihareva. Analyses 8–13 are argillic altered tuffs and andesites; samples were analyzed at the central analytic laboratory of GEOCHI RAS, analysts E.V. Besrogova and N.V. Budarina.*

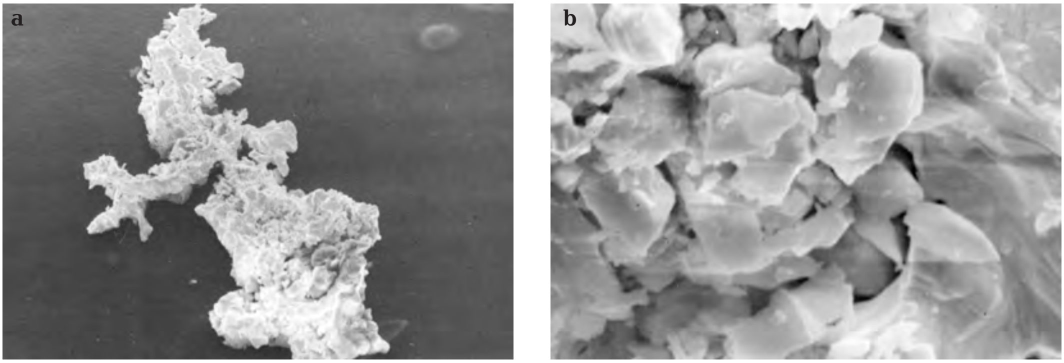
grains usually have applanate, dendrite, wire-like or isometric shape. The color of the gold particles is mainly yellow, sometimes with red or white tint.

Scanning electron microscopy (SEM) study of the particles morphology showed that there are flat or stepped areas on the surface of applanate and dendrite grains (Fig. 1). Subblock and granular structure of some grains was observed under higher magnification. Sometime some unidentified inclusions of porous and honeycomb phases were seen in gold grains (Fig. 2). Lighter strings of presumably more pure gold on the boundary of the blocks were observed in some cases (Fig. 3). Interstitial gold in quartz has curved boundaries that follow the contours of quartz grains or resemble amoeba-like pads on it (Fig. 4).

The structural peculiarities observed, that are granular and block structure, stepped pattern as well as phase heterogeneity of grains, are common for native gold in general, whereas very fine grains and ultra small size of their surface elements are characteristic for gold ores of low depth deposits (Petrovskaya, 1973, Novgorodova, 1983). Relation of gold grains with quartz show that they crystallized simultaneously or, sometime, gold formed a little later than adjacent quartz.

The studied gold can contain up to 32 wt.% of silver. Bi, more rarely Se and Te are also present in its composition (Table 2). According to Nina V. Petrovskaya (Petrovskaya, 1980), impurity of bismuth usually characterizes gold from deposits of medium depths, while Te and Se are the typical admixture for the mineral from ores of low depth deposits. Fineness of the gold from Mutnovskoe corresponds to the most common gold found in nature (Petrovskaya, 1973). The highest fineness characterizes one of the smallest grains (Table 2, an. 3). We did not observe any compositional zoning of the grains; although morphological or phase heterogeneity found under electron microscope could be caused by various Ag content. For instance, porous and honeycomb inclusions can possibly have higher Ag content because they look darker (Fig. 2) and therefore have lighter overall atomic weight. The paler veinlets at the blocks edges (Fig. 3) probably correspond to the composition with higher Au content than the matrix. Possibly, these gold veinlets formed as a result of matter rearrangement within or after the ore deposition. It is also possible that the heterogeneity in gold may represent inclusions of other minerals containing bismuth or tellurium.

X-ray powder diffraction data of native gold are given in the Table 3. The unit-cell parameter is 4.076 Å; it corresponds to gold-silver alloys with about 70 at.% Ag (Moiseyenko, 1977) confirming the determined composition of the mineral.



