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The Use of Typomorphic Features of Placer Gold of the Anabar Region for Determining Its Sources

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Abstract: Typomorphic features of placer gold of the Anabar region were studied as predictive-exploration criteria. The target of the study was to determine the typomorphic features of placer gold related to the intermediate sources (paleo-placers) and the supposed nearby primary ore occurrences. Two varieties of placer gold were identified. The first variety is well-rounded high-fineness lamellar gold with a highly modified internal structure. This native gold is associated with intermediate sources, Neogene–Quaternary watershed pebble beds. The second type includes slightly rounded gold with a wide variation in fineness (494‰–999‰). Its indicator is a block heterophase internal structure. The set of typomorphic features of this variety of placer gold indicates the vicinity of the primary source, what was the prerequisite for constructing prospecting traverses in order to find ore occurrences. As a result of these studies, hydrothermal-metasomatic formations with gold-sulfide mineralization were identified. The main primary substrate for them is fractured near-fault carbonate rocks of the Cambrian and Vendian–Cambrian age. Along with this, hydrothermalites developed on slightly cemented fine-pebble quartz conglomerates of the Middle Permian age were found in the core of exploration wells. Two types of metasomatic rocks are identified: quartz-potassium feldspar and jasperoid. The main ore minerals were galena and pyrite, different ratios by sites were revealed. Gold was identified in the form of small particles in the carbonate and siliceous substrate of hydrothermal-metasomatic formations. The lithological factor was one of the leading favorable factors for the ore formation due to the presence of near-fault highly permeable fractured carbonate and slightly cemented terrigenous rocks. The structural control of the studied ore occurrences is determined by their localization in the Mayat–Logoy and Dogoy–Kuoy faults of the Molodo–Popigay system of discontinuous faults. We assume a two-stage formation of the gold ore occurrences: during the first stage, the ore components in the form of primary hydrothermal-sedimentary ores in the near-gault zones were formed. The second stage was related to the processes of the Mesozoic tectonic-magmatic activation, when the intrusion of basite dikes initiated the mobilization of ore components the gold-sulfide occurrences were formed in the near-fault zone as a result of silicic-potassic metasomatosis of the carbonate and terrigenous rocks.

Keywords: typomorphic features; placer gold; fineness; internal structure; Anabar placer area; hydrothermal-metasomatic formations; K-feldspathization; jasperoids; ore mineralization; fault zone; ore gold; sulfides

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1. Introduction

Numerous placer occurrences of fine gold are known in the vast territory of the northeastern part of the Siberian platform. The predecessors had no consensus about the age, genetic characteristics, and location of the primary sources of native gold. Most researchers associated the placer gold content of the studied area with the Precambrian quartz and quartz-carbonate veins [1–3]. Along with this, the Mesozoic age of the ore sources has been assumed [4,5]. At the present stage of research, based on the results of studying the typomorphic features of placer gold from ancient intermediate sources and modern alluvium, two types of gold related to primary sources of different ages have been identified [6]. Z.S. Nikiforova and co-authors, based on the study of the mineralogical and geochemical features of native gold, proved two main stages of ore formation for the entire east of the Siberian platform, including the studied territory, Precambrian and Mesozoic [7,8].

However, a few prospecting works have not led to the discovery of gold deposits until recently. This is due to the fact that certain difficulties emerge when predicting and searching for gold ore occurrences in the northeast of the Siberian platform, since the studied area is overlaid by a thick cover of the Cenozoic sediments, where traditional methods of searching for gold deposits are ineffective. Meanwhile, the methodology of studying the mineralogical and geochemical features of placer gold is successfully used to establish the types of gold mineralization and localization of primary sources, which is reflected in many publications [9–32]. In Russian geological science, the main provisions on the typomorphism of native gold were laid down in N.V. Petrovskaya's fundamental monograph "Native Gold, 1973" [9]. The use of a complex of typomorphic features (granulometry, morphology, chemical composition, and internal structure) of placer gold for predicting primary sources is reflected in well-known publications of Russian authors [10–13]. A number of researchers have been studying the typomorphism of placer gold in the northeastern part of the Siberian Platform [2,3,6–8,14]. There are many scientific papers focused on the methodology of studying the microchemical characteristics of placer gold: fineness, trace elements, and mineral inclusions in order to identify the types of gold mineralization, localization of sources, and clarification of regional metallogeny [16–19]. Researchers also pay great attention to the study of changes in native gold in the hypergene environment and paleo-placers [20–26]. In general, studies using the methodology of studying the typomorphism of native gold are carried out in many regions of the world [27–33].

In this regard, it is advisable to study in detail the complex of typomorphic features of placer gold, as a carrier of the most important genetic information necessary for the development of mineralogical criteria for predictive assessment of placer and ore gold content.

The Anabar river basin belongs to the placer area of the same name in the northeastern part of the Siberian platform and is located on the territory of the Lena–Anabar polymineral placer subprovince [34]. The studied area is characterized by a total background placer gold content with a gold content in quaternary sediments from 10 to 20 to 300 mg/m^3. Gold is found in the alluvium of the modern riverbed and terraces, in the Neogene–Quaternary relict pebbles on watersheds, as well as in basal horizons of the Permian age. According to B.R. Shpunt (1974) [2], gold from the Permian conglomerates is represented by small lamellar particles. Gold from the Neogene–Quaternary sediments developed on watersheds is characterized mainly by small fractions of 0.1–0.2 mm, flattened plates with a polished surface [3]. According to the predecessors, the sources of gold in modern placers were ancient paleo-placers of the Neogene–Quaternary and Permian age [3,4]. One of the most important unsolved problems is the identification of the primary sources of fine gold. Until recently, there was no data on the ore occurrences of gold, which served as the primary sources for placer gold. At the same time, the results of our previous studies of the typomorphism of placer gold in the area indicate the presence of a local ore source [6–8].

The publication presents the results of studying the typomorphism of placer gold as search signs for identifying primary gold-bearing sources on the example of two gold-bearing placer occurrences, "Billyah" and "Nebaibyt". Mineralogical features of hydrothermal-metasomatic formations with gold-sulfide mineralization, first discovered in fault zones, were also studied.

The target of the study was to determine the typomorphic features of placer gold related to the intermediate sources and the supposed nearby primary ore occurrences.

2. Materials and Methods

Native gold from alluvial sediments of the Billyakh river, right inflow of the Anabar river (35 samples) with a total weight of 950 mg and the Nebaibyt river, right inflow of the Bolshaya Kuonamka river (20 samples) with a total weight of 728.5 mg, was studied.

Samples were taken from exploration pits made by "Almazy Anabara" JSC in alluvial sediments for the exploration of placer diamonds.

Granulometric sieving of samples was performed using a set of mineralogical sieves, of which cell size corresponds to the classes of the granulometric scale, namely: +2 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm, and −0.25 mm. After that, the sample material was fractionated by density in a heavy liquid (bromoform). Monomineralic fractions of gold were isolated from the resulting ultrafiltration retentate using a binocular microscope.

The prospecting traverses were carried out on artificial sites (artificial channels, landfills of worked placers, and road clearing sites) and natural outcrops of hydrothermally altered dolomites of the Anabar formation of the Middle Cambrian and dolomitic limestones of the Vendian–Cambrian age. Hand specimen and rock samples were taken mainly in crush zones confined to the faults. The weight of the hand specimen samples ranged from 5 to 10 kg. More than 200 hand specimens and samples were picked. A total of 120 polished sections and 80 thin sections were made and analyzed.

The selection and description of core samples were performed at the core storage of the "Mayat" mine of "Almazy Anabara" JSC. The core from the exploration lines of core drilling holes in the watershed of the Mayat and Morgogor rivers were studied too (Figure 1).

