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Typomorphism of Native Gold (Geological-Industrial Types of Gold Deposits in the North-East of Russia)

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Abstract: This study presents the typomorphic features of native gold grains from three different geological-industrial types (GIT) of gold deposits in the North-East of Russia: (1) gold–arsenic-sulfide in black shale strata (Natalka, Degdekan, Karalveem, Maldyak deposits), (2) gold–quartz veins in granitoids (Dorozhnoye, Butarnoye, Shkolnoye, Maltan deposits), and (3) gold–silver adularia in volcanogenic strata (Kupol, Olcha, Kubaka, Burgali, Primorskoe, Dalnee deposits). The reliability of the geological interpretation is directly related to mineral associations, fineness variations, its internal structure and the content of microimpurities. Native gold is a reliable indicator for identifying various GIT of gold deposits at the early geological-prospecting stages of studying gold-bearing areas. Typomorphic features of native gold for each of the considered GIT are stable and do not depend on the age and scale of mineralization. It is shown that using an integrated approach obtains genetic information about a particular ore object, which makes it possible to predict the vertical range of mineralization and outline the technology for processing ores. The information obtained can also be effectively used in the search for placer deposits in nearby watercourses. Identification of typomorphic features of ore and placer native gold opens up wide opportunities for delineating the distribution areas of placer deposits.

Keywords: geological-industrial types; ore formations; typomorphic features of native gold; gold deposits in the north-east of Russia

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1. Introduction

Successful exploration for gold is impossible without scientifically based forecasts, the reliability of which increases significantly due to the improvement of methods for integrated study of gold ores and the formation of their industrial grouping on this basis. Fundamentals of the geological and industrial grouping of mineral deposits were laid down by [1], who defined the geological-industrial type (GIT) as "a group of geologically similar deposits that have proven themselves in world and domestic practice as a real supplier of this type of mineral raw material". It was V.M. Kreiter who proposed to classify as industrial such natural geological and mineralogical types of deposits that provide more than 1% of the world production of a certain mineral type. It should be noted that, due to the fact that each deposit has some specific features, the unified technological schemes of concentrating plants at large mines are set up to process ores of one bulk geological and industrial type with all the range of its mineral varieties [2].

V.M. Kreiter's followers continued working in this direction [3–8]. They showed that the geological and industrial grouping of deposits is determined by their geological homogeneity and belonging to certain gold formations—groups of deposits with a similar material composition of ores and genesis. In Northeast Asia, gold deposits are most widely developed, which are grouped into the following GIT types: gold–arsenic-sulfide in black shale strata, gold–quartz veins in granitoids, gold–silver adularia in volcanogenic strata [3]. When studying a particular deposit and its geological and industrial typification, it often turns out that each mineral variety of ores may well be mistaken by researchers for a new or unconventional GIT. This often occurs on poorly studied fragments of gold deposits, ore fields and nodes. In this regard, at an early stage of prospecting and exploration, when predicting the industrial type, an important role belongs to the establishment of a set of typomorphic features of native gold obtained during its study. To be precise, these features give contrasting differences for each group of deposits. The methodical manual for the study of native gold in [9] allows researchers to develop a scientifically based forecast.

The description of the typomorphic features of native gold for each particular gold deposit makes it possible to obtain genetic information about a particular object. Native gold, due to chemical resistance, is capable of such information. To date, plenty of factual material has been obtained on the indicator properties of native gold in the study of ore and placer deposits for various regions of the world [10–23]. The beginning of a comprehensive study of this mineral was laid by outstanding works [24,25].

The concept of the typomorphism of minerals was formulated by A.E. Fersman [26] and developed in the form of the teaching of N.P. Yushkin [27,28]. It is that the mineral composition and properties contains information about its genetic nature, indicating conditions for the formation of the entire deposit. The authors of the doctrine emphasize that over the course of geological time, such information may be erased. In this regard, native gold can be attributed to one of the most stable minerals, preserving genetic information for a long time due to the ability to resist chemical weathering and the absence of brittle deformations. Thus, the complexity of constitutional features of native gold (composition, structure, mineral intergrowths) has excellent indicator qualities.

This study presents a solid dataset of using typomorphism of native gold grains from various types of gold deposits in northeastern Russia as examples to show the importance of applying such a concept. This will allow, with a limited amount of material, at an early prospecting and exploration stage of geological research, to determine the type of deposit, to predict the vertical range of mineralization and a possible method of processing ores.

2. Regional Geological Setting and GITs of Gold Deposits

2.1. Geological and Structural Position of Northeast Asia

In geological and structural terms, the north-east of Russia is a complex composition of the Kolyma Chukchi and Primorsky terranes of passive continental margins, island-arc and oceanic terranes, as well as middle cratons. According to A.I. Khanchuk [29], all layers of the earth's interior—from the Precambrian strata to the modern majestic volcanoes of Kamchatka—are exposed in this region and are available for the most detailed studies. Large gold deposits in the region are characterized by different tectonomagmatic stages of their development. The GITs of the deposits considered by us are confined to large structural elements, including the following: the passive margin of the Siberian craton (deposits of the Verkhoyansk complex); collisional structures in the zone of the Tenka deep fault with large zones of tectonomagmatic activation, Omolon cratonic terrane, Kedon—Late Paleozoic and Okhotsk-Chukotka—Mesozoic marginal-continental volcanic belts (Figure 1).

The article will consider three, contrastingly different, GITs of gold deposits in the north-east of Russia: (1) gold–arsenic-sulfide in black shale strata (Natalkinskoye, Degdekan, Maldyak, Karalveem); (2) gold–quartz veins in granitoids (Shkolnoye, Butarnoye, Dorozhnoye, Maltan), (3) gold–silver adularia in volcanogenic strata (Kubaka, Kupol, Olcha, Burgali, Primorskoe, Dalnee). Further in the text and captions, the abbreviated names of these GITs will be used—gold–arsenic-sulfide, gold–quartz veins and gold–silver adularia.

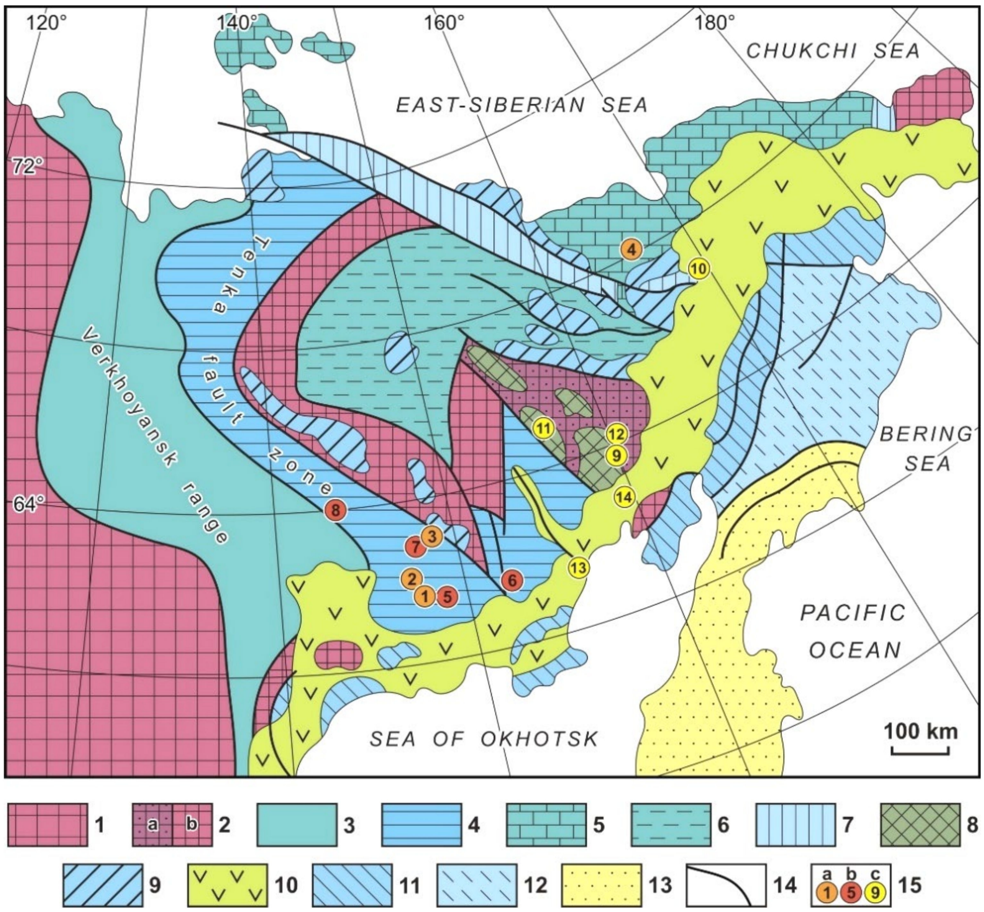

Figure 1. Location of research objects on a schematic geological and structural map of the north-east of Russia. The image was constructed by the authors of the present paper using data from [30]. The legend contains the following: 1—Siberian craton; 2—terranes with continental crust of the Siberian Craton (a—Omolon, b—others); 3, 4—deposits of the passive margin of the Siberian craton: 3—Paleozoic-Mesozoic deposits, 4—Mesozoic deposits; 5—folded cover of the Chukotka; 6—Paleozoic-Mesozoic deposits of the Verkhoyansk complex; 7, Late Mesozoic collisional sutures; 8—Kedon Late Paleozoic continental marginal volcanic belt; 9—Late Jurassic-Early Cretaceous volcanic belts; 10—Okhotsk-Chukotka Late Cretaceous volcanic belt; 11–13, Koryak–Kamchatka accretionary belt: 11—Late Jurassic–Early Cretaceous island-arc systems, 12—Late Mesozoic volcanic belts, 13—Cenozoic volcanic belts; 14—deep faults; 15—the main GITs of gold deposits: a—gold–arsenic-sulfide in black shale strata (1—Natalka, 2—Degdekan, 3—Maldyak, 4—Karalveem), b—gold–quartz veins in granitoids (5—Shkolnoye, 6—Butarnoye, 7—Dorozhnoye, 8—Maltan), c—gold–silver adularia in volcanogenic strata (9—Kubaka, 10—Kupol, 11—Olcha, 12—Burgali, 13—Primorskoe, 14—Dalnee).

