

## Article

# Typomorphic Features and Source of Native Gold from the Sykhoi Log Area Placer Deposits, Bodaibo Gold-Bearing District, Siberia, Russia

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**Abstract:** The Bodaibo gold-bearing district in the Lena gold province of Siberia is one of the largest and oldest placer gold-bearing provinces in the world. Approximately 1650 tons of gold has been extracted from the region. Precise studies on the source of these unique placer deposits are lacking and still controversial. Native gold from four different locations was gathered to investigate its morphology, chemical signatures, structure and inclusions. Some data on primary bedrock mineralization were obtained from the published literature. The linear weathering crusts developed along the zones of disjunctive dislocations near the Sukhoi Log gold deposit were researched. If they coincided with zones of low-grade veinlet-disseminated gold–quartz–sulphide mineralization with small gold grain sizes, a supergene replacement of primary mineralization was known to have occurred, accompanied by the formation of gold-rich rims and an increase in the size, content and purity of gold. Such mineralization associated with linear weathering crusts can be a source of local eluvial–proluvial placers, while placers of large valleys are formed due to low-sulphide gold–quartz lodes.

**Keywords:** placer; native gold; typomorphysm; linear weathered crust; Sukhoi Log deposit



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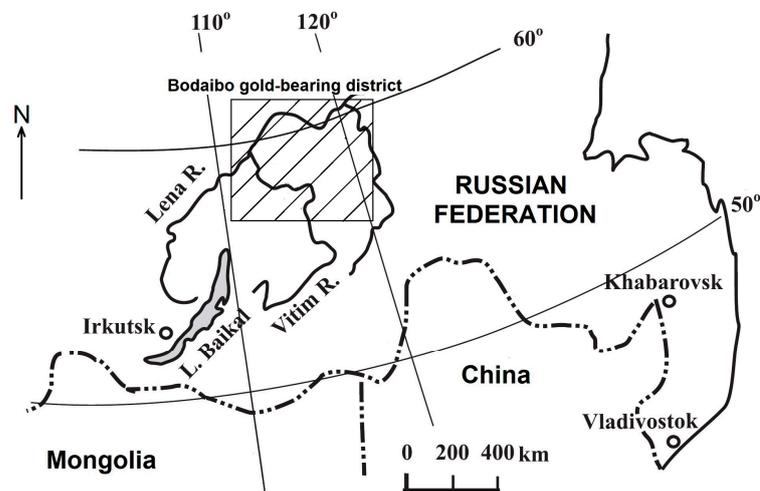
## 1. Introduction

The Bodaibo gold-bearing district of Lena gold province is located in Siberia, in the Irkutsk region of Russia (Figure 1). The first placer gold of the region was obtained in 1841. It is one of the largest and oldest placer gold-bearing provinces in the world [1,2]. Over the 180 years in which gold prospecting and extraction were carried out in the area, approximately 1500 tons of placer gold and more than 150 tons of primary gold (mainly during the last twenty years) have been extracted from the gold deposits of the region. The total potential amount of resources is estimated at about 4000 metric tons, with an annual gold production of over 20 metric tons [3]. In spite of the fact that the main prospects for the gold mining industry in the region are associated with primary ores being developed and prepared for development, placer deposits still provide about half of the gold mined.

Although it has been investigated for over a century, some aspects of gold mineralization are still unclear, in particular concerning the source of this placer gold.

The Bodaibo gold-bearing district is a unique region not only in Russia, but also in the world in terms of placer reserves, a significant part of which has already been mined out [4]. This district also contains large primary bedrock deposits, including the largest deposit in Russia, the Sukhoi Log, whose reserves are associated with scattered vein-disseminated gold–quartz–sulphide mineralization. The main problem is that vein gold–quartz placer-forming deposits with large-size gold have a limited distribution, and large deposits such as the Sukhoi Log are not direct sources of placers because of the fine size of the gold grains. For example, more than 95% of the native gold found in the Sukhoi Log has a grain size

of less than 0.1 mm [5]. Native gold of this size is far too small for gravity enrichment and does not accumulate well in the placer deposits. Additionally, the giant gold deposit Sukhoi Log could not be a source of gold placers in the surrounding area because it has a low erosion level; the main ore body is not exposed on the surface [6].



**Figure 1.** Map of the Bodaibo gold-bearing district.

The sulphide-poor quartz–gold-bearing lodes favourable for the formation of placers are of subordinate importance in the territory of the Bodaibo District. We can only assume that the placers were formed due to giant primary, mainly quartz–gold lode deposits, which are now completely eroded [7–10].

This point of view considers only the mechanical processes of placer formation due to the disintegration of bedrock gold deposits. However, a number of researchers believe that under supergene conditions, sulphide-associated gold changes significantly, becomes coarser and transforms into a gravitationally enriched placer-forming class up to the formation of nuggets weighing up to tens of kilograms [11–14]. Such a process can lead to the formation of placer deposits in the absence of significant bedrock gold sources due to poor disseminated gold–sulphide mineralization. One piece of evidence for the growth of gold particles under supergene conditions is the presence of gold-enriched rims on the particles.

The linear weathering crusts (LWCs) developed along the zones of disjunctive dislocations near the Sukhoi Log gold deposit were researched. The deposit consists of yellow-brown clay with weathered shale and quartz detritus. The conducted studies have revealed that even with low concentrations or disseminations of gold in the host rocks, the clay contains gravitationally enriched native gold of economic grade. This gold has evidence of grain growth such as a high-grade gold rim.

The main task of the study was to assess the role of LWCs in the transformation of fine gold of veinlet-disseminated quartz–sulphide mineralization into larger placer-forming classes, as well as the influence of this gold on the processes of placer formation in order to assess the prospects for the exploitation of such placers. Along the way, a conclusion was made about the possible sources of gold for the formation of the unique placers of the Bodaibo gold-bearing district.

## 2. Geology and Metallogeny of Bodaibo Gold-Bearing District

### 2.1. Geological Structure, Stratigraphy and Metallogeny of Pre-Cenozoic Stage

The study area is located within a complicated regional structure known as the Bodaibo synclinorium, corresponding geographically to the Patom Highlands. Early, Middle and Late Riphean metasediments of the Bodaibo synclinorium, which correspond to

the Bodaibo internal depression (Figure 2), unconformably overlie Archean–Proterozoic metamorphic rocks.

Lower Riphean stratigraphic divisions consist of greenschist facies conglomerates, sandstones, shales and volcanogenic and volcano-terrigenous rocks. Andesite, andesite–basalts and tuffs are intercalated with sandstones and conglomerates and ferruginous quartzites.

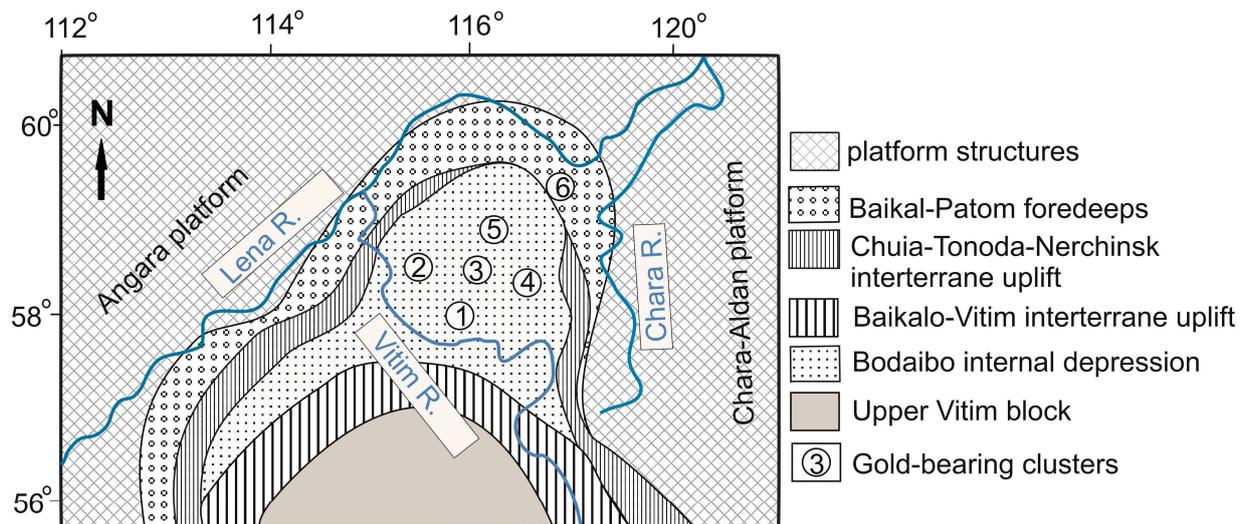
The Middle Riphean, which is up to 2500 m thick, consists mainly of terrigenous gravel–sand–siltstone sediments, succeeding calcareous sandstones and limestones. Middle and Late Riphean sedimentary rocks of the Nigry Group are divided into the Buzhuikhtha, Ugokhan, Khomolkho and Imnyakh Formations with a total thickness up to 1500 m. There, rocks mainly form the Bodaibo internal depression.

The flysch of the Khomolkho Formation hosts all of the gold mineralization in the Sukhoi Log deposit. The silty and calcareous carbon-bearing shales contain abundant diagenetic sulphides. Rhythmically interbedded sandstones, shales, carbonaceous shales, limestones and sandstones of the Vendian Bodaibo Group up to 2500 m thick terminate the Late Proterozoic sequences.