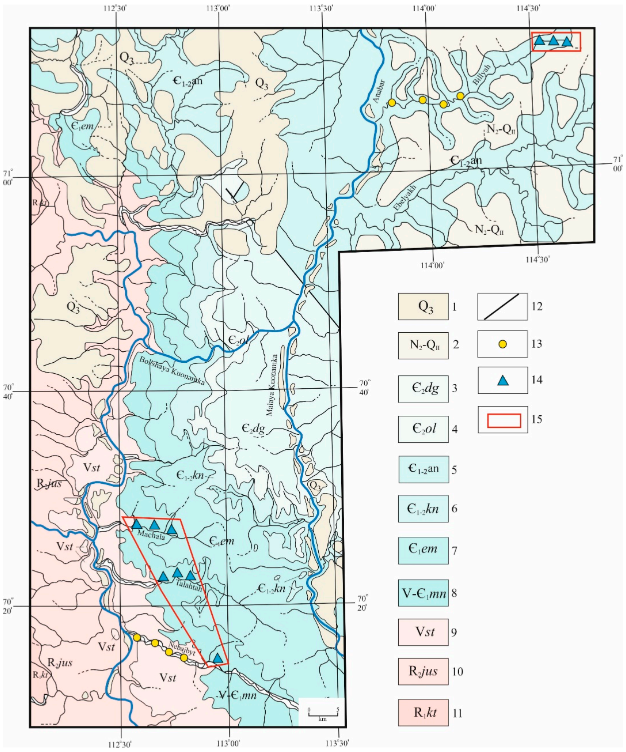

Figure 1. The scheme of the geological structure of the Anabar placer area [35,36]: 1—Quaternary alluvial sediments; 2—Neogene-Quaternary pebbles; 3–7—Cambrian sediments; 3—limestones of the Dzhakhtar formation; 4—clay and dolomitic limestones, marls of the Olenek formation; 5—dolomites of the Anabar formation; 6—clay, bituminous, organogenic-clastic limestones, combustible, siliceous, bituminous shales, siliceous and calcareous claystones, siltstones of the Kuonamskaya formation; 7—clay, dolomitic, algal, silty limestones and marls of the Emyaksin formation; 8—dolomitic limestones of the Manykai formation of the Vendian–Cambrian age; 9—dolomites, clay shales, gritstones and conglomerates of the Starorechenskaya formation of the Vendian; 10—dolomites, sandstones, siltstones, gritstones and conglomerates of the Yusmastakh formation of the Late Riphean; 11—sandy, clay dolomites, sandstones, gritstones, conglomerate-breccias of the Kotuikan formation of the Early Riphean; 12—faults; 13—places of collection of exploratory samples; 14—places of collection of hand specimen samples; 15—areas where hydrothermal-metasomatic formations were found.

Determination of the quantitative composition of native gold, the composition of minerals in polished sections, photographing of samples and mapping of the distribution of elements by area were performed on a scanning electron microscope JEOL JSM-6840LV (Tokyo, Japan) with an energy dispersion spectrometer Energy 350 Oxford Instruments (Abingdon, UK). Quantitative analysis and processing of the results were performed using the XPP method Software INCA Energy version Oxford instruments INCA the microanalysis Suite Issue 4.17. Shooting conditions: accelerating voltage 20 kV, measure current 1.07 nA, spectrum set time during quantitative optimization on cobalt and samples, 7 s. The error of the analysis of the main components is −1%–1.5%. The detection limit for most elements is −0.2%–0.8% and 1% or more for "heavy" elements. Reference samples were used: for Au, Ag-Au850, and Hg-HgTe. Analytical work was performed in the Department of physical–chemical methods of analysis of DPMGI SB RAS (analyst Khristoforova N.V.). Measurements were performed both in the central part and along the periphery of individual gold particles for determining the degree of their chemical transformation, which is expressed in the formation of shells and areas with a fineness of 990‰–1000‰ or in the complete transformation of grains. Analyses of the peripheral parts of native gold grains were not considered in the calculations. The number of determinations included in the calculations is 825.

The gradation of the fineness of gold is provided according to the classification of N.V. Petrovskaya [9].

The internal structure of native gold was studied by etching it in mounted thin sections according to a proven technique [37], using a reagent: HCl + HNO_3 + $FeCl_3 \times 6H_2O$ + CrO_3 + thiourea + water (next in text—aqua regia). The reagent was applied to the surface of polished gold mounted in an artificial polished section. The gold particles were etched from 10 to 30 s in several approaches. After each etching procedure, the polished section was washed under a strong stream of water, then dried. After that, the revealed internal structures were studied in detail using a Polar 3 (Observation instruments llc., Saint-Petersburg, Russia) ore microscope and a JEOL scanning electron microscope JSM-6480LV (JEOL Ltd., Tokyo, Japan). The interpretation of the features of internal structures was performed in accordance with the recommendations of N.V. Petrovskaya [9,35], L.A. Nikolaeva [10,12], N.E. Savva, and V.K. Preis [11].

Abbreviations of mineral names are provided according to L.N. Warr [38].

3. Geological and Structural Position of the Region

The geological structure of the studied territory includes the Riphean terrigenous formations, Cambrian carbonate rocks, Permian terrigenous sediments, and Triassic volcanogenic formations overlain by the Neogene and Quaternary poorly consolidated sediments (Figures 1 and 2) [39].

Igneous rocks are represented by intrusive bodies of basic and alkaline-ultrabasic composition of the Triassic age (Figure 2) [39]. The studied placers are located within the Lena–Popigai swell, complicated by structures of the II order, the Ebelyakh uplift and the Billyakh depression, as well as the northeastern framing of the Anabar shield. According to the predecessors, disjunctive faults were of great importance in the development of the area. They form a number of systems of the north-western, north-eastern, latitudinal, and meridional directions, with zones of increased fracturing. It is important to emphasize that the rejuvenation of ancient deep fault systems (Molodo–Popigai, Anabar–Eekit, and Zhigansk) took place in the studied area during the Mesozoic tectonic-magmatic activation, which led to the formation of a whole series of new faults [6,40]. It should be noted that most modern rivers inherited paleovalleys of the Mesozoic watercourses formed on tectonic deformations.

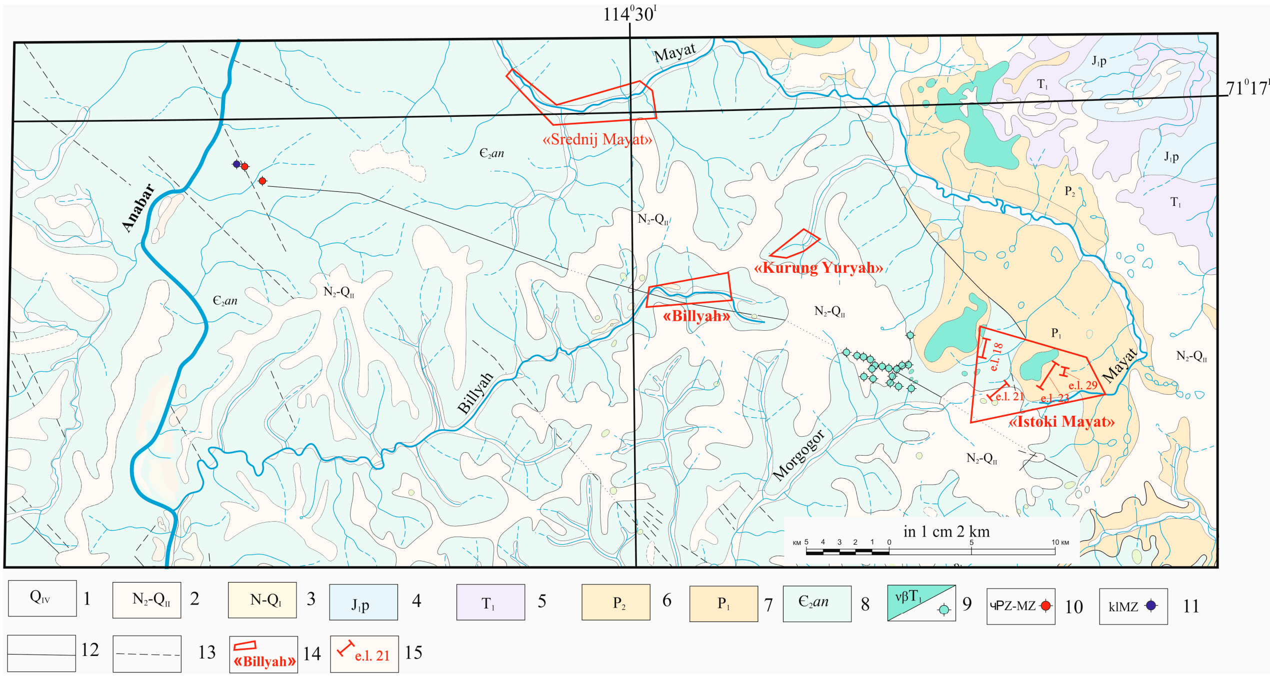

Figure 2. Schematic geological map of the basin of the middle flow of the Anabar river [39]: 1—Quaternary sediments; 2—Upper Pliocene—Middle Quaternary loams, sands, pebbles; 3—Neogene—Lower Quaternary relict pebbles; 4—Jurassic sandstones, siltstones; 5—Triassic basalts and their tuffs; 6—Late Permian sandstones; 7—Early Permian sandstones, conglomerates; 8—dolomites of the Anabar formation of the Cambrian; 9—Mesozoic intrusive formations; 10—kimberlite pipes; 11—dikes of alkaline picrites; 12—determined tectonic deformations; 13—assumed tectonic deformations; 14—areas where hydrothermal-metasomatic formations have been found; 15—exploratory core drilling lines.