2.2. GITs of Gold Deposits

2.2.1. Gold–Arsenic-Sulfide in Black Shale GIT

In genetic terms, these are hydrothermal-metamorphogenic deposits, localized mainly in the Permian-Triassic sedimentary strata. In the north-east of Russia, deposits of this type are mainly concentrated in the area of the Kularo-Nera terrane and are controlled by the Tenkinsky deep fault zone, which forms all gold deposits into a single Yano-Kolyma gold-bearing belt. In Chukotka, a similar type of deposits is also noted in the area of the Chukchi terrane. All the deposits of this GIT described the similarity of tectonomagmatic conditions of formation, paragenetic associations, as well as similar conditions for the development of the ore process, can be attributed to the gold–quartz geological formation of the medium-deep type.

Natalka Deposit

The Natalka deposit is one of the largest in Russia (the giant deposit) and is located in the Tenkinsky district of the Magadan region. Structurally speaking, the deposit is confined to the zone of the Tenkinsky deep fault and is associated with the collisional stage of development of the Yano-Kolyma gold-bearing belt as part of the Verkhoyansk-Chukotka folded system. The age of the host rocks is Late Paleozoic (P_3-T_1), and the ores are presumably Mesozoic (J_3-K_1). The NW bearing of the ore deposit (320–340°) in hydrothermally altered, predominantly silicified Permian-Triassic sedimentary strata is a mineralized zone penetrated by a network of quartz veins, lenses, brecciation areas, thin branching or parallel veinlets, with areas of massive silicification and arsenopyritization of varying intensity. The most common ore minerals are arsenopyrite and pyrite, less common are galena, chalcopyrite, sphalerite, pyrrhotite, rutile, and native gold. The size of gold grains is from 0.01 to 2 mm. A detailed description is given in [31].

Maldyak Deposit

The Maldyak deposit is located in the basin of the Berelekh river (upper reaches of the Kolyma river). It occurs in the Kularo-Nera terrane in the influence zone of the Tenka deep fault. The deposit was explored in 1938–1949, partially exploited in 1945–1948, and on a small scale in 1994–1998. It is estimated as large. At individual intersections defined by drilling, the concentration of Au in ores reaches 20.1 g/t [32]. Currently, prospecting and exploration work has been resumed at the Maldyak field. The ore field area of about 20 km^2 is composed of Middle Jurassic marine terrigenous deposits (J_2): shale, siltstone, sandstone. Intrusive rocks are represented by felsic and intermediate dikes belonging to the Ner-Bokhapcha complex ($\gamma\alpha J_3$ nr-bhr). The rocks form a complex linear folded structure with a general northwest bearing of 340°. Mineralization is developed both in sedimentary rocks and in dikes. Hydrothermal transformations of sedimentary rocks—silicification, in dikes—propylitization and beresitization. Ore bodies are represented by differently oriented veins, veinlets, and veined and veinlet-disseminated ore folds with a thickness of 0.5 to 3 m. Their mineral composition is dominated by quartz, accompanied by calcite, dolomite, sericite, chlorite, carbonaceous matter, and among ore minerals there is arsenopyrite, pyrite and native gold [10]. The size of gold grains is 0.01–3.50 mm.

Karalveem Deposit

The Karalveem deposit is located in the Bilibinsky district of the Chukotka Autonomous Okrug. Structurally, it is confined to the Anyui subterrane of the Chukchi terrane, which is considered as a fragment of the Late Paleozoic–Early Mesozoic passive margin of the continent [30]. The mineralization is located among Triassic gabbro-diabase sills, which, together with the enclosing sand-shale deposits of the same age, were turned into folds. The ore field, 15 km by 3 km in size, is elongated in a northwesterly direction along folded structures and is surrounded by outcrops of granitoids (K_1) that intersect diabases. Sedimentary rocks have intense contact changes and are transformed in a halo of about 1 km into cordierite-andalusite-biotite hornfelses. The mineralization is located among the Triassic gabbro-diabase sills, which, together with the enclosing sandy-shale deposits of the Triassic age, are crumpled into folds. The age of mineralization dated by K-Ar method is 130 Ma (SVKNII FEB RAS). The ores are partially transformed by Early Cretaceous granitoids (according to U-Pb determinations, 112 Ma). The deposit belongs to the vein type, where NW-bearing quartz vein bodies have a thickness of 0.5 to 2 m. The main vein minerals are quartz, ankerite, scheelite, ore minerals are arsenopyrite, galena, and native gold. The bonanza distribution of gold in veins with grades from traces to 190 g/t is typical [32].

Degdekan Deposit

The Degdekan deposit is located in the Tenkinsky district of the Magadan region (60 km north of the Natalka deposit). The ore-bearing area is confined to the Omchak-

Nelkoba metallogenic zone, which was revealed based on the interpretation of gravimetric data. Structural features of the Degdekan ore field are due to different scale manifestations of dynamometamorphism in Permian carbonaceous shales ($P_{2–3}$). Sedimentary rocks are intruded by Upper Jurassic (J_3) diorite porphyry dikes and Late Cretaceous (K_1) rhyodacites and dolerites of the Nera-Bokhapcha complex. Metasomatic transformations are represented by intense silicification, to a lesser extent by Fe-Mg carbonatization and albitization with cuts in carbonaceous matter. The ore bodies are represented by gold-bearing quartz-vein zones and quartz veins of sublatitudinal bearing (340–350°) up to 2 m thick. The main vein minerals are quartz, carbonates and ore minerals such as pyrite, pyrrhotite, marcasite, and chalcopyrite. The size of gold grains is from 0.1 to 1.5 mm. The age of gold mineralization dating is estimated at 133–137 Ma [33], i.e., the ore formation refers to the upper Jurassic—the beginning of the Early Cretaceous (J_3-K_1).

2.2.2. Gold–Quartz Veins in Granitoids GIT

Deposits of this type are predominantly concentrated in the Kularo-Nera terrane, along which the thick Tenkinskaya fault zone extends, cutting through the Permo-Triassic sedimentary sequences. A zone of tectonic-magmatic activation is oriented along this zone, marked by a series of Mesozoic granitoid intrusions (Figure 1). It is assumed that the main contribution of gold to intrusive magmatic systems was provided by gold-bearing Permo-Triassic sedimentary strata. Deposits of gold–quartz veins in granitoids or porphyry gold [5,7] of the GIT are associated with granitoid intrusions that by according to the level of formation, deep and medium–deep.

Shkolnoye Deposit

The Shkolnoye deposit is located in the Tenkinsky district of the Magadan region. Its structural position is determined by its confinement to the southeastern flank of the Yano-Kolyma gold-bearing belt, its Ayan-Yuryakh segment (Duskaninsky ore cluster). Fissure sublatitudinal fault tectonics had a great influence on the formation of ore bodies. The mineralization is confined to the Burgaginsky stock of granitoids with an area of about 2.6 km^2. The stock is composed of diorites, gabbro-diorites, tonalites, granodiorites, and biotite granites. The age of granitoids according to Rb/Sr determination by the North-East Common Use Center of the SVKNII FEB RAS is 127–152 Ma (J_3-K_1). Gold mineralization is localized in granodiorites and adamelites. Metasomatic changes are represented by silicification, muscovitization, carbonatization. The ore bodies are quartz veins up to 5 m thick and have a sublatitudinal bearing. They are confined to zones of cracking and increased fracturing of rocks. Gold is predominantly free in the ore. Gold mineralization is accompanied by the following: arsenopyrite, fahlore, silver lead sulfosalts; Au:Ag ratio—1:12 [34].

Butarnoye Deposit

The Butarnoye deposit is located in the Khasyn district of the Magadan region. It is confined to the central part of the Khurchan-Orotukan zone of tectonic-magmatic activation, traced in the submeridional direction for 150 km, with a width of 20–50 km. It is localized in a slightly eroded Late Jurassic-Early Cretaceous granitoid stock (J_3-K_1). The Butarny stockwork with an area of 4.6 km^2 is elongated in the submeridional direction for 2.9 km with a width of about 1.5 km. Granitoids of the Butarny stockwork belong to the Late Jurassic complex (J_3). Judging by the K–Ar dates obtained at the North-East Common Use Center of the SVKNII FEB RAS, the age of the granitoids is 142 ± 5 Ma. This age was also confirmed by U-Pb zircon dating at 150 ± 3 Ma [35]. The deposit is dominated by subvertical quartz veins and veinlets, NE-bearing (30–35°) with dip angles from 75° to vertical. The gold content in veins and veinlets reaches tens of grams per ton (up to 93.8 g/t). The ore bodies are represented by quartz veins up to 2 m thick and veinlets feathering them with poor nested-disseminated sulfide mineralization. Arsenopyrite predominates among ore minerals, rare finds of galena, galenobismuthite, Bi sulfotellurides, and maldonite are noted [36].

Dorozhnoye Deposit

The Dorozhnoye deposit is located on the right bank of the middle course of the Dorozhny brook in the Magadan region. It is localized in the Sylgytar granitoid intrusion. The territory is confined to the central part of the Burustakh synclinorium, which is part of the Inyali-Debinsk megasynclinorium of the Yano-Kolyma belt. It is composed of miogeosynclinal terrigenous sandy-silty flyschoid deposits of the Verkhoyansk complex ($J_{1–2}$). Ore bodies are gold-bearing quartz veins. They are gently dipping plates, 0.1–2.0 m thick, up to 800 m long, lying vertically inside the granitoid stock at intervals of 100–120 m. Presumably, these are contraction (concentric) and radial cracks that arose during the cooling of granitoids. Their bearing is as follows: northeast, dip northwest 10–15°. When leaving the granites in the hornfelses, the veins branch and wedge out. The average content of Au ranges from 8 to 17 g/t, and Ag from 10 to 350 g/t. The Au/Ag ratio varies from 1:1 to 1:20. At the Nadezhda site, the veins are steeply dipping (radial) cracks and veining zones, the prevailing thickness is 10–30 cm, the zones are up to 2 m, their bearing is as follows: sublatitudinal and northeast, dip to the northwest at an angle of 60–80°, length up to 125 m. Au content is from 6 to 25 g/t and Ag up to 300 g/t. The deposit is described in detail in a number of publications [37].