Terrigenous and carbonaceous layers rich in organic carbon are characteristic of the region. Carbon-bearing sediment deposition reached a maximum in the Middle and Late Riphean. The amount of organic matter increases from carbonate to sandstone to siltstone to pelite, following the normal sequence of a sedimentary succession.

Terrigenous carbonaceous rocks can be found in a continental margin sea basin. Minor amounts of Lower Riphean volcanics are intercalated with coarse-grained clastics and ferriferous quartzites. At the same time, ophiolitic units, including ultramafic rocks and tholeiitic volcanics, formed nearby and developed during the Early Paleozoic Bodaibo synclinorium.

The central part of the synclinorium has been metamorphosed to the biotite subfacies of the greenschist facies. Peripheral rocks have experienced epidote–amphibolite and amphibolite facies regional metamorphism associated with the formation of granite–gneiss domes and paligenetic granitoid plutons. Small-to-middle rank magmatic bodies occur within the Bodaibo synclinorium, but large Paleozoic granite intrusions, such as the Dzhegdakar massif, are exposed on the periphery [15].



**Figure 2.** Tectonic scheme of Bodaibo gold-bearing district (modified after [16]). Gold-bearing clusters: 1—Artemovskiy, 2—Marakansky, 3—Kropotkinsky (including Sukhoi Log deposit), 4—Svetlinsky, 5—Khomolkho, 6—Dalnetaiginsky.

The two types of primary lode gold mineralization found in the Lena province are the veinlet-disseminated and quartz lode types. The veinlet-disseminated gold–quartz–sulphide mineralization is the most important economic type, which occurs at mine mineral deposits of economic importance, including the Sukhoi Log, Vysochaishee, Verninskoe (Kropotkin-

sky cluster), Nevskoe (Svetlinsky cluster) and Chertovo Koryto (Khomolkho cluster). This mineralisation is controlled by linear and overturned anticlines, and fault zones in their axial parts and flanks. The largest deposits are hosted in black shales metamorphosed to the sericite–chlorite greenschist facies. Minor gold deposits occur in rocks metamorphosed to the epidote–amphibolite and amphibolite facies, although they are confined to a zone of retrograde metamorphism (Figure 3).



**Figure 3.** Quartz lode gold mineralization from Verninskoe deposit (Kropotkinsky cluster).

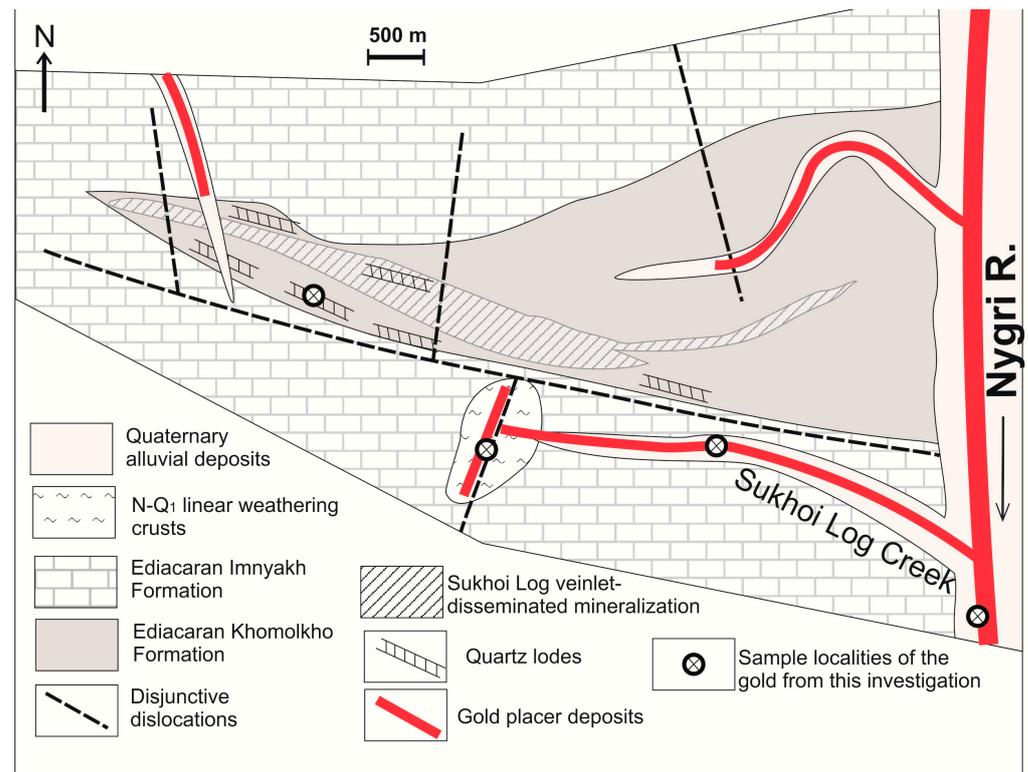
The quartz vein type or gold–sulphide–quartz mineralization is confined to sublatitudinal linear vein zones in the axial parts of anticlines, tectonic faults, shear zones and tension fractures, including those concordant to the bedding plane (Pervenets, Dogaldyn, Krasnoe deposits) and those of cross-cutting settings (Kavkaz). The largest vein clusters are Centralnoe in the Sukhoi Log camp and Dogaldyn in the Artemovskiy camp [6].

## 2.2. Sukhoi Log Deposit

The geology of the Sukhoi Log is described in much detail elsewhere [3,6,15–19] and the references therein.

The Sukhoi Log is located in the Mama–Bodaibo synclinorium. It is hosted in sedimentary rocks of the Khomolkho Formation and partially in the overlying dolomite-dominated Imnyakh Formation. Igneous rocks in the vicinity of the deposit are confined to the small Konstantinovskiy granitoid stock, 6 km south of the deposit [20].

The largest orebody, which has the same name, is about 4 km<sup>2</sup> in area and is composed of veinlet-disseminated gold–quartz–sulphide stockwork-type mineralization, which is confined to the core of the anticline and is surrounded by a wider aureole of barren sulphides. The deposit is hosted mostly in carbonaceous quartz sericite–carbonate shales to sandstones metamorphosed to the sericite and locally sericite–chlorite subfacies of the greenschist facies (Figure 4).



**Figure 4.** Geological scheme of Sukhoi Log gold deposit with bedrock and placer gold metallogeny (based on [6,16]). Exposure of the veinlet-disseminated gold–quartz–sulphide mineralization on the current surface.

The major gold reserves of the deposit are in quartz–sulphide veinlet-disseminated mineralization (VDM). Low-sulphide gold–quartz veins are of subordinate importance. Outside the economic area the rocks are usually barren or contain only low-grade mineralization.

Gold in veinlet-disseminated ores is found in native rock, mainly in the form of microscopic and thin inclusions in pyrite. The size of gold particles varies from a few microns up to 0.4 mm, while more than 95% of gold is in the order of less than 0.1 mm [16].

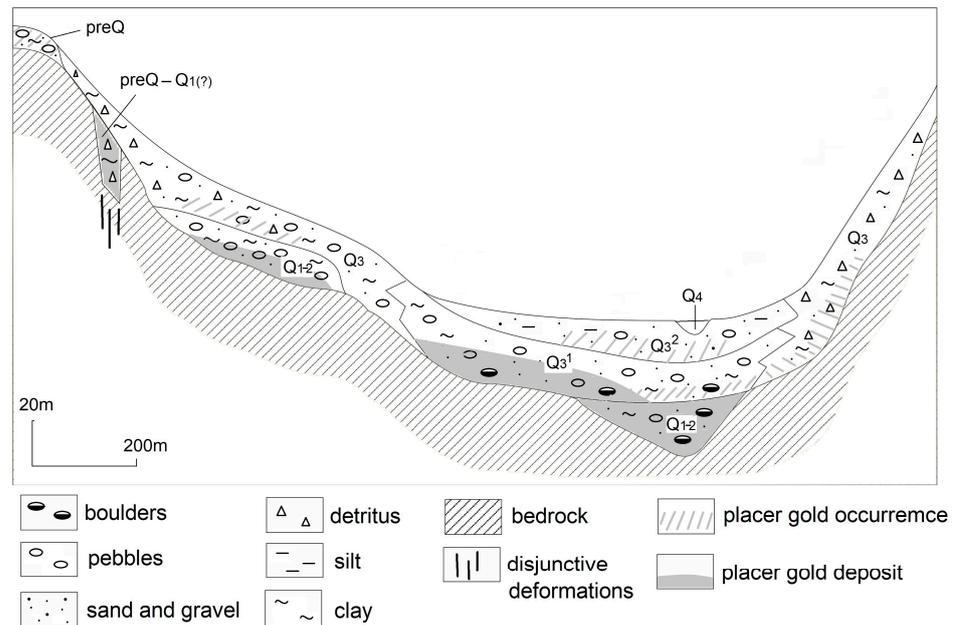
The shape of the gold particles is varied and dominated by interstitial secretions, occasionally lumpy, more or less massive interstitial secretions with a complex porous and spongy surface. Plates and scales with uneven edges and a predominantly complex cellular surface are widespread.

