minerals

MDPI

Article

Internal Structures of Placer Gold as an Indicator of Endogenous and Exogenous Processes

Nikiforova Zinaida

Diamond and Precious Metal Geology Institute, SB RAS, 677000 Yakutsk, Russia; znikiforova@yandex.ru; Tel.: +7-4112-33-58-72

Abstract: The study of the internal structures of placer gold on the territory of the east of the Siberian platform, overlain by a thick cover of Mz-Kz deposits, where traditional methods of searching for gold deposits are not effective, allowed us to determine, for the first time, the stages of ore formation and conditions of its occurrence. The identified indicators of the internal structures of placer gold (structures of primary recrystallization, secondary recrystallization, thick high-grade shells) indicate that placer gold content is formed mainly due to the supply and repeated redeposition of native gold from ancient gold-bearing deposits of the Precambrian stage of ore formation to younger ones. The discovered coarse-, medium-grained, mono-grained, unclear-zonal, granulation and disintegration structures suggest a supply of gold from nearby ore sources of the Mesozoic stage of ore formation. In the weathering crust, a high-grade shell is formed. In the hydrodynamic environment, the internal structures of gold practically do not change and fully correspond to the internal structures of endogenous gold. In aeolian conditions, the internal structures are transformed. In ancient gold-bearing conglomerates, under the impact of lithostatic pressure, as well as in metamorphogenic conditions, when the PT conditions change, the internal structure changes. Thus, for the first time, on a huge factual material, it is proved that the internal structures contain extensive information both about the endogenous origin of gold (the stages of ore formation—Precambrian and Mesozoic) and about its transformation in various exogenous conditions. The identified indicator of the internal structures of placer gold for certain types of sources contribute to a more correct selection of methods for searching for ore and placer gold deposits in closed territories and assessing their prospects. The use of this method makes it possible to develop criteria for forecasting different sources and types of gold deposits based on internal structures.

Keywords: placer gold; internal structures; stages of ore formation; endogenous and exogenous conditions; coarse-grained structure; high-grade shell; recrystallization; granulation; deformation structures

Citation: Zinaida, N. Internal Structures of Placer Gold as an Indicator of Endogenous and Exogenous Processes. *Minerals* **2023**, *13*, 68. https://doi.org/10.3390/min13010068

Academic Editors: Galina Palyanova and Huan Li

Received: 23 November 2022
Revised: 26 December 2022
Accepted: 27 December 2022
Published: 30 December 2022

1. Introduction

The indicators of placer gold (morphology, impurity elements, microinclusions, internal structures, etc.) carry extensive information about the nature of native gold, both in endogenous and exogenous conditions [1–11]. In exogenous conditions, the evolution of placer gold occurs, but it retains the "memory" of its primary sources. In this connection, the idea arose that, based on the results of studying the typomorphism of placer gold, in particular internal structures, in the first approximation, it is possible to assume the type of ore source and the depth of its formation, which can serve as an effective method for determining the genesis of placers and the nature of gold ore sources.

The results of studying the internal structures of placer gold, depending on the conditions of its occurrence, allow us to conclude about the stages of ore formation and exogenous transformations. The internal structures of placer gold were first studied by

Petrovskaya and Fastalovich [12]. Then, Nikolaeva [2], Popenko [3], Savva and Preis [4], Nikolaeva et al. [8] and Savva et al. [5,13] studied the internal structures of placer gold. They studied the internal structures of native gold from endogenous sources, as well as zones of hypergenesis and alluvial placers. As a result of the study, it was found that endogenous internal structures of the Mesozoic stage of ore formation are characterized by coarse-grained and medium-grained structures, sometimes structures of granulation, disintegration, zonal and unclear-zonal structures and others. In the oxidation zone, they identified the formation of a high-grade shell on low-grade gold, as well as the presence of high-grade veinlets. According to L.A. Nikolaeva et al. [8], the structures of primary crystallization and structures caused by intra- and post-ore transformations are recognized in ore gold. The authors revealed that the gold of shallow-depth deposits is characterized by zonal structures, with a gold fineness of less than 800‰, and the gold of medium-depth deposits with a fineness of more than 800‰ is characterized by unclear zonal structures. They found that during the crystallization of gold in more stable conditions, simple twins are formed and, in less stable conditions—polysynthetic twins are formed. They refer to ordered structures, the same orientation, polysynthetic often discontinuous twins, spotty heterogeneity, relics of early gold, etc., to the signs of recrystallization. It is proved that the recrystallization structures indicate more intensive multiple recrystallizations.

Analysis of the published foreign literature devoted to the study of the mineralogy of placer gold and its typomorphic features showed that the internal structures of gold have not been studied in depth [14–24]. The published articles present the results of studying the morphology of placer gold, chemical composition and microinclusions in order to determine the type of ore source and its location [14–35]. Their research on the mineralogical and geochemical features of placer gold is mainly aimed at studying the relationship between placers and potential ore sources. This approach allowed them to improve the classical method of exploration based on the interpretation of distribution of placer gold to determine the location and type of source from which the placer was formed. Only in two publications, for example, the articles of Groen et al. [36,37] described the change in the internal structure in placers (gold amalgam and other secondary phases in placers) and also studied the process of formation of a high-grade shell on electrum grains in placers. The authors explained the discovery of a high-grade shell by the dissolution of silver under exogenous conditions. Leake et al. [38] studied the internal structure of Au-Pd-Pt grains with respect to low-temperature transport and deposition. Cabral et al. [39] studied brittle microstructures in gold nuggets. Kerr et al. [40] identified the deformation of placer gold related to transfer into a hydrodynamic medium. Stewart et al. [41] studied low-temperature recrystallization of placer gold in alluvial deposits. Chapman et al. [42] examined crystalloblastic deformations at the grain scale. In general, judging by the published works of foreign researchers, there is scattered information on the internal structures of placer gold and, currently, there are no generalizing works on this problem.

This article presents the results of studying the internal structures of gold, the placer gold content of the south-east of the Siberian platform, in order to identify the genesis of placers and their ore sources. Placer gold content has been known for more than a century and a half, but the types of ore sources and their location have not yet been identified. This is due to the fact that this area is overlain by a thick cover of Mz-Kz sediments, where traditional search methods do not bring positive results. In this regard, it became necessary to develop a new approach to study the mineralogical and geochemical features of placer gold and the mechanisms of its distribution in the studied area in order to determine the genesis of placers and types of ore sources. The mineralogical method developed by us—the study of the mineralogical and geochemical features of placer gold and the mechanisms of its distribution to identify the genesis of placers and their ore sources—was noted as the most important achievement of the Russian Academy of Sciences, Earth Science [43].

2. Materials and Methods

The article is based on the results of a long-term study of internal structures and mechanical dispersion in the east of the Siberian platform (Figure 1). The objects of the study in the south-east of the Siberian platform were placer gold, panned out from alluvial and aeolian deposits of the Lena-Vilyui interfluve (200 sampling points) and from alluvial deposits of the basins of the middle Lena (100 sampling points) and Upper Amga (70 sampling points). For several decades, during field work, tray-type sampling of alluvial and aeolian deposits has been carried out, and placer gold was panned out then extracted by conventional methods and studied under binoculars (shape, size, surface, etc.) and on modern devices in order to identify the chemical composition, microinclusions and internal structures. In total, about 24,000 grains were analyzed, about 2000 grains in the Lena-Vilyui interfluve, in the basin of the rivers of the middle Lena (200 grains), Upper Amga (170 grains).