Maltan Deposit

The Maltan deposit is located in the Tenkinsky district of the Magadan region. The deposit is located on the northwestern flank of the Taryn ore-placer cluster. The ore field is limited by the adjacent Malo- and Bolshetarynskaya branches of the Adycha-Tarynsky fault, which separates the zone of the Verkhoyansk fold-thrust belt from the Kular-Nersky shale belt. It is localized in echeloned backstage (fractured bodies) of biotite gabbro, quartz diorite, granodiorite-porphyry and Cretaceous porphyritic granite cutting sedimentary rocks of the Middle and Upper Triassic (T_2–T_3). The length of the veins is 2.5–3.0 km. Mineralization is controlled by NE-bearing fractures, which are transverse with respect to the elongation of fractured intrusions. There are quartz, quartz-carbonate, and sulfide-quartz veins with a length of a few hundred meters, up to 50 cm thick. Together with gold, ore veins contain Bi (0.001–0.5%), As (0.1–1%) and W up to 1.0%; in rare cases, Mo is noted. The vein bodies are composed of quartz with large cluster-disseminated ore mineralization of arsenopyrite, native gold and bismuth, maldonite, bismuth tellurides, scheelite, and rarely molybdenite. The concentration of gold in ores is from 0.5 to 20 g/t. Gold mineralization is closely associated with bismuth and tellurium minerals.

2.3. Gold–Silver Adularia GIT

Gold–silver adularia GIT refers to the epithermal-volcanogenic, the most developed in the north-east of Russia. The deposits are confined to various volcanogenic belts. The considered objects are located in the Okhotsk-Chukotka and Kedonsky volcanic belts (Figure 1). According to the conditions of formation, the deposits are classified as shallow and near-surface. Most of them are composed of low-sulfidation, enriched ores.

2.3.1. Kubaka Deposit

The Kubaka deposit belongs to the class of large deposits. It is located in the basin of the Pravaya Aulandzha River in the North-Evensky district of the Magadan region. The ore field is composed of volcanics of the Kedon series ($D_{2–3}$-C_1 kd), represented by tuff sandstones, tuff siltstones, tuffs, and ignimbrites of intermediate and felsic composition. The structure of the ore field is a collapse caldera that underwent resurgent dome formation during intrusion of subvolcanic bodies and was influenced by Jurassic and Early Cretaceous magmatism (C_3-K_1). The ore bodies are composed veins and stockwork-type zones. The subscripts of the veins are sublatitudinal, and the thickness is unsteady along the strike with bulges up to 20 m and constrictions up to 10 cm, averaging 1–10 m. A series of ore veins stretches for 2 km [31,36]. Main minerals are quartz and adularia, and ore minerals in early veins are native gold, and in later veins include native gold, pyrite, arsenopyrite, acanthite, Sb-Ag and As-Ag sulfosalts and Ag selenides. The average grades of Au and Ag in the ore bodies of the Central zone are in the range 11–33 g/t and in the late ones the range is 12–23 g/t, with Au/Ag ratios of 1:1 and 1:100, respectively [31].

2.3.2. Kupol Deposit

The Kupol deposit is large in terms of reserves, located in the Anadyr region of the Chukotka Autonomous Okrug in the northwestern part of the Anadyr Highlands. The Kupolsky ore cluster is confined to the Upper Yablonsky metallogenic zone of the Central Chukotka sector of the Okhotsk-Chukotka volcanogenic belt. Currently, its first stage has already been put into operation. The ore field is composed of Late Cretaceous andesite lavas (K_1), less often basaltic andesites with interlayers of ash tuffs and Late Cretaceous tuffites. The ore body is a single thick (25–30 m) vein over 3 km long, presumably the mouth of a fissure volcano. Mineralization has been traced to a depth of more than 400 m. The mineral composition of the veins is quartz-adular, ore minerals are native gold, acanthite, Sb-Ag and As-Ag sulfosalts and Ag selenides. The concentration of Au in ores is from 0.1 to 230 g/t. Au/Ag ratio 1:10–1:100. Currently, Kinros LLC continues its operational work. The deposit is described in [31,38,39].

2.3.3. Olcha Deposit

Olcha deposit, average in reserves. It is located on the watershed part of the Khebikendzha mountains and the Yukagir plateau. The ore field is composed of sedimentary-volcanogenic strata attributed to the Kedon series of the Middle-Upper Devonian–Carboniferous ($D_{2–3}$-C_1), which are underlain by Archean gneisses, granite-gneisses, and other various Cambrian and Ordovician rocks. The recent relationships between Devonian volcanics and basement strata of different ages are tectonic. In the central part, the ore field is intersected by an extended and thick post-ore granodiorite-porphyry dike of northeastern orientation and rare thin submeridional dikes of andesitic porphyrites. The ore bodies of the deposit are multidirectional quartz, carbonate-quartz and adularia-quartz veins and vein zones of a simple lenticular and bead-like shape. The host rocks are predominantly rhyodacite tuffs. Ore bodies are a series of echelon-shaped quartz-adularia veins with a thickness of 0.4 to 8 m. More than 40 mineral species were identified in the ores of the Olcha deposit, but quartz, adularia, native gold, acanthite, selenides and Ag sulfoselenides predominate [40–42]. The ores are characterized by low sulfide content (no more than 2%, and in bonanza the amount of ore minerals reaches 70%). The distribution of useful components in ores is uneven—on average 10–15 g/t, Ag 70–120 g/t, and the Au content in bonanza is up to 14 kg/t, Ag is up to 10 kg/t; Au/Ag ratio in ores 1:1–1:100.

2.3.4. Burgali Deposit

The Burgali deposit is located in the Severo-Evensky district of the Magadan region. The deposit is present in the Kedon volcanic belt. The ore field is composed mainly of rhyodacite tuffs of the Kedon volcanic series (D_3-C_1 kd). The structure of the ore field is blocky. From the north and south, it is controlled by northeast-trending thrusts (20–35°), from the west and east—by steeply dipping northwest-trending faults (350°). Within these limits, a system of intersecting faults of a lower order (NE 40–45° and NE 60–65°) is developed. The gold-bearing stockwork is controlled by this fault system and consists of parallel enchelon zones, characterized by the most intense veining of quartz and carbonate-quartz composition. The stockwork is traced along the strike for 3700 m. The thickness of individual veins is 1.5–2 m, the length is 300–500 m [43]. Au in veins vary from 5 to 50 g/t, Ag—5–200 g/t, Au/Ag ratio—1:4. The vertical range of mineralization, according to exploration data, is about 250 m.

2.3.5. Primorskoye Deposit

The Primorskoye deposit is located in the south of the Omsukchansky district of the Magadan region. The territory is located at the junction of the Omsukchan (Balygychano-

Sugoi) tectonomagmatic zone with the Okhotsk volcanic zone of the Okhotsk-Chukotka volcanogenic belt, which developed on the folded base of the Sugoi marginal trough. The ore field is confined to an intrusive-dome structure and is localized in a gently sloping sequence of Late Cretaceous rhyolite ignimbrites (K_{1-2}) more than 700 m thick, which is intruded by dykes of intermediate and basic composition. The array of leucocratic granites (K_2), according to drilling data, is located under the deposit at a depth of 400–500 m. Metasomatic changes are largely due to the intruded intrusion and are represented by skarnoid associations of garnet–epidote–rhodonite composition. The veins and vein zones are 250–600 m long and 1–3 m thick, with a vertical span of 150 m [44]. The distribution of useful components is uneven. In the veins, Au content reaches 10–15 g/t, Ag reaches 100–150 g/t, and in ore columns values are 100 and 17,000 g/t, respectively. The Au/Ag ratio averages 1:10.

2.3.6. Dalnee Deposit

The Dalnee deposit, average reserves. It is located on the territory of the Severo-Evensky district of the Magadan region. The structure of the ore field is determined by its location in the southwestern part of the Gizhigin trough, with the structures of the Chukotka branch of the Okhotsk-Chukotka volcanic belt (Even volcanic zone) superimposed on it. In terms of Au reserves, the deposit belongs to the class of small deposits. A series of veins was found at the deposit, confined to faults of the northwestern and northeastern directions with a steep and vertical dip. These veins, together with subparallel smaller veins, form a veined and veinlet-disseminated system about 1300 m long and 150–300 m wide. The host rocks are represented by Late Cretaceous andesites (K_1). Isotopic determinations for host rocks by K-Ar are 92 ± 2 to 81 ± 2 Ma, and the age of Rb-Sr mineralization is 80 ± 5 Ma [45]. The ore bodies are represented by steeply dipping quartz, adularia-quartz veins and zones of explosive breccias with poor sulfide mineralization. Metasomatic alterations of host rocks are kaolinite-quartz-sericite. Vein minerals are mainly quartz and adularia, and ore minerals are predominantly pyrite, to a lesser extent native gold and silver, acanthite, pyrargyrite, and polybasite. Gold in ores is unevenly distributed and, on average, its content is 5.2–12.9 g/t, and in bonanza it is up to 500 g/t. The Au/Ag ratio ranges from 1:20 to 1:50. A detailed description of the deposit is given in the works [46,47].

3. Research Methods and Objects

3.1. Research Objects

The research objects for the study were ore samples and samples with visible gold from deposits of various GITs (see Sections 2.2.1 and 2.2.2), selected by the authors of this article in geological prospecting routes at a scale of 1:10,000 in different years of work, from 1978 to 2015. We also used technological samples provided to us for mineralogical study in different years by geologists of industrial organizations.

To date, the ore fields have been studied with varying degrees of details, since some of them are already in operation (Natalka, Butarnoye, Shkolnoye, Kubaka, Kupol, Primoskoye, Dalnee), while others (Maldyak, Degdekan, Maltan, Olcha, Burgali) are at the stage of detailed exploration.

3.2. Research Methods

From ore samples containing visible gold, silicates were dissolved with hydrofluoric acid and grains of native gold were isolated, which were then transferred to spectral quantitative analysis, and also placed in a compound for the preparation of polished sections.

The determination of microimpurities in native gold was carried out by a quantitative spectral method on a spectrograph from a micro-sample according to the method [48]. The advantage of this method is that before analysis, gold undergoes pre-treatment by rolling gold particles into the thinnest plate, followed by acid treatment to release it from mechanical mineral impurities.