The fineness of the studied gold particles varied from 846 to 908. Silver is a permanent component of the alloy, and its content varies from 9 to 14 wt.%. Additionally, trace elements were detected, including mercury (up to 0.25%), iron (up to 0.97%), copper (up to 0.11%) and nickel (up to 0.06%) [5].

### 2.3. The Structure and Composition of The Sedimentary Cover and Placer Deposits of The Bodaibo District

The area of the Bodaibo District is a deeply dissected lowland. The height of the main part of the watersheds is 850–950 m. The depth of the river valleys is 200–500 m, and the width of their upper contours is 2–4 km. The width of the floodplains is 200–400, occasionally reaching 800 m. The valleys are filled with a sediment sequence of 20–25 to 140–170 m thick. In the buried relief of the valleys, deep thalwegs and terraces are found.

According to Y.P. Kazakevich and M.V. Reverdatto [21], four stages are assigned to the Quaternary history of the development of the present-day relief and placer gold formation (Figure 5).



**Figure 5.** The generalized cross-sections of the deposits of the Nigri Valley (based on [21]. PreQ—uncertain Cenozoic (pre-Quarter) cover gravel; PreQ-Q<sub>1</sub>(?)—supposed Cenozoic–Lower Quaternary linear weathered crusts; Q<sub>1</sub>—Lower Quaternary, Q<sub>2</sub>—Middle Quaternary, Q<sub>3</sub>—Upper Quaternary, Q<sub>4</sub>—Holocene alluvial and deluvial deposits.

The first stage was characterized by moderate tectonics, planar denudation and the formation of a peneplain surface covered by alluvial gravel (mostly well-rounded and medium-rounded pebbles of quartz (60%), quartz–feldspar sandstone (30%) and small pebbles of marl and limestone) with a typical red-colour sandy–clay matrix. Fragments of the weathering crust of kaolinite composition can be found. Now, deposits can sometimes be found on the flat watersheds and highlands. The gravel deposits are weakly gold-bearing. The deposits date back to the Pre-Quaternary, presumably the Miocene [21].

Apparently, at the same time, formation of the linear weathering crusts (LWCs) began. This is associated with zones of disjunctive dislocations in the bedrock (Figure 6). At the intersection of these dislocations with gold–sulphide lodes, these linear weathering crusts carry gold mineralization of considerable economic potentiality.



**Figure 6.** Clay deposit of linear weathering crust.

Y.P. Kazakevich and M.V. Reverdatto (1972) describe this type of placer deposit in the upper part of Sukhoi Log Creek [21], p. 124: “Sukhoi Log Creek, right tributary of the R. Nygri, is a small watercourse, in which two gold-bearing layers are known. One rests on the bedrock of the buried terrace. It is composed of brightly colored rock debris with in yellow and red clay matrix. The formation was distinguished by a very high gold content, present throughout its thickness. The placer was worked out in 1890–1896. The second placer layer lies in the deep thalweg in poorly-sorted alluvial deposits”.

The second stage (Early to Middle Pleistocene) began with neotectonic activation and block uplift that resulted in a change in planer denudation to linear deep erosion, which resulted in the cutting of valleys to a depth of 300 to 900 m. This formed a series of erosion terraces covered by pebbles with eroded weathering crusts. The deposits of buried thalwegs of the valleys are also assigned to the second stage. The thalweg deposits contain big blocks and boulders up to 2–3 m in diameter that are evidence of the high hydrodynamic activity of this stage (Figure 7). In the bottoms of the valleys, upon the transition to bedrock, the eluvial horizon is commonly observed to contain angular particles of quartz gruss and clay. The terrasses and thalwegs deposits contain placer gold mineralization of economic importance. Nuggets are often found here.



**Figure 7.** Cross-section of deposits of the placer of R. Nygri. (A) man-made tailing dumps; (B) the deposits of the second stage.

In the beginning of the Late Pleistocene, the intensity of the tectonic activity decreased and the change from vertical erosion to lateral erosion resulted in expansion of the valleys, forming the slope sedimentary complex and the main part of the alluvial deposits filling the valleys. Colluvial deposits are represented by detritus of local rocks with a sandy–clay matrix. Alluvium consists of pebbles and boulders mostly of local rocks with a clay–sand matrix. A significant number of the economic placers in the district are associated with alluvial deposits of this stage. In the zones of primary ore mineralization, the slope (colluvial) deposits contain placer gold, which can be a source of alluvial placers but has own economic importance.

During the second part of Late Pleistocene stage, there was a stabilization of the topography and formation of a barren sequence which covers the main gold-bearing strata. It consists of gravel with a sand–silt matrix of alluvial and fluvial–glacial genesis. Holocene sediments form the channels of modern water courses.

Although the total placer gold production from the middle of the 19th century to the present was about 1500 tons, 130 tons of the measured and indicated resources is estimated to be present [22]. The placers continue to be worked by Lena Gold Company and independent prospectors.

### 3. Sample Collection and Analysis

Native gold from four different locations was obtained and researched (Figure 4). Bulk samples of the sediments each with an approximate weight of 20 kg were taken from (1) the quartz lodes of the Sukhoi Log deposit, (2) the LWC located on the periphery of the Sukhoi Lod gold field, (3) the alluvial deposits of the Sukhoi Log Creek, which erode the LWC and the rocks outside the economic area with low-grade mineralization and (4) the giant Nygri placer downstream of the mouth of the Sukhoi Log Creek. Hand panning was carried out in the field to reduce the weight of the sample and to obtain 20–30 g of heavy mineral concentrates. To obtain the final concentration, the gold grains were separated by heavy liquid (bromoform, 2.89 g/cm<sup>3</sup>) in the laboratory of IGEM RAS. All obtained grains were used for research on the grain size of the gold particles.

Twenty gold grains were extracted from every sample for further research with scanning electron microscopy (SEM) and electron microprobe analysis (EMPA) in grains and polished sections. Morphology, grain size analysis and chemical composition of the native gold from veinlet-disseminated gold–quartz–sulphide mineralization was obtained from the geological literature [5,17,23].

Informed speculation on the nature of the source bedrock mineralization and supergene changes is possible through comparison of the microchemical signature of placer grains with the generic characteristics of gold from different styles of mineralization [24]; therefore, the placer gold grains' morphology, inner structure and inclusions were compared with documentation of the available and possible bedrock gold mineralization.

Backscattered electron (BSE) images of the gold were taken for all grains using a scanning electron microscope (SEM), GSM 5610LV, and energy-dispersive spectrometer, INCA-Energy 450 (analyst L. Ivanova).

After SEM investigation, the grains were studied for composition, inclusions and inner structure. The grains were mounted into resin blocks, and the blocks were crushed and polished to provide a cross-section of every grain.

The grains were later analysed with an electron microprobe at the Analytical Laboratory of IGEM RAS (Moscow, Russia) using a JEOL JXA-8200 electron microprobe (Japan) with five wavelength-dispersive spectrometers and an energy-dispersive spectrometer under the following operating conditions (Table 1) by the analyst E. Kovalchuk.

**Table 1.** Measurement conditions of electron microprobe analysis.

	Ag	Au	Hg	Cu	Fe
Accelerating voltage (kV)	20	20	20	20	20
Sample current (nA)	20	20	20	20	20
Beam diameter (μm)	1	1	1	1	1
X-ray	Lα	Lα	Mβ	Kα	Kα
Crystal analyser	PETH	LIF	PETH	LIF	LIF
Time on peak (s)	20	20	20	20	20
Time on back (s)	10	10	10	10	10
Standard name *	AgSbS <sub>2</sub>	Au_s	HgS_s	Cu_s	CuFeS <sub>2</sub>
D.L. 3σ	0.04	0.33	0.11	0.07	0.07

\* Approved internal laboratory standards of pure gold without impurities (99.99%) and synthetic materials were used in the analysis.

The grade of the gold in the alloys varied from 71.9 wt.% to 100 wt.%. Silver was present above the detection limit (3 σ) of 0.04 % in all grains. Ag content varied from 0.11% to 28.1%. Cu, Hg and Fe were found above the detection limit (0.07 wt.%, 0.11 wt.% and 0.07 wt.%, respectively) in several grains. Additionally, inclusions and grains with pronounced rim–core zonation were studied in detail with electron microprobe analysis.

The composition of Au grains that had visible core–rim zonation was analysed for every grain in the core and in the rim.

Interpretation of gold compositions was based on a multivariate treatment of the information available. The type of information may vary between sample populations, e.g., minor elements may be detectable or not, and inclusion suites may be more or less representative of the actual population depending on sample size. When available, inclusion suites provide clear evidence of genetic relationships between sample populations and strong indications of the deposit type [25,26]. Ranges of Ag compositions are useful to establish “same or different” criteria and may find application in speculating on zonal relationships between mineralization within the same hydrothermal system, as a consequence of the significant control of the temperature of the depositional environment over the Au–Ag ratio within the alloy. The importance of minor alloying metals (Cu, Hg and Fe) varies according to the degree to which they are present and as well as their concentration [27].