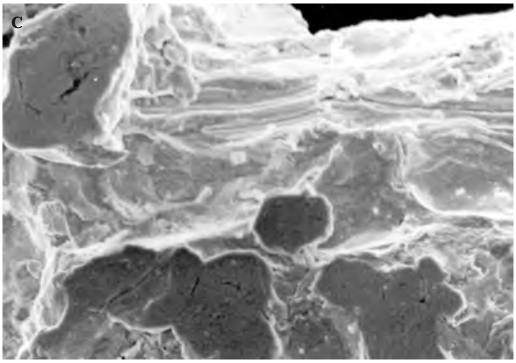
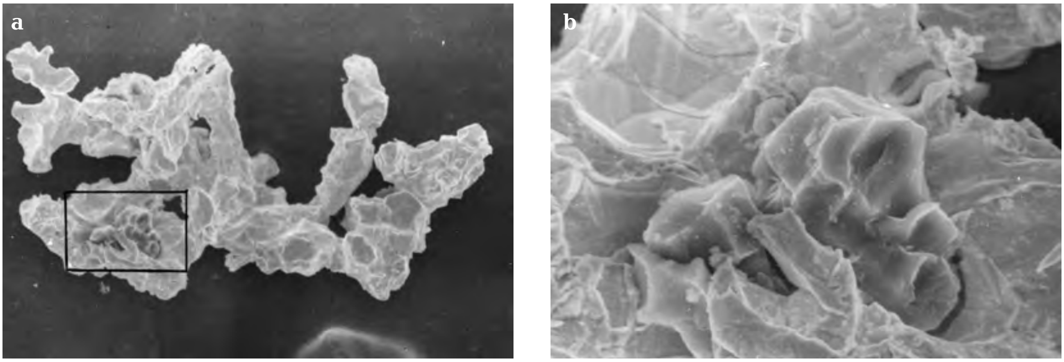


*Fig. 1. Shape and texture of native gold grains from Mutnovskoe ore occurrence. Scanning electron microscope (SEM) images. a — general view of the gold grain #1 (Table 2, an. 1), ×350; b — granular structure of the grain #1, ×3500; c — stepped pattern on the surface of the grain #2 (Table 2, an. 2), ×1500.*

*Fig. 2. Honeycomb inclusion in native gold: a — general view of the gold grain (Table 2, an. 3), ×500; b — area with the honeycomb phase, ×2000.*



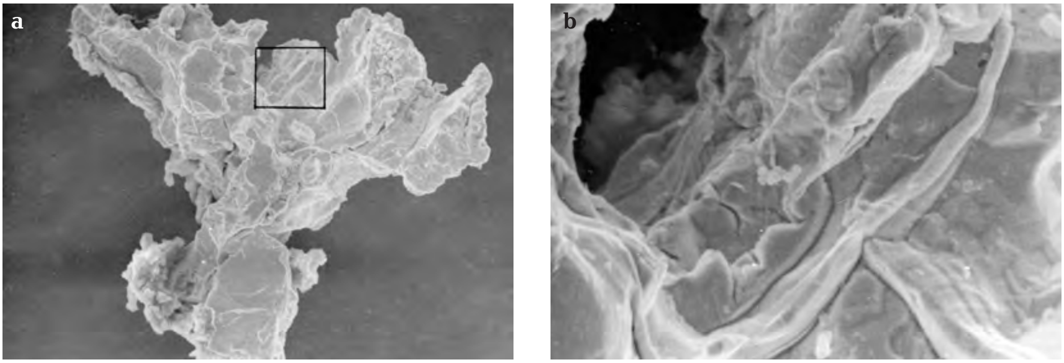


*Fig. 3. Subblock structure of a gold grain: a — general view of the gold grain #4 (Table 2, an. 4), ×500; b — area with bright veinlets (possibly purer gold) on the blocks boundaries, ×3500.*