The mineragraphic study of polished sections was carried out using optic microscopy (OM) on a Carl Zeiss AXIOPLAN Imagin reflected light microscope (Oberkochen, Germany). In these sections, minerals intergrown with native gold were studied and photographed using the MC-LCD visualization complex with the MMC software (LOMO, Petersburg, Russia).

The internal structure of native gold was revealed by etching the polished surfaces of the grains with standard reagents: for high-grade gold (HCl + CrO_3 of various concentrations) and for medium- and low-grade gold (HCl + $4HNO_3$). Interpretation of the nature of internal structures was carried out in accordance with the recommendations from [9]. Photographing of mineral intergrowths and internal structures of native gold was carried out using a microphotographic attachment on a reflected light microscope.

The determination of the native gold fineness was carried out in polished sections on a modernized POOS-1 microspectrophotometer with an internal standard and a high degree of stabilization of the illuminator and PMT power source according to the method of L. N. Vialsova [49], fineness in each grain was measured by 3–5 points. In each ore sample, measurements were carried out by the authors on 30–50 grains of native gold. Processing of measurement results by methods of mathematical statistics was carried out in the GOLD program developed by S.V. Preis. A significant part of the gold was analyzed by X-ray spectral electron probe microanalysis (XSMA) on the CAMEBAX device, for four main elements—Au, Ag, Cu, Hg—by the operator E.M. Goryacheva (North-East Common Use Center of the SVKNII FEB RAS, Magadan); on the same device, equipped with the mounting attachment "OXFORD INSTRUMENT", photographing of native gold in reflected electrons was performed.

4. Results

4.1. Typomorphic Features of Native Gold

4.1.1. Gold–Arsenic-Sulfide in Black Shale Strata GIT

Fineness of Native Gold

This geological and industrial type is characterized by native gold of medium and high purity with maxima of this value in the areas of 750‰ and 950‰ (Figure 2). Trial histograms are unimodal with a relatively low dispersion of this indicator (from 600‰ to 1000‰).

Trace Elements

It has been established that, in addition to Ag, native gold grains constantly contain microimpurities of As, less often Sb, Pb, and Fe, and in rare cases Cu, Bi, Hg, and Sn. As concentrations range from 0.5 to 120 g/t, all other impurities do not exceed 50 g/t (Table 1). Sn microimpurities are usually associated with the influence of granitoids on the geochemistry of gold mineralization.

Table 1. Concentration of microimpurities in native gold from ores of gold–arsenic-sulfide GIT deposits.

Deposit (No. in Figure 1)	Element Concentrations, g/t							
	As	**Sb**	**Cu**	**Bi**	**Fe**	**Hg**	**Pb**	**Sn**
Natalka (1)	0.5–18.7	1.5–16.0	–	–	–	0.5–12.2	1.0–17.0	–
Degdekan (2)	1.0–41.0	0.1–11.3	10.2–35.3	–	1.5–9.6	–	–	–
Maldyak (3)	8.4–89.2	1.2–37.9	–	0.1–5.7	1.0–10.5	–	0.7–12.5	0.01–5.4
Karalveem (4)	5.0–120.1	–	1.0–45.5	–	–	–	0.5–10.4	–

Notes: —–below detection limit.

Minerals in Intergrowth

In most cases, the study of mineral parageneses reveals an association of native gold with arsenopyrite, less often with galena and sphalerite. Gold mineralization is associated with late stages of mineralization evidenced by superimposing and filling cracks in previously deposited minerals and intergranular space (Figure 3a,b). A significant part of native gold is deposited directly in quartz. This type of deposit is favorable for enrichment of ores and is called "free gold".

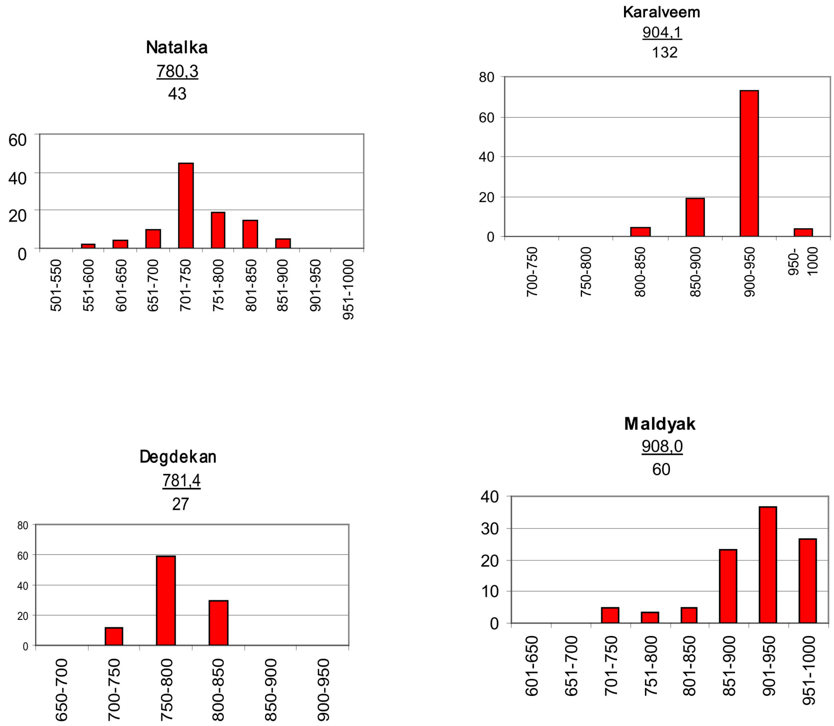

Figure 2. Histograms showing fineness of native gold for deposits of gold–arsenic-sulfide GIT on the abscissa axis—frequency of occurrence, %; along the *x*-axis, fineness intervals, ‰; in the numerator—fineness, ‰, in the denominator—the number of determinations.

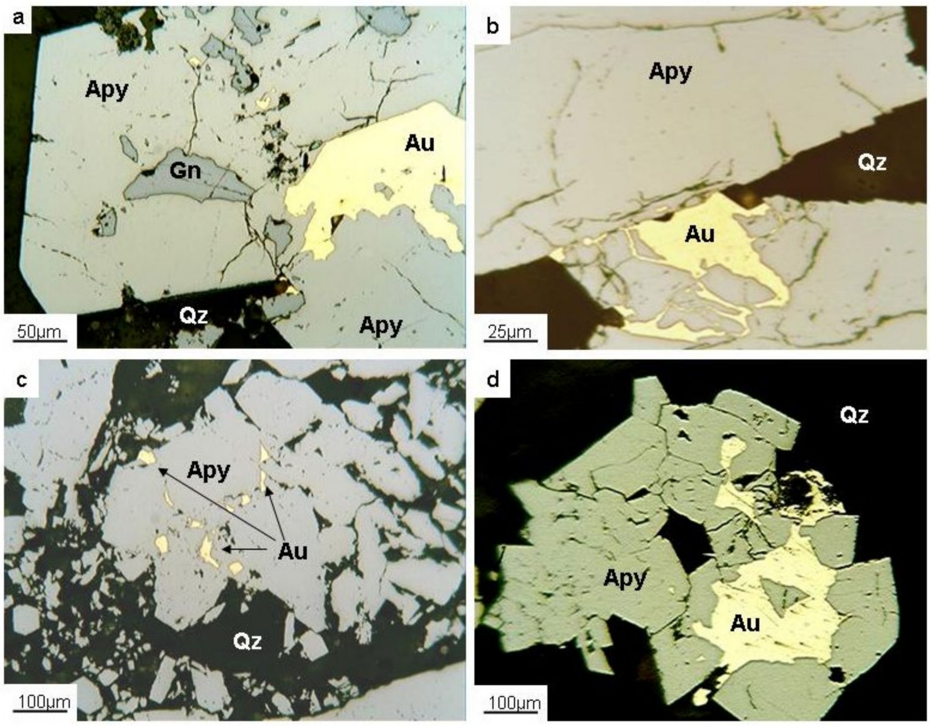

Figure 3. Typical mineral intergrowths of native gold in ores of gold–arsenic-sulfide GIT deposits: (**a**) intergrowth with arsenopyrite (Natalka); (**b**) development of native gold along cracks in arsenopyrite (Karalveem); (**c**) small inclusions of native gold in a single crystal of arsenopyrite (Degdekan); (**d**) overlay of native gold on an intergrowth of arsenopyrite crystals (Maldyak).

Internal Structures

Structural etching revealed a homogeneous polygonal-grain structure of native gold with simple twins (Figure 4), which indicates the medium-deep formation of this GIT and relatively stable conditions for gold crystallization. We associate the occurrence of twins with the formation of gold segregations in a turbulent tectonic setting, which is often evidenced by arsenopyrite cataclasis.

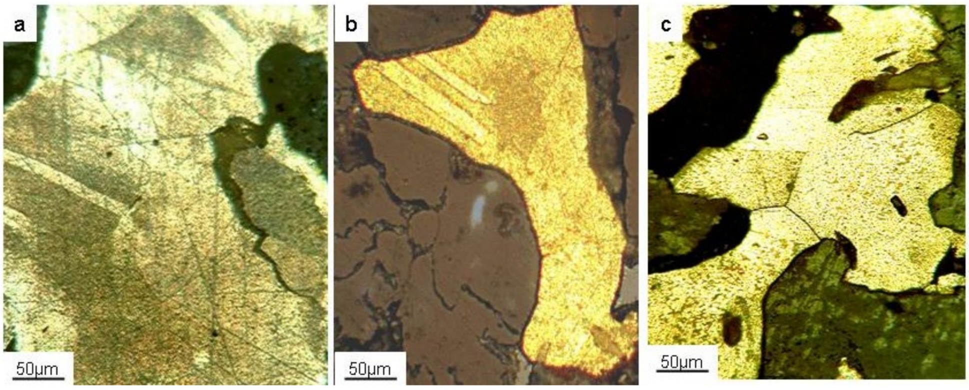

Figure 4. Polygonal-granular structure of native gold with simple twins in ores of various deposits of gold–arsenic-sulfide GIT: (**a**) Natalka, (**b**) Degdekan, (**c**) Maldyak.