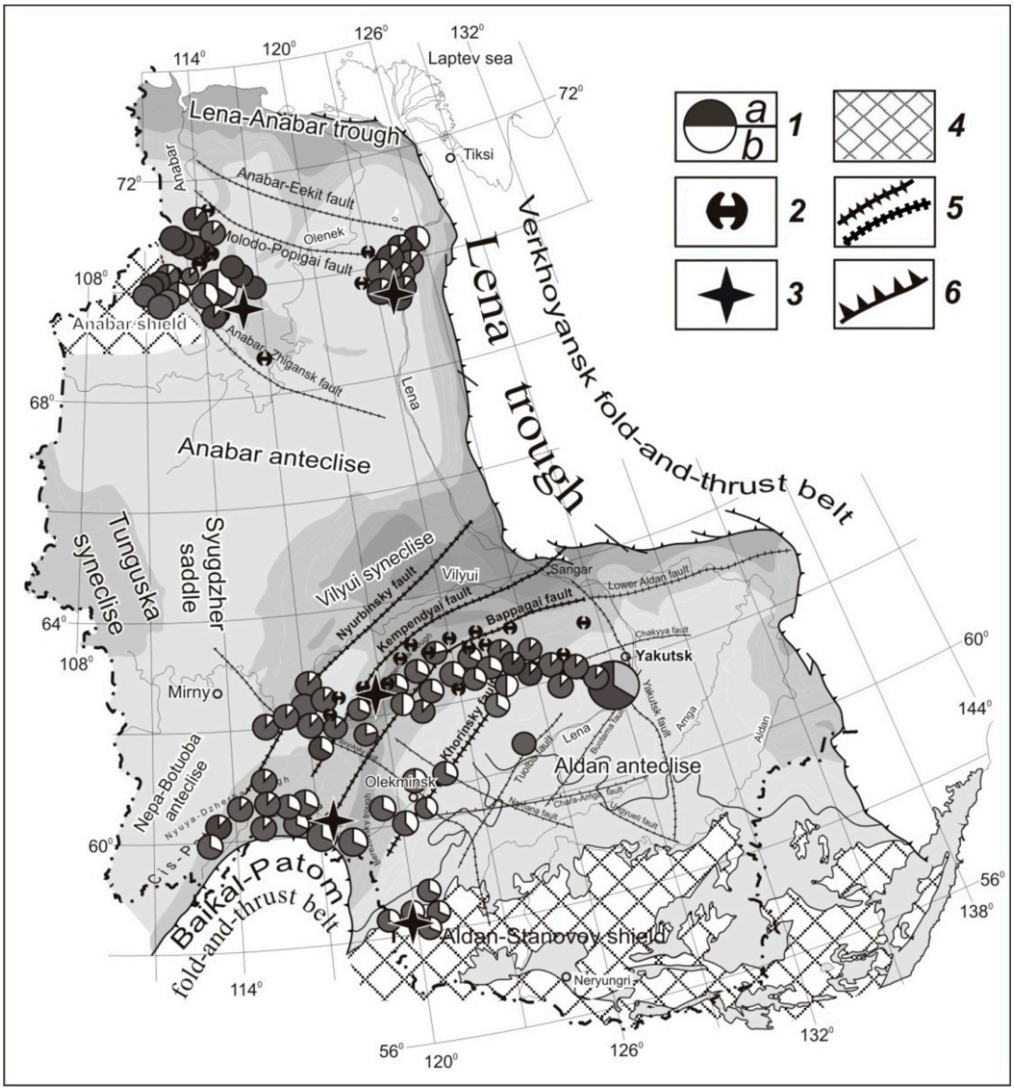

Figure 1. Diagram of the studied area and area of distribution of aeolian and two types of gold in the East Siberian platform: 1—types of gold and their ratio (%): a—I type: size 0.10–0.25 mm, fineness >900‰, b—II type: size >0.25 mm, fineness 600–800‰; 2—aeolian gold; 3—places of discovery of ore gold; 4—outcrop areas of the rocks of the crystalline basement; 5—faults; 6—front of the Phanerozoic belts.

Typomorphic features (morphology, chemical composition, microinclusions, internal structure) of native gold were studied using well-known mineralogical and geochemical methods. All analytical work was carried out in the laboratory of physical–chemical methods of analysis, DPMGI SB RAS (Yakutsk). The study of the morphology, surface structures and internal structure of the gold particles was carried out using a scanning electron microscope "JEOL JSM-6480LV" (Japanese Electron Optics Laboratory, Tokyo, Japan), stereoscopic microscope "LEICA MZ6" (KaVo, Biberach an der Riss, Germany) and an ore microscope "JENAVERT SL 100" (Carl Zeiss AG, Oberkochen, Germany). The trace element composition of native gold was analyzed on an X-ray microanalyzer, "JXA-50A", "JSM-6480LV" (Japanese Electron Optics Laboratory, Tokyo, Japan). The content of impurity elements was studied via atomic emission spectrography. Microinclusions in native gold were identified using a scanning electron microscope "JEOL JSM-6480LV", with an energy-dispersive spectrometer Energy 350 of Oxford Instruments (London, UK), Software Oxford Instruments INCA the microanalysis Suite Issue v.4.17. Quantitative analysis and processing of the results were carried out using the XPP method in the software INCA Energy.

The internal structures of native gold were studied according to the generally accepted method [12] using a reagent: HCl + HNO_3 + $FeCl_3 \times 6H_2O$ + CrO_3 + thiourea + water. The etching of gold was repeated several times. The reagent was applied to the surface of polished gold mounted in epoxy resin. The gold particles were etched from 10 to 30 s, at several approaches. After each etching procedure, the polished section was washed under a strong stream of water, then dried. Polyphase particles were etched differentially: first, the low-grade phases of gold were etched, and then, with a stronger solution, the high-grade phases [4]. Standard reagents were used for etching (HNO_3 + CrO_3 – kustelite; HCl + CrO_3 + thiourea − electrum; HCl + CrO_3 of various concentrations - medium-grade gold; HCl+4HNO_3 – high-grade gold). After that, the observed internal structures after special preparation were studied in detail using the NEOPHOT 32 ore microscope and the JEOL JSM-6480LV scanning electron microscope. The interpretation of internal structures was carried out in accordance with the ideas of N.V. Petrovskaya [1], N.E. Savva, V.K. Preis [4] and L.A. Nikolaeva et al. [8].

3. Results

The internal structures of placer gold were studied from materials collected in the southeast of the Siberian Platform in the basins of the rivers of the middle Lena (the mouth of the Vitim, Bol. Patom, Dzherba, Tokko, Torgo rivers), the Upper Amga and the rivers of the Lena-Vilyui interfluve (Tonguo, Chebyda, Kempendyai, Namana, etc.) [9].

Generalization of the results of studying the typomorphic features of placer gold and analysis of the mechanisms of its distribution in the southeastern part of the Siberian platform on the territory of the Lena-Vilyui interfluves, basin of the middle Lena and Upper Amga allowed us, for the first time, to distinguish two types of gold with certain indicators, corresponding to two stages of ore formation—Precambrian and Mesozoic (Table 1, Figure 1) [9].

The first type of gold is represented mainly by flake and lamellar forms, with a size of 0.1–0.25 mm, very high fineness (>950‰) with a surprisingly small set of impurity elements and almost complete absence of microinclusions (Table 1). At the same time, it was determined that placer gold of the Precambrian stage of formation is very much changed, has certain internal structures and depends on the duration and conditions of stay in exogenous environment. The internal structure of placer gold is mainly primarily recrystallized and secondarily recrystallized, with deformation structures (Luders lines, etc.) and thick high-grade shells (10–20 μm) (Figure 2).

Table 1. Typomorphic features of two types of placer gold from the east of the Siberian platform.