#### 4. Results

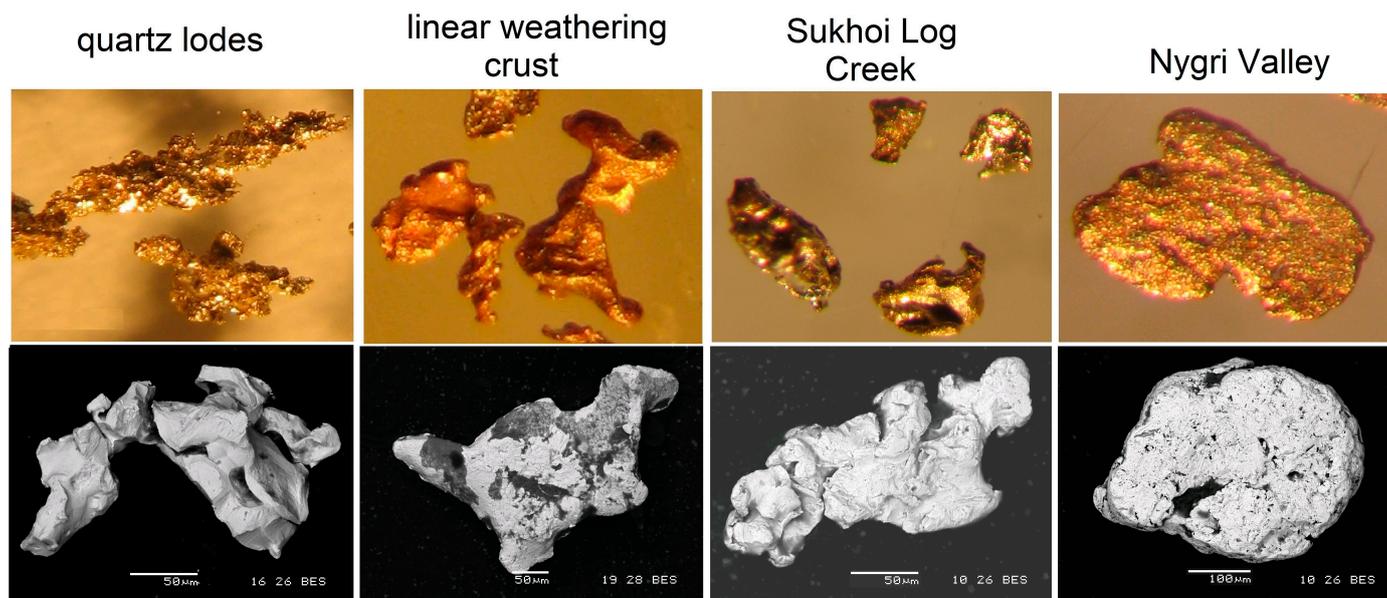
Studies of the morphology, chemical composition and mineral inclusions of gold grains have been widely used in gold exploration [28–37].

The native gold from four studied collected samples (quartz lodes, LWC, Sukhoi Log Creek and placer of Nygri Valley) and one from the published geological literature (veinlet-disseminated gold–quartz–sulphide mineralization) differ by morphology, composition, microchemical signature and internal structure, indicating difference in the genesis and supergene changes in the gold [38].

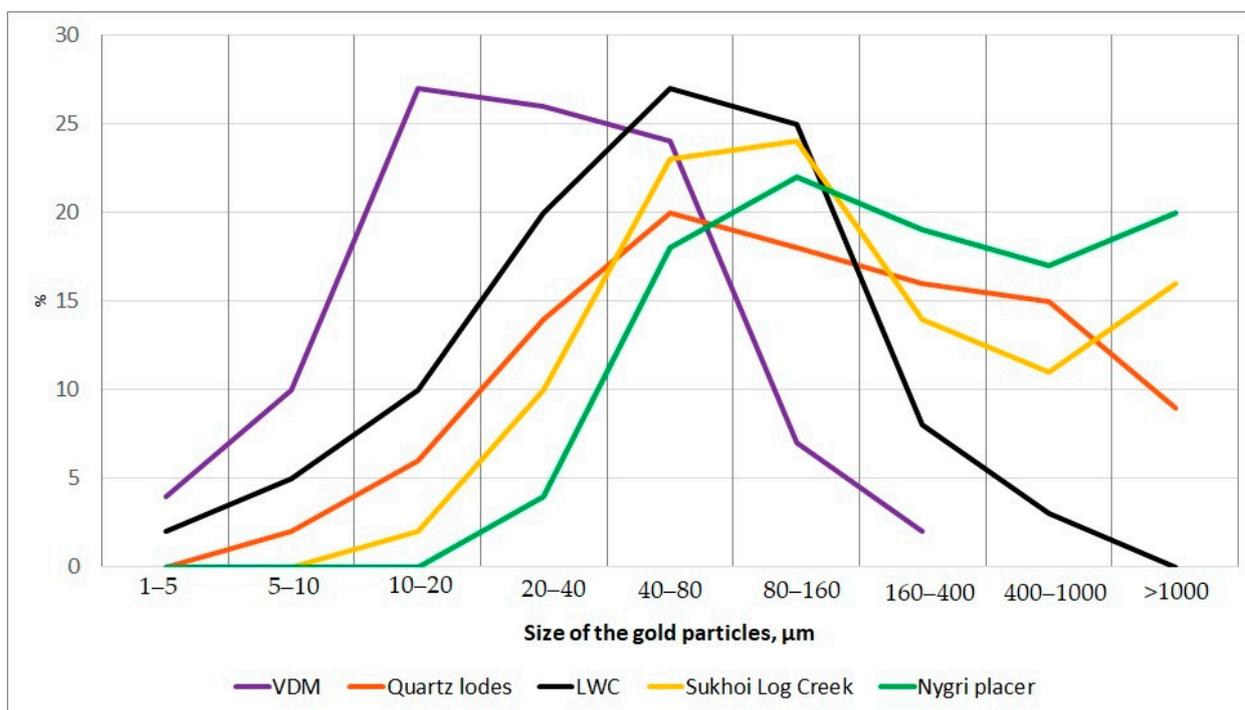
##### 4.1. Gold Particle Size and Morphology

The morphologies of gold grains may indicate the distance they were transported from the source, the chemical compositions and mineral inclusions they contain, may represent the hypogene source and possibly help in distinguishing between primary sources [34,39–41].

The shape and the surface of the gold grains from collected samples are depicted in Figure 8. The size and other typomorphic features are represented on Figure 9 and Table 2.



**Figure 8.** Examples of gold particles from different localities. Optical with binocular (upper line) and SEM (BSE) (lower line) images of examples of native gold from bedrock quartz lodes, weathering crust and placers of Sukhoi Log Creek and Nygri Valley, showing contrasting morphologies indicative of different origins and supergene histories (see text).



**Figure 9.** The grain size of the gold grains of studied samples—veinlet-disseminated ore, quartz lodes, linear weathering crusts, Sukhoi Log Creek and Nygri placer.

**Table 2.** Typomorphic characteristics of native gold from studied types of bedrock and placer mineralization.

		Size of the Grains (mm)		Fineness in the Core		C <sub>h</sub> *		Trace Elements Above Detection Limit, wt.%
		min	max	min	max	min	max	
quartz lodes	variation	0.01	>1	868	949	0.97	1.03	Ag (4.5–10.1)—all grains, Cd–1.29 (single), As–0.88 (single)
	average	0.37		910		1.00		
VDM	variation	0.001	0.4	803	895	-	-	Ag (9.5–14.36)—all grains, Cu (0–0.11), Fe (0–0.97), Hg (0–0.25)
	average	0.04		870		1.00(?) **		
LWC	variation	0.02	0.8	771	928	1.00	1.18	Ag (7.2–22.9)—all grains. Cu–0.11 (single), Fe–0.15, 0.22 (two analysis)
	average	0.1		875		1.08		
Sukhoi Log Creek	variation	0.02	>1	719	952	0.97	1.23	Ag (4.8–28.1)—all grains, Hg–0.18 (single) Fe–0.23 (single)
	average	0.48		881		1.05		
Nygri placer	variation	0.04	>1	910	971	0.97	1.03	Ag (2.9–9.0)—all grains
	average	0.6		941		1.00		

\* C<sub>h</sub>—coefficient of the heterogeneity ratio of the Au content in the core and in the rim of the grains. \*\*—there are no data on the distribution of gold content within the grains, but the grains on polished surfaces (Figure 5 in [5]) display homogeneity of the inner structure.

The gold from low-sulphide–quartz lodes had an irregular shape with angular edges, and the surface was uneven and smoothed, with no traces of supergene influence. Numerous intergrowths with quartz were observed. The grains obtained from quartz lodes of the Sukhoi Log during this study ranged in size from less than 0.01 mm to 1.2 mm (maximum dimension) (Figure 9). According to previous research, the grains from the lodes reach 1–2 cm and more in size [16].

The grains from the LWC had an irregular shape, but smoothed edges and surfaces. The grains were often coated with a film of iron hydroxides and iron oxyhydroxides. Very often, iron hydroxides filled depressions and pits on the surface of grains. The size of the grains of the studied samples ranged from 0.02 mm to 0.8 mm.

The gold grains from the Sukhoi Log Creek were of two different typomorphic types. The first one (up to 60% of the grains) was represented by grains of an irregular shape with smoothed edges and weak traces of roundness. Pits, grooves and traces of dragging were found on the surface of the grains. Iron hydroxide crusts were sometimes observed in the depressions and pits of the grains. The size of the studied grains varied from 0.02 mm to more than 1 mm.

