minerals

MDPI

Article

Paragenetic Association of Platinum and Gold Minerals in Placers of the Anabar River in the Northeast of the Siberian Platform

Alexander Okrugin and Boris Gerasimov *

Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, 39 Lenin Street, Yakutsk 677000, Russia
* Correspondence: bgerasimov@yandex.ru

Abstract: Areal placers of diamond and precious metals (platinum and gold) of unknown origin are widespread in the Anabar River basin on the northeastern part of the Siberian Platform. This article discusses the typomorphic features of palladium gold (porpezite) and ferroan platinum, which, in addition to fragmented individual grains, sometimes form close growths, which indicates their obvious genetic relationship. This can be used to delimit the primary sources of commercial components of complex placers by their genetic types. The composition of minerals was determined on a Camebax-Micro (Cameca, France) microprobe analyzer, and their microstructural relationships were studied using the scanning microscope JSM-6480LV JEOL. Determination of the structure and parameters of elementary lattices of minerals was carried out on the D8 Discover diffractometer. According to microprobe analysis, the Pd content in porpezite ranges from 0.73% to 12.83%, Ag does not exceed 2.75% and Cu reaches 3–4%. Considering the composition, such a gold–platinum mineral association from placers of the Anabar river is close to precious metals from placers of the Gulinsky massif, as well as Au–PGE ore occurrences related to ultramafic–mafic intrusions of other regions of the world. Complex gold–platinum-metal mineralizations are usually closely related to parent rocks and are often observed in sulfide and chromite ores of layered ultramafic–mafic intrusions with complex metasomatic and hydrothermal transformations. It is shown that in such cases gold and platinum form a magmatogenic paragenesis of minerals that coexist until the separation of hydrothermal solutions from magma, which, as a rule, transports Au and Ag with a small fraction of PGE from the fluid-ore-magmatic system in accordance with the model of the formation of gold–porphyry deposits. Within the Anabar diamond-bearing region, according to modern geophysical data, a significant number of local gravimagnetic anomalies associated with the presence of intrusive massifs of basic and alkaline-ultrabasic rocks in the cover and within the basement have been identified. This allows us to assume that the buried parent rocks of the Anabar Au–Pt placers may be located in both the Precambrian and Phanerozoic strata.

Keywords: platinum group minerals; gold; porpezite; alkaline-ultrabasic rocks; Anabar shield; Siberian Platform

Citation: Okrugin, A.; Gerasimov, B. Paragenetic Association of Platinum and Gold Minerals in Placers of the Anabar River in the Northeast of the Siberian Platform. *Minerals* **2023**, *13*, 96. https://doi.org/10.3390/min13010096

Academic Editor: Maria Economou-Eliopoulos

Received: 15 December 2022
Revised: 4 January 2023
Accepted: 5 January 2023
Published: 7 January 2023

1. Introduction

In the northeast of the Siberian Platform, areal diamond-bearing placers are known [1,2] containing a number of quantities of associated precious metal—gold and platinum [3–8]. Although they were formed as a result of spatial combination (parasteresis) in placers of phases stable under exogenous conditions, it is possible to recognize paragenetic associations of minerals in them. This can be used to delimit the primary sources of commercial components of complex placers by their genetic types. In the last 30 years, we have been conducting regional mineralogical and geochemical typification of platinum group mineral (PGM) associations in placers. On this basis, it is possible to carry out systematic zoning of platinum-bearing placers of the Siberian Platform in order to identify their possible genetic types of primary sources [9,10].

Numerous fragmented placer occurrences of the same mineralogical-geochemical type are sometimes found in vast areas limited by the borders of certain geological structures. This indicates the connection of these placers with autonomous primary sources of the same type, formed during certain tectonic-magmatic stages of activation of platform structures, and therefore they are united into a single platinum-bearing area. If such areas cover regional structural elements, they can even be considered a single province [6].

2. Lena–Anabar Precious-Rare-Metal-Diamond-Bearing Province

In the northeast of the Siberian Platform, the formation of complexes of ultrabasic alkali rocks with carbonatites (UAR), kimberlites, picrites, carbonatites and alkali basites in the Anabar, Olenek and lower Lena River basins took place during several tectonic-magmatic cycles in the Phanerozoic. All these magmatites have a mantle nature and are characterized to varying degrees by diamond, rare-earth and precious-metal specialization. This allows us to identify this ore-bearing area as a single independent Lena–Anabar precious-rare-metal-diamond-bearing metallogenic province (Figure 1), belonging to the polycyclic platform type and requiring a special integrated approach when prospecting and forecasting possible deposits within this vast territory [11]. To discover potential primary sources of diamonds, precious metals and minerals of rare elements in the northeast of the Siberian Platform, having probably different, but paragenetically similar types of primary sources, complex search methods are required, including the study of the typomorphism of indicator minerals [12–18].

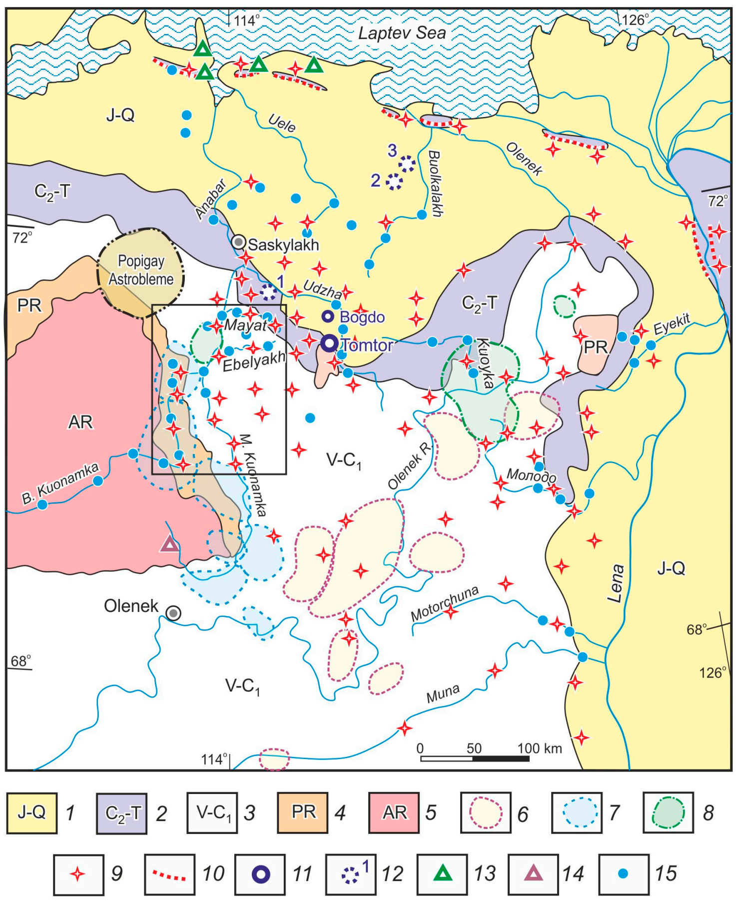

Figure 1. Distribution scheme of diamond, gold, and platinum in placers of the Lena–Anabar province (modified after [11]): 1—Jurassic–Cenozoic sediments; 2—Carboniferous–Triassic sandstones and siltstones;

3—Vendian–Carboniferous dolomites, limestones and sandstones; 4—Proterozoic rocks; 5—Archean metamorphic complexes; 6–8—Fields of kimberlites and carbonatites according to [17]: Middle Paleozoic (6), Early Mesozoic (7) and Late Mesozoic (8); 9—diamonds in placers [17]; 10—diamonds in tuffite of the Carnian stage [18]; 11—Tomtor and Bogdo massifs; 12—massifs assumed according to geophysical data [12]; 13—picrite-basalts, mouth of the Anabar river [13,14]; 14—dike of meimechite-like rocks [15]; 15—gold and platinum in placers [3,16]. The rectangle frame is the location of the research area.