Types of Gold	Size	Shapes	Surface	Fineness and Impurity Elements	Intergrowths	Microinclusions	Internal Structure
I type	−0.5 mm	Flake, lamellar, lumpy	Shagreen, often with casts of pressing of minerals	900–1000‰; Cu: 0.2–1.2%, Hg: 0.1–0.2%	Pseudo-intergrowths with rounded minerals (ilmenite, zircon, quartz)	Quartz, pyrite, arsenopyrite	Complete recrystallization, lines of plastic deformations, thick high grade-shells (20–30 μm)
II type	0.5–1 mm 1 mm and >	Tabular, lumpy, lumpy-angular of ore habit	Rough-shagreen, pitted-tubercular, porous	800–899‰—30–70%, 700–799‰—10–35%, 600–699‰—up to 15%, Hg: up to 6.2%; As: 0.1%; Pb: 0.005%; Sn: 0.02%; Sb: 0.0008%; Fe: 0.1%; Pt: up to 0.1%	Intergrowths with chalcedony quartz	Quartz, albite, sulfides (pyrite, arsenopyrite, etc.), tellurides (petzite, etc.)	Unchanged mono- or coarse-grained structure with clear grain boundaries, unclear zonal structures, thin high-grade shells (the first microns), sometimes the structures of endogenous transformations are granulation and disintegration

It is known that gold is an inert metal that practically does not change in exogenous conditions; however, we found that when staying in various exogenous conditions for billions of years and repeated redeposition, primary recrystallization and secondary recrystallization of gold occurred with the removal of silver and impurity elements [1,2,4,8]. When studying the internal structure of placer gold from the Quaternary deposits in the east of the Siberian Platform, it was found that almost all flake gold of type I with a size of 0.1–0.25 mm, of high fineness, is characterized by primarily recrystallized and secondarily recrystallized internal structure. Flake gold with such structures of primary recrystallization and secondary recrystallization is found in all watercourses, as in the north-east of the Lena-Anabar interfluve—Bol. Kuonamka, Udzha, Sololi, etc., and in the central and southern part of the east of the Siberian platform of the Lena-Vilyui interfluve (Chebyda, Kempendyai, Tonguo, Namana rivers, etc.) and the basin of the middle Lena with left-bank and right-bank tributaries. The identification of such structures indicates the repeated redeposition of placer gold from the Precambrian sources into younger ones.

At the same time, some regularity in the mineralogy of placer gold of the Precambrian stage of ore formation was revealed. This stage of ore formation is characterized mainly by fine gold with a size of 0.1–0.25 mm, has a very high fineness—more than 900‰—a surprisingly small range of variations in fineness and a low content of impurity elements (Ag, Cu, Hg). This is explained by the fact that with repeated redeposition from ancient gold-bearing deposits of the Precambrian age into younger ones, gold is purified in exogenous conditions, silver and impurity elements are removed with a change in the internal structure. As a result, the internal structure of this gold was significantly transformed; primary recrystallization, secondary recrystallization structures, deformation lines and thick high–grade shells (10–30 μm) were formed in it, indicating a long stay of gold in various exogenous environments—the hypergenesis zone, hydrodynamic, aeolian conditions and others.

When studying the distribution mechanisms of placer gold, it was found that gold with primarily recrystallized and secondarily recrystallized internal structures of deformations (Luders lines, etc.) and thick high-grade shells (10–30 microns) is very widespread (Figure 1).

It is proved that primary recrystallization and secondary recrystallization structures occur on the places with a disturbed crystal structure of small grains (Figure 2a–c). The identified structures are formed mainly during a prolonged stay in exogenous conditions in weathering crusts, in buried placers or during repeated redeposition from ancient levels to younger ones.

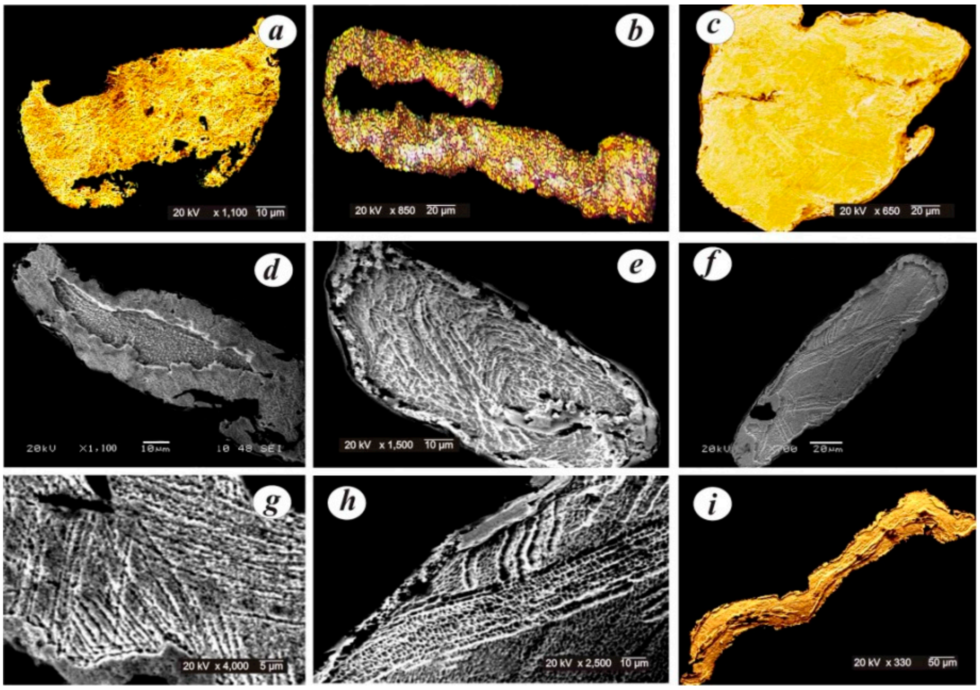

Figure 2. Internal structures of placer flake gold of the Precambrian stage of ore formation: (**a**) primary recrystallization with deformation lines; (**b**) secondary recrystallization; (**c**) complete recrystallization on high-grade gold with fine deformation lines; (**d**) thick high-grade shell (20–30 µm) on low-grade gold; (**e**,**f**) high-grade shells on gold particles with deformation lines; (**g**–**i**) multidirectional deformation lines at different magnifications.

It is found that the recrystallization structures with deformation lines are characteristic of the platy gold particles from the basin of the mouth of the Vitim river (Figure 1). The structures of complete recrystallization are characteristic of the flake gold of the Lena-Anabar and Lena-Vilyui interfluves, as well as for the middle Lena basin (Figure 2b,c). Structures of complete recrystallization on high-grade flake gold with thin deformation lines were found in the middle Lena basin, both in left-bank and right-bank tributaries (Figure 2c).

Thick high-grade shells are formed in the hypergenesis zone due to the removal of silver. Further, thick, dense, high-grade shells of 20–40 microns are characteristic of placer gold, which has been repeatedly deposited from ancient levels to younger ones (Figure 2d–f). It has been revealed that such thick high-grade shells are characteristic of type I flake gold, which is very widespread in the east of the Siberian Platform. Thick high-grade shells (20–30 microns) on low-grade flake gold were found both in the northeast of the Siberian Platform in the basin of the Udzha river and in its central part in the Chebyda, Namana, Tonguo rivers and in its southern part in the basin of the middle Lena river (Figure 2d) [9,10]. The identified high-grade shells on gold particles with deformation lines are extremely rare (Figure 2e,f).

Numerous multidirectional deformation lines at various magnifications in placer gold were found only in the basins of the Tokko and Torgo rivers (southwest of the Siberian Platform) (Figure 2g–i). They were found where the river valleys are drained by the Precambrian metamorphogenic formations, granite-gneisses of the Archean and Lower Proterozoic age and where occurrences with a gold content of 0.6–1 g/t in ferruginous quartzites in the Borsalinskaya series of the Archean age have been identified. The formation of such numerous deformation lines probably occurs in metamorphic strata, with known deposits of ferruginous quartzites with a gold content of up to 10 g/t. The presence of such internal structures and high-grade shells on gold particles with numerous deformation lines is an indicator for predicting metamorphogenic gold deposits.