4. Results and Discussion of the Study

4.1. Typomorphism of Placer Gold

4.1.1. Native Gold of the Billyakh River Placer

The Billyakh complex gold–platinum–diamond-bearing alluvial placer is located in the middle flow of the watercourse of the same name, the right inflow of the Anabar river (Figure 1). The river valley flows in the dolomites of the Anabar formation of the Middle Cambrian. The productive horizon is represented by sand–pebble material containing silty, clay, and boulder sediments in various ratios. The average thickness of the producing bed in the upper part of the placer is 1.75 m, the average width of the commercial contour is 75.4 m. The slopes of the valley are mostly gentle, swamped, only in the lower reaches, where the riverbed cuts the bedrock. There are steeper areas covered with boulder screes of the dolomites of the Anabar formation. Fragments of alluvial sediments of Middle-Upper Quaternary and Neogene age are observed on the slopes of the valley [39].

The granulometric composition of the studied native gold is as follows: 1–2 mm, 1.5%; 0.5–1 mm, 1.5%; 0.25–0.5 mm, 30%; and −0.25 mm, 67%. The fineness of native placer gold varies very widely (Table 1): 951‰–999‰, 78%; 950‰–900‰, 8%; 800‰–899‰, 8%; 700‰–799‰, 3%; and 400‰–699‰, 3% (Figure 3). The impurity elements Cu and Hg are determined only at the level of the detection limit of the device, 0.2%.

Table 1. The most typical analyses of the chemical composition of native gold of the Billyakh river placer on gradations of gold fineness.

№	Cu	Hg	Au	Ag	Total	The Fineness
1	nd	nd	99.83	0.67	100.5	
2	nd	nd	98.71	0.73	99.40	Very high
3	nd	nd	98.23	0.31	98.50	
4	nd	nd	91.93	8.40	100.30	
5	nd	nd	90.35	9.97	100.30	High
6	nd	nd	92.01	7.81	99.80	
7	nd	nd	87.93	11.59	99.50	
8	nd	nd	88.04	11.17	99.20	Medium
9	nd	nd	85.24	13.95	99.10	
10	nd	nd	76.69	21.57	98.20	
11	nd	nd	71.39	27.18	98.50	Relatively low
12	nd	nd	72.85	25.58	98.40	
13	nd	nd	68.42	29.70	98.10	
14	nd	0.60	68.64	29.26	98.50	Low
15	nd	nd	51.17	48.17	99.50	

Notes: 5 groups; all values in %; nd: not detected.

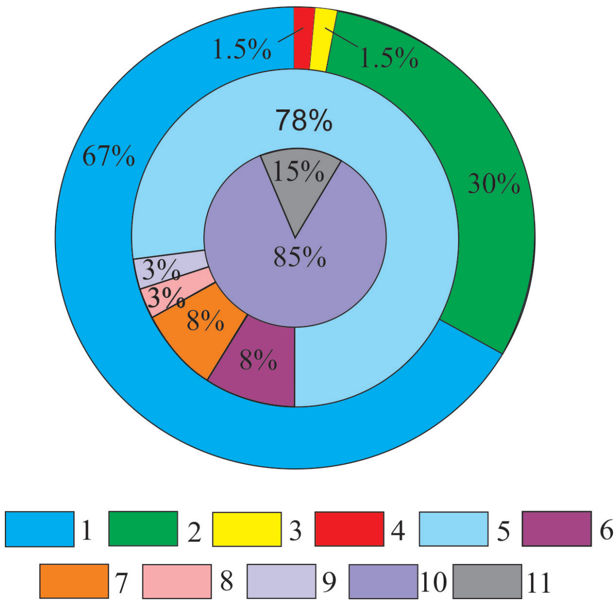

Figure 3. The main typomorphic features of the Billyakh river basin gold: 1–4—granulometric composition: 1—<0.2 mm, 2—0.2–0.5 mm, 3—0.5–1 mm, 4—1–2 mm; 5–9—fineness: 5—951‰–999‰ (very high-fineness), 6—950‰–900‰ (high-fineness), 7—800‰–899‰ (medium–fineness), 8—700‰–799‰ (relatively low-fineness), 9—400‰–699‰ (low-fineness); 10–11—morphology: 10—lamellar and scaly, 11—slightly rounded gold.

Considering the morphological features, the main part of gold is characterized by a well-rounded scaly (Figure 4a) and lamellar shape with a thin, coarse, shagreen surface (Figure 4b). Quite often there are plates with faults and holes (Figure 4b). Lamellar gold has an intensely transformed internal structure, which is expressed by the structures of recrystallization, granulation, and the formation of a thick high-grade shell (Figure 4c–f). In flake gold particles, high-fineness gold almost completely replaces primary lower-fineness gold. In such particles, relict primary gold is preserved only in their central parts (Figure 4g). In general, lamellar and scaly gold is characterized by high fineness (900‰–999‰). The set of the identified typomorphic features of the main part of the studied gold indicates the long-time residence in exogenous conditions and its redeposition from intermediate sources (paleo-placers).

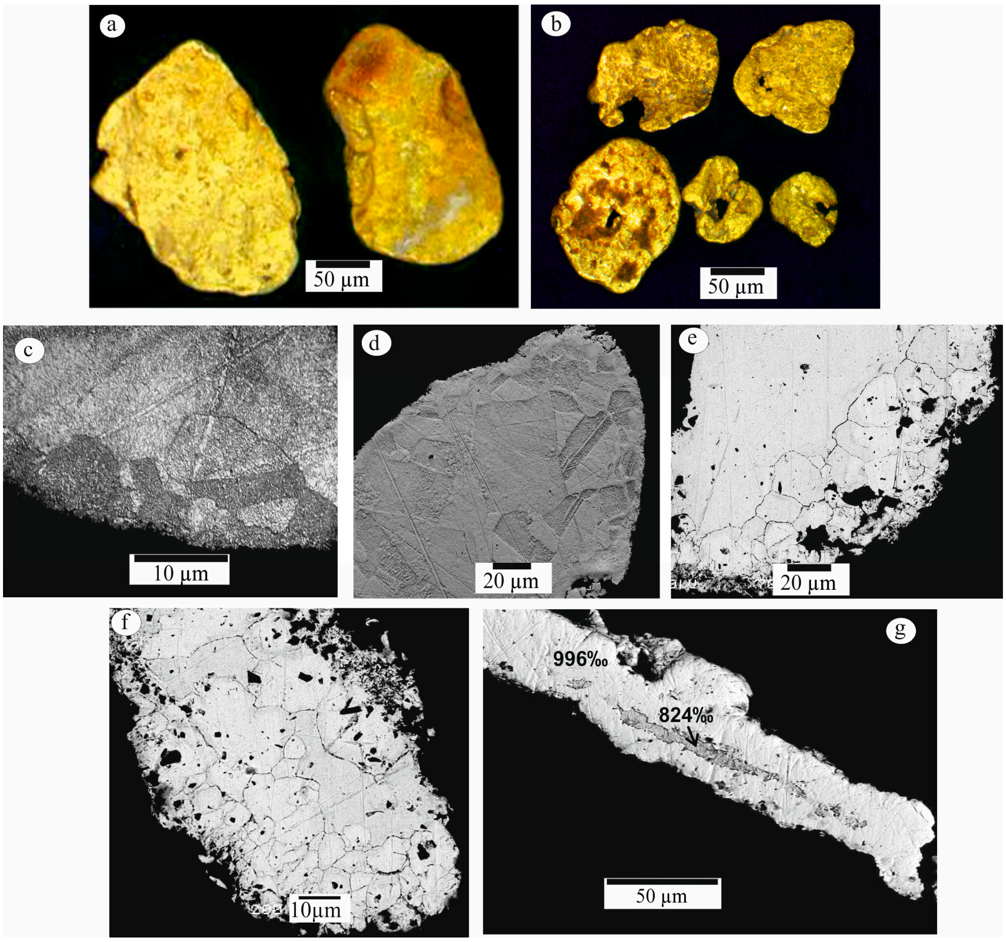

Figure 4. Morphology and internal structure of rounded high-fineness gold from the Billyakh river placer, supplied from intermediate sources: (**a**) scaly gold; (**b**) lamellar gold with casts of pressing of minerals on the surface and with through holes; (**c**,**d**) recrystallization structures; (**e**,**f**) granulation structures, etched with a reagent based on aqua regia; (**g**) relics of medium-fineness gold in the central part of the scale almost completely replaced by high-fineness gold; (**c**–**g**) shot in BSE mode.