3. Materials and Methods

The purposeful study of precious metals—gold and platinum—by the authors began in the early 1990s as part of the Institute's state financed case studies, as well as during contractual research and production work with the JSCs Nizhne-Lenskoye and Almazy Anabara. Single small (up to 0.5–1 mm) grains of gold and platinum are often found in the alluvial deposits of the Anabar river, but in some places the content of precious metals can reach 100 mg/m^3. During the mining of diamond-bearing placers of the rivers Mayat, Ebelyakh, Khara-Mas, etc. (Figure 1) large grains of gold (up to 5–8 mm) and platinum (up to 3 mm) were found. Here the precious metal content can reach 1–2 g/m^3. In the course of these works, extensive material has been collected on stream sediment samples of watercourses of the Anabar river basin, which are the subject of ongoing specialized research in order to identify potential primary sources of paragenetically related mineral associations. Such typomorphic associations of minerals include palladium gold and platinum group minerals (PGM); their paragenetic link is established not only by their close growths [19–21], but also the repeatability in various known magmatogenic deposits of platinum and gold [22–30]. In this article we present new data on such gold–platinum parageneses from placers of the Anabar river basin.

The composition of minerals was determined using a Camebax-Micro (Cameca, France) microprobe analyzer and their microstructural relationships were studied using the scanning microscope JSM-6480LV JEOL at DPMGI SB RAS; analysts: N.V. Leskova, S.K. Popova, L.M. Popova and N.V. Khristoforova. The surveys were carried out under the following conditions: accelerating voltage 20 kV; probe current 1.09 nA; measurement time 7 s; analytical lines: Au—Mα, Ag—α, other elements—Kα. Standardized minerals, pure metals and their alloys were used as standards X-ray studies on determining the structure and parameters of the elementary lattices of minerals were carried out at the URS-0.3 facility at DPMGI SB RAS (analysts: N.V. Zayakina, T.I. Vasilieva) and also on the D8 Discover diffractometer at MIN SB RAS by L.N. Gorokhova.

4. Results and Discussion

Mineralogical description of the association of platinum and gold in placers of the Anabar river basin, as indicated above, are presented in the works of many researchers who have given a variety of interpretations regarding their supposed primary sources [3–8,19–21,31–34]. Here we will focus in more detail on some typomorphic aspects that prove the paragenetic relationship of gold with PGM.

4.1. Mineralogical Characteristics of PGM and Gold in Placers of the Anabar River

One of the paragenetic associations of minerals is obviously platinum metals and gold with a high Pd content (up to 12.8 wt.%) and Pt (up to 0.4%). Porpezite palladium gold in the northeast of the Siberian Platform was first found in an ultra-heavy concentrate of stream sediment samples in Bolshaya Kuonamka, Anabar, Kuoyka and Molodo rivers [16], then in the diamond-bearing placers of the Mayat and B. Kuonamka rivers [19–21] (Figure 1). The largest amount of porpezite was observed in tail concentrates of the diamond-bearing placer of the Mayat river, where it is usually associated with PGM (Figure 2a) and is represented by separate well-rounded grains of scaly and lamellar habit with a size of 0.1–0.5 mm, and less often up to 1 mm (Figure 2b). Small grains have flattened and lumpy shapes. In contrast to the typical bright yellow native gold (Figure 2c), often found in these placers, porpezite has a dull bronze color and a finely shagreen surface, sometimes giving the metal an earthy appearance.

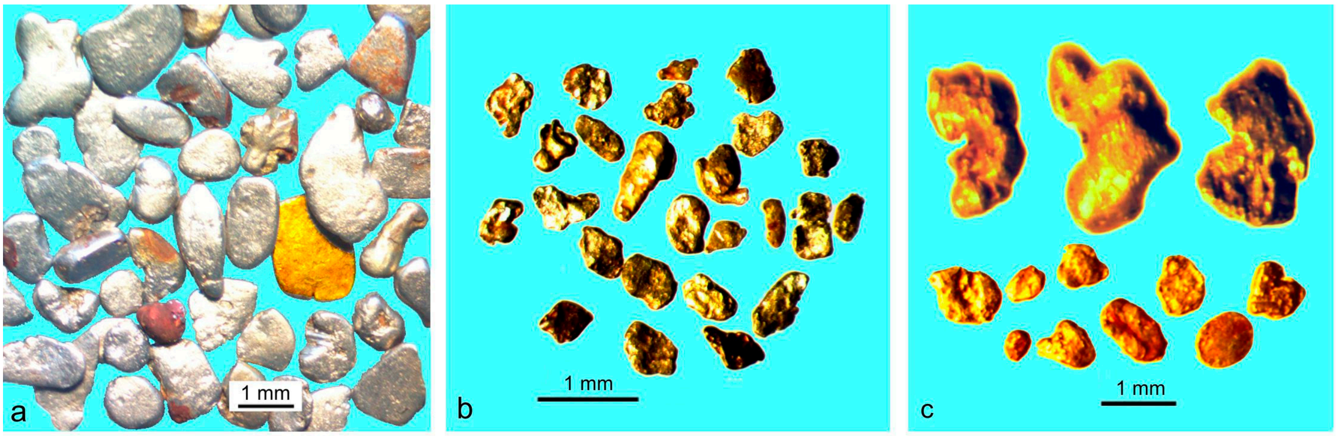

Figure 2. Morphology of platinum and gold mineral grains from the placer of the Mayat river: (**a**) well-rounded flattened grains of platinum (gray) with gold (yellow); (**b**) palladium gold; (**c**) large lumpy (upper row) and small scaly grains (lower row) of gold.

Platinum group minerals from the placer of the Mayat river, as in other placers of the Anabar river basin, are mainly represented by Fe–Pt alloys and minerals of Ru–Ir–Os composition (Table A1), and are found in smaller quantities (95–99% of the total mass of PGM). Fe–Pt alloys are represented by well-rounded silvery-light gray grains with a matte rough surface. The particle sizes mainly range from 0.25 to 0.5 mm, and some of the grains reach 1–3 mm in diameter (Figure 2a). According to microprobe analysis, their Pt content varies from 64.5% to 90.6 wt.%, and Fe from 4.1% to 13.9%. The main impurities of ferroan platinum are Rh up to 12%, Ru—9.7%, Ir—12%, Pd—12%, Os—3.2%, Ni—2.7% and Cu—5.1%.