In general, it has been established that the features of the internal structures of placer gold of the flake form of the Precambrian stage of ore formation are an indicator of the multiplicity of redeposition and the duration of stay in various exogenous conditions (Figure 1). The results of studying the distribution mechanisms of type I flake gold with recrystallized structures and thick high-grade shells showed that it is characteristic of all rivers of the east of the Siberian Platform and only at certain objects, along with type I gold, type II gold with sharply different internal structures was found.

The second type of placer gold of the Mesozoic stage of ore formation is characterized by a larger size (>0.25 mm, 1–2 mm), lamellar and lumpy forms, sometimes of gold particles and has mainly a medium, 800–900‰, and low 700–800‰ fineness (less often 500–600‰). In gold of this type, a wide range of impurity elements is noted, indicating its shallow origin (Table 1). Such gold was discovered by us in the south-east of the Siberian Platform at the sources of the Namana, Kempendyai rivers (Vilyui syneclise, Kempendyai dislocations), at the mouth of the Bol. Patom river (Urinsky anticlinorium), as well as in the Upper Amga river basin.

The internal structure of type II placer gold is practically unchanged, characterized mainly by mono-grain and coarse-medium-grained structures; sometimes, very thin high-grade shells are noted (Table 1; Figure 3). In addition, it has been found to contain unclear-zonal and interblock structures, as well as a porous, spongy structure characteristic of gold from near-surface deposits, found at the mouth of the Bolshoi Patom river, indicating the proximity of the primary source [9,10].

Type II placer gold has a mainly coarse-grained, inequigranular structure of high-grade gold with manifested granulation, medium-grained internal structure (Figure 3a–c). In the placer gold of the Upper Amga river basin, two- and three-phase gold of various fineness is observed (Figure 3d,e); sometimes, gold forms intergrowths with quartz, potassium feldspar, hematite, limonite and other minerals (Figure 3f).

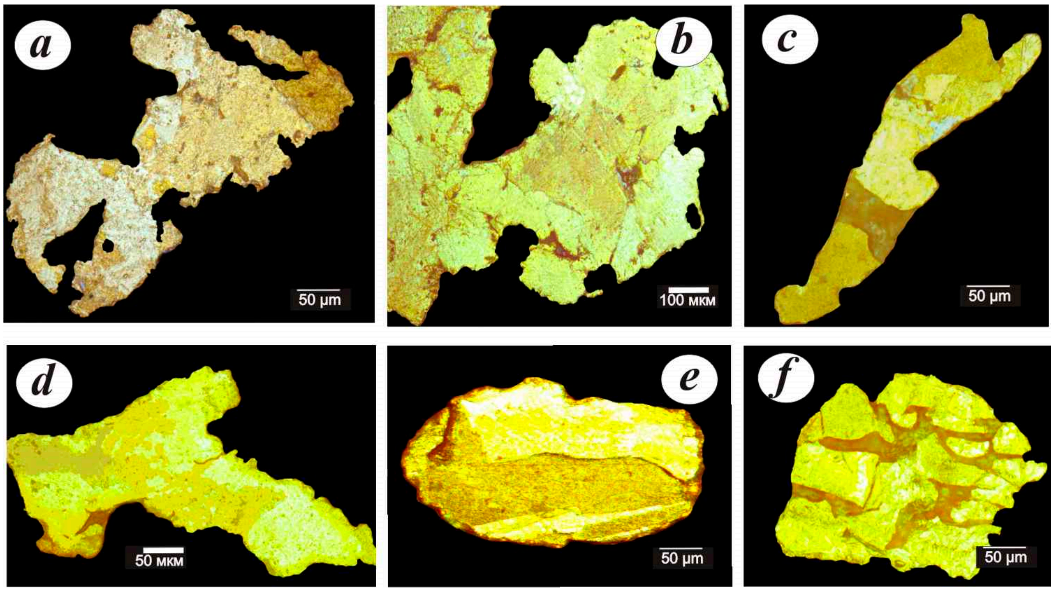

Figure 3. Internal structures of placer gold of the Mesozoic stage of ore formation (Upper Amga river basin): (**a**) coarse-grained structure of high-grade gold; (**b**) inequigranular structure of high-grade gold with manifested granulation; (**c**) the inequigranular structure of high-grade lamellar gold (930–980 ‰); (**d**) emulsion intergrowth of three phases of gold close to the fineness (light yellow—950 ‰; yellow—890‰; dark yellow—999‰); (**e**) polygonal intergrowth of two phases of native gold: light yellow—fineness 900‰, dark yellow—999‰; (**f**) polygonal-grained structure of high-grade native gold (940‰) in intergrowth with quartz-hematite-limonite composition.

The placer gold of the Mesozoic stage of ore formation is also characterized by granulation, disintegration structures (Figure 4a–c) and unclear-zonal structures (Figure 4d,e), found in the basin of the middle Lena, along with gold, whose internal structures are the structures of primary recrystallization and secondary recrystallization. Granulation and disintegration structures are extremely rare and have been found at the mouth of the Dzherba and Bol. Patom rivers. The revealed primary structures of granulation and disintegration in placer gold indicate its direct supply from the primary source. Unclear-zonal structures have been identified only in the placer gold of the Tokko and Torgo river basins, which also indicates the proximity of the ore source of the Mesozoic stage of ore formation. In low-grade placer gold, the development of thin high-grade shells is sometimes noted (Figure 4f). The presence of a thin high-grade shell on low-grade placer gold suggests that the placer was formed due to a nearby ore source of the Mesozoic stage of ore formation. The supposed ore sources are formed along the zones of deep faults Bappagaysky (the mouth of the Dzherba river, Bol. Patom), Sensky (Tokko and Torgo rivers), activated in the Mesozoic.

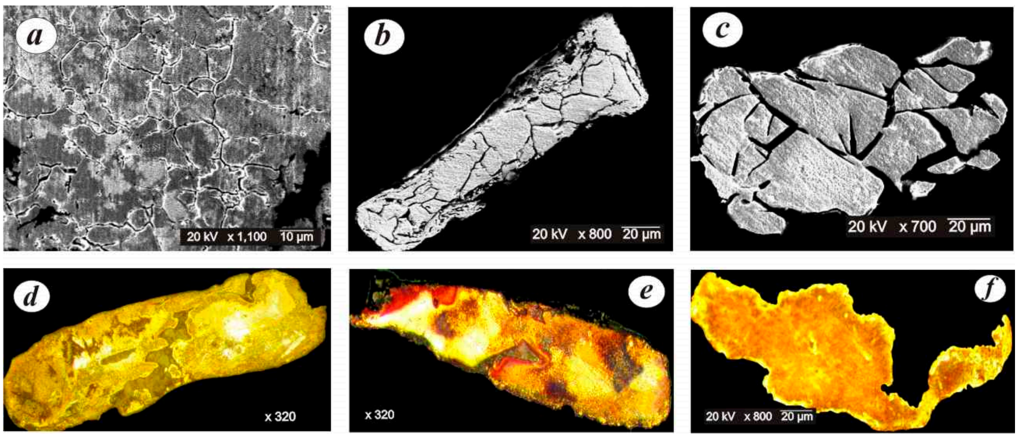

Figure 4. Internal structures of placer gold: (**a**) granulation; (**b,c**) disintegration structures (Dzherba, Bol. Patom rivers); (**d,e**) unclear-zonal structures (Tokko, Torgo rivers); (**f**) thin high-grade shell on low-grade gold (Torgo river).