Along with this gold, very fine (−0.2 mm) slightly rounded with lamellar and angular, lumpy forms were found in all studied samples, up to 15% (Figure 5a,b). Their surface is rough, spongy, and porous. The fineness varies in very wide intervals, from low (514‰) up to very high (999‰) (Table 1). The analysis of the fineness of gold and its morphological features has shown that exclusively gold particles of ore habit have relatively low (799‰–700‰) and low (699‰–500‰) fineness. The main feature of this gold is its heterogeneous heterophase internal structure, with a block nature. A low-fineness (500‰–600‰) phase was identified in the central part of the gold particles (Figure 5c), and a relatively low-fineness one along the periphery (750‰). An intermittent very thin (the first microns) high-fineness phase, characterized by a lighter shade, is observed along the marginal parts of relatively low-fineness gold (Figure 5d, is shown by yellow arrows). The sharpness and discontinuity of the high-fineness margin indicate a short-time residence of this gold in exogenous conditions. In general, the set of typomorphic features of this gold indicates the presence of nearby primary sources.

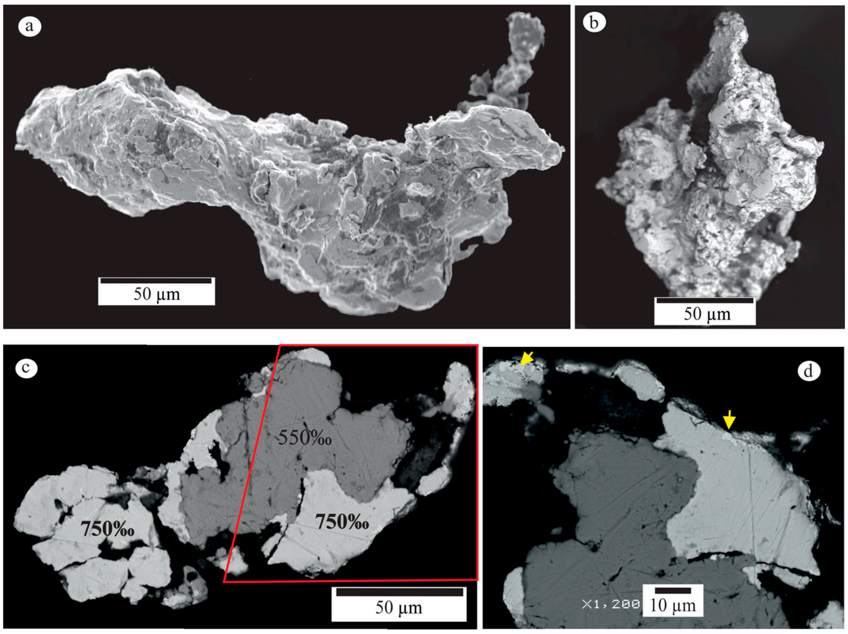

Figure 5. Morphology and features of the internal structure of slightly rounded gold of the Billyakh river placer: (**a**) slightly rounded gold particle; (**b**) angular, lumpy gold with an rough porous surface; (**c**) block nature of the internal structure of multiphase gold (detalized area marked in red); (**d**) detalized area: multiphase gold, the yellow arrows show the high-fineness phase, etched with a reagent based on aqua regia; (**a**,**b**) shot in SEI mode; (**c**,**d**) shot in BSE mode.

4.1.2. Native Gold of the Nebaibyt River Placer

The Nebaibyt river valley drains the northeastern slope of the Anabar massif and flows through dolomitic limestone of the Vendian–Cambrian and terrigenous-carbonate sediments of the Vendian age (Figure 1).

The granulometric composition of the studied gold is as follows: 1–0.5 mm, 5%; 0.25–0.5 mm, 40%; and −0.25 mm, 55%. Its fineness throughout the placer is as follows: 951‰–999‰, 80%; 950‰–900‰, 8%; 800‰–899‰, 4%; 700‰–799‰, 3%; 600‰–699‰, 1%; and <600‰, 4% (Figure 6).

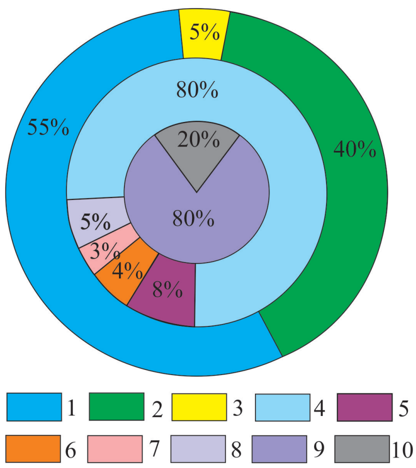

Figure 6. The main typomorphic features of the Nebaibyt river basin gold: 1–3—granulometric composition: 1—<0.2 mm, 2—0.2–0.5 mm, 3—0.5–1 mm; 48—fineness: 4—951‰–999‰ (very high-fineness), 5—950‰–900‰ (high-grade), 6—800‰–899‰ (medium-grade), 7—700‰–799‰ (relatively low-grade), 8—400‰–699‰ (low-grade); 9–10—morphology: 9—lamellar and scaly, 10—slightly rounded gold.

Native gold is mainly represented by a lamellar morphology with a coarse-shagreen surface. Lamellar gold has a high fineness (900‰–999‰) and is characterized by a highly modified internal structure with recrystallization and granulation structures, and by thick high-grade margins and very high-grade intergranular veinlets (Figure 7). This indicates the repeated redeposition of gold from ancient intermediate sources into younger sediments.

At the same time, in all the samples studied, up to 15%, slightly rounded gold was identified, which is represented by isometric crystals, angular-lumpy and lamellar forms, as well as peculiar hook-shaped individuals (Figure 8). As a rule, slightly rounded gold is marked in the −0.25 mm class. Its fineness varies very widely, from low (494‰) to very high (more than 950‰) (Table 2). Its internal structure also has a heterogeneous heterophase nature (Figure 8c), similar to the internal structure of slightly rounded placer gold of the Billyakh river placer (Figure 5c,d). Gold particles have not shown signs of transformation in hydrodynamic conditions, which indicates the vicinity of their primary source.

Table 2. The most typical analyses of the chemical composition of native gold of the Nebaibyt river placer on gradations of gold fineness.

№	Cu	Hg	Au	Ag	Total	The Fineness
1	0.60	nd	99.06	0.34	100.02	Very high
2	nd	nd	97.66	0.84	98.50	
3	nd	nd	99.13	0.87	100.30	
4	nd	nd	92.77	5.89	98.68	High
5	nd	nd	94.94	4.97	99.90	
6	nd	nd	91.22	8.05	99.30	
7	nd	nd	87.79	10.96	98.70	Medium
8	nd	nd	83.65	15.21	98.80	
9	nd	nd	86.22	11.89	98.10	
10	nd	nd	71.23	28.98	100.20	Relatively low
11	nd	nd	77.49	22.48	100.00	
12	nd	nd	74.85	24.58	99.40	
13	nd	nd	66.14	31.87	98.00	Low
14	nd	nd	64.10	36.34	100.40	
15	nd	nd	54.96	46.58	101.50	

Notes: 5 groups; all values in %; nd—not detected.