*Table 2.* **Composition of the native gold by EPMA, wt.%**

| № an. | Size of the gold grains, μm | Au | Ag | Bi | Total | Fineness |
|---|---|---|---|---|---|---|
| 1 | 5 | 78.8 | 19.5 | n.d. | 98.3 | 802 |
| 2 | 100 | 79.7 | 19.3 | n.d. | 99.0 | 805 |
| 3 | 5 | 82.4 | 14.4 | n.d. | 96.8 | 851 |
| 4 | 10 | 74.4 | 22.8 | n.d. | 97.2 | 765 |
| 5 | 10 | 75.0 | 22.9 | n.d. | 97.9 | 766 |
| 6 | 20–30 | 68.3 | 28.7 | 0.4 | 97.4 | 701 |
| 7 | 20–30 | 64.1 | 32.0 | 0.6 | 96.7 | 663 |
| 8 | 20–30 | 66.4 | 29.2 | 0.7 | 96.3 | 690 |
| 9 | 20–30 | 67.9 | 27.7 | 0.5 | 96.3 | 705 |
| 10 | 20–30 | 69.0 | 27.1 | 0.6 | 96.7 | 714 |
| 11 | 20–30 | 66.1 | 29.3 | 0.5 | 96.0 | 689 |

*Note: accelerating voltage 22 kV, Au, Ag and Cu pure metals, PbTe, ZnSe were used as etalons. Analyses 1–5 were done by analyst L.T. Soshkina with JXA 50A microprobe. Cu, Bi, Te and Se were not detected (n.d.) Analyses 6–11 were done by analyst V.M. Chubarov with Camebax 244 microprobe. Cu, Se, Te, Zn, Pb, Fe, Sn and Sb were not detected except of analyses # 9 (Se and Te 0.1 wt. % ). Low sums of the analyses are possibly due to the small grain size.*

*Table 3.* **X-ray diffraction data for the native gold**

| This study data | | A.S.T.M., # 4-0786 | | |
|---|---|---|---|---|
| $a_o$ = 4.076 Å | | $a_o$ = 4.0786 Å | | |
| *I* | *d* | *I* | *d* | *hkl* |
| 100 | 2.349 | 100 | 2.355 | 111 |
| 50 | 2.035 | 52 | 2.039 | 200 |
| 40 | 1.438 | 32 | 1.442 | 220 |
| 60 | 1.227 | 26 | 1.230 | 311 |
| 45 | 1.178 | 12 | 1.1774 | 222 |
| 10 | 1.0185 | 6 | 1.0196 | 400 |
| 30 | 0.9338 | 23 | 0.9358 | 331 |
| 40 | 0.9116 | 22 | 0.9120 | 420 |
| | | 23 | 0.8325 | 422 |

*Note: diffractogram was obtained with DRON 1 diffractometer with Co X-ray source using quartz as an internal etalon. Parameters of the unit cell were measured with a precision method by E.A. Borisova.*

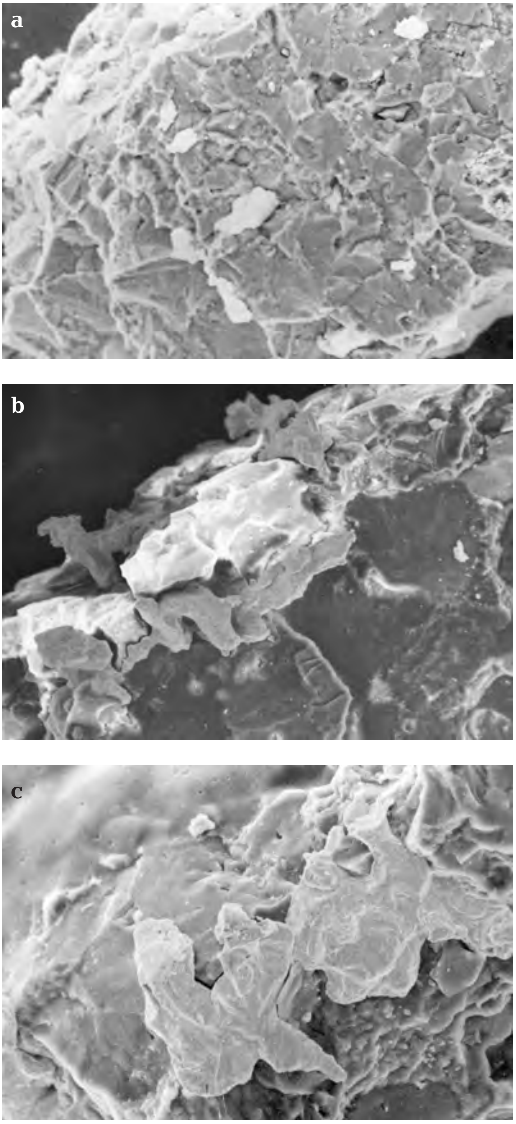


*Fig. 4. Relations between native gold and adjacent quartz grain (SEM image); native gold – white and bright grey, quartz – dark grey. a, b – ×350; c – ×750.*