In general, the results of studying the internal structures of type II gold showed that it has a local distribution and is confined to certain geological structures. Placer gold of the Mesozoic stage of ore formation is less changed, as it is finely dispersed and large (up to 1–2 mm or more), it has a low to high gold fineness and a wide range of impurity elements has been found. It is characterized mainly by single grains, coarse- and medium-grained internal structures; it occurs along with type I gold with altered internal structures of primary recrystallization, secondary recrystallization and thick high-grade shells. The results obtained indicate that nearby gold-bearing mineralizations of the Mesozoic stage of ore formation were the ore sources for the formation of such placers.

Internal structures in exogenous conditions were changed, depending on the conditions where native gold was located [10].

In the hypergenesis zone, morphological forms and material composition of primary gold are changed depending on the mineral type of endogenous mineralization. In the weathering crusts developed along Au-Te and Au-Sb ores, "secondary" gold is formed, which has certain internal structures—porous, kidney-shaped and mustard (Figure 5a,b). Along with the change in the morphology of gold particles, an increase in its fineness is recorded. Simultaneously, with an increase in fineness of, on average, up to 1000 ‰, impurity elements, especially Cu, Pb, Hg, Bi, etc. [26,29,36], are removed in the marginal parts of gold. In this case, a high-grade shell is formed, which has a porous structure and sharply differs from a high-grade dense shell formed in aeolian conditions (Figure 5c).

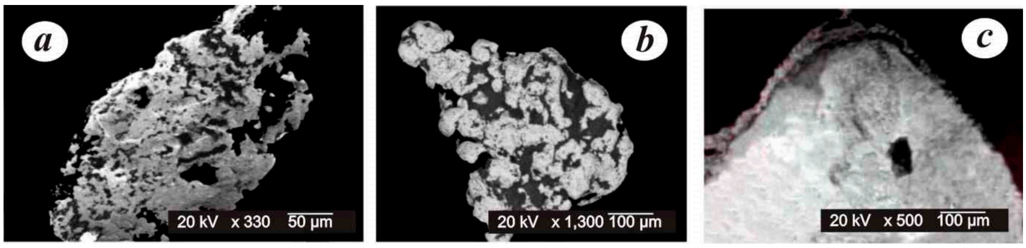

Figure 5. Internal structures of placer gold from the hypergenesis zone: (**a**) porous, mercury removal; (**b**) kidney-shaped, removal of tellurides; (**c**) loose, high-grade shell on mono-grain.

In a hydrodynamic environment, there is practically no change in the internal structure of gold. The internal structure of placer gold depends on the stage of ore formation and on the mineral type of the gold source. Some mechanism of the change in internal structure for placer gold of the Precambrian stage of ore formation in the east of the Siberian Platform has been revealed. This gold is characterized by primary recrystallization, secondary recrystallization structures and thick high-grade shells. This is due to the fact that with repeated redeposition from the Precambrian ancient gold-bearing deposits to younger ones, gold is being purified in exogenous conditions, silver and impurity elements are removed and the internal structure is changed. As a result, the internal structure of this gold is significantly transformed, primary recrystallization, secondary recrystallization structures are formed, as well as thick high-grade shells (10–30 microns) (Figure 2*),* indicating a long stay of gold in various exogenous environments.

Placer gold of the Mesozoic stage of ore formation is less changed. It is mainly represented by monograins and coarse- and medium-grained internal structures. The identified indicator internal structures of placer gold of the two stages of ore formation practically are not changed in the hydrodynamic environment (river flow, coastal and beach conditions, etc.). Only single simple deformation lines can be found in gold in a river stream [40,42].

In aeolian conditions, there is a change not only in the form, but also in the material composition, and, as a consequence, the internal structure (Figure 6). Aeolian gold has a very wide distribution in the east of the Siberian Platform and was discovered by us in the aeolian deposits of the riverheads of the Lena-Anabar and Lena-Vilyui interfluves (Figure 1).

Aeolian gold includes toroidal and spherical-hollow gold particles, 0.1–0.25 mm in size [11]. Toroidal gold is usually larger in size and spherical-hollow forms are somewhat smaller. Toroidal gold includes flake gold particles with ridge-like edges, measuring 0.1–0.25 mm. Spherical-hollow gold particles have a partition inside that divides the ball into two chambers. Gold of this shape is characterized by a high degree of grading by size and a rather narrow size range—0.1–0.16 mm. Analysis of the distribution mechanisms of toroidal and spherical-hollow gold according to the literature data revealed that similar forms of gold particles are widespread on all platforms and are found in sediments from the Proterozoic to the Cenozoic, in particular, in the east of the Siberian and European, North American, South American, African and Australian platforms.

It was identified for the first time that the mechanogenic transformation of native gold under aeolian conditions is actively influenced by mechanical and chemical processes and, in this regard, a change was found not only in the shape, but also in the material composition, as well as the internal structure. A clear mechanism has been revealed: an increase in the fineness of gold, a decrease in impurity elements and, as a result, a change in the internal structure.

Toroidal gold is mainly characterized by a fine-grained structure with a partially or completely recrystallized shell. Occasionally, there are gold particles with well-developed fine-grained high-grade shells with preserved relics of an unchanged medium-grained core having a lower fineness. Spherical-hollow forms are usually completely recrystallized with the formation of the fine-grained internal structure of gold.

The results of the study by microprobe analysis of the fineness of individual sections of aeolian gold showed that flakes with thin ridge-like edges with a fineness from 747 to 780‰ have a medium-grained structure. Toroidal shapes with a fineness of 900–970‰ are characterized by a partially recrystallized structure. A completely recrystallized structure was found in toroidal gold with a maximum fineness of 990–1000‰. In spherical-hollow gold of very high fineness, especially in the shell, a complete recrystallization structure is identified. Therefore, for example, in grain (Figure 6c), 17 definitions are 1000‰ [10].

In general, the study of the internal structure of aeolian gold showed that gold with fine-grained structures prevails, mainly of very high fineness, with a minimum content of impurity elements in it (Figure 6a–c). The internal structure of flake gold particles is characterized by the following internal structures—the presence of medium and fine grains, Luders lines (deformations) and well-developed high-grade shells (Figure 6a). Toroidal and spherical-hollow gold particles have mainly recrystallized fine-grained structures (Figure 6b,c).

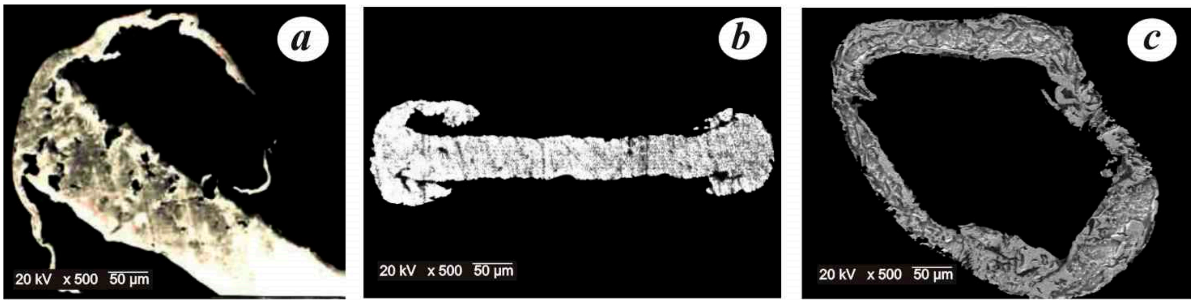

Figure 6. Internal structures of aeolian gold (cross section): (**a**) flake gold particle with a thin ridge along the edge and a recrystallized structure; (**b**) toroidal gold particle with fine-grained recrystallized structure; (**c**) spherical-hollow gold of high fineness 1000‰, the shell of the sphere is completely recrystallized.