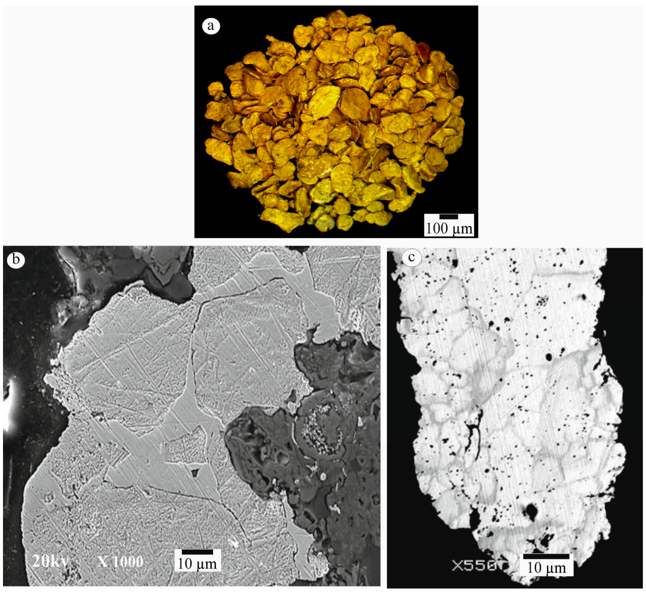

Figure 7. Morphology and internal structure of gold of the Nebaibyt river placer: (**a**) lamellar gold (general view); (**b**) very high-grade (990‰) intergranular veinlets in high-grade gold (950‰); (**c**) granulation structures of high-grade gold, etched with a reagent based on aqua regia; (**b**,**c**) shot in BSE mode.

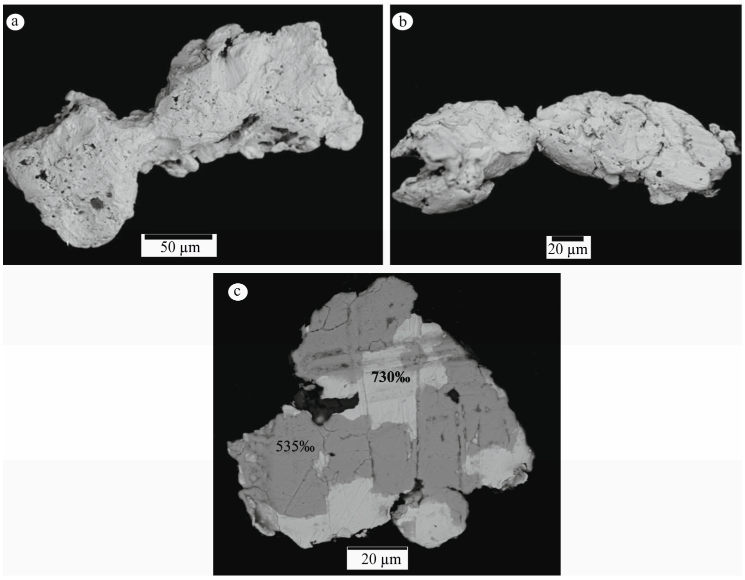

Figure 8. Morphology and internal structure of slightly rounded native gold of the Nebaibyt river placer: (**a**,**b**) slightly rounded gold; (**c**) block nature of the internal structure of multiphase gold, etched with a reagent based on aqua regia; (**a**,**b**) shot in SEI mode; (**c**) shot in BSE mode.

Native gold is mainly represented by a lamellar morphology with a coarse, shagreen surface. Lamellar gold has a high fineness (900‰–999‰) and is characterized by a highly modified internal structure with recrystallization and granulation structures, and by thick high-grade margins and very high-grade intergranular veinlets (Figure 7). This indicates the repeated redeposition of gold from ancient intermediate sources into younger sediments.

No mineral inclusions were found in gold except for small inclusions of quartz.

Since at this stage of research, in gold of the placers of the Billyakh and Neibabyt rivers no ore inclusions were found, we provide data on mineral inclusions in gold of the Mayat river placer, which was studied by us earlier [6,8]. The Mayat river joins the Anabar river just north of the Billyakh river and flows almost parallel to it (Figure 2).

The fineness of gold of the Mayat river varies widely: 951‰–999‰, 35%; 950‰–900‰, 15%; 800‰–899‰, 30%; 700‰–799‰, 10%; and 400‰–699‰, 10%. Inclusions of pyrite, arsenopyrite, galena, quartz, and potassium feldspar were found in slightly rounded gold with a grain size of more than 0.5 mm (Figure 9).

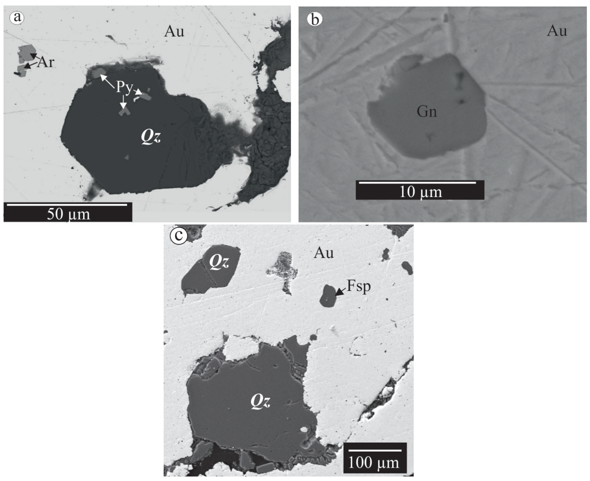

Figure 9. Mineral inclusions in placer gold of the Mayat river (BSE mode): (**a**) quartz (Qz), pyrite (Py) and arsenopyrite (Ar) inclusions in native gold (Au); (**b**) galena inclusion (Gn) in native gold (Au); (**c**) quartz (Qz) and potassium feldspar inclusions (Fsp) in native gold (Au), shot in BSE mode.

As can be seen in Figure 10, three groups of native gold are identified by the nature of the Ag distribution. The first, most common group (about 70%–85% of the whole number of samples) contains up to 15 wt. % silver. The next group with an Ag content of up to 20 wt. % is about from 10% to 20% of the samples. The least represented group (about 5%–7% of the samples) is characterized by a silver content of 20 to 45 wt. %. According to Chapman et al. [28] samples populations that show either bimodal Ag content or a wide range of Ag values, do not necessarily indicate multiple sources. In our case, the totality of the studied typomorphic features allows us to talk about two types of sources of gold in modern placers: (1) an intermediate source (paleo-placers), which can serve the Neogene–Quaternary watershed pebbles (group 1 by Ag content); (2) and nearby ore occurrences (2 and 3 groups by Ag content).

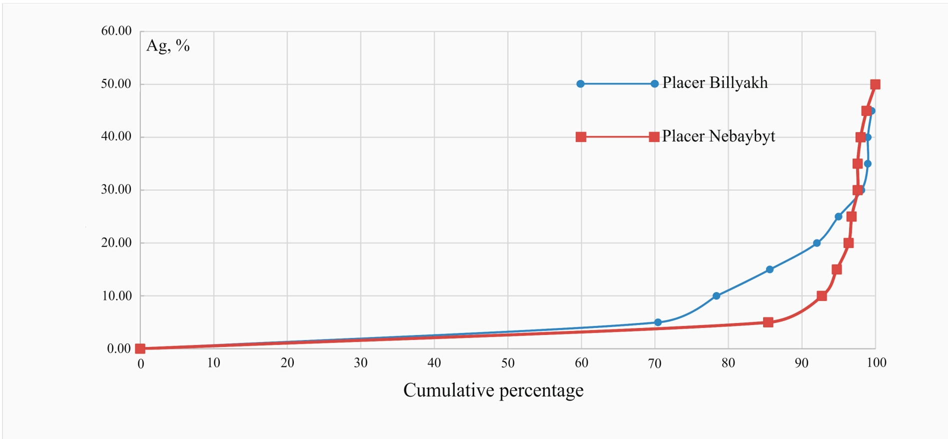

Figure 10. Cumulative Ag content chart. According to the data of 578 (Billyakh placer) and 247 (Nebaibyt placer) determinations of the chemical composition of native gold.

Thus, according to the set of typomorphic features of native gold in the studied watercourses, two varieties of native gold were identified.