As X-ray studies have shown, they mainly have a face-centered disordered lattice with unit cell parameters of 3.87–3.88 Å, that is, according to the classification of Fe–Pt alloys [35], these minerals belong to ferroan platinum. Only in one case out of nine definitions, a radiograph of the P-lattice was obtained, i.e., this phase has an ordered structure with a unit cell parameter of 3.86 Å, corresponding to the mineral isoferroplatinum—an intermetallic compound Pt_3Fe.

The triple diagram (Pt + Fe)–(Ir + Os)–(Ru + Rh) with an expanded Pd system shows that in the MPG in the placers of the Anabar river basin (Figure 3A, [14,27,36–41]), high-Ru–Rh platinum of the "Vilyui" type prevails, but a significant amount of platinum is plotted along the "Inagli" Ir-trend. It can be assumed that there are these two types of primary sources or one aggregate complex of rocks combining both types of mineralization, which is most likely. Some points of the compositions fall into the intermediate region occupied by the MPG from chromite ores of the Krasnogorsk massif, belonging to the alpinotype ultramafic island-arc type of the northwestern sector of the Pacific mobile Belt [36].

Minerals of Ru–Ir–Os composition in Anabar placers are observed in the form of small inclusions in ferroan platinum, but they are often found in the form of independent lamellar grains, usually up to 0.5 mm in size, rarely reaching 1–2 mm. Considering the composition according to the nomenclature of Ru–Ir–Os alloys [42], they mainly correspond to osmium, whereas ruthenium and iridium grains are less often found. (Figure 3B). They generally overlap the fields of mineral compositions from the Vilyui and Inagli placers. However, in the placers of the Vilyui River, Ru–Ir–Os alloys are mainly represented by rutheniridosmine, and in the placers of the Inagli massif, osmium and iridium are found in the form of inclusions in isoferroplatinum. Particular osmium grains mainly fall into the field of mineral compositions from placers of the Gulinsky massif, which suggests the possible presence of analogs of the Gulinsky complex of alkaline-ultrabasic rocks in this area.

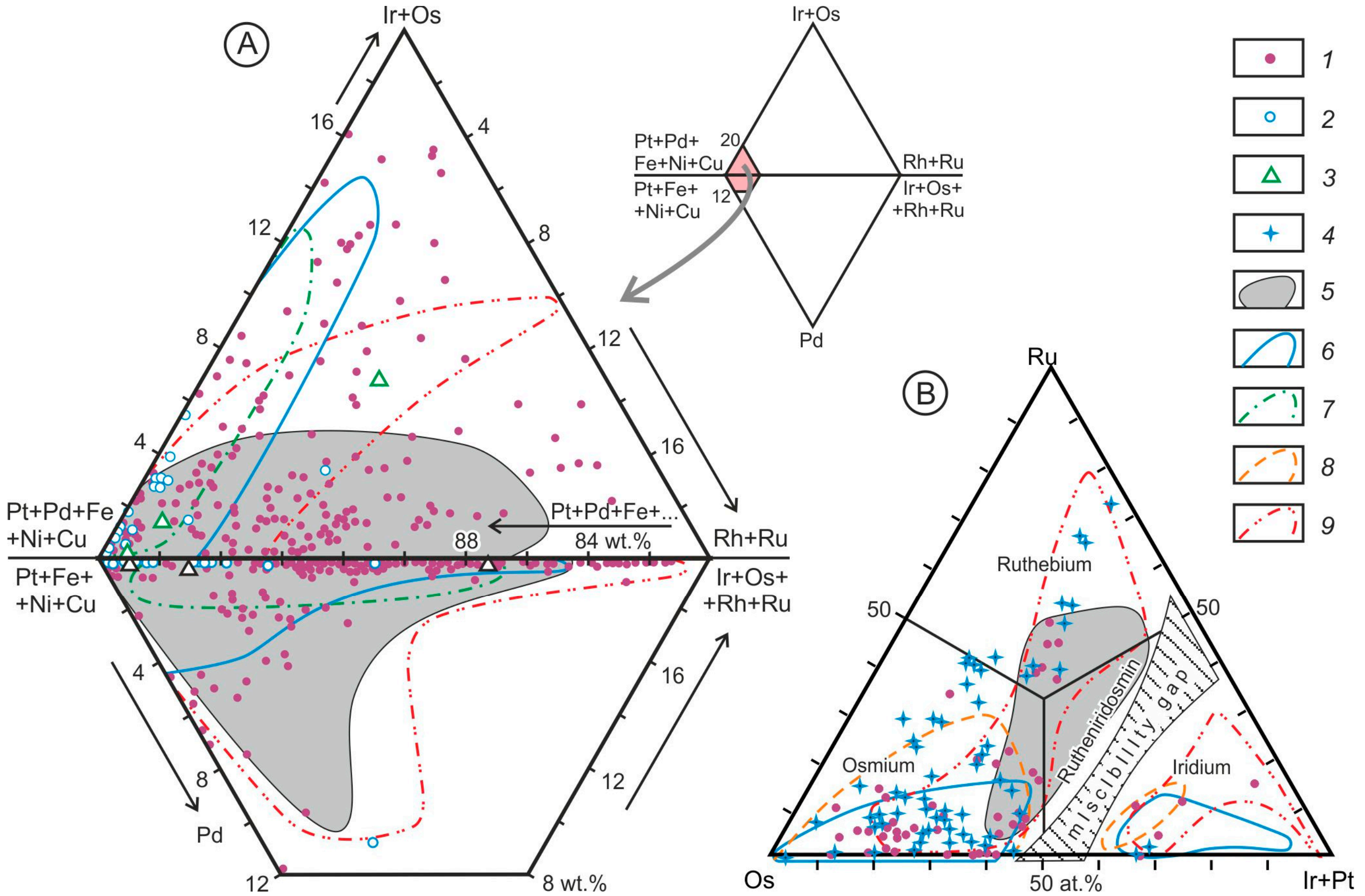

Figure 3. Diagrams of the compositions of Fe–Pt (**A**) and Ru–Ir–Os alloys (**B**). 1—Placers of the Bolshaya, Kuonamka and Anabar rivers [14]; 2—Gulinsky massif [37–40]; 3—placers of the Bor–Uryakh massif [41]; 4—inclusions of Ru–Ir–Os minerals in ferroan platinum from placers of the Anabar river. 5–9—Mineral composition fields from placers of the Vilyui river (5); Inagli massif (6); Ural (7) according to [27], Gulinsky massif (8) according to [37–39] and chromite ores of the Krasnogorsk massif (9) according to [36].

In addition to osmium, ruthenium and iridium, small inclusions are found in ferroan platinum, represented by different sulfides of platinum group elements (PGE): laurite RuS_2, erlichmanite OsS_2, prassoite $Rh_{17}S_{15}$, bowieite Rh_2S_3, vasilite $(Pd, Cu)_{16}S_7$ and others. Arsenides and tellurides PGE are less common, as well as Au-containing (up to 7.4 wt.%) intermetallide PdCu—skaergaardite. Detection of close growth of porpezite with ferroan platinum in the placer of the Bolshaya Kuonamka river [20], along with the presence of similar inclusions of palladium tellurides in the scattered grains of ferroan platinum and porpezite—kotulskite, telluropalladinite and keithconnite (Figure 4), obviously indicates the paragenetic nature of these minerals, which have a common primary source.