Thus, during the technogenic process of exposure of sand material to flake gold in aeolian conditions, not only its morphological features are transformed, caused by a complex deformation of the original individual, but also the internal structure. Each stage of complex deformation of flakes in aeolian conditions under the influence of mechanical and chemical processes corresponds to a regular change in its internal structure. The internal structure of flake gold particles is characterized by the presence of medium and fine grains, Luders lines and well-developed high-grade shells. Toroidal and spherical-hollow gold particles have mainly recrystallized fine-grained structures with pronounced high-grade shells.

In ancient gold-bearing conglomerates (buried placers), the internal structures of placer gold (pseudo-ore gold) are transformed. Pseudo-ore gold includes gold of scaly shape in "growth" with quartz, ilmenite, zircon and other minerals of the host deposits, as well as flake gold particles with casts of pressing of minerals, traces of scars, scratches and slickensides on the surface, sometimes with ragged edges or with through holes. The surface of such gold particles is coarse-pitted and finely cellular. The size of the gold particles is 0.1–0.25 mm; it is mainly of high fineness with primarily recrystallized and secondarily recrystallized internal structures. The genesis of such forms of gold is explained by the influence of the lithostatic pressure of the overlying strata on the formed placer, while the minerals of the host deposits are pressed into the gold that has been proven experimentally [10,11].

The study of pseudo-ore gold and its internal structures revealed the following.

Due to the influence of lithostatic pressure of overlying strata on gold in ancient conglomerates, namely, at constant temperatures and pressure, there is a recrystallization of gold with the removal of silver and impurity elements, which leads to the purification of gold, an increase in the fineness of gold particles and the formation of high-grade shells (Figure 7). It is established that during horizontal movements, numerous deformation lines are formed in gold (Figure 7a,b), the predecessors [1,8], explained by the influence of mechanical processes in the hydrodynamic environment. Sometimes, single gold particles with granulation structures are found in gold-bearing conglomerates, which are generated as a result of the substitution of medium-grade gold with the removal of silver (Figure 7c).

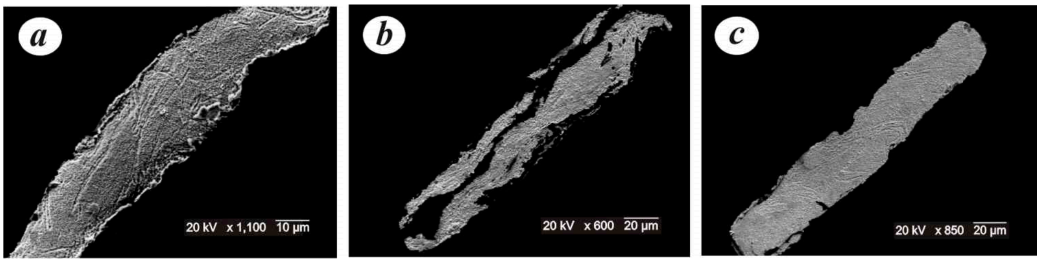

Figure 7. Internal structures of pseudo-ore flake gold (cross section): (**a,b**) flake gold particles with numerous lines of deformations; (**c**) granulation structures and numerous deformation lines.

4. Discussion

The study of the internal structures of widespread high-grade flake placer gold in the east of the Siberian Platform with a surprisingly small set of impurity elements, with recrystallization structures, thick high-grade shells and numerous deformation lines allowed us to assume that this gold has been repeatedly redeposited and supplied from ancient Precambrian sources. The sources of type I gold with such internal structures were ores of low-sulfide gold quartz, gold–copper–porphyry, gold–platinum, gold–iron–quartzite mineralization.

It was found that placer gold originating from metamorphic strata of Archean and Early Proterozoic age is characterized by structures of primary recrystallization, secondary recrystallization and numerous deformation lines (Figure 2g–i). Such internal structures are characteristic of metamorphogenic gold, since with the metamorphism of sedimentary strata, under the influence of constant temperature and pressure, gold is transformed [44]. At the same time, there is a process of changing the internal structure of primary gold, involving the removal of silver and impurities, which contributed to the formation of structures of primary recrystallization, secondary recrystallization and with dynamometamorphism (horizontal movements)—numerous plastic deformations. Indeed, according to A.V. Kopeliovich [45], with deep epigenesis—prolonged exposure to constant pressure—a kind of "transit" of impurity elements from the inner parts of minerals to the edges is carried out. In connection with this, the minerals are "self-cleaning" from the impurities contained in them.

The discovery of native gold with structures of primary and secondary recrystallization with numerous deformation lines indicates that the ore sources for placer occurrences of the middle course of the Tokko and Torgo rivers were ferruginous quartzites of the Archean age with a gold content from 0.6 to 1 g/t, giving reason to predict the deposits of gold–ferruginous–quartzite deposits in this area. Gold deposits of ferruginous–quartzite mineralization with a gold content of up to 10 g/t are widespread in southern Yakutia (iron-ore deposits Tarynnakh, Ymalakh, etc.), which confirms this assumption.

Thus, the identification of numerous deformation lines in placer gold indicates that these structures were formed in metamorphic strata and are an indicator for predicting ore deposits of gold–ferrous–quartzite mineralization. We draw attention to the fact that, although metamorphogenic gold has been studied earlier [1,3,4,8], this problem needs to be addressed in additional research.

Thus, the study of the internal structures of placer gold and the mechanisms of its distribution revealed that type I gold with primarily recrystallized and secondarily recrystallized structures has a wide distribution and is found in all watercourses of the east of the Siberian Platform.

Along with transformed primarily recrystallized and secondarily recrystallized structures with numerous deformation lines, indicating the influence of metamorphogenic processes in certain territories, in particular in the southeast of the Siberian Platform in the basin of the Torgo, Tokko rivers, placer gold was found with an unclear-zonal structure, with granulation and disintegration structures indicating the presence of primary sources of the Mesozoic stage of ore formation.

The presence on individual objects of placer gold with coarse-grained, medium-grained and fine-grained structures, multiphase gold sometimes with a thin high-grade shell, with unclear zonal structures, and also with granulation and disintegration structures (Figures 3 and 4) indicates that this gold belongs to the Mesozoic stage of ore formation, the sources of which could be ores of various mineralization (gold–silver, gold–sulfide-quartz, gold–rare metal).

According to L.A. Nikolaeva et al. [8], discovery of multiphase gold (Figure 3d,e) indicates the supply of gold from ore deposits of gold–quartz–sulfide mineralization (Sukhoy Log type), gold–polysulfide–quartz (Darasun type) or gold.

For example, the internal structures found in the gold of the mouth of the Lena-Vilyui interfluve (Kempendyai dislocations, Vilyui paleorift, volcanic activity of andesite–dacite composition), namely, a high-grade shell on low-grade gold with a high silver content up to 25–40% (Figure 8a,b), as well as intergranular high-grade veinlets (Figure 8c) are typical for gold of near-surface deposits. The discovered internal structures indicate the supply of gold from gold–silver sources. The presence of gold with such mineralogical and geochemical features and specific internal structures, namely, high-grade shells on low-grade gold, intergranular high-grade veinlets give reason to assume that gold and silver deposits (such as Cripple Creek) are predicted in this territory.

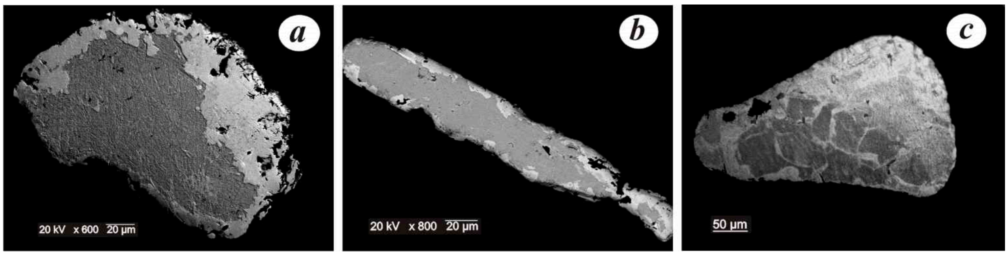

Figure 8. The internal structure of placer gold of the sources of the rivers of the Kempendyai dislocations: (**a**) monocrystalline structure with a dense high-grade shell with a thickness of 20–40 microns; (**b**) very thin fragmentary high-grade shell on low-grade gold; (**c**) intergranular high-grade veinlets.