The shape of the second type of grain from the Sukhoi Log Creek varied from irregular to semi-spherical with a crumpled structure. It had no iron hydroxide crusts. The surface had traces of transportation. The size varied from 0.08 mm to more than 1 mm.

The gold grains from the Nygri placer deposit had a spherical to semi-spherical and flattened shape, medium to well-rounded with a smooth pitted surface (Figure 8). The size of the studied grains ranged from 0.04 up to 1 mm, whereas according to the experience of gold miners, 30% of gold grains are more than 2 mm in size, and nuggets weighing hundreds of grams are common [21].

The data on typomorphic features of native gold from veinlet-disseminated gold–quartz–sulphide mineralization were obtained from the published literature [5,6,16,17]. As shown in these studies, native gold in ores is found mainly (85%) in the form of microscopic and thin inclusions in pyrite, and only 15% is located in the host rocks outside the pyrite grains [5]. Native gold is usually observed in the form of individual independent inclusions, and very seldomly it is found intergrown with other common ore minerals, as well as at the boundary with inclusions of vein minerals or in quartz microveinlets [42]. The size of gold grains reaches up to 0.4 mm, and most gold particles have a size of 0.01–0.08 mm. The shape of gold grains is mostly irregular with angular edges and a complex nostril-porous and spongy surface.

The grain size of the gold grains from the studied samples (quartz lodes, LWC, Sukhoi Log Creek and Nygri placer) and those obtained from previous studies on VDM [5,16] are represented in Figure 9 and Table 2.

#### 4.2. Gold Alloy Composition

The four samples of native gold obtained from the studied area were classified by composition, microchemical signature and internal structure.

The fineness of the gold from quartz lodes varied from 868 to 949 (average 910). The alloys contained Ag (4.54–10.1 wt.%, average 7.47 wt.%). In single grains, Cd–1.29 wt.% and As–0.88 wt.% were detected above the detection limit.

Study of Au–Ag alloys from LWCs revealed core–rim zonation of the grains. The average fineness in the core was 875 with variation from 771 to 928. All grains contained Ag (7.20–22.9 wt.% in the core). In a single grain, Cu–0.11 wt.% and Fe (two grains)–0.15 wt.% and 0.22wt.% were detected above the detection limit. The fineness in the rim varied from 976 to 998.

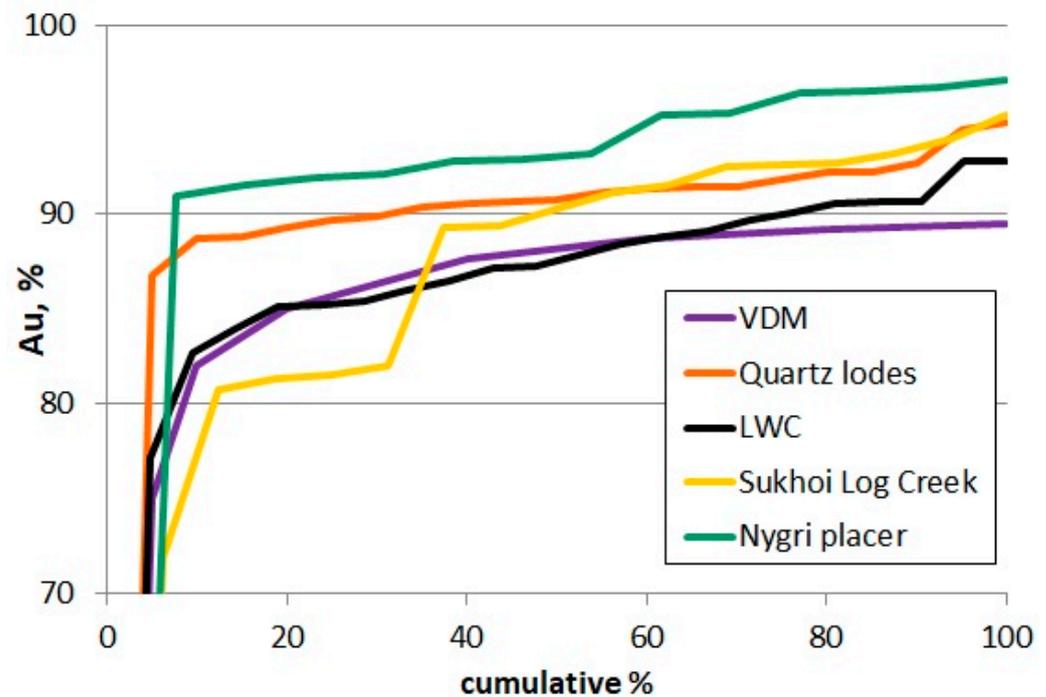
The fineness of the first type (irregular smoothed) of grains from Sukhoi Log Creek was 850–980. All grains contained Ag (4.80–28.1 wt.%). The single grain with maximum Ag content (28.1 wt.%) contained Hg–0.18 wt.%. Additionally, in one grain, Fe was detected above the detection limit (0.23 wt.%). The fineness of the second type (irregular to semi-spherical) was 920–960. All grains contained Ag (4.90–8.12 wt.%). Other trace elements were not detected.

The fineness of the gold alloys from the Nygri placer varied from 910 to 971 (average 941). All grains contained Ag (2.90–9.0 wt.%). Other trace elements were not detected.

The fineness of the gold alloys from VDM was estimated to range from 500 to 980 [16] or 800 to 900 [5], but most of the alloys had a fineness of 840–900.

The cumulative frequency plots of the alloy compositions in the Au grain cores from the studied samples are represented in Figure 10. The cumulative plot for the alloy fineness for quartz lodes and the Nygri placer had a certain conformity. The coefficient of correlation (R) of the fineness for the sample populations was 0.60 (the critical value with a confidence

coefficient of 0.95 is 0.504). There is also a strong similarity between the plots of VDM and LWC: the correlation coefficient is 0.66.



**Figure 10.** The cumulative frequency plots of the alloy compositions in the Au grain core from quartz lodes, veinlet-disseminated mineralization (VDM), linear weathering crusts (LWC), Sukhoi Log Creek and placer of Nygri Valley.

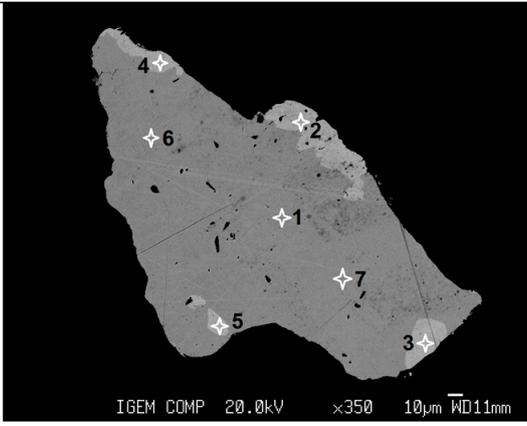
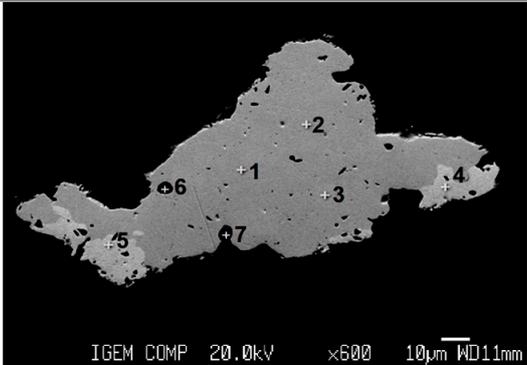
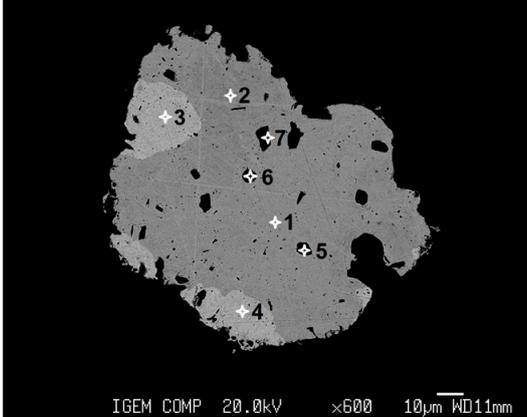
Gold samples from Sukhoi Log Creek exhibited a fineness profile between these end members. The resulting profile shape with curve kinks suggests two probably overlapping compositional fields based on Au concentrations in the alloy. One of them, located in the field of relatively low-grade gold, corresponded to VDM–LWC alloys, whereas the second, with high-grade gold, was similar in fineness to quartz lode alloys.

The results of research on the inner structure and conclusions about the alloys are shown in Figures 11 and 12 and Table 2. For populations of homogenous gold grains, duplicate sampling generates reproducible data [43]. In order to establish the degree of heterogeneity within both heterogeneous and apparently homogeneous grains, it is necessary to analyse it at several point locations in their sections [39]; therefore, the inner structure of the complex alloys was studied at several points [44].