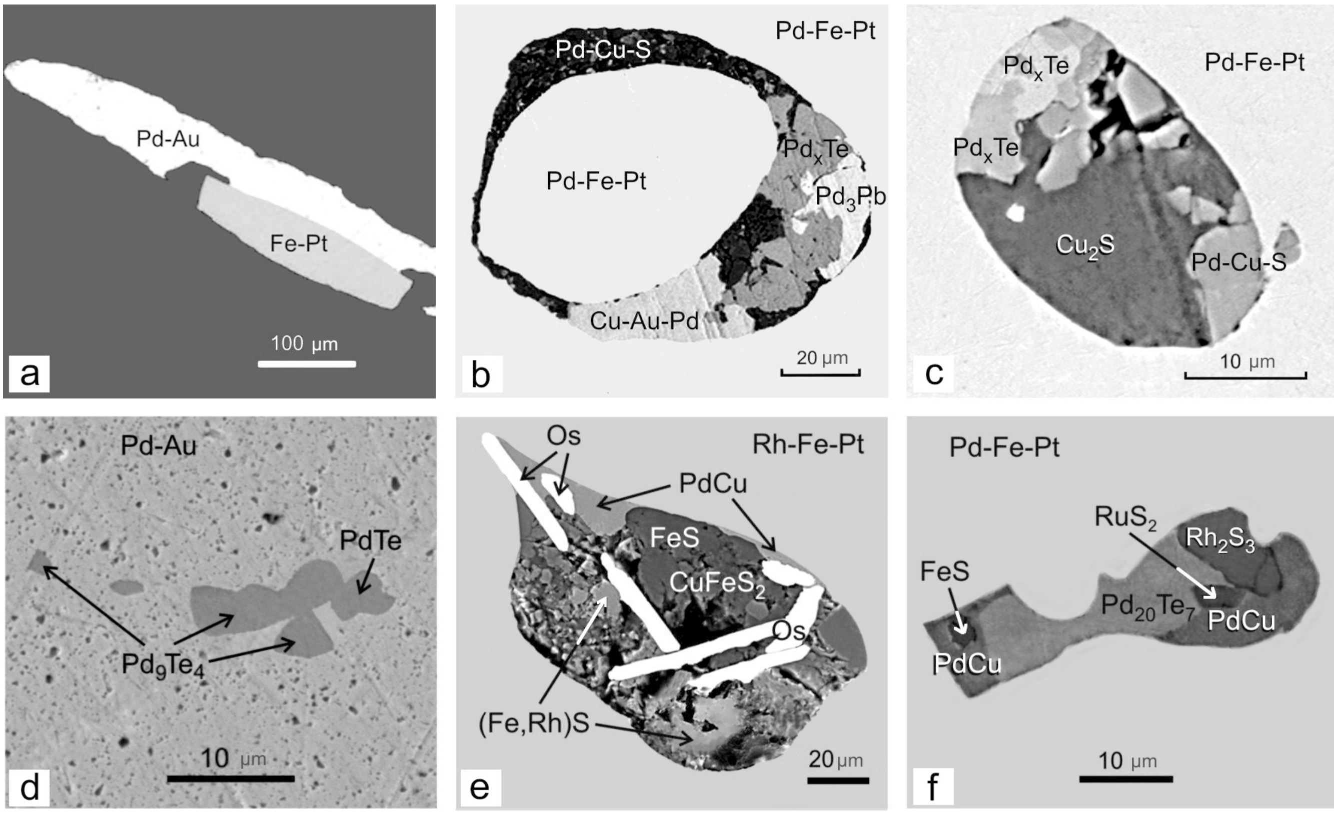

Figure 4. Forms of intergrowths of ferroan platinum and porpezite with inclusions of PGM-containing minerals from the Anabar river placers: (**a**) intergrowth of porpezite (Pd–Au) and ferroan platinum (Fe–Pt), Bolshaya Kuonamka river; (**b**,**c**) inclusions of other minerals in palladium-ferroan platinum (Pd–Fe–Pt) from the placer of the Malaya Kuonamka river; (**d**) inclusions (dark grey) of Pd tellurides in the gray matrix of palladium gold (Pd–Au) of the Mayat river; (**e**,**f**) polymineral inclusions in platinum of the Mayat river. Minerals: Os—osmium; FeS—troilite; $CuFeS_2$—chalcopyrite; Cu_2S—chalcosine; RuS_2—laurite; Rh_2S_3—bowieite; PdCu—skaergaardite; Pd–Cu–S—vasilite; Pd_3Pb—zvyagintsevite; PdTe—kotulskite; $Pd_{20}Te_7$—keithconite; Pd_9Te_4—telluropalladinite; Cu–Au–Pd alloy composition is given in Table A2—sample MK-11. Backscatter electron (BSE) images.

In porpezite, according to microprobe analysis, the Pd content varies from 0.77% to 12.83%, Ag does not usually exceed 2.75% and the Cu impurity rarely reaches 3% (Table A2). In one grain of ferroan platinum with a high content of Pd (up to 9%) and Cu (up to 4%) from the placer of the Malaya Kuonamka River has a small inclusion (Figure 4b), for which the composition (MK-11 in Table A2) corresponds to the formula ratio $Cu_{0.33}Pd_{0.44}Au_{0.23}$. Such an alloy corresponds to the transition series from Pd–gold to Au-containing skaergaardite—PdCu; this inclusion is often found in ferroan platinum (Figure 4e,f). As X-ray determinations have shown, the parameters of the palladium gold unit cell decrease to a = 4.06–4.03 Å, while silver–gold from the placer of the Mayat river has a standard value for gold a = 4.07–4.08 Å.

Porpezite was previously found by us in the Makylgan and Inagli placers in the Central Aldan region, this mineral on the Aldan shield has also been found in placers and in magnetite–phlogopite–pyroxene rocks of the Kondersky massif [26], where palladium gold has a high Cu content up to the formation of Pd-tetra-auricupride AuCu. In gold–iridium–osmium placers associated with the Gulinsky massif with Ir–Os minerals and gold of different fineness, there is tetra-auricupride and porpezite with a Pd content of up to 8–11 at.% [30]. Comparative compositions of palladium gold from various types of deposits are shown in the diagram (Au + Cu)–Pd–Ag (Figure 5).