4.1.2. Gold–Quartz Veins in Granitoids GIT

Fineness of Native Gold

Gold–quartz veins GIT is characterized by native gold of medium and high purity with maxima of this value in the regions of 850–950‰ (Figure 5). Fineness histograms are predominantly unimodal with a higher dispersion of this indicator (from 500‰ to 1000‰) compared to gold–arsenic-sulfide GIT. Often, in the frame of this type of deposits, there is a sharp decrease in the fineness of native gold and the appearance of silver mineralization (stephanite, freibergite, polybasite, acanthite, pyrargyrite).

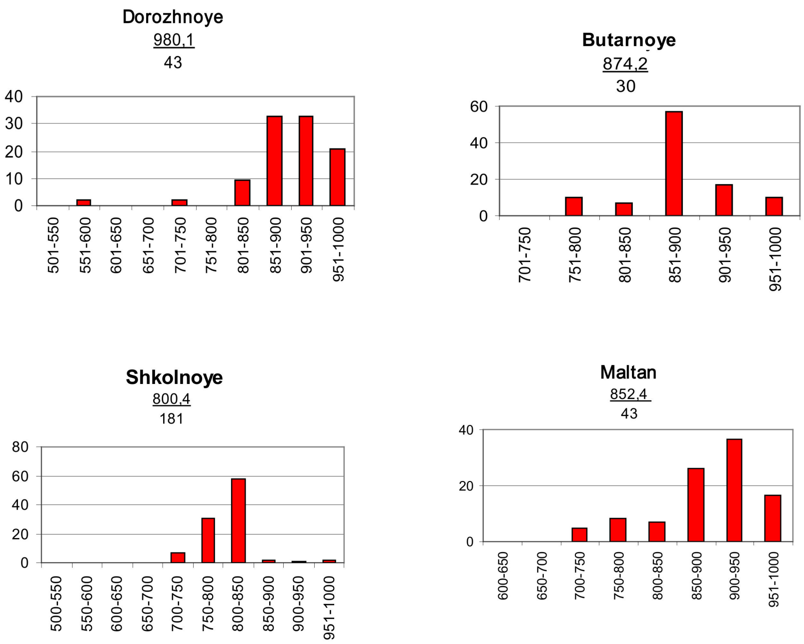

Figure 5. Fineness histograms of native gold for deposits of gold–quartz veins GIT along the abscissa axis—frequency of occurrence, %; along the *x*-axis, fineness intervals, ‰; in the numerator—fineness, ‰, in the denominator—the number of determinations.

Trace Elements

It has been established that native gold from deposits of this type constantly contains As in significant concentrations and Bi, Sb, Pb, Cu, and Fe are less common, while Hg, Sn are noted in rare cases (Table 2). As concentrations range from 0.8 to 300 g/t, all other impurities do not reach 50 g/t. Bi and Sn are classified by most researchers as granitogenic elements. Among the deposits of gold–quartz veins GIT, a gold-rare metal formation stands out [44–46], where Bi and Sn, and often W, form noticeable concentrations and are included, along with gold, in the list of useful components.

Table 2. Concentration of microimpurities in native gold from ores of gold–quartz veins GIT deposits.

Deposit (No. in Figure 1)	**Element Concentrations, g/t**							
	As	**Sb**	**Cu**	**Bi**	**Fe**	**Hg**	**Pb**	**Sn**
Shkolnoye (5)	100.0–300.0	1.0–30.0	1.0–7.5	1.5–12.4	30.0–100.4	30.1–99.6	–	1.7–31.1
Butarnoye (6)	0.8–100.0	–	–	1.5–22.3	1.0–12.7	–	–	–
Dorozhnoye (7)	1.0–15.3	–	–	1.5–21.0	–	–	1.0–82.0	–
Maltan (8)	10.0–150.0	2.5–16.3	–	1.0–50.0	–	–	1.5–12.3	–

Notes: —–below detection limit.

Mineral Intergrowths

The widespread association of gold–quartz veins GIT is naturally quartz, which was the reason for its name. In addition, the diversity of mineral associations of native gold is determined by its intergrowth with Sb and Bi minerals, and often Te (fahlore, joseite, native bismuth, bismuthine, etc.), as well as with Fe-Sb sulfosalts (Figure 6). Intergrowths with vein minerals are characterized by the features of host rocks—granitoids. At the Dorozhnoye deposit, native gold often forms intergrowths with muscovite (Figure 6h). Figure 6a–f shows mineral intergrowths of native gold in the ores of the Shkolnoye deposit for various horizons. Changes in the average fineness value with depth change in waves, but the dispersion of this indicator naturally falls from the upper horizon to the lower one (Table 3).

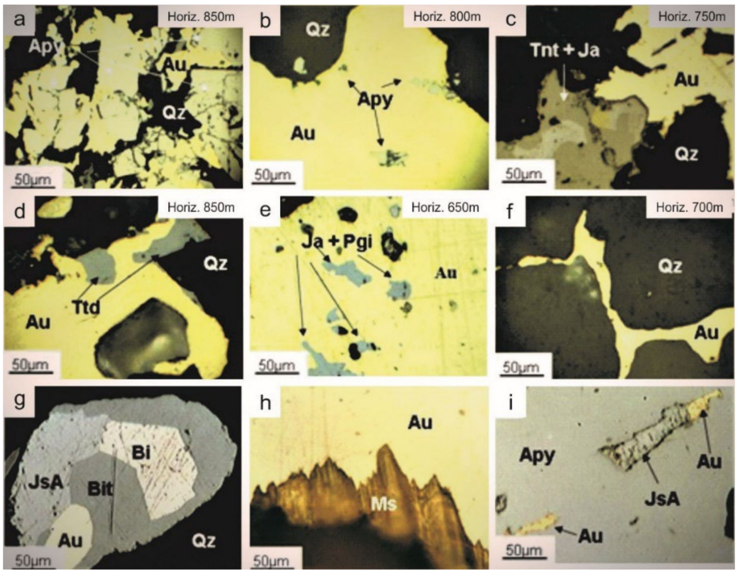

Figure 6. Intergrowths of native gold typical for gold–quartz veins GIT: (**a**–**f**) for different horizons of the Shkolnoye deposit: (**a**) native gold in the intergranular space of arsenopyrite, (**b**) in quartz with inclusions of small grains of arsenopyrite, (**c**) intergrowth with tennantite and jamesonite in quartz, (**d**) intergrowth with tetrahedrite in quartz, (**e**) inclusions in native gold of jamsonite and plagionite, (**f**) gold in the intergranular space of quartz; (**g**) (Maltan) inclusion of native gold in an intergrowth of bismuth, bismuthine, and joseite A; (**h**) (Dorozhnoye) intergrowth of native gold with muscovite; (**i**) (Butarnoye) small segregations of native gold in arsenopyrite intergrown with joseite A.

Table 3. Characteristics of native gold from ores of different horizons of the gold–quartz veins GIT Shkolnoye deposit.

Horizon, m	Scatter of Fineness Values Average, ‰	Fineness Dispersion	Mineral Paragenesis
850	250–850 / 775.4	11,375	Native gold + quartz + arsenopyrite + fahlore
800	700–850 / 782.7	1060	Native gold + quartz + arsenopyrite + tennantite
750	750–850 / 804.9	271.5	Native gold + quartz + arsenopyrite + tetrahedrite + jamsonite
700	700–800 / 753.5	223.5	Native gold + quartz + arsenopyrite + tetrahedrite
600	750–850 / 806.4	191.5	Native gold + quartz + arsenopyrite + jamsonite + plagonite

Internal Structures

For gold–quartz veins GIT deposits localized in granitoids, the structure of native gold is coarse-grained with rare simple and polysynthetic twins and patchy heterogeneity, presumably associated with the incorporation of microparticles of native Bi, which, unlike gold, undergoes intense etching even in air (Figure 7). A similar type of patchy heterogeneity for gold from deposits in granitoids was previously described in [8].

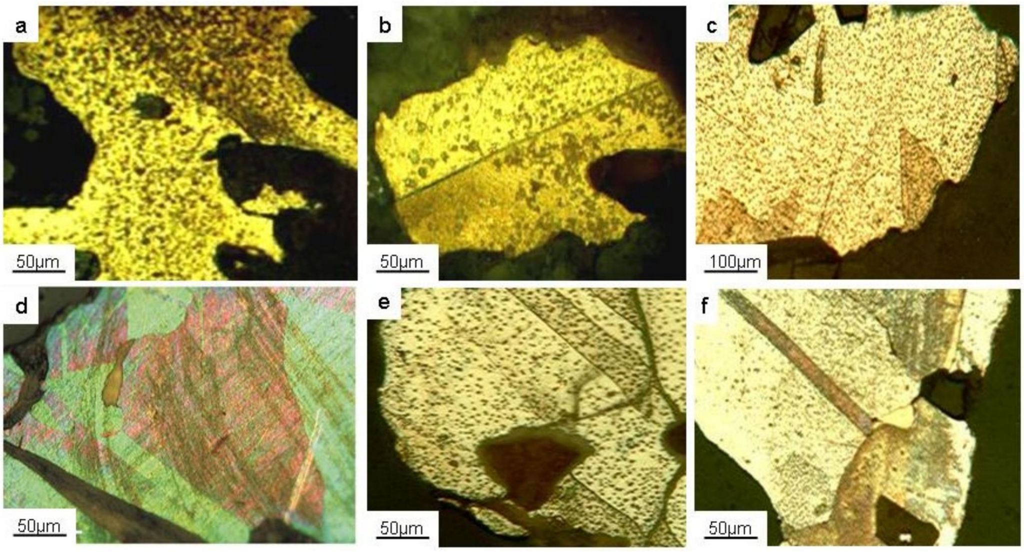

Figure 7. Polygonal-granular structure with simple polysynthetic twins and fine spotted heterogeneity in native gold from ores of gold–quartz veins GIT deposits: (**a**,**b**) Butarnoe; (**c**,**e**) Shkolnoye; (**d**) Maltan, (**f**) Dorozhnoye.

4.1.3. Gold–Silver Adularia in Volcanogenic Strata GIT

Fineness of Native Gold

The gold–silver adularia GIT is characterized by native gold of a relatively low fineness with a polymodal distribution on fineness histograms. The spread of the values of this indicator lies in the areas of 200–850‰ (Figure 8).