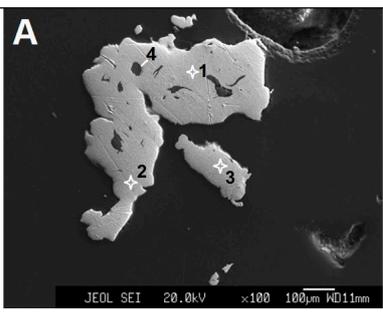
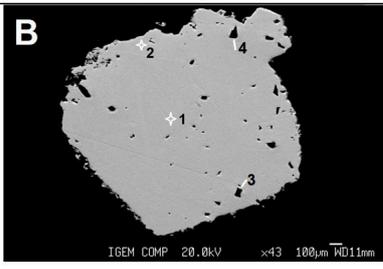
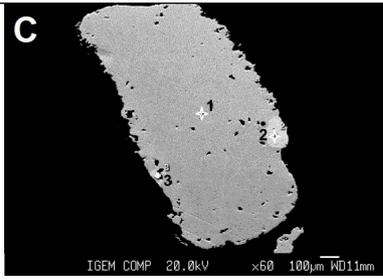
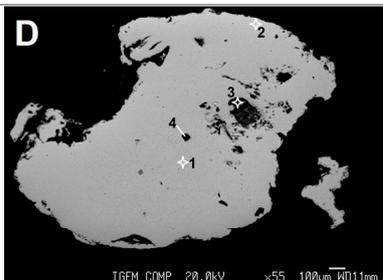
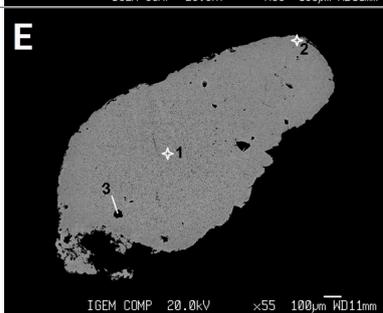
The analysis of the inner structure of polished grains revealed that there were two main varieties of gold alloys—monotonous and distinct heterogeneous alloys with rim–core zonation and gold-rich inner fracturing zones.

Heterogeneous alloys were obtained mainly from the LWC (70% of the alloys from the sample) and partly from Sukhoi Log Creek (50% of the alloys from the sample) (Figures 11 and 12 C). The concentration of gold in the rim and gold-rich inner fractured zones varied from 98.53 wt.% to 100 wt.% with Ag contents ranging from 0 to 0.85 wt.% (average 0.22 wt.%) and complete absence of Cu, Fe and Hg. The coefficient of heterogeneity (ratio of rim–core concentrations of gold) reached 1.18 for the LWC and 1.23 for Sukhoi Log Creek, with an average of 1.08 and 1.05 for the samples, respectively.

Regarding the alloys from quartz lodes, the Nygri placer, (apparently) and VDM, 40% of the grains from the LWC and 80% of the grains from Sukhoi Log Creek were homogeneous.

	Type of gold	Point	Content, wt. %				
			Au	Ag	Cu	Hg	Fe
 <p>IGEM COMP 20.0kV x350 10µm WD11mm</p>	LWC	1	90.06	8.96	0.00	0.00	0.00
		2	99.26	0.65	0.00	0.00	0.00
		3	100.00	0.00	0.00	0.00	0.00
		4	100.00	0.00	0.00	0.00	0.00
		5	98.63	0.14	0.00	0.00	0.00
		6	89.83	8.64	0.00	0.00	0.00
		7	88.87	9.37	0.00	0.00	0.00
 <p>IGEM COMP 20.0kV x600 10µm WD11mm</p>	LWC	1	86.19	11.69	0.00	0.00	0.00
		2	86.60	11.93	0.00	0.00	0.00
		3	85.29	11.70	0.00	0.00	0.00
		4	99.69	0.00	0.00	0.00	0.00
		5	99.01	0.12	0.00	0.00	0.00
	6	Iron hydroxide (Fe – 53.4, O – 28.1)					
	7	Iron hydroxide (Fe – 57.7, O – 35.6)					
 <p>IGEM COMP 20.0kV x600 10µm WD11mm</p>	LWC	1	91.47	8.54	0.11	0.00	0.22
		2	90.01	7.65	0.00	0.00	0.15
		3	99.60	0.19	0.00	0.00	0.00
		4	100.00	0.00	0.00	0.00	0.00
	5	Sphalerite (Zn – 56.9, S – 21.2, Fe – 1.69)					
	6	Iron hydroxide (Fe – 57.2, O – 37.6)					
	7	Pyrite (Fe – 46.3, S – 51.6)					

**Figure 11.** The composition of the placer gold grains from the LWC, with BSE images of the polished sections. Content of detected elements was determined through electron microprobe analysis on different points of the polished surface. The grains had a gold-rich rim and inclusions of sphalerite, pyrite, chlorite and iron hydroxide. Remnants of polishing powder and defects of polishing occasionally resemble inclusions in the SEM images.

	Type of gold	Point	Content, wt. %				
			Au	Ag	Cu	Hg	Fe
	Quartz lode	1	91.48	7.26	0.00	0.00	0.00
		2	90.87	8.73	0.00	0.00	0.00
		3	92.07	7.62	0.00	0.00	0.00
		4	Quartz (Si – 48.30, O – 50.15)				
	Sukhoi Log Creek	1	71.87	27.38	0.00	0.18	0.00
		2	71.26	28.30	0.00	0.00	0.00
		3	Iron hydroxide (Fe – 52.4, O – 28.8)				
		4	Chlorite				
	Sukhoi Log Creek	1	89.36	11.10	0.00	0.00	0.00
		2	100.00	0.25	0.00	0.00	0.00
		3	99.65	0.44	0.00	0.00	0.00
	Nygri placer	1	93.15	7.23	0.00	0.00	0.00
		2	92.79	7.39	0.00	0.00	0.00
		3	Iron hydroxide (Fe – 53.4, O – 28.1)				
		4	Quartz (Si – 46.03, O – 50.41)				
	Nygri placer	1	95.87	4.63	0.00	0.00	0.00
		2	95.67	4.67	0.00	0.00	0.00
		3	Pyrite (Fe – 46.32, S – 52.88)				

**Figure 12.** The composition of the placer gold grains from quartz lode (A), Sukhoi Log Creek (B,C) and the placer of Nygri Valley (D,E) with BSE images of the polished sections. Content of detected elements was determined through electron microprobe analysis on different points of the polished surface. The grains from Sukhoi Log Creek sometimes had a gold-rich rim. Other grains had a monotonous structure. The grains from the Nygri placer had inclusions of pyrite, quartz and iron hydroxide. Remnants of polishing powder and defects of polishing occasionally resemble inclusions in the SEM images.

#### 4.3. Mineral Inclusion

Most of the sample populations were homogenous, inclusion-free gold particles. The small number of revealed inclusions is not enough to enable statistical processing of the inclusion suite [45], but available data allow preliminary conclusions about the primary mineralization type of the gold.

The most common were iron hydroxide inclusions, which were revealed in the LWC, Sukhoi Log Creek and Nygri placer. The inclusions were located both inside the grains and filling depressions and pits on the surface of grains. The studied sample population of quartz lodes and VDM did not contain iron hydroxide inclusions.

In the studied samples, Au-Ag alloys from quartz lodes contained quartz inclusions only (Si–48.30 wt.%, O–50.15 wt.%). The low-sulphide character of this type of mineralization suggests the presence of sulphide inclusions in these alloys.

Alloys from the VDM were not studied in this research, but based on previous studies of VDM [5], it is assumed that alloys of this type may contain sulphide inclusions and accretions (pyrite, sphalerite and galena).

Alloys from the LWC contained inclusions of iron hydroxide (Fe–53.4–57.7 wt.%, O–28.1–37.6 wt.%), sphalerite (Zn–56.9 wt.%, S–21.2 wt.%, Fe–1.69 wt.%) and pyrite. The analysis of the inner structure of polished grains revealed that there were two main varieties of gold alloys—monotonous and distinct heterogeneous alloys with rim–core zonation and gold-rich inner fracturing zones.

Heterogeneous alloys were obtained mainly from the LWC (70% of the alloys from the sample) and partly from Sukhoi Log Creek (50% of the alloys from the sample) (Figures 11 and 12 C). The concentration of gold in the rim and gold-rich inner fractured zones varied from 98.53 wt.% to 100 wt.% with Ag contents ranging from 0 to 0.85 wt.% (average 0.22 wt.%) and complete absence of Cu, Fe and Hg. The coefficient of heterogeneity (ratio of rim–core concentrations of gold) reached 1.18 for the LWC and 1.23 for Sukhoi Log Creek, with an average of 1.08 and 1.05 for the samples, respectively.

Regarding the alloys from quartz lodes, the Nygri placer, (apparently) and VDM, 40% of the grains from the LWC and 80% of the grains from Sukhoi Log Creek were homogeneous. (Fe–46.3 wt.%–51.6 wt.%) (Figure 11).

Alloys from Sukhoi Log Creek contained undetermined contents of chlorite and iron hydroxide (Fe–52.4 wt.%, O–28.8 wt.%)

The gold grains from the Nygri placer contained inclusions of pyrite (Fe–46.32 wt.%, S–52.88 wt.%), iron hydroxide (Fe–53.4 wt.%, O–28.1 wt.%) and quartz (Si–46.03 wt.%, O–50.41 wt.%) (Figure 12).

#### 4.4. Gold-Rich Rims

A significant number of alloys from the LWC and Sukhoi Log Creek had gold-rich rims. The individual rims of the various grains ranged from 10 to 50  $\mu\text{m}$  in thickness. The boundary between the individual cores and rims was generally sharp, could be visually demonstrated in reflected light and was confirmed by microprobe analyses in polished sections (Figures 11 and 12C).