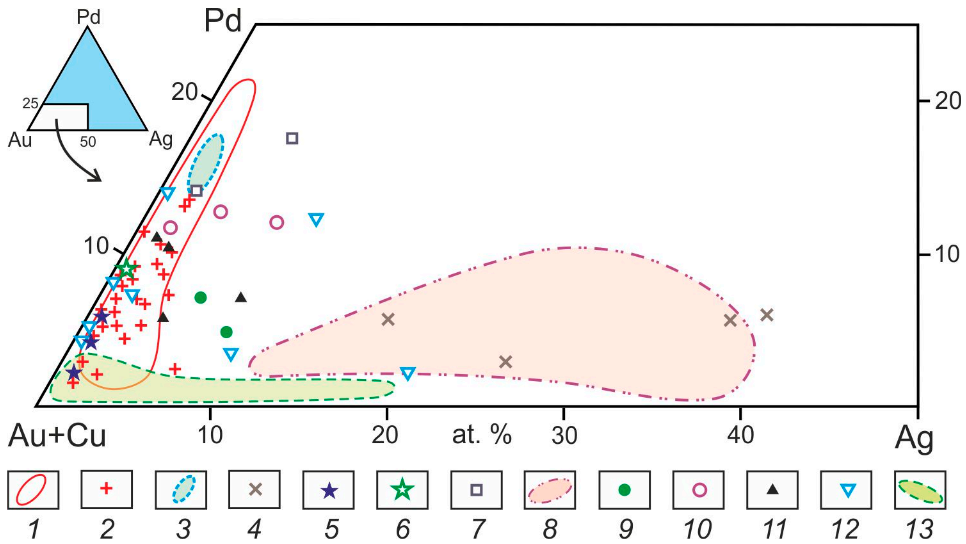

Figure 5. Diagram of palladium gold compositions: 1—Mayat river placer [19]; 2—Bolshaya Kuonamka river (authors data); 3—Guli placer [30]; 4—Norilsk PGE–Cu–Ni deposits, Russia [43]; 5—Inagli placer; 6—Kondersky massif [26]; 7—Itabira placer, Brazil [27]; 8—Merensky Reef, Bushveld, South Africa [23]; 9—Lac des Îles, QC, Canada [24]; 10—Stillwater, OK, USA [22]; 11—Pana massif, Kola Peninsula [25]; 12—Matagania–Sigiri placers, Guinea [29]; 13—Kozhimsky massif, Ural [28].

Porpezite was identified for the first time in 1798 in the Porpez region in Brazil in itabyrite deposits in the form of disseminations in deposits of itabirites—layered quartzites with magnetite and hematite. Here in placers, it is associated with Fe–Pt alloys, tu-lameenite Pt_2FeCu, osmium, arsenopalladinite $Pd_8As_{2.5}Sb_{0.5}$ and atheneite $(Pd, Hg)_3As$. In the primary platinum deposits, porpezite occurs in the form of small disseminations in the ores of layered intrusions of Bushveld, South Africa [23], Lac des Îles, QC, Canada [24], Stillwater, OK, USA [22] and in the Pana massif on the Kola Peninsula [25]. In the streams of Guinea, draining large Mesozoic stratified mafic–ultramafic massifs of the Matagania–Sigiri zone, along with the gold of medium fineness, there is so-called "white gold", with a Pd content of 1.1%–7.71% [29]. Here, in the porpezite, the smallest inclusions of sperrylite $PtAs_2$ and braggite (PdPt)S were identified. In the crushed samples of the Proterozoic metasedimentary rocks within the near-contact parts of the basite–hyperbasite massif, sub-ore gold particles were found with an admixture of Pd up to 1%, Pt 6.6% and Ag 15%, as well as PtFe tetraferroplatinum containing 20.6% Pd. Transition from the early typical magmatic PGE–Cu–Ni mineralization in ultramafic rocks to the late PGE–Cu–Au–Te sulfide mineralization in phlogopite-rich shonkinites was determined in the Mordor dunite–shonkinite–syenitic alkaline complex in Australia [44].

A new Au–Pd type of hydrothermal mineralization was discovered in the Kozhimsky region of the Circumpolar Urals, where visible disseminations (up to 2–8 mm) of Ag-, Cu-, Hg-, and Pd-containing gold in association with PGMs—mertieite, atheneite and an unknown Pd–As phase—were found in fuchsite stringers formed in the foliated Riphean rhyolites [28]. The authors of these studies consider that Au, Pd, Cu, Cr and Ca were redeposited into metasomatically altered rhyolites from underlying basalts and dykes of gabbro-diabases and picrites.

4.2. Possible Primary Sources of MPG and Porpezite in the Anabar River Basin

The complex diamond-bearing placers of the Anabar river are located within the eastern slope of the Anabar shield, where carbonate-terrigenous deposits and volcanogenic formations of the Riphean, Vendian, Cambrian, Permian, Triassic, Jurassic and Cretaceous are developed, intruded by the Late Precambrian, Middle Paleozoic and Mesozoic magmatites, belonging to a variety of mineral types—from kimberlites, alkaline-ultrabasic rocks and carbonatites to subalkaline and tholeiitic basites. Within the Anabar diamond-bearing region, according to modern geophysical data by I.V. Polyansky [19], a significant number of local gravimagnetic anomalies have been revealed, which are associated with the presence of intrusive massifs of basic and alkaline-ultrabasic rocks in the cover and within the basement. In this area, aeromagnetic high-precision survey (AMS-10) revealed 10 probable hidden intrusions (Figure 6), which are located between the metamorphic complex of the Anabar shield and the Riphean rocks of the Udzhinsky uplift [19]. This allows us to assume that the parent rocks of the Anabar Au–Pt placers may be located in both Precambrian and Phanerozoic strata. The buried Precambrian sources in the Phanerozoic could be brought to the surface, within the limits and frames of the Anabar shield and the Udzhinsky uplift, then washed into the area of the Udzhinsky aulacogen, at the same time, stable minerals will be preserved in basal intermediate reservoir rocks and fall from there into modern river valleys, forming halos of dispersions without visible primary sources.