Microhardness was measured for the biggest gold grain found. It varies in the range of 15–20 kg/mm$^2$ (3 measurements on PMT-3 with 5 g load) that is much lower than it was described for native gold before (Petrovskaya, 1980, Moiseyenko, 1977). This is most likely due to heterogeneity and internal structure of the grains which were observed under SEM. Also it needs to be mentioned that the Mutnovskoe ore occurrence is located in young region with active tectonics (Okrugin *et al.*, 2010). Therefore it could be possible that ores and gold suffered numerical temperature fluctuations resulted from temperature anomalies typical for the region and within the erosion-tectonic caldera. Temperature fluctuations might result in recrystallization of the gold grains and disorder of their structure. Nina V. Petrovskaya presumed that the low gold microhardness is related to structural disorder resulted from recrystallization, induced by near-intrusive heat (Petrovskaya, 1973). Valentin G. Moiseyenko provided data on heated and quenched Au-Ag alloys been softer and

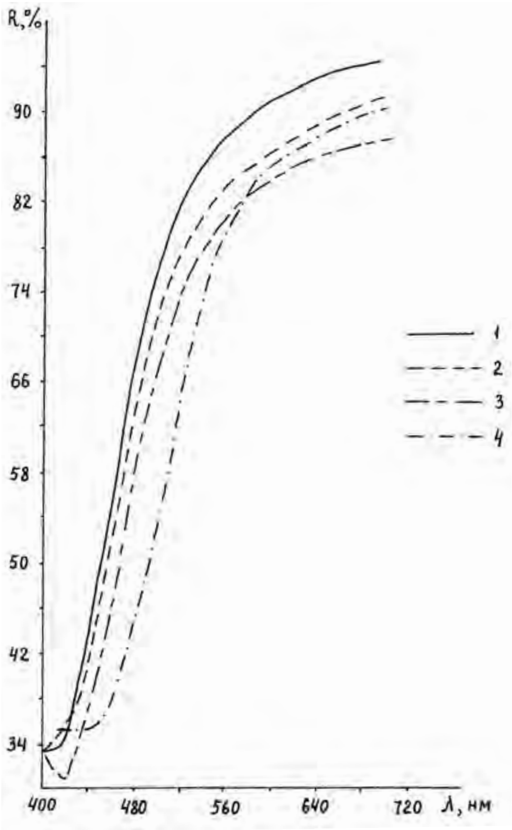


*Fig. 5. Spectral reflection curves of the native fold from Mutnovskoe ore occurrence: 1 and 2 – gold grain #2 (Table 2, an. 2), 3 – gold grain #3 (Table 2, an. 3); 4 – reference data for native gold (Identification..., 1973).*

more malleable in comparison to ones gradually heated and cooled (Moiseyenko, 1977).

The curves of reflectance spectrum measured on two gold grains (Table 2, an. 2, 3), are shown on Figure 5. According to the partial dispersion $\alpha = R_{640}/R_{480}$ and the correlation between $\alpha$ and gold fineness (Identification..., 1973) composition of the second gold grain (an. 3) includes more Au than that of the first one (an. 2) as it has been determined by microprobe too (Table 2). The shape of reflectance spectrum curves of the two grains are also different. The curve of the second grain (an. 3) has a dip at 420 nm and more gradual rise in the red part of the spectrum which is characteristic for gold with high fineness.

## Conclusions

Gold particles from Mutnovskoe ore occurence are very fine in size, have complex morphology, structure heterogeneity and inclusions of unidentified phases. Fineness of the studied gold is in the range of 660 – 850 which is most common for native gold-silver alloys. The mineral contains 14.4 to 32 wt.% of Ag and sometime has Bi, Te, and Se in its composition. Physical properties of the gold connected to its composition and complex grain structure. The studied native gold is characteristic for low depth hydrothermal deposits (Petrovskaya, Safonov, 1976) formed in conditions of frequent temperature change.

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