Discovery of porous spongy placer gold up to 40% (Figure 5a,b) with an increased mercury content (>6%) at the mouth of the Bol. Patom river in the middle Lena basin in the south-east of the Siberian Platform indicates that gold-bearing hydrothermal–metasomatic formations of gold sulfide quartz mineralization were the ore sources of this gold. The following internal structures were found in placer gold: mono- and coarse-grained with thin intermittent high-grade shells, sometimes unclear zoning, spotty heterogeneity, porosity, multiphase nature, granulation and disintegration. The above indicators for internal structures are characteristic of mineralization of the gold sulfide quartz formation. According to the identified complex of mineralogical and geochemical features, placer gold is similar to the gold of the Kuranakh ore-placer cluster. In this regard, the formation of a gold deposit of the Kuranakh type (Carlin) is predicted in this territory.

Thus, it was determined for the first time that native gold has certain internal structures depending on the stage of ore formation and conditions of stay in exogenous environments. Gold of the Precambrian stage of ore formation is characterized by primary recrystallization and secondary recrystallization structures and numerous deformation lines, as well as the presence of a thick high-grade shell. Gold of the Mesozoic stage of ore formation has mainly coarse-medium-grained and inequigranular structures; sometimes, it is marked by multiphase gold, granulation, disintegration and unclear-zonal structures and the development of thin high-grade shells is observed in some of them.

In the hypergenesis zone, the formation of a high-grade shell is observed, gold recrystallization occurs in buried placers or ancient deposits, as well as the formation of deformation lines under the influence of lithostatic pressure of the overlying strata. Pseudo-ore gold with numerous deformation lines is characteristic of all platform areas and occurs in alluvial placers. The discovery of gold particles with such structures can serve as the basis for the search for gold ore metamorphic sources

Recrystallization structures predominate in gold particles in the aeolian medium due to complex deformation. The study of the internal structure of aeolian gold particles and their chemical composition showed that gold with a fine-grained structure prevails, mainly of very high fineness, with a minimum content of impurity elements in it. It is identified that the deformation of gold involves its primary recrystallization with the removal of silver and secondary recrystallization, which contributes to the removal of impurity elements from gold. In aeolian conditions, this process is pronounced and caused by a complex deformation. Each stage of complex deformation of flakes in aeolian conditions under the influence of mechanical and chemical processes corresponds to a regular change in its internal structure due to increased fineness and a decrease in the content of impurity elements. Indeed, due to the intensive transformation of gold during its complex deformation, the thinnest films of gold are stretched, which, overlapping each other, form a shell of spherical shapes. At the same time, the surface of gold increases for active chemical interaction with the components in the medium. Therefore, a long conversion time contributed to the maximum removal of silver and impurity elements and a change in the internal structure.

5. Conclusions

The long-term study of the internal structures of placer gold in the east of the Siberian Platform and the generalization of these results for the first time allowed us to establish the stages of ore formation and the evolution of placer gold under exogenous conditions in hypergenic, hydrodynamic and aeolian environments.

Based on the identification of a complex of indicators of the internal structures of type I placer gold, the sources that made possible the formation of placer gold content (weathering crusts, gold-bearing reservoir rocks, metamorphic strata), were identified for the first time in the east of the Siberian platform. The stages of ore formation (Precambrian and Mesozoic) are also proved.

The indicators of the internal structures of placer gold of the Precambrian stage of ore formation include the presence of structures of primary recrystallization, secondary recrystallization, numerous deformation lines and thick high-grade shells. The indicator signs of the internal structures of placer gold of the Mesozoic stage of ore formation are coarse-medium-grained structures, mono-grains, unclear-zonal, structures of granulation and disintegration.

It is identified that the above-mentioned indicators of the internal structures of placer gold of the Precambrian stage of ore formation are characteristic of almost all placer occurrences of the entire east of the Siberian platform, and indicators of the internal structures of placer gold of the Mesozoic stage of ore formation are characteristic only of certain geological structures.

The revealed internal structures typical for endogenous and exogenous conditions can serve as an effective method for determining the genesis of placers and the nature of gold ore sources. The use of this method makes it possible to develop criteria for forecasting ore sources and types of gold deposits based on internal structures.

Funding: The research was carried out within the framework of the state task of the Diamond and Precious Metals Geology Institute, Siberian Branch, Russian Academy of Sciences, funded by the Ministry of Science and Higher Education of the Russian Federation project № 0381-2019—0004.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares that there are no conflict of interest.

References

1. Petrovskaya, N.V. *Native Gold*; Nedra: Moscow, Russia, 1973; 347p. (In Russian)
2. Nikolaeva, L.A. *Genetic Features of Native Gold as a Criterion in the Search and Evaluation of Ores and Placers*; Nedra: Moscow, Russia, 1978; 100p. (In Russian)
3. Popenko, G.S. *Mineralogy of Gold of the Quaternary Placers of Uzbekistan*; FAS: Tashkent, Russia, 1982; 144p. (In Russian)
4. Savva, N.E.; Preis, V.K. *Atlas of Native Gold of the North-East of the USSR*; Nauka: Moscow, Russia, 1990; 293p. (In Russian)
5. Savva, N.E.; Shilyaeva, N.A.; Aleyevskaya, N.L. *Topomineralogy of Constitutional Features of Native Gold of the Lower Amur Placer Area*; SVKNII DVO RAN: Magadan, Russia, 2004; 172p. (In Russian)
6. Samusikov, V.P. Elements-impurities in native gold—Criteria for determining the formational belonging of gold deposits. *RAS Rep.* **2003**, *1*, 99–103. (In Russian)
7. Kalinin, Y.A.; Roslyakov, N.A.; Prudnikov, S.G. *Gold-Bearing Weathering Crusts of Southern Siberia*; "Geo" Academic Publishing House: Novosibirsk, Russia, 2006; 339p. (In Russian)
8. Nikolaeva, L.A.; Gavrilov, A.M.; Nekrasova, A.N.; Yablokova, S.V.; Shatilova, L.V. *Native Gold of Ore and Placer Deposits of Russia*; TsNIGRI: Moscow, Russia, 2015; 200p. (In Russian)
9. Nikiforova, Z.S.; Gerasimov, B.B.; Glushkova, E.G.; Kazenkina, A.G. Gold content of the east of the Siberian platform (placers—primary sources). *Geol. Ore Depos.* **2013**, *55*, 305–315. https://doi.org/10.7868/S0016777013040060.
10. Nikiforova, Z.S.; Kalinin, Y.A.; Makarov, V.A. Evolution of native gold in exogenous conditions. *Russ. Geol. Geophys.* **2020**, *61*, 1244–1259. https://doi.org/10.15372/RGG2020109.
11. Nikiforova, Z.S. Criteria for determining the genesis of placers and their different sources based on the morphological features of placer gold. *Minerals* **2021**, *11*, 381–403. https://doi.org/10.3390/min11040381.
12. Petrovskaya, N.V.; Fastalovich, A.I. *Morphological and Structural Features of Native Gold. Materials on the Mineralogy of Gold*; TsNIGRI: Moscow, Russia, 1952; 101–150. (In Russian)