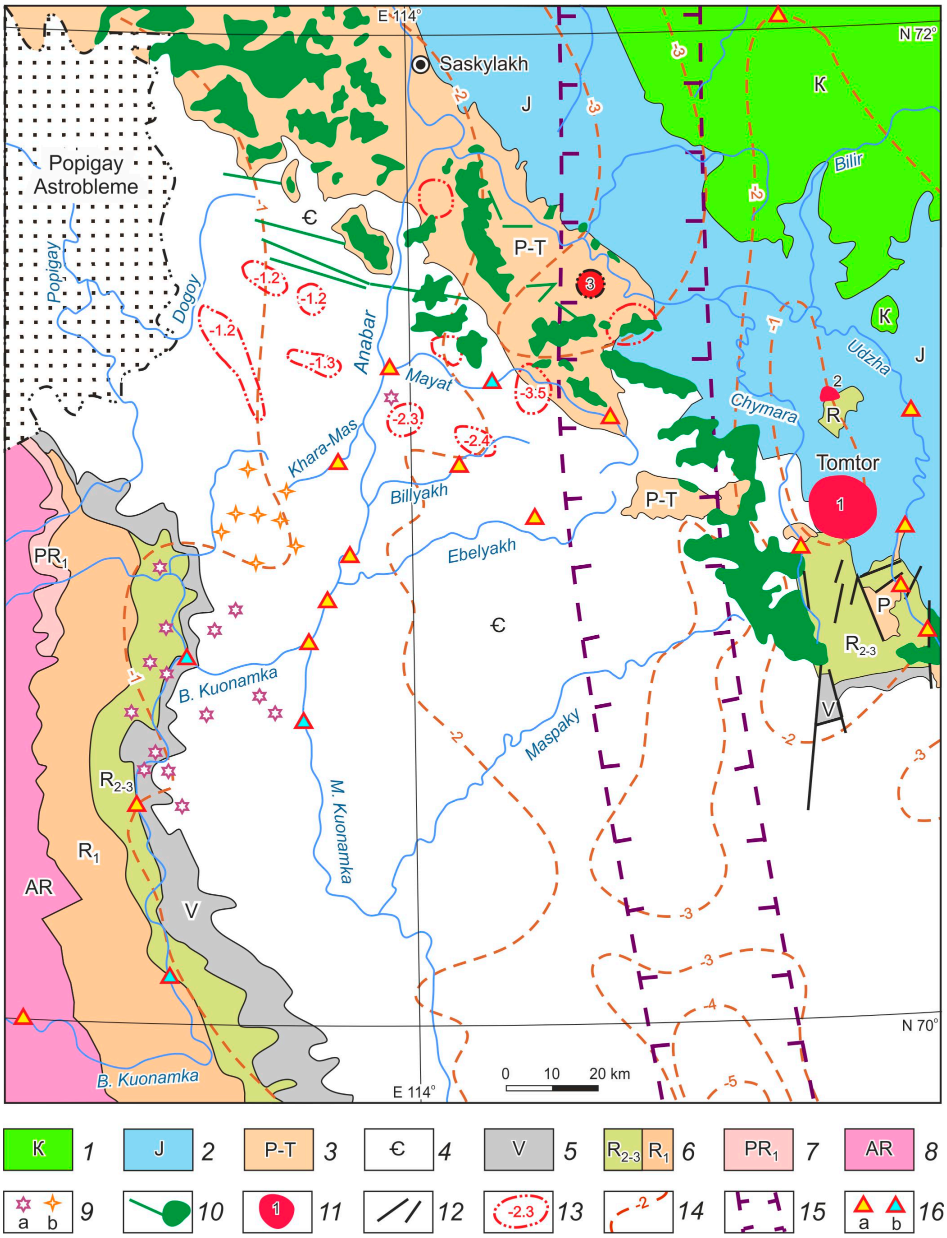

Figure 6. Schematic geological map of the distribution of gold–platinum-bearing placers in the basin of the middle course of the Anabar river (modified after [19]): 1—Cretaceous sands, silts and gravels;

2—Jurassic conglomerates, sandstones, siltstones; 3—Permian and Triassic sandstones, siltstones; 4—Cambrian dolomites, limestones and sandstones; 5—Vendian sandstones, siltstones and conglomerates; 6—middle-upper Riphean (R_{2-3}) and lower Riphean (R_1) conglomerates, sandstones, siltstones, argillite and dolomites; 7—Lower Proterozoic rocks; 8—Archean metamorphic complexes; 9—kimberlite (a) and carbonatite (b) pipes of the Orto–Yargin field; 10—dykes and sills of P–T basites; 11—complexes of alkaline-ultrabasic rocks with carbonatites (1—Tomtor, 2—Bogdo, 3—Chyuempe); 12—faults; 13—anomalies of the potential intrusive massifs of basic, alkaline-ultrabasic rocks in the basement and lower layer of the platform cover (based on geophysical data), figure-estimated depths (-n km) of occurrence; 14—isolines of basement surface (-n km); 15—borders of the Udzhinsky aulacogen; 16—sampling sites of the placer samples of platinum and gold (a) and PGM in association with palladium gold (b). Scheme is based on Geological and Tectonic maps of Yakutia at a scale of 1:1,500,000.

Summarizing the above facts, it can be concluded that the primary sources of the association of palladium gold and ferroan platinum in placers of the Anabar river basin are complex ultramafic–mafic ore-magmatic assemblages, which include alkaline-ultrabasic massifs with carbonatites. They can have a wide time range of development (evolution) from the the Riphean to the Permian–Triassic eruption of alkaline rocks, which covered not only the largest Maimecha–Kotui province, but also the Eastern Anabar region with a very wide range of basitic, alkaline-ultrabasic, carbonatite and kimberlite rocks. The presence of ferroan platinum with polymineral inclusions in the placers of the Anabar river, also including osmium, indicates that the gold–platinum association, along with Pd, contains other PGE, including the highest-temperature Os. In addition, the similarity of the typochemical features of low- and medium-grade gold with a high Cu content and the presence of tetra-auricupride AuCu [16] further brings the paragenetic divergence of the primary sources of the complex gold–platinum placers of the Anabar river with gold–iridium–osmium placers of the Gulinsky massif closer [30].

5. Conclusions

Based on the brief overview of the joint finding of palladium gold, Cu–Au–Pd alloys of different composition with PGM in placers and ores of ultramafic–mafic complexes of the Siberian Platform and other regions of the world, the authors believe that the association of palladium gold and PGM found in placers represents a close paragenetic relationship. Complex gold–platinum-metal mineralizations are usually closely related to parent rocks and are often observed in sulfide and chromite ores of layered ultramafic–mafic intrusions with complex metasomatic and hydrothermal transformations. The concentration of Au and Pd alloys along with sulfides and tellurides of non-ferrous metals and PGE in isolated teardrop inclusions of ferroan platinum (Figure 4) indicates the separation of an excessive number of more easily mobile Au–Pd–Cu–Te–S–As phases from the groundmass of refractory native osmium, iridium and platinum already crystallizing in magmatic conditions. It is obvious that here gold and platinum still form a coexisting magmatogenic paragenesis of minerals; however, at the post-magmatic stage of separation of pneumatic-hydrothermal solutions from magmatic melts due to sharply differing degrees of affinity of PGE and gold to fluid components, these metals are separated. As a result, the groundmass of the PGE–Cu–Ni triad is preserved in the magmatic system itself and its exocontact zone, and with the separating hydrotherms. Au, Ag and a number of non-ferrous metals with Te, As, S and a small fraction of PGE are carried away from the fluid-ore-magmatic system according to the model of formation of gold–porphyry deposits [45]. In typical hydrothermal ores associated with granitoid magmatism, gold is practically sterile relative to PGE. Sometimes small impurities of PGE (up to 0.1%–0.2% Pt and Pd) are detected by spectral analysis in gold from hydrothermal deposits; apparently, they associated with the involvement of deeper basic magmatites in the composition of the parent rocks. Hydrothermal easily mobile Au-containing complexes inherited their distant genetic characteristics of these deep basic magmatites.

Author Contributions: Conceptualization, A.O. and B.G.; methodology, A.O. and B.G.; software, A.O.; validation, A.O. and B.G.; formal analysis, A.O. and B.G.; investigation, A.O.; resources, A.O.; data curation, A.O.; writing—original draft preparation, A.O. and B.G.; writing—review and editing, A.O.; visualization, A.O. and B.G.; supervision, A.O.; project administration, A.O.; funding acquisition, A.O. All authors have read and agreed to the published version of the manuscript.

Funding: The study was conducted within the framework of Russian Science Foundation (regional contest) project No 22-27-20151.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to A.L. Zemnukhov and R.Y. Zhelonkin from Almazy Anabara JSC for contributing to the collection of the placer material in the field, as well as their colleagues from DPMGI SB RAS who participated in analytical and laboratory work.