Deposits in genetic terms belong to the volcanogenic class, but often fall into areas of tectonomagmatic activation with late intrusions, which leads to the superposition of high-temperature processes on ores of early stages, to thermometamorphism of ores, differentiation and redistribution of matter, and staged mineral formation. It is these factors that are reflected in the histograms of gold in the form of polymodal graphs. Heterogeneity in fineness due to thermometamorphism can manifest itself within one grain of native gold (Figure 9).

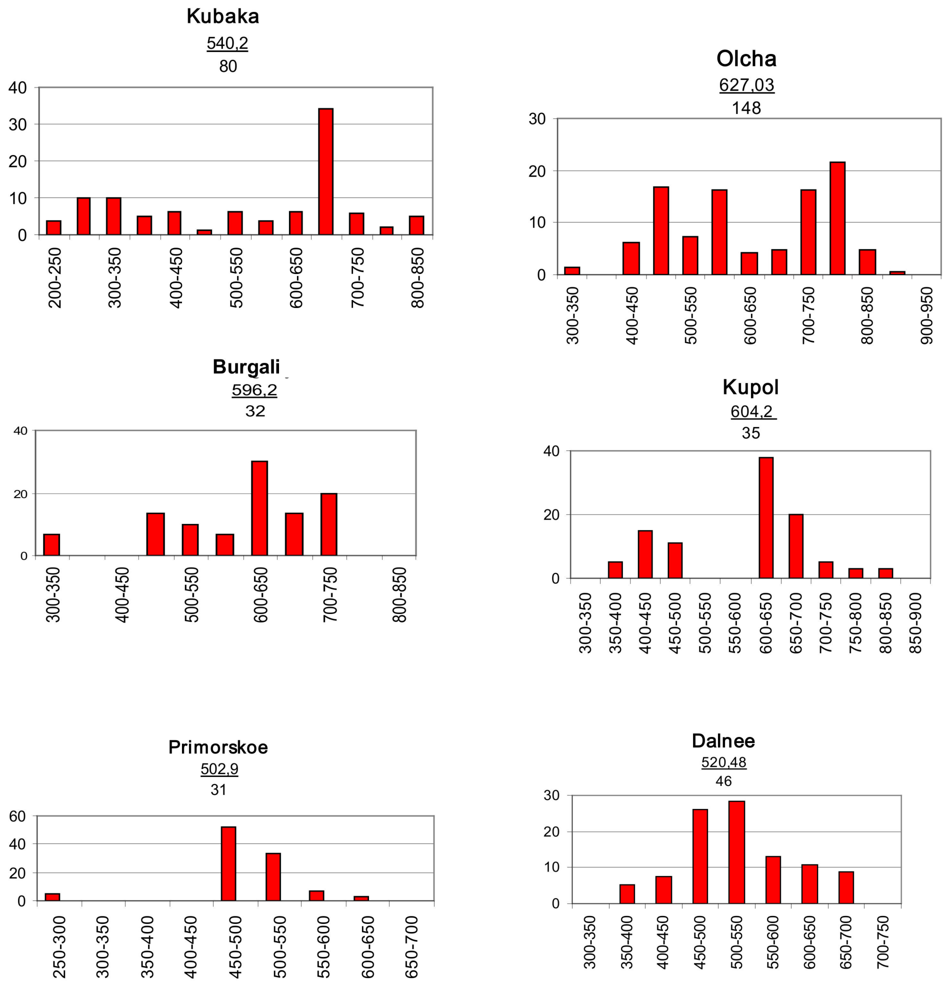

Figure 8. Fineness histograms of native gold for deposits of gold–silver adularia GIT: along the abscissa axis—frequency of occurrence, %; along the *x*-axis, fineness intervals, ‰; in the numerator is the fineness, ‰, in the denominator is the number of determinations.

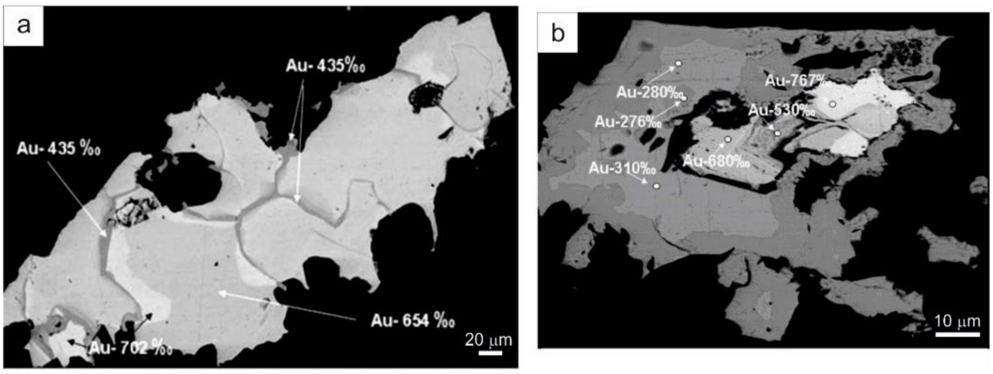

Figure 9. Heterogeneity of native gold within one grain: (**a**) Kupol deposit (from 435‰ to 702‰); (**b**) Dalnee deposit (from 276‰ to 767‰), taken in reflected electrons.

Trace Elements

It has been established that native gold from deposits of this type constantly contains impurities of Sb, Cu, Hg in noticeable concentrations (Table 4), and the highest concentrations reach Hg up to 1000 g/t in gold from the Dalnee deposit. Quite often, Fe is found, from 1.5 to 26.5 g/t (Kubaka, Burgali, Primorskoye), and also As, from 0.1 to 27.3 g/t (Kupol, Primorskoe, Dalnee).

Table 4. Concentration of microimpurities in native gold from ores of gold–silver adularia GIT deposits.

Deposit (No. in Figure 1)	Element Concentrations, g/t							
	As	**Sb**	**Cu**	**Bi**	**Fe**	**Hg**	**Pb**	**Sn**
Kubaka (9)	–	0.8–1.3	0.6–35.0	–	1.5–15.0	0.5–60.0		
Kupol (10)	0.1–27.3	0.1–25.5	–		–	0.1–1700.0		
Olcha (11)	–	1.3–16.4	0.8–45.3	–	–	0.7–45.5		
Burgali (12)	–	2.4–12.8	0.1–16.4	–	0.8–26.2	0.5–11.8		
Primorskoye (13)	0.1–0.9	1.0–12.3	2.0–68.4	1.0–24.4	0.3–14.7	0.1–65.2		
Dalnee (14)	2.7–12.1	1.5–21.1	0.1–7.3	–	–	0.1–1000.0		

Notes: —–below detection limit.

Mineral Intergrowths

The ores of the gold–silver adularia GIT deposits are characterized by a wide variety of mineral intergrowths with Ag sulfides, selenides, and sulfosalts. The sharply gradient conditions for the formation of epithermal Au–Ag deposits predetermine the predominantly fine-grained character of native gold segregations and its intergrowth with a wide range of Cu, Pb, Zn, Fe sulfides and Ag sulfosalts and sulfoselenides. The deposits of the Omolon cratonic terrane show intergrowths of native gold with magnetite and hematite. This is due to the peculiarities of the rocks of the base of volcanic apparatuses, among which Archean-Proterozoic ferruginous quartzites are widely developed. At the same time, volcanic activity manifested itself much later—on the border of the Devonian and Carboniferous periods. Segregation forms are predominantly xenomorphic; in quartz they are interstitial. On the example of only one Olcha deposit, we have shown an exceptional variety of such intergrowths (Figure 10). For other deposits of this GIT, examples of the most common intergrowths of native gold in ores are given—with pyrite, tetrahedrite, sphalerite, galena, acanthite, polybasite (Figure 11).

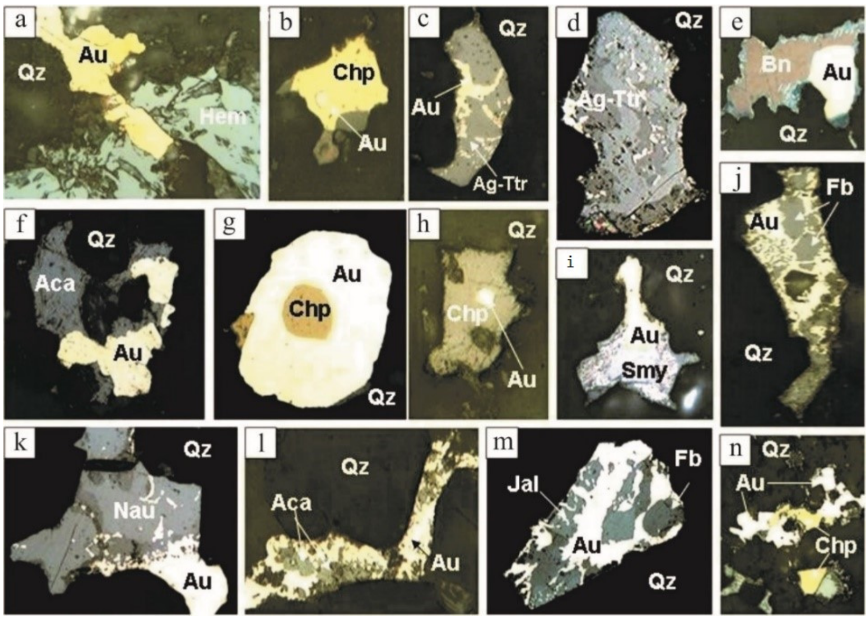

Figure 10. Types of intergrowths of native gold with ore minerals in quartz-sericite vein material at the Olcha deposit: (**a**) gold with hematite; (**b**) inclusion of kustelite in chalcopyrite; (**c**) close intergrowths of gold with argentotetrahedrite; (**d**) vein-like intergrowths of gold with argentotetrahedrite; (**e**) gold with bornite; (**f**) gold with acanthite; (**g**) inclusion of chalcopyrite in gold; (**h**) inclusion of gold in chalcopyrite; (**i**) intergrowth of gold with acanthite and stromeyerite; (**j**) gold with freibergite; (**k**) complex intergrowth of gold with naumannite and stromeyerite; (**l**) gold with acanthite; (**m**) gold-freibergite + jalpaite; (**n**) gold with chalcopyrite. (All taken at 100× magnification).