The first variety is well-rounded high-grade gold of lamellar and scaly morphology with a naturally treated surface. Its internal structure is intensively modified, represented by recrystallization structures, granulation structures, and thick very high-grade shells (Figures 4c–g and 7b,c). According to L.A. Nikolaeva and co-authors [12], the structure of gold, which was in ancient conglomerates for a long time, reflects profound changes caused by its transformation in conditions of not only ancient crust and placer formation, but also diagenesis and epigenesis of sediments. At the same time, a high-grade shell can reach a thickness of 0.25 mm or more, partially or completely replacing the primary matrix. Mechanical deformations contribute to the processes of recrystallization of the peripheral parts of the gold particles, which is expressed by the formation of a micrograin structure. With a long-time residence at rest, the process of collective recrystallization occurs and leads to an even deeper transformation of the high-grade shell. The most intense changes in the internal structure of gold occur after the burial of sediments and their lithification as a result of temperature exposure, involving intense diffusion of silver. Disintegration of gold grains occurs, which leads to the formation of granulation structures [12]. Stewart et al. [27] explained the presence of relatively thick (>100 microns) gold-rich shells in gold particles from the point of view of recrystallization during physical deformation related to the transfer of gold particles during successive fluvial downcuttings in a tectonically active region. According to their data [27], grains of native gold that were processed through paleo-placers can completely recrystallize. The degree of recrystallization, in their opinion, depends on the amount of deformation of the gold particles. According to Chapman et al. [28], the heterogeneity spatially associated with grain boundaries is formed much later than the time of precipitation of native gold. Thus, significant internal crystallographic transformations in gold particles in the conditions of paleo-placers contribute to the acceleration of their chemical changes. In general, the results of the study of the internal structure of the well-rounded gold of the studied placers indicate its redeposition through intermediate sources. Gold-bearing watershed pebbles the of Neogene–Quaternary age, widely developed in the studied areas, probably served as intermediate sources [5]. According to B.R. Shpunt, the Precambrian gold-bearing quartz veins served as the primary sources of gold for them [2].

The second variety is slightly rounded native gold with a wide variation in fineness: from low (494‰) to very high (999‰). The most specific feature is its block heterophase internal structure (Figure 5c,d; Figure 8c). The heterophase nature of these gold particles can be explained by the specific conditions of formation. Firstly, heterophase nature can be caused by fluctuations in the degree of supersaturation of solutions during their growth in shallow conditions. According to V.P. Samusikov [41], short-term pulsational changes in the degree of supersaturation of solutions occurred in the shallow conditions of ore formation: a sharp increase or decrease, since the thermodynamic conditions were extremely unstable. At the same time, with an increase in the degree of supersaturation of solutions, the concentration of Ag increased, and with a decrease, it decreased [41]. Secondly, sulfide minerals predominate in the composition of the ores of the ore occurrences we discovered, described below, so it can be assumed that sulfide sulfur dominated in ore-bearing solutions. According to I.V. Gaskov [42], as the temperature of solutions decreases and the groundmass of sulfides is deposited, the amount of sulfur and its activity in solutions drops sharply and silver is more concentrated in native gold, which causes a decrease in the fineness of native gold from its early to late generations. According to Chapman [28] and co-authors, the substitution of gold with silver, independent of grain boundary control, is the result of a developing hydrothermal system, whereas Ag-rich intergranular veinlets may form later. According to the same authors, lower ore formation temperatures contribute to a higher Ag content in Au–Ag alloys. Thus, these data indicate a low-temperature shallow environment for the formation of the second variety of gold.

The complex of typomorphic features of this gold (slight rounding, wide variation in fineness, heterophase internal structure unchanged in exogenous conditions) is direct evidence of the vicinity of the primary source formed in shallow conditions. In this regard, it was suggested that in the sources of the Billyakh and Nebaibyt rivers, in the field of development of carbonate rocks in fault zones, gold ore occurrences can be localized, and potential primary sources of very fine gold of the second variety. This became a prerequisite for the execution of prospecting traverses in order to identify ore occurrences. This assumption was confirmed, we identified gold-bearing hydrothermal-metasomatic formations for the first time in the studied area as a result of these traverses. The following sub-chapter provides some of the features of these ore occurrences obtained at this stage of research.

4.2. Ore Occurrences of Native Gold

As a result of the prospecting traverses, hydrothermal-metasomatic formations with gold-sulfide mineralization localized in fault zones were identified (Figures 1 and 2). The prospecting traverses were performed on artificial sites (artificial channels, landfills of worked placers, and road clearing sites) and natural outcrops of hydrothermally altered dolomites of the Anabar formation of the Middle Cambrian (Anabar river basin) and dolomitic limestone of the Vendian–Cambrian age (Bolshaya Kuonamka river basin). Hand specimen and rock samples were collected mainly in crush zones confined to the faults. In additional, core samples that were taken by "Almazy Anabara" JSC for the searching of kimberlite bodies in the watershed of the Mayat and Morgogor rivers (Figure 2) were studied too.

4.2.1. Mineralogical Features of Ore-Bearing Hydrothermal-Metasomatic Formations

The initial substrate for hydrothermal-metasomatic formations in the Anabar region was mainly near-fault fractured dolomites of the Anabar formation of the Middle Cambrian and dolomitic limestones of the Vendian–Cambrian ages. In addition, hydrothermalites developed from slightly cemented fine-pebble quartz conglomerates of the Early Permian age were found for the first time in the core of exploration wells (Figure 2). The fragmented nature of sampling does not yet allow us to reliably determine the shape and type of ore body occurrence.

Considering epigenetic mineral associations, quartz-potassium feldspar and siliceous-quartz (jasperoids) hydrothermal-metasomatic formations were identified.

Quartz-potassium feldspar hydrothermal-metasomatic formations have yellowish and rusty-brown tint. Their structure is predominantly banded, net-vein, due to the development of differently oriented veinlets of iron oxides, decomposition products of sulfides (Figure 11a,b). Potassium feldspar in apocarbonate hydrothermalites is represented by very small (1–5 microns) crystals, mainly diamond-shaped, which has a diffuse distribution throughout the groundmass (Figure 11c,d) or it is developed in thin (up to 150 microns) veinlets of quartz-ferruginous-aluminosilicate composition penetrating the dolomite (Figure 11e,f). In the Permian terrigenous rocks, this mineral is characterized by larger sizes (up to 1 mm) and rectangular shapes (Figure 12).

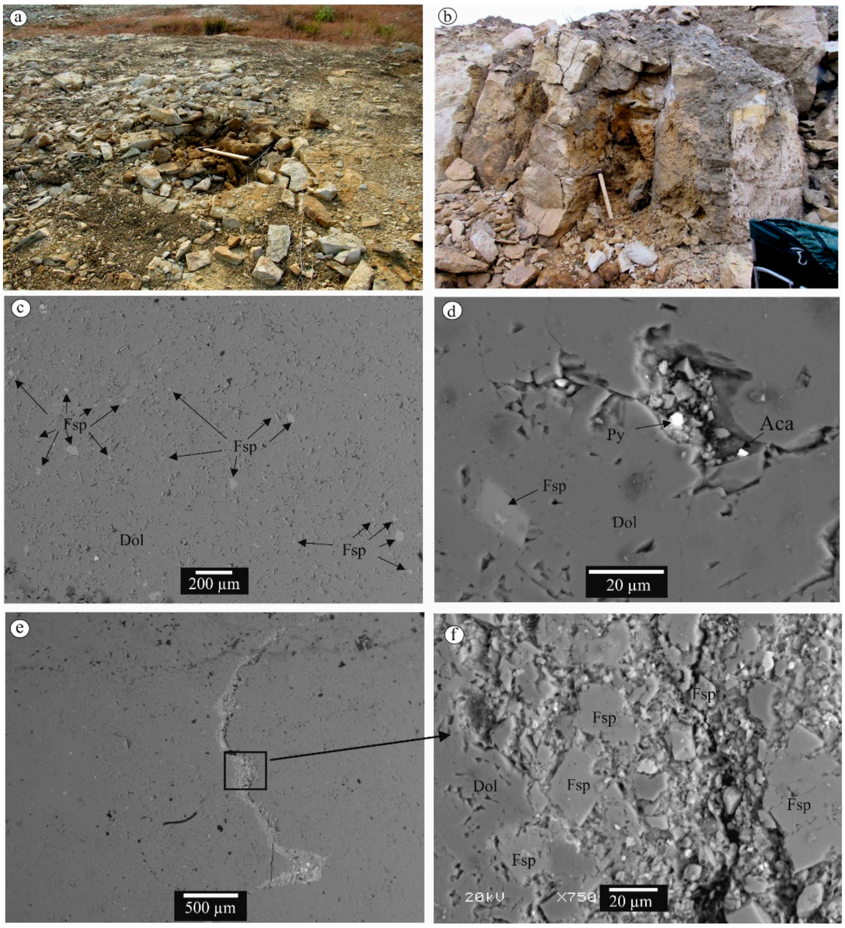

Figure 11. Apocarbonate quartz-potassium feldspar metasomatites: (**a**) the cataclase zone in bedrock of the worked placer, where hydrothermalites are developed (Kurung Yuryakh site); (**b**) weathered hydrothermal-metasomatic formations in the wall of the artificial channel at the sources of the Billyakh river; (**c**,**d**) disseminated potassium feldspar mineralization (BSE mode); (**e**,**f**) potassium feldspar in veinlets of variable quartz-iron-aluminosilicate composition (BSE mode). Fsp—potassium feldspar; Dol—dolomite; Py—pyrite; Aca—acanthite.