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

Appendix A

Table A1. Representative analyses of platinum group minerals from placers Anabar R., wt.%.

Sample	Pt	Ir	Os	Ru	Rh	Pd	Fe	Ni	Cu	Total
					Fe–Pt alloys					
99/95	87.42	1.25	0.03	0.04	0.03	0.23	9.84	0.13	0.92	99.89
52/95	86.24	3.68	0.13	0.01	0.24	0.00	9.21	0.11	0.76	100.38
49/95	71.68	0.30	0.08	0.05	0.40	10.00	14.66	0.06	1.65	98.88
93/95	83.40	1.54	0.17	0.01	0.59	0.11	11.58	1.13	0.87	99.40
83/95	86.39	0.66	0.18	0.00	0.67	0.05	10.16	0.11	2.49	100.71
87/95	86.35	2.85	1.16	0.32	0.87	0.09	7.27	0.75	0.30	99.96
80/95	78.56	10.05	1.77	0.17	1.21	0.06	6.88	0.26	0.54	99.50
77/95	86.31	0.93	0.25	0.00	1.27	0.20	9.65	0.10	1.01	99.72
67/95	82.20	4.16	0.64	0.39	1.59	0.03	10.57	0.31	0.41	100.30
89/95	70.42	12.53	1.11	1.46	2.46	0.07	9.77	0.53	0.46	98.81
63/95	82.84	0.43	0.11	0.50	2.65	0.07	12.49	0.18	1.02	100.29
59/95	78.75	1.15	0.51	1.92	6.61	0.15	10.43	0.39	0.55	100.46
76/95	73.23	0.97	0.89	4.08	8.23	0.15	11.66	0.17	0.61	99.99
24/16	72.11	0.99	1.49	6.90	6.89	2.73	7.11	0.32	0.40	98.94
25/16	73.63	2.99	1.87	8.38	3.61	1.58	8.15	0.38	0.40	100.98
81/78	75.87	0.00	0.32	2.81	11.12	1.06	7.16	0.26	0.30	98.90
					Ru–Ir–Os alloys					
96/95	0.41	38.28	60.34	0.57	0.28	0.04	0.04	0.02	0.07	100.05
70/95	0.31	25.64	70.63	2.48	0.06	0.15	0.17	0.05	0.06	99.55
32/72	2.23	30.16	63.50	2.56	0.71	0.00	0.26	0.00	0.00	99.42
80/78	2.45	38.20	50.05	7.53	0.36	0.00	0.09	0.03	0.06	98.77
61/95	4.08	38.82	41.99	14.74	0.38	0.06	0.17	0.05	0.03	100.32
56/95	1.86	35.94	39.98	21.89	0.05	0.04	0.26	0.08	0.08	100.18

Table A2. Representative analyses of porpezite, skaergaardite [1] and Cu–Au–Pd alloy [2], wt.%.

Sample	Au	Ag	Cu	Hg	Pd	Total
			Mayat river			
4/158	96.06	2.62	0.00	0.34	0.77	99.79
11/158	93.65	2.75	0.02	0.17	2.20	98.79
7/158	92.59	1.21	0.13	0.03	5.76	99.72
37/154	89.78	0.91	3.00	-	6.37	100.07
29/154	87.91	1.54	0.37	0.06	9.43	99.31
6/158	85.51	1.09	0.25	0.04	12.83	99.72
Ma-1 [1]	7.24	0.10	26.94	-	54.42	98.88 *

Table A2. *Cont.*

Sample	Au	Ag	Cu	Hg	Pd	Total
			Bolshaya Kuonamka river			
97/104	97.10	2.07	0.13	-	0.73	100.03
183/104	95.66	0.65	0.79	0.06	2.50	99.67
225/104	94.86	0.67	0.68	1.40	1.44	99.05
Vp-1–1	94.28	3.94	0.89	0.13	1.45	100.70
Vp-1–2	93.26	0.70	1.54	0.55	2.93	98.98
Vp-1–3	91.69	1.06	4.17	0.07	3.08	100.70
Vp-1–4	93.13	1.68	0.15	0.05	4.96	99.97
Vp-1–5	89.84	1.13	0.05	0.08	7.47	98.58
			Malaya Kuonamka river			
MK-11 [2]	38.50	-	17.37	-	39.37	95.24

Note: dash—content of the element is below the sensitivity of the microprobe analysis method; *—the total also includes 7.43% Pt and 1.64% Fe.

References

1. Rozhkov, I.S.; Mikhalev, G.P.; Prokopchuk, B.I.; Shamshina, E.A. *Diamond-Bearing Placers of the Western Siberian Platform*; Nauka: Moscow, Russia, 1967. (In Russian)
2. Grakhanov, S.A.; Shatalov, V.I.; Shtyrov, V.A.; Kychkin, V.R.; Suleymanov, A.M. *Diamond Placers of Russia*; Academic Publishing House "Geo": Novosibirsk, Russia, 2007. (In Russian)
3. Shpunt, B.R. Platinum minerals in Quaternary deposits of the Anabar-Olenek Uplift. *Geol. Rudn. Mestorozhdenii* **1970**, *2*, 123–126. (In Russian)
4. Shpunt, B.R. Typomorphic features and genesis of placer gold in the north of the Siberian platform. *Geol. Geophys.* **1974**, *9*, 77–78. (In Russian)
5. Okrugin, A.V.; Izbekov, E.D.; Shpunt, B.R.; Leskova, N.V. Platinum metal minerals of anthropogenic deposits of the Vilyui syneclise and Anabar anteclise. In *Typomorphism and Geochemical Features of Minerals of Endogenous Formations of Yakutia*; Publishing House YSC: Yakutsk, Russia, 1985; pp. 40–50. (In Russian)
6. Okrugin, A.V. Placer platinum content of the Lena province. *Otechestvennaya Geol.* **1997**, *9*, 29–32. (In Russian)
7. Okrugin, A.V.; Grakhanov, S.A.; Selivanova, V.V.; Popov, A.A. Gold and platinum in diamond-bearing placers of Western Yakutia. *Sci. Educ. Yakutsk* **2000**, *3*, 19–22. (In Russian)
8. Gerasimov, B.B.; Nikiforova, Z.S. Placer gold content of the Mayat river of the Anabar river basin. *Otechestvennaya Geol.* **2005**, *5*, 38–41. (In Russian)
9. Okrugin, A.V.; Kim, A.A. Topomineralogy of platinoids from placers of the Eastern part of the Siberian platform. In *Rare Native Metals and Intermetallides of the Primary and Placer Deposits of Yakutia*; Publishing House YSC: Yakutsk, Russia, 1992; pp. 77–102. (In Russian)
10. Okrugin, A.V.; Kim, A.A.; Izbekov, E.D.; Shpunt, B.R.; Selivanova, V.V.; Filippov, V.E.; Blinov, A.A.; Mikhailov, V.A.; Zolotonog, A.V.; Surnin, A.A. Platinum-bearing placers of the Siberian Platform and their prospects. In *Platinum of Russia: Problems of Development of the Mineral Resource Base of Platinum Metals in the XXI Century*; Book 2; CJSC Geoinformmark: Moscow, Russia, 1999; Volume 3, pp. 319–333. (In Russian)
11. Okrugin, A.; Tolstov, A.; Baranov, L.; Zemnukhov, A. Lena-Anabar precious-rare-metal-diamond-bearing metallogenic province. In *Geology and Mineral Resources of the North-East of Russia: Materials of the X All-Russian Scientific and Practical Conference with International Participation*; NEFU Publishing House: Yakutsk, Russia, 2020; pp. 272–277. (In Russian)
12. Porshnev, G.I.; Stepanov, L.L. Geology and mineralogy of the Udzhinsky province (north-west of the Yakut ASSR). *Sov. Geol.* **1981**, *12*, 103–106. (In Russian)
13. Milashev, V.A.; Tomanovskaya, Y.I. Occurrences of Alkaline-Ultrabasic Magmatism in the Coastal Part of the Laptev Sea. In *Kimberlite Volcanism and Prospects of the Primary Diamond Content of the Siberian Platform*; Publishing House NIIGA: Leningrad, USSR, 1971; pp. 127–133. (In Russian)
14. Okrugin, A.V.; Zaitsev, A.I.; Borisenko, A.S.; Zemnukhov, A.L.; Ivanov, P.O. Gold-platinum-bearing placers deposits in the river basin of Anabar and their possible relation to alkali-ultrabasic magmatic rocks in the northern Siberian platform. *Otechestvennaya Geol.* **2012**, *5*, 11–20. (In Russian)
15. Muzyka, G.M.; Chumirin, K.G. Manifestation of maimechit analogues on the southern margin of the Anabar massif. In *Geology, Petrography and Mineralogy of Magmatic Formations of the Northeastern Part of the Siberian Platform*; Nauka: Moscow, Russia, 1970; pp. 183–190. (In Russian)
16. Okrugin, A.V. *Platinum-Bearing Placers of the Siberian Platform*; Publishing House YaF SO RAN: Yakutsk, Russia, 2000. (In Russian)