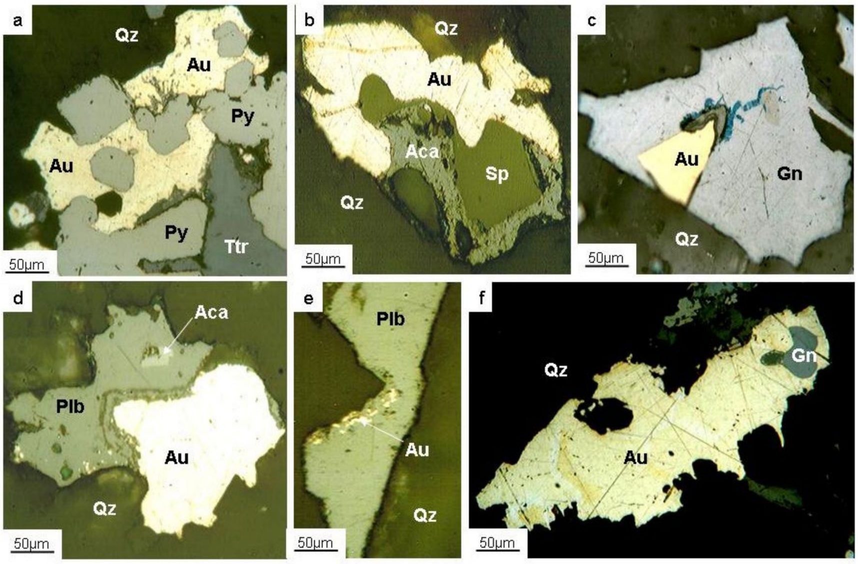

Figure 11. Mineral intergrowths of native gold from ores of gold–silver adularia GIT deposits in quartz: (**a**) with pyrite and tetrahedrite (Dalnee deposit); (**b**) with acanthite and sphalerite (Dalnee); (**c**) with galena (Primorskoe); (**d**) with polybasite and acanthite (Burgali); (**e**) with polybasite (Burgali); (**f**) heterogeneous in fineness of native gold with the inclusion of galena (Kupol deposit).

Internal Structures

The internal structures of native gold for gold–silver adularia GIT are predominantly zonal and are well identified by structural etching (Figure 12). In the case of thermometamorphism of ores, patchy heterogeneity often appears (Figure 13a) and there are granulation structures with the expansion of boundaries (Figures 12a and 13b,d) with expansion of grain boundaries. At the Olcha deposit, native gold has an unusual gulf-like shape with a zonal structure. This is due to the fact that it crystallized in quartz vacuoles filled with highly concentrated hydrothermal solutions (Figure 13).

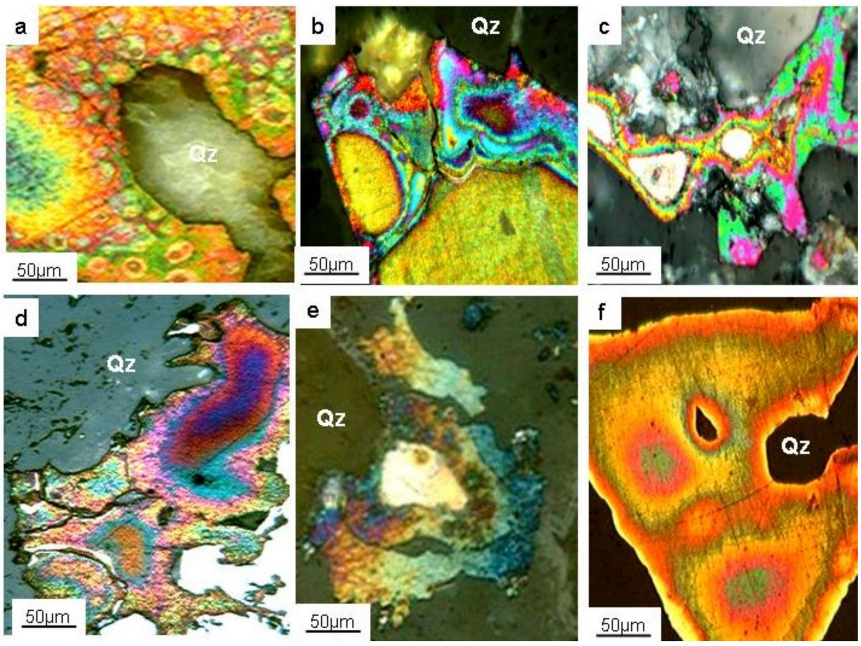

Figure 12. Internal structures of native gold from ores of gold–silver adularia GIT deposits: (**a**) spotted (Kubaka); (**b**) clear zonal (Dalnee); (**c**) zonal (Olcha); (**d**) zonal with a break in the boundaries (Kupol); (**e**) zonal (Burgali); (**f**) zonal (Primorskoe).

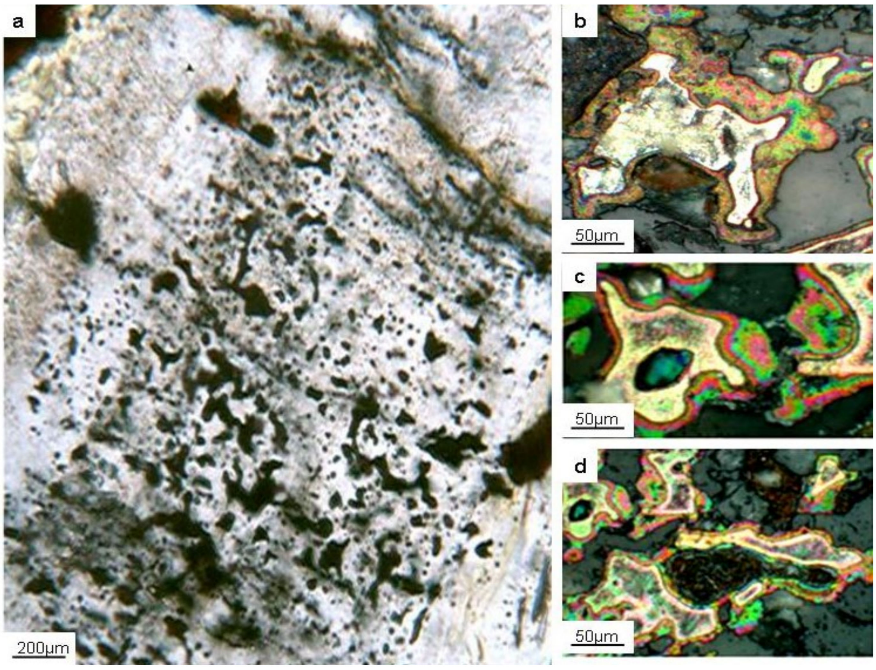

Figure 13. Filling of vacuoles with native gold in quartz at the Olcha deposit ((**a**) quartz in transmitted light without analyzer, black—vacuoles; (**b**–**d**) in reflected light, native gold in quartz, structural etching).

5. Discussion

All considered GIT deposits are hydrothermal and most of the features of native gold are associated with the depths of formation of these deposits. It is the depth that determines the duration, stability, and temperature zoning of mineral formation. To no lesser extent, the metallogeny of ore regions affects the formation of certain GIT deposits and their specific mineral types.

In genetic terms, the three most common GITs are generally accepted:

1. Orogenic [4]—hydrothermal-metamorphogenic in sedimentary strata (in most cases, these are black shale strata that have experienced metamorphism, mid-deep and deep (gold-sulfide quartz in sedimentary strata);
2. Porphyry (“intrusion-related”) [7,9,50,51]—gold deposits associated with granitoid intrusions, deep and medium deep (gold–quartz veins in granitoids);
3. Volcanogenic (epithermal) [52]—in volcanic belts of any age associated with volcanic activity in basic volcanic rocks of the oxidized type, shallow (gold–silver adularia).

At medium-deep and deep deposits in GITs 1 and 2, the hydrothermal system is in a relatively stable state with a long cooling process. This creates conditions for the growth of large individuals during the crystallization of both native gold and any other mineral. A different picture in the shallow type of deposits is GIT type 3, where, during the outburst of volcanoes, sharply gradient conditions are created with high initial temperatures and a rapid cooling of the ore-forming system, which generally prevents the differentiation of natural gold-silver compounds (high content of silver in gold and, accordingly, its reduced fineness). In this unstable environment with a limited cooling time of the system, no conditions are created for the growth of large gold individuals—more often it is fine-grained. Therefore, the first two types are placer-forming (large gold, which quickly precipitates and accumulates in a water stream), and volcanic—although it carries fine and fine gold with a water stream during the destruction of ores, it precipitates more slowly, and in most cases, does not give industrial accumulations.

The scope of mineralization is determined mainly by the depth of deposit formation and the largest has an “orogenic” GIT (many hundreds of meters)—volcanogenic, 50–100 m—but in the case of localization of mineralization in the vent facies, it can reach 300–400 m.

At an early stage of geological prospecting at ore deposits, we do not consider the size of native gold as an indicator property, since the amount of gold particles found in specimens and lump ore samples is not representative enough for sieve analysis. However, in the study of placer gold, this typomorphic feature can be of great importance, in combination with roundness and flatness.

To determine the GIT at an early stage of prospecting and exploration at ore gold deposits, we considered the following typomorphic features of native gold: microimpurities, average fineness and fineness distribution of gold on histograms in combination with fineness dispersion value, as well as mineral intergrowths and internal structures of native gold. The given descriptions and examples of typomorphic features of native gold deposits for various GIT showed characteristic differences for each type (Table 5).

Table 5. Main typomorphic features of native gold for various GITs.

Geological and Industrial Type	Fineness Variations, ‰ / Dispersion	Microimpurities	Mineral Intergrowths	Internal Structures
Gold–arsenic-sulfide in black shale strata	780–908 / 408–1746	As (Pb)	Quartz + arsenopyrite + galena	Polygonal-grained with simple twins
Gold–quartz veins in granitoids	852–980 / 2127–5626 (191–11,375) *	As, Bi, Sn (W)	Quartz + arsenopyrite + minerals BiTe + Sb-Fe-(Ag) sulfosalts	Proligonal-granular with patchy heterogeneity
Gold–silver adularia	502–627 / 6320–17,287	Sb, Cu, Hg (As, Fe)	Quartz + hydromica + Pb, Zn Cu sulfides + pale ores + Ag sulfides and sulfosalts + Ag, Cu, Pb selenides	Clear and unclear zonal with border extension

Note: * for the Shkolnoye deposit, the dispersion values are determined horizontally (see Table 3).