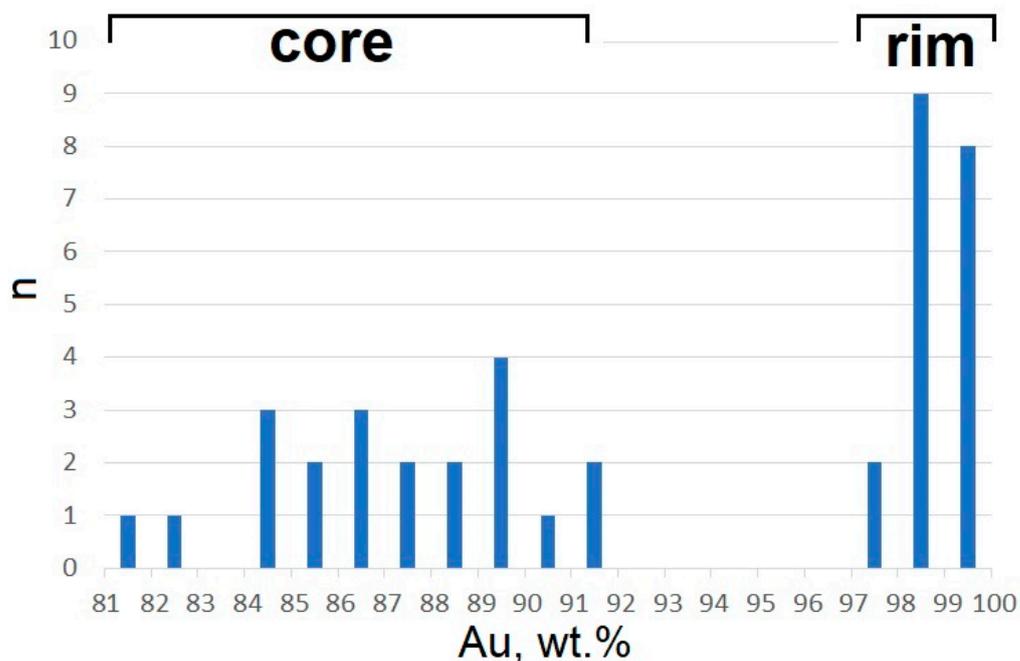
The relatively high Ag content of the gold cores and the presence of mineral inclusion species unstable in the surface environment indicate that they are relics of a hypogene gold particle source rather than authigenic gold or gold altered by weathering [43]. While the composition of the alloy's homogeneous cores demonstrates source mineralization, the rim–core composition differences expressed by the coefficient of heterogeneity reflect both residual features of a primary grain's structure and supergene transformation of the alloys [46].

Gold grains experience both physical and chemical changes during weathering, transportation and post-depositional processes. During the influence of supergene conditions, grains of placer gold develop an outer rim of nearly pure gold on the more silver-rich electrum core. The rim has very close contact with the core, and appears to be the result of

electrochemical processes occurring in weathered crusts, streams and stream sediment conditions. The thickest rims are generally found on grains with a long supergene history [47].

In the studied zonal alloys, the gold content in the rim reached 100.0 wt.% with a silver content of not more than 2.25 wt.% and a Cu and Hg content below the detection limit. Gold-rich rims developed mainly on the projections of grains and sometimes in the gold-rich inner fractured zones.

From the Au content–frequency ( $n$ ) diagram (Figure 13), it can be seen that the ore and rim assays were completely different and contradict the model of a gradual transformation of the core material into a rim.



**Figure 13.** Analysis of the chemical composition of zonal alloys from the LWC and Sukhoi Log Creek for core and rim parts of the gold grains.

#### 4.5. Main Types of Native Gold

Additional information for the classification of the placer alloys can be obtained from the plot of Au content (wt.%) vs. coefficient of heterogeneity ( $C_h$ ). While the fineness of gold in the core is associated primarily with the hypogene factors of its formation, the coefficient of heterogeneity indicates the degree of its supergene transformation [46,48].

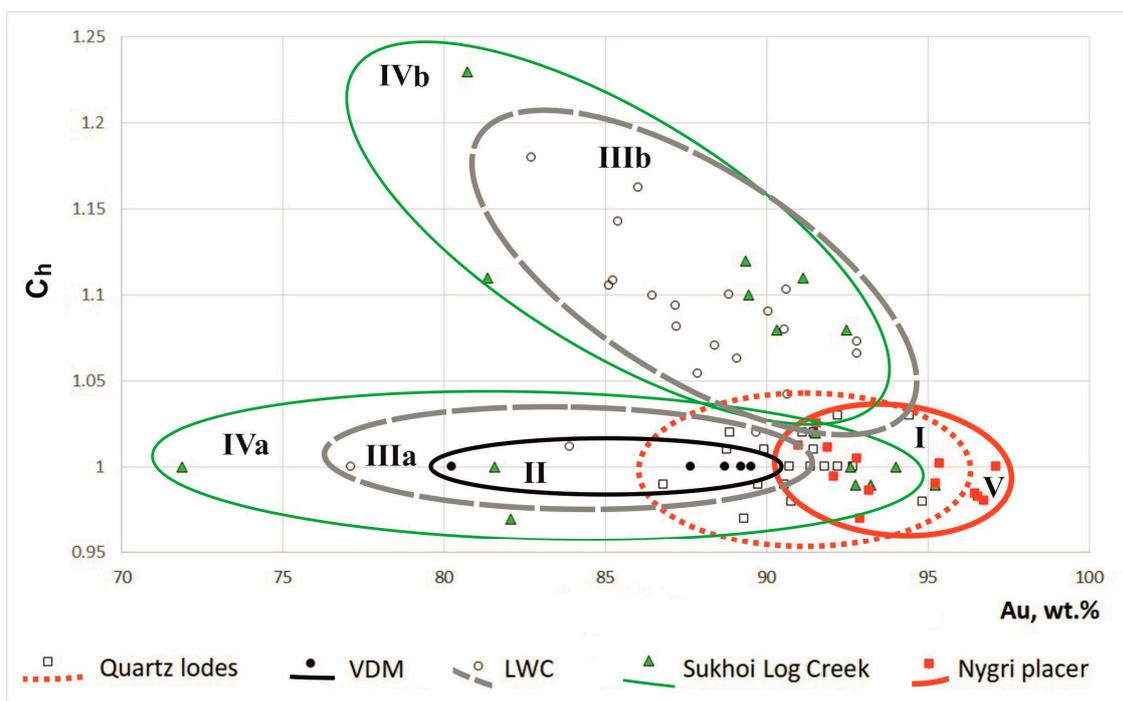
The plot illustrates a visual division of the sample population into seven individual fields (Figure 14).

Two primary bedrock types of native gold (low-sulphide gold quartz lodes, field I, and VDM, field II) form fields in their own area of  $C_h$  close to 1, which shows an insufficient effect of supergene transformations of these types of gold.

The alloys from the LWC form two separate fields: the first one (field IIIa) is located in the area  $C_h \approx 1.0$  and closely corresponds to VDM field II. The second one (with core–rim zonation) is located in the area  $C_h > 1.02$ .

Alloys from Sukhoi Log Creek also form two separate fields, IVa and IVb, which correspond to LWC fields IIIa and IIIb. The field of the Nygri placer alloys largely coincides with the field of the Au–Ag alloys from low-sulphide quartz lodes.

An interpretation of the plot data will be given in next section, “Discussion”.



**Figure 14.** Au content in the core of grains (wt. %) vs. coefficient of heterogeneity ( $C_h$ ) plot for studied sample population. The diagram distinguishes the types of gold grains both by primary hypogenic characteristics and supergenic features. I—quartz lode field; II—VDM field; IIIa—LWC zonal alloys field; IIIb—LWC homogeneous alloys field; IVa—Sukhoi Log Creek zonal alloys field; IVb—Sukhoi Log Creek homogeneous alloys field; V—Nygri placer field.

## 5. Discussion

Many gold-bearing regions, even those that have been studied for a long time, have a number of unresolved issues. Bodaibo District is no exception. Three problems are under discussion: (1) the sources of the placer gold; (2) evidence of the transformation of native gold in supergenic conditions and features of this process; (3) the mechanism for the formation of gold-rich rims; (4) the possibility of discovering of new placers in Bodaibo District.

### 5.1. Sources of the Placer Gold

One of the problems is locating the source of unique alluvial placers, from which approximately 1500 tons of gold has been mined over more than 150 years of operation. Taking into account that only 5 to 20% of gold eroded from bedrock sources accumulates in placers [16], the volume of eroded primary gold ores can be estimated to be from 8 to 32 thousand tons, which is comparable in volume to such giant deposits as Carlin or Witwatersrand [49–51]. At the same time, it should be borne in mind that the most common veinlet-disseminated quartz–sulphide mineralization on the territory of the Bodaibo District contains native gold of a small size, which is poor at forming placer deposits.

Analysis and interpretation of the Au content in the core (wt.%) vs. coefficient of heterogeneity ( $C_h$ ) plot allows identification of the sources of gold placers in the studied and surrounding area [46].

The close connection between the geochemical signatures of the gold from quartz lodes (Figure 14, field I) and gold alloys from the Nygri placer (Figure 14, field V) indicates that the gold in the placer is largely a result of erosion of this type of primary bedrock mineralization [52,53].