13. Savva, N.E.; Kravtsova, R.G.; Anisimova, G.S.; Palyanova, G.A. Typomorphism of Native Gold (Geological-Industrial Types of Gold Deposits in the North-East of Russia). *Minerals* **2022**, *12*, 561. https://doi.org/10.3390/min12050561.
14. Giusti, L.; Smith, D.G.W. An electron microprobe study of some Alberta placer gold. *Tschermaks Mineral. Petrogr. Mitt.* **1984**, *33*, 187–202.
15. Freyssinet, P.; Zeegers, H.; Tardy, Y. Morphology and geochemistry of gold grains in lateritic profiles of southern Mali. *J. Geochem. Explor.* **1989**, *32*, 17–31.
16. Knight, J.B.; Mortensen, J.K.; Morison, S.R. Lode and placer gold composition in the Klondike District, Yukon territory, Canada: Implications for the nature and genesis of Klondike placer and lode gold deposits. *Econ. Geol.* **1999**, *94*, 649–664.
17. Chapman, R.J.; Leake, R.; Moles, N.R.; Earls, G.; Cooper, C.; Harrington, K.; Berzins, R. The application of microchemical analysis of alluvial gold grains to the understanding of complex local and regional gold mineralization: A case study in the Irish and Scottish Caledonides. *Econ. Geol.* **2000**, *95*, 1753–1773.
18. Chapman, R.J.; Mortensen, J.K. Application of microchemical characterization of placer gold grains to exploration for epithermal gold mineralization in regions of poor exposure. *J. Geochem. Explor*. **2006**, *91*, 1–26.
19. Dill, H.G. Grain Morphology of Heavy Minerals from Marine and Continental Placer Deposits, with Special Reference to Fe-Ti Oxides. *Sediment. Geol.* **2007**, *198*, 1–27.
20. Dill, H.G. Geogene and Anthropogenic Controls on the Mineralogy and Geochemistry of Modern Alluvial-(Fluvial) Gold Placer Deposits in Man-made Landscapes in France, Switzerland and Germany. *J. Geochem. Explor*. **2008**, *99*, 29–60.
21. Dill, H.G. Gems and Placers-A Genetic Relationship Par Excellence. *Minerals* **2018**, *8*, 470.
22. Melchiorre, E.B.; Henderson, J. Topographic gradients and lode gold sourcing recorded by placer gold morphology, geochemistry, and mineral inclusions in the east fork San Gabriel River, California, USA. *Ore Geol. Rev.* **2019**, *109*, 348–357.
23. Maftei, E.A.; Buzatu, A.; Damian, G.; Buzgar, N.; Dill, H.G.; Apopei, A.I. Micro-Raman—A Tool for the Heavy Mineral Analysis of Gold Placer-Type Deposits (Pianu Valley, Romania). *Minerals* **2020**, *10*, 988. https://doi.org/10.3390/min10110988.
24. Chapman, R.J.; Banks, D.A.; Styles, M.T.; Walshaw, R.D.; Piazolo, S.; Morgan, D.J.; Grimshaw, M.R.; Spence-Jones, C.P.; Matthews, T.J.; Borovinskaya, O. Chemical and physical heterogeneity within native gold: Implications for the design of gold particle studies. *Miner. Depos.* **2021**, *56*, 1563–1588.
25. Solberg, T.N.; Craig, J.R. Chemical variations in gold from the central Appalachians of Virginia. *Microbeam Analysis.* **1981**, 163–166.
26. Mann, A.W. Mobility of gold and silver in lateritic weathering profiles: Some observations from Western Australia. *Econ. Geol.* **1984**, *79*, 38–49.
27. Falconer, D. M.; Craw, D.; Youngson, B.; Faure, K. Gold and sulfide minerals in tertiary quartz pebble conglomerate gold placers, Southland, New Zealand. *Ore Geol Rev.* **2006**, *28*, 525–545.
28. Nysten, P. Gold in the volcanogenic mercury- rich sulfide deposit Ldngsele, Skellefte ore district, northern Sweden. *Miner. Depos*. **1986**, *21*, 116–120.
29. Stoffregen, R. Observations on the behavior of gold during supergene oxidation at Summitville, Colorado, U.S.A., and implications for electrum stability in the weathering environment. *Appl. Geochem.* **1986**, *1*, 549–558.
30. Craig, J.R.; Callahan, J.E. Paleoplacer gold in the Lilesville sand and gravel deposits, North Carolina. *Ga. Geol. Surv. Bull.* **1989**, *117*, 121–141.
31. Driscoll, A.J.; Hall, D.L.; Craig, J.R. Placer gold: An unrealized potential for characterizing lodes. *Ga. Geol. Surv. Bull.* **1991**, *105*, 95–118.
32. Craw, D.; McLachlan, C.; Negrini, M.; Becker, N. Quantification and prediction of bulk gold fineness at placer gold mines: A New Zealand example. *Minerals* **2017**, *7*, 226.
33. Dongmo, F.W.N.; Chapman, R.J.; Bolarinwa, A.T.; Yongue, R.F.; Banks, D.A.; Olajide-Kayode, J.O. Microchemical characterization of placer gold grains from the Meyos-Essabikoula area, Ntem complex, southern Cameroon. *J. Afr. Earth Sci*. **2018**, *1*, 151, 189-201.
34. Dunn, S.C.; Bjorn, P.; Rozendaal, A.; Taljaard, R. Secondary gold mineralization in the Amani placer gold deposit, Tanzania. *Ore Geol. Rev.* **2019**, *107*, 87–107.
35. Erasmus, C.S.; Sellschop, J.P.F.; Watterson, J.I.W. New evidence on the composition of mineral grains of native gold. *Nucl. Geophys.* **1987**, *1*, 1–23.
36. Groen, J.C.; Craig, J.R.; Rimstidt, J.D. Gold-amalgam and other secondary phases in placers. *Abstr. Programs—Geol. Soc. Am.* **1986**, *19*, 621p.
37. Groen, J.C.; Craig, J.R.; Rimstidt, J.D. Gold–rich rim formation on electrum grains in placers. *Can. Mineral.* **1990**, *28*, 207–228.
38. Leake, R.C.; Bland, D.J.; Styles, M.T. Internal structure of Au-Pd-Pt grains from south Devon, England, in relation to low-temperature transport and deposition. *Min. Metall*. **1991**, 100, 159–178.
39. Cabral, A.R.; Suh, C.E.; Kwitko-Ribeiro, R.; Rocha Filho, O.G. Brittle microstructures in gold nuggets: A descriptive study using backscattered electron imaging. *Ore Geol. Rev*. **2008**, *33*, 212–220.
40. Kerr, G.; Falconer, D.; Reith, F.; Craw, D. Transport-related mylonitic ductile deformation and shape change of alluvial gold, southern New Zealand. *Sediment. Geol.* **2017**, *361*, 52–63.
41. Stewart, J.; Kerr, G.; Prior, D.; Halfpenny, A.; Pearce, M.; Hough, R.; Craw, D. Low temperature recrystallisation of alluvial gold in paleoplacer deposits. *Ore Geol. Rev*. **2017**, *88*, 43–56.

42. Chapman, T.; Clarke, G.L.; Piazolo, S.; Robbins, V.A.; Trimby, P.W. Grain-scale dependency of metamorphic reaction on crystal plastic strain. *J. Metamorph. Geol.* **2019**, *3*, 1021–1036.
43. *Report on the State of Fundamental Sciences in the Russian Federation and on the Most Important Scientific Achievements of Russian Scientists in 2014*; Most Important Achievements; Earth Sciences: Moscow, Russia, 2014; 181p. (In Russian)
44. Moiseenko, V.G. *Metamorphism of Gold Deposits of the Amur Region*; Khabarovsk Publishing House: Blagoveshchensk, Russia, 1965; 127p. (In Russian)
45. Kopeliovich, A.V. *Epigenesis of Ancient Strata of the South-West of the Russian Platform*; Nauka: Moscow, Russia, 1965; 311p. (In Russian)