For gold–arsenic-sulfide GIT in black shale strata there is relatively coarse Au and high fineness with low dispersion of this index, polygonal-grained structures with simple twinning and a constant microimpurity of As in the composition; for the gold–quartz-porphyry type in granitoids—coarse gold predominates, fineness decreases slightly and its dispersion increases, heterogeneities are noted in the structures, and granitogenic elements Bi, Te, W, Sn act as microimpurities; for the epithermal gold–silver adularia GIT is characterized by fine, relatively low-grade Au with a high dispersion of this indicator, up to native Ag, a constant increased admixture of Sb, Cu and Hg, zonal internal structures complicated by heterogeneities during thermometamorphism of ores.

The study of the typomorphic features of native gold, tied to the geological environment and named by N.P. Yushkin [28] with topomineralogy, is a rational way to display the features of native gold. It makes it possible to establish the spatial patterns of the distribution of these features in connection with the geological structure and morphostructure of the territory.

Here, we give an example of such a study for the Maldyak deposit (gold–arsenic-sulfide in black shale strata GIT). It was the indicator properties of native gold that made it possible to speak about the existence of a granitoid pluton under the deposit, as well as about the dome-ring structural position of the Maldyak ore field (Figure 14). The conclusion is justified by the concentric-zonal arrangement of typomorphic features of native gold associated with the radial and concentric orientation of ore bodies. The ubiquitous presence of Bi impurities and the appearance of Sn and W impurities suggest that they were introduced by an undiscovered intrusion that formed a dome-shaped structure. All this made it possible to predict the different positions of gold-bearing veins (ore-bearing cracks), both radial—steeply dipping, and concentric—consistent with the schistosity of sedimentary rocks, crumpled into folds. Thanks to this approach, one of the rich ore bodies, previously unknown, was identified during exploration work at the deposit in 2001 by geologist, who called it the “Sedlovidnya vein”, due to its confinement to a radial crack and a sharp bend (fold) in the black shale sedimentary sequence.

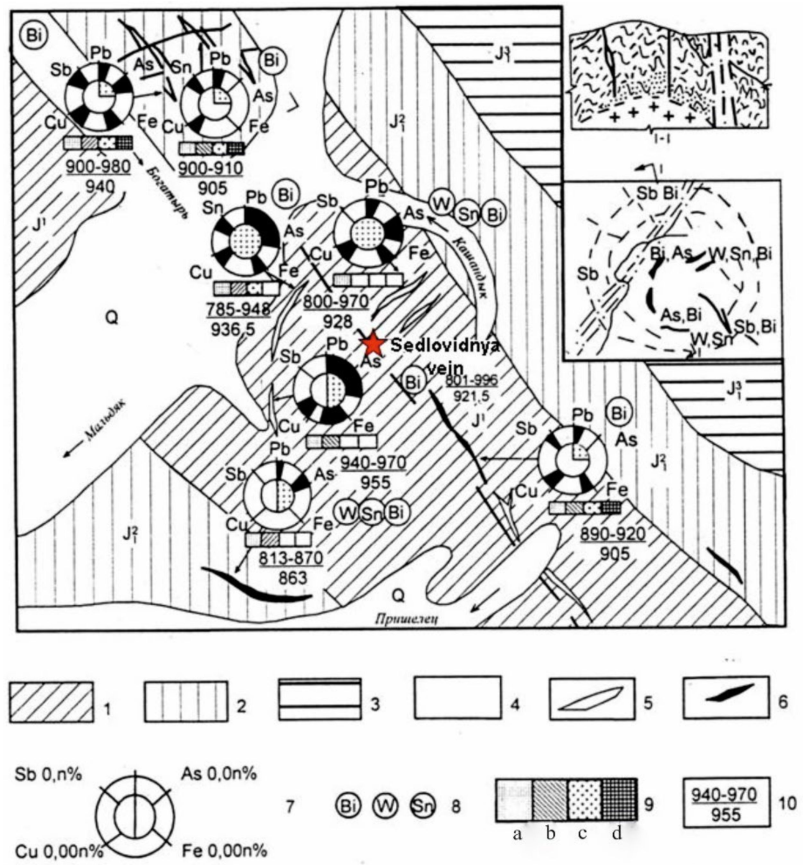

Figure 14. Topomineralogical map of typomorphic features of native gold in the Maldyak ore field. The image was constructed by the authors of the present paper using data from [10] with additions. 1–3—sedimentary deposits of the Jurassic age: 1—lower mudstone-siltstone sequence; 2—middle argillite sequence; 3—upper predominantly sandstone strata; 4—quaternary deposits; 5—residential zones; 6—mineralized dikes; 7—on the pie chart along the periphery shows the content of impurity elements Pb, As, Fe, Cu, Sb (the sector is 100%), in the center—the degree of hypogene transformations in native gold; 8—other microimpurities found in native gold; 9—mineral associations of native gold: a—gold–quartz, b—gold–arsenopyrite, c—gold-galena-sphalerite, d—gold-sulfoantimonite; 10—sample of native gold (in ppm): numerator—variations, denominator—average value.

For the Shkolnoye deposit (gold–quartz veins in granitoids GIT), we analyzed the average fineness value of native gold from well cores from six ore horizons. It turned out that changes in the average fineness value change with depth in waves, but the dispersion of this indicator naturally falls from the upper horizon to the lower one, indicating an increase in a more stable situation in this direction, as well as a consistent differentiation of gold-silver from the lower horizons to the upper ones (Figure 6a–f, Table 3).

It should be noted that the metallogeny of the region can influence the formation of various GITs. In this article, we considered the typomorphism of native gold for the North-eastern region—the Yano-Kolyma orogenic belt with its specific As, Sn, W metallogeny and block terrane composition with an extended covering complex of the Okhotsk-Chukotka volcanogenic belt, as well as the Kedon volcanic belt in a rigid block—Omolon craton terrane with Au–Ag specialization. The main axis of the orogenic gold mineralization here is the Ayan-Yuryakhsky anticlinorium with the Tenkinsky deep fault extending along it.

At the same time, the Verkhoyansk fold system adjacent to the Northeast from the west has an independent collisional terrane structure of the Verkhoyansk-Chukotka thrust belt and its own metallogenic Sb-Hg and Ag-Pb-Zn specialization. Here, along the Adycha-Taryn deep fault, gold deposits related to the gold–arsenic-sulfide (gold–antimony–mercury) GIT prevail—the Sarylakh, Kyuchus and other deposits. The study of the typomorphic features of native gold from this province showed the presence in its composition of high concentrations of As, Sb, especially Hg. Native gold may contain from 5 to 15 wt.% Hg (Figure 15). In intergrowths, along with arsenopyrite, aurostibite, antimonite, and berthierite are often found; a higher sulfide content of ores (up to 15%) is typical. For this GIT, the appearance of native gold is significantly different (Figure 15b), the most common spongy gold with a fineness of 940–970‰ intergrown with antimonite [53,54]. In the north-east of Russia, gold–antimony–mercury GIT deposits have not yet been found.

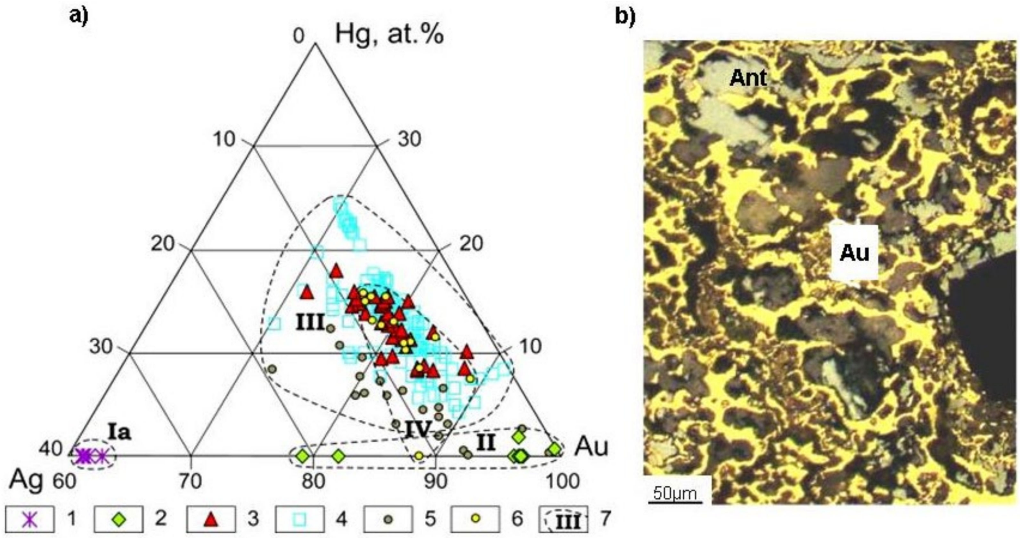

Figure 15. Typomorphic features of native gold (gold–antimony–mercury) GIT: (**a**) Ag-Hg-Au diagram of native gold of the Kyuchus deposit. The image was constructed by the authors of the present paper using data from [54]; (**b**) spongy gold intergrown with antimonite, Sarylakh deposit.

6. Conclusions

Summing up our study, we can state that native gold is an indicator mineral for various GITs of gold deposits. In a comprehensive study, it allows us to obtain the physical and chemical parameters of the main useful component of ores, to determine the deposit GIT, as well as genetic information about a particular object. All this makes it possible to preliminarily assess the scope of mineralization and outline schemes for processing ores, as well as to plan exploration work in order to identify placers.

On the example of different GITs and geological formational types of gold deposits in the north-east of Russia (gold–arsenic-sulfide—Natalka, Degdekan, Karalveem, Maldyak; gold–quartz veins—Dorozhnoye, Butarnoye, Shkolnoye, Maltan; gold–silver adularia—Kubaka, Olcha, Burgali, Kupol, Primorskoye, Dalnee) a comparative description of the typomorphism of native gold was carried out and it was shown that the reliability of geological interpretation is directly related to a comprehensive study of this mineral, including fineness variations, a spectrum of trace elements, internal structure and mineral intergrowths.

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