The similar character of the inclusion in the gold grains of quartz lodes and the Nygri placer also indicates a relationship between these types of gold (Figure 12A,D,E). Alloys

from the Nygri placer contain inclusions of quartz and pyrite; in our samples of lode alloys, pyrite was not found, but the presence of pyrite was assumed due to the gold–sulphide character of this mineralization. Alloys from the placers contained iron hydroxide inclusions, which apparently are a result of weathering of primary pyrite inclusions. The presence of both iron hydroxide and pyrite inclusions in placer alloys indicates that the weathering process was not deep and prolonged. The lack of Au-rich rims provides no evidence of supergene precipitation, which suggests that the grains were transferred directly from a hypogene source to a surficial and fluvial system [54]. So, the absence of a gold-rich rim on the alloys from the Nygri placer and presence of inclusions of pyrite are evidence of the direct deposition of gold from primary sources into placers, bypassing weathering crusts and intermediate hosts.

The lode mineralization occurring at the Sukhoi Log deposit at the current erosional level is insufficient for the formation of large and rich placers, similar to the placer of the River Nygri. A study on the Verninskoye deposit located in this area, where the gold–quartz lode mineralization is much more pronounced, showed that the vertical range of this mineralization exceeds 300–400 m, being replaced by VDM at greater depths. At the same time, the gold content and the scale of lode mineralization decrease with depth [55].

Drawing an analogy with the Sukhoi Log deposit, we can conclude that the thickness of the eroded ore horizon is several hundred meters, and the gold content in the eroded part is significantly higher than at the level of the current surface. In this scenario, the eroded part of the Sukhoi Log deposit and other ore fields located in this region could provide for the formation of large and unique placers in the Bodaibo District.

Sources of gold for small local placers (such as Sukhoi Log Creek) and eluvial LWC placers will be discussed in the next section.

### *5.2. Evidence for Transformation of Native Gold in Supergenic Conditions and Features of This Process*

More than 90% of VDM gold is in the order of less than 0.1 mm in size and therefore has a very low potential for placer formation. In addition, outside the mineralized area of the Sukhoi Log deposit, the rocks are usually barren or contain only low-grade mineralization. However, within the LWC in this zone, rich placers were formed. They were worked out during the initial stages of development of the Bodaibo District.

Research on native gold from the LWC revealed that 70% of the alloys have core–rim zonation, which is evidence of supergenic transformation (Figure 14, Field IIIb).

The growth of gold grains due to the formation of gold-rich rims leads to an increase in their size. If the main grain size of the VDM ranges within 10–80 µm, then for the LWC, this value is 40–160 µm (Figure 9). This leads to an increase in the placer productivity of the deposits and an increase in the overall fineness of gold.

Some alloys (30%) have no evidence of supergene changes (Figure 14, Field IIIa), which indicates the limited nature of the supergene process and later disintegration of pyrite grains containing Au–Ag alloys. According to their typomorphic characteristics, such grains are similar to VDM gold.

The placer deposit of Sukhoi Lod Creek has, at least, two sources. The first one is the LWC, containing both homogeneous and core–rim zonal alloys. The second source (approximately, 30%) corresponds to gold of quartz lodes exposed on the watershed in the upper course of Sukhoi Log Creek. Single alloys of a relatively low fineness (719) and Hg content of 0.18wt.% (Figure 12B) allow us to make an assumption about the existence of low-temperature hydrothermal mineralization in this zone [43,56–60].

### *5.3. Origin of Gold-Rich Rims*

The gold particles in the bedrock do not have a gold-rich rim, so it is quite reasonably assumed that they were formed in the process of supergene transformations of the alloys [47]. There are two opinions regarding the reason for the formation of this feature of placer gold: selective leaching of Ag and other trace elements from the rim zone [61],

and self-electrorefining of placer electrum grains, which probably operates in tandem with dissolution–precipitation (cementation) [47]. Some researchers [12,14] propose that the rims are a result of adhesion to small gold particles as well as the transition and deposition of chemical gold by organic–metallic complexes in supergenic environments.

Observed natural gradients of silver in the rim zone (Figures 11, 12C and 13) illustrate that the profile of silver content contradicts the gradual leaching model. The observed sharp rim–core contact in the gold alloys from the LWC and Sukhoi Log Creek corresponds to the precipitation model. A similar situation was observed in the gold alloys of the Vagran gold-bearing cluster of North Urals [46].

Groen G.C. et al. [47] believe that the development of the rim occurs mainly during gold grain transportation, meaning that the “transportation” is the period in which a surficial environment occurs, whether by actively moving particles or containing them within stream sediments. We believe that taking into consideration that the phase of active movement of the grains in the stream is incomparably shorter than their retention within the sediments, the growth of gold-rich rims in the sediments is obviously more efficient. Moreover, the growth of gold-rich rims is compensated for by the erosion of grains during their transportation in alluvial streams. Additionally, the concentration of gold ions in groundwater is two orders greater than in stream (Figure 9a in [47]). While “a gold-rich rim apparently forms by precipitation of gold from the surrounding solution” [47], p.207, these factors confirm the validity of our opinion that the inner condition in the sediments is more favourable to rim forming than the stream environment itself.

According to [47], p. 224, “The rim generally is thickest on flake-shaped (most transported) grains and thinnest or absent on irregular (least transported) grains”. In our case, gold-rich rims were present in grains that did not move (LWC) or had very restricted movement (Sukhoi Log Creek), while most transported grains (Nygri placer) did not have a rim. So, the residence of the grains in an LWC is more favourable to rim formation than their residence in dynamic stream conditions. The stream environment has a significant influence on the shape of the grains, but only a moderate influence on the inner structure of the alloys.

The gold alloys in LWCs do not experience significant transportation, but they do experience long chemical reactions within infiltrating fluid conditions, which results in the growth of a gold-rich rim.

#### *5.4. Perspectives of Discovering of New Placers in Bodaibo District*

The study and exploitation of gold placers in the Bodaibo District has been ongoing for more than 150 years. During this period, about 1500 tons of gold was mined, and the measured and indicated resources of the placer gold are estimated to total 130 t. Considering this, the discovery of new placers seems unlikely, and the main prospects for the mining industry are associated with bedrock primary ores.

Scattered gold–sulphide–quartz veins, stockworks and disseminated ores with a low gold content, in the case of preliminary disintegration and enrichment of weak gold-bearing deposits in the weathered crusts, in combination with intermediate hosts, could form a significant source of placer clusters [62,63].

The conducted studies allowed us to identify a new promising type of gold placer in the Bodaibo region, associated with eluvial formations and tectonically controlled by LWCs. Promising objects are associated with disjunctive dislocations located in zones of low-grade disseminated mineralization. In such zones, a supergene transformation of low-grade disseminated sulphide mineralization occurs, accompanied by an increase in the size, content and fineness of gold. There are cases where such placers have been successfully mined [21], but in the presence of large and high-potential alluvial placers, they have rarely attracted the attention of gold miners. Where such features are located on flat watersheds, they have very limited secondary halos and may be missed by standard exploratory surveys. To identify such objects, it is necessary to map disjunctive dislocations (including those without displacement along the fault zone) in zones from the intersection

with fields of low-grade disseminated sulphide mineralization. Lithologically, such zones are characterized by the presence of LWCs, represented by multicoloured (brown, yellow, red) clays with weathered rock debris.

Stratigraphic control consists of the localization of this type of mineralization within the distribution of the Khomolkho and Imnyakh formations. For a more accurate and detailed forecast of eluvial placers associated with LWCs, additional studies are needed to map the zones of development of supergenic changes associated with zones of disjunctive dislocations within the most promising formations. It is possible to use digital forecasting methods using the analysis of multifactor spaces and overlay techniques [64].

## 6. Conclusions

This study of typomorphic features of bedrock gold mineralization and placer gold alloys allowed for the determination of primary sources of gold placers in the Sukhoi Log cluster and surrounding area.

Native gold from the giant Nygri placer as well as other alluvial gold placers in the Bodaibo District contain gold that has significant similarity with the gold from low-sulphide lodes; the absence of a gold-rich rim on the alloys and presence of inclusions of pyrite are evidence of the direct deposition of gold from primary sources into placers, bypassing weathering crusts and intermediate hosts.

The microgeochemical study of gold and mineral inclusions of unconverted alloys from LWCs and composition of the core of zonal alloys indicated a close connection with the gold from the VDM zone.

The appearance of Au-Ag alloys with a gold-rich rim indicates gold particles that have resided for a long time in weathering crusts.

The gold from VDM transformed in LWCs had a significant influence on proximal placer deposits in the small watercourses near the source, but its role was less significant in the main placer valleys.

Data materialized in our research allow us to identify a new promising type of gold placer in the Bodaibo region, associated with eluvial formations and tectonically controlled by LWCs.

**Author Contributions:** Conceptualization, A.L.; methodology, A.L., A.G. and L.I.; software, A.K.; validation, A.G. and L.I.; formal analysis, A.L.; investigation, A.L., A.G., A.K. and L.I.; data curation, A.G. and L.I.; writing—original draft preparation, A.L. and A.K.; writing—review and editing, A.L.; visualization, A.L. and A.K. All authors have read and agreed to the published version of the manuscript.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author. The data will not be publicly available until the submission of the PhD thesis of A.K.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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