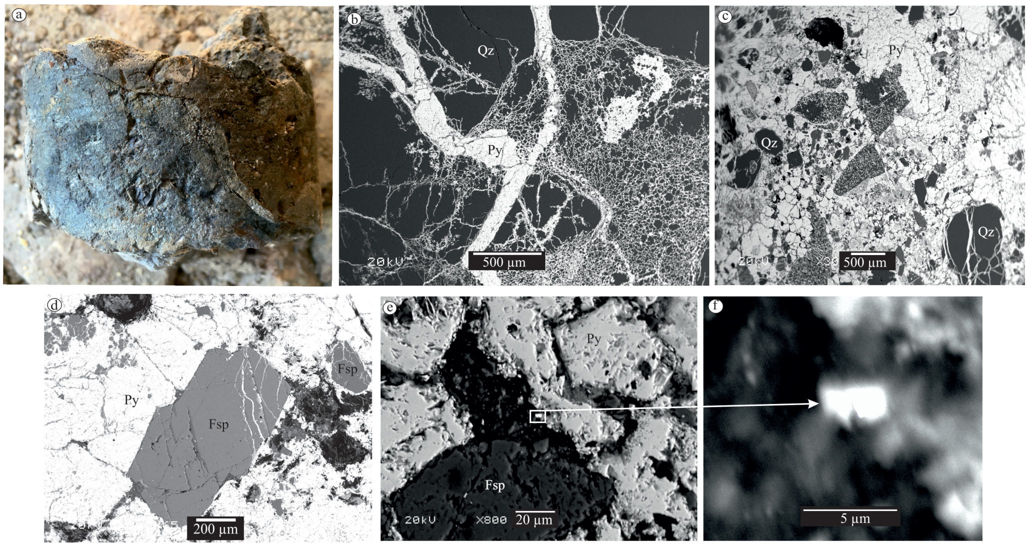

Figure 12. Hydrothermal-metasomatic formations developed by slightly cemented fine-pebble quartz conglomerates of the Early Permian age of the Anabar region: (**a**) core sample of pyritized conglomerate (interval 39.7–40 m of well A-3 of exploration line 21; sample 21-A3-5, microphotography); (**b**,**c**) types of pyrite mineralization (BSE mode): (**b**) net-vein; (**c**) entire; (**d**) pyrite-potassium feldspar mineralization in quartz conglomerates (BSE mode); (**e**,**f**) the smallest gold particle in a mineralized conglomerate (BSE mode). Qz—quartz; Fsp—potassium feldspar; Py—pyrite.

Jasperoids are apocarbonate rocks with a SiO_2 content from 81 to 96.5%. Their characteristic feature is the oolitic structure. In these formations chalcedonic quartz almost completely replaces dolomites (Figure 13). Only very small relics of them are observed in the central parts of the oolites.

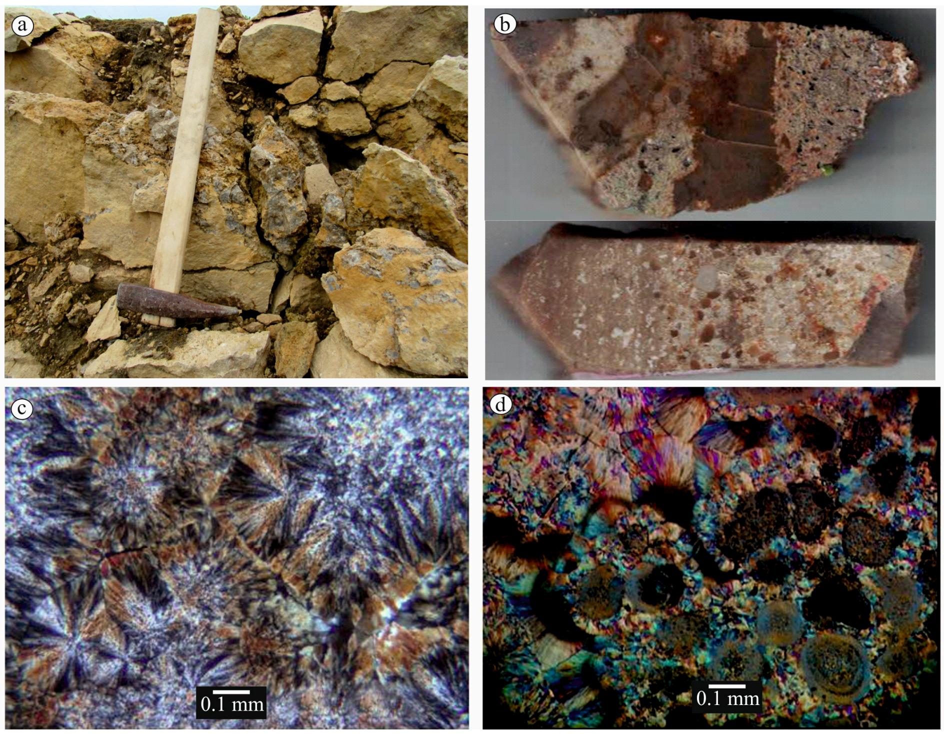

Figure 13. Features of jasperoids: (**a**) jasperoid veins developed in the cataclasis zone on the "Billyakh" site; (**b**) polished sections made of jasperoids; (**c**) chalcedonic quartz (thin section); (**d**) veinlets of chalcedonic quartz and siliceous oolites (thin section).

Ore mineralization is represented by sulfides, native gold, and silver. The main sulfide minerals are galena and pyrite, which ratios vary by different sites. At this stage of research, no differences in the composition of ore components in the above-mentioned types of hydrothermal-metasomatic formations were revealed.

Native gold was found in the form of very small (up to 15 microns) isometric grains in microcracks of a carbonate or siliceous substrate (Figure 14a,b). The smallest particle of gold with a size of about 4 microns was found at the border of the growth of pyrite and potassium feldspar in the Permian mineralized conglomerate (Figure 12e,f). Hg and Cu are defined as impurity elements in gold. The maximum content of Hg in gold reaches 2.4%, which is determined at the "Billyakh" site. At the "Istoki Mayat" site, a very fine gold particle with Cu admixture with a content of up to 18% was found in the abundantly pyritized dolomite of the core sample (Figure 14c).

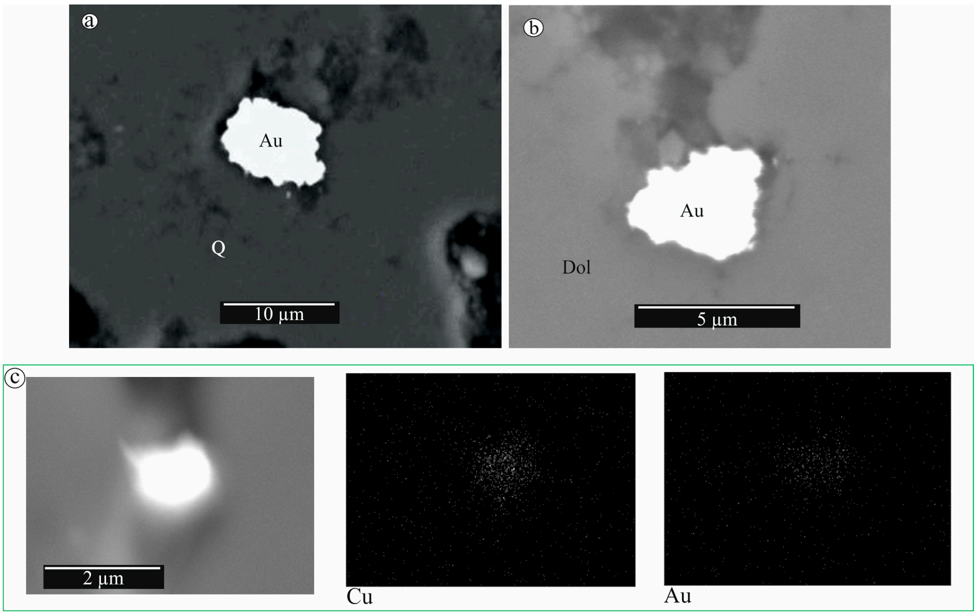

Figure 14. Fine gold (Au) particles in (**a**) jasperoid, (**b**) apocarbonate quartz-potassium feldspar metasomatites (**c**) copper gold (Cu—18%) and impurity elements in gold in the apocarbonate quartz-potassium feldspar hydrothermal-metasomatic formation (shot in X-ray Au and Cu). Q—quartz; Dol—dolomite.

Galena is characterized by very small (the first microns) isometric grains (Figure 15a). Pyrite in modified dolomites occurs in the form of small inclusions (Figure 15a), and in hydrothermal-metasomatic formations formed on the Permian conglomerates, it has a veined and continuous nature of distribution, penetrating into the gaps between quartz pebbles, sometimes completely replacing conglomerate cement and sometimes quartz pebbles (Figure 11b,c). Silver sulfide (acanthite?) is quite widespread in apocarbonate formations and is represented by crystals, and their aggregates are up to 20 microns in size (Figure 15b). Large grains of sphalerite (about 5 mm) were found in the calcite veinlet of quartz-potassium feldspar dolomite (Figure 15c). In peripheral areas and cracks, it is replaced by zincite. Very fine galena and relatively large pyrite were identified as inclusions in sphalerite (Figure 15d). Single smallest (first microns) particles of chalcopyrite, stibnite and arsenopyrite are observed in hydrothermally altered dolomites of all studied sites.

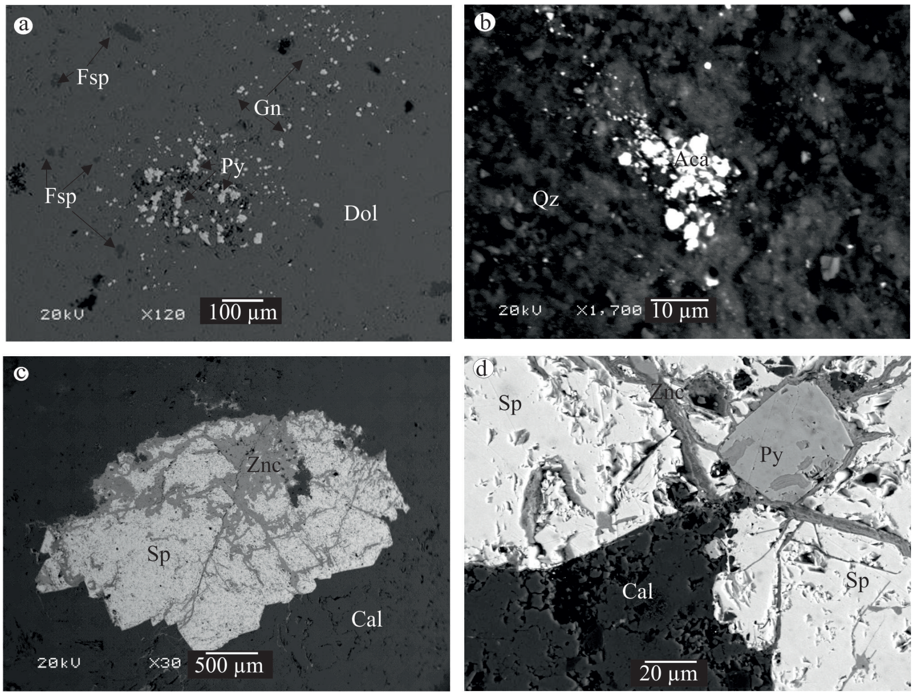

Figure 15. Sulfide minerals of hydrothermal-metasomatic formations (BSE mode): (**a**) inclusions of galena and pyrite in quartz-potassium feldspar dolomite; (**b**) aggregate structure of acanthite in quartz metasomatite; (**c**) large sphalerite developed in calcite veinlet, replaced by zincite along cracks and periphery; (**d**) inclusions of pyrite in sphalerite with thin veinlets of zincite. Qz—quartz; Fsp—potassium feldspar; Dol—dolomite; Py—pyrite; Gn—galena; Sp—sphalerite; Aca—acanthite; Cal—calcite; Znc—zincite.

4.2.2. Lithological and Tectonic Factors of Mineralization

Lithological factors played an important role in the formation of gold mineralization. First, this refers to the degree of permeability of the ore deposition medium, which is determined by the presence of voids and pores in rocks. In our case, the near-fault permeable zones of tectonic fracturing of carbonate rocks and slightly cemented fine-pebble conglomerates were favorable for ore deposition.

The tectonic factor of mineralization control has a great importance. The studied hydrothermal-metasomatic formations are clearly confined to the Dogoy–Mayat and Dogoy–Kuoysky faults of the Molodo–Popigai system of faults (Anabar river basin), as well as the Zhigansky fault zone (Bolshaya Kuonamka river basin). Dikes of the basic rocks of the Mesozoic age are localized within the Dogoy–Kuoysky fault (Figure 2). The latter can be either the actual sources of mineralization, or can serve as a catalyst for the mobilization of dispersed primary hydrothermal-sedimentary ore matter. The first assumption is supported by the findings of pyrite and chalcopyrite in dolerites. According to A.V. Okrugin and co-authors, the presence of sulfide minerals in igneous rocks indicates the saturation of magmatic melts with sulfides and their potential ore content [43]. In addition, the discovery of gold with an admixture of Cu (up to 18%) in apocarbonate hydrothermalites of core samples (Figure 14c) may indicate its connection with basic magmatism [44].

For the section of the middle flow of the Anabar river, two stages of mineralization formation can presumably be distinguished. In the first stage, ore matter in the form of primary hydrothermal ores were formed in the near-fault zone. The second stage is related to the processes of the Mesozoic tectonic-magmatic activation, when dikes of the basic composition intrude along the fault zones, and at the same time, there was a redeposition of ore matter, as well as, possibly, additional supply due to sulfide-saturated magmatic melts. As a result of these processes, gold-sulfide fluid solutions spread along the feathering faults into the discharge zones, forming gold-bearing hydrothermal-metasomatic formations.

5. Conclusions

Thus, our study showed that typomorphic features of native gold from placers can be used as additional criteria in forecasting and searching for primary ore sources of gold. According to the results of the study, the indicators of gold in modern placers are associated with two different sources: intermediate sources (paleo-placers) and nearby ores. These results were a prerequisite for setting prospecting traverses, which resulted in discovery of gold-bearing hydrothermal-metasomatic formations for the first time in the Anabar region.

The identified composition of mineral inclusions in gold of the Mayat river is identical to the mineral paragenesis of gold in considered ore occurrences, this indicates that these ore formations were additional sources of gold for modern placers of the studied area.

Very interesting in our opinion is the identification of specific multiphase internal structures of very fine slightly rounded gold. The fact that they were found at sites remote from each other (more than 120 km), where near-fault apocarbonate gold-bearing hydrothermal-metasomatic formations were formed, allows us to assume that the identified internal structures are indicator signs for native gold of hydrothermal-metasomatic formations of the Anabar region.

Of course, the discovered gold-bearing hydrothermal-metasomatic formations of the Anabar region require further detailed study. Strong turfness, overlapping by the Quaternary cover and, as a result, the fragmented nature of sampling, does not yet allow us to reliably determine the shape and nature of the occurrence of ore bodies. Moreover, the extent of gold-sulfide mineralization was not determined. However, apparently, near-fault hydrothermal-metasomatic formations are quite widespread in the northeast of the Siberian platform. This is evidenced by the discovery of silicified carbonate rocks, similar in composition and structure, with sulfide and precious metal mineralization in the area of the southeastern flank of the Molodo–Popigai fault system. Here, as a result of studying the petrographic features of the pebbles of the alluvial sediments of the Molodo river basin, silicified rocks with an oolitic structure with inclusions of pyrite, silver, and gold were found [45].

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