17. Afanasiev, V.P.; Lobanov, S.S.; Pokhilenko, N.P.; Koptil', V.I.; Mityukhin, S.I.; Gerasimchuk, A.; Pomazanskii, B.; Gorev, N. Polygenesis of diamonds in the Siberian platform. *Russ. Geol. Geophys.* **2011**, *52*, 259–274. [CrossRef]
18. Grakhanov, S.A.; Smelov, A.P. Age of predicted primary sources of diamonds in northern Yakutia. *Otechestvennaya Geol.* **2011**, *5*, 56–63. (In Russian)
19. Okrugin, A.V.; Mazur, A.B.; Zemnuhov, A.L.; Popkov, P.A.; Sleptsov, S.V. The palladium gold-PGM association in the placers of the Anabar River basin, NE part of the Siberian platform, Russia. *Otechestvennaya Geol.* **2009**, *5*, 3–10. (In Russian)
20. Gerasimov, B.B.; Nikiforova, Z.S.; Pavlov, V.I. Mineralogical and geochemical characteristics of placer gold in the Bolshaya Kuonamka river. *Educ. Sci. Yakutsk, Russia.* **2014**, *3*, 74–78. (In Russian)
21. Okrugin, A.V.; Gerasimov, B.B. Magmatogenic paragenesis of platinum and palladium gold in placers of the Anbar river on the Siberian platform. In Proceedings of the Geology and Mineral Resources of the North-East of Russia: Materials of the XII All-Russian Scientific and Practical Conference Dedicated to the 65th Anniversary of the Institute of Geology of Diamond and Precious Metals, Siberian Branch of the Russian Academy of Sciences, Yakutsk, Russia, 23–25 March 2022; pp. 224–229. (In Russian).
22. Cabri, L.J.; Laflamme, J.H.G. Rhodium, platinum and gold alloys from the Stillwater Complex. *Can. Mineral.* **1974**, *12*, 399–403.
23. Kingston, G.A.; El-Dosuky, B.T. A Contribution on the platinum-group mineralogy of the Merensky reef at the Rustenburg platinum mine. *Econ. Geol.* **1982**, *77*, 1367–1384. [CrossRef]
24. Cabri, L.J. (Ed.) *Platinum-Group Elements: Mineralogy, Geology, Recovery*; Canadian Institute of Mining and Metallurgy: Montreal, QC, Canada, 1989; Volume 23, p. 267.
25. Krivenko, A.P.; Tolstykh, N.D.; Veselovsky, N.N.; Mayorova, O.N. Gold-bearing tellurides of platinoids and palladium gold in gabbro-norites of the Pana massif, Kola Peninsula. *Rep. AS USSR* **1991**, *319*, 725–729. (In Russian)
26. Nekrasov, I.Y.; Lennikov, A.M.; Oktyabrsky, R.A.; Zalishchak, B.L.; Sapin, V.I. *Petrology and Platinum Potential of Ring Alkaline-Ultrabasic Complexes*; Nauka: Moscow, Russia, 1994. (In Russian)
27. Cabri, L.J.; Harris, D.C.; Weiser, T.W. Mineralogy and distribution of platinum-group mineral placer deposits of the Wold. *Expl. Min. Geol.* **1996**, *5*, 73–167.
28. Tarbaev, M.B.; Kuznetsov, S.K.; Moralev, G.V.; Soboleva, A.A.; Laputina, I.P. New gold-palladium type of mineralization in the Kozhim region of Circumpolar Ural (Russia). *Geol. Ore Depos.* **1996**, *1*, 15–30. (In Russian)
29. Bozhko, E.N. Problem of the hard-rock types of the auriferous-plstiniferous mineralization of the Matagania-Sigiri structural-formational zone (Guinea, West Africa). *Proc. Voronezh State Univ. Geol.* **2005**, *1*, 193–203. (In Russian)
30. Badanina, I.Y.; Malich, K.N.; Goncharov, M.M.; Tuganova, E.V. Precious-metal placers of the Gulinsky massif (north of the Siberian platform): Native gold: Typomorphism of mineral associations and conditions of deposit formation. In *Proceedings of the All-Russian Conference*; IGODPMG RAS: Moscow, Russia, 2010; Volume 1, pp. 56–58. (In Russian)
31. Okrugin, A.V.; Okhlopkov, S.S.; Grakhanov, S.A. Complex placer occurrences of precious metals and gems in the Anabar river basin (northeast of the Siberian Platform). *Otechestvennaya Geol.* **2008**, *5*, 3–13. (In Russian)
32. Gerasimov, B.B.; Nikiforova, Z.S. Assumed mineragenic types of the primary sources of gold of the Anabar region (northeast of the Siberian Platform). *Sci. Educ.* **2017**, *2*, 11–16. (In Russian)
33. Tolstov, A.V. Prospects for the gold content of Anabar anteclise. *Bull. Goskomgeol.* **2002**, *1*, 44–49.
34. Smelov, A.P.; Berezkin, V.I.; Zedgenizov, A.N. New data on the composition and ore content of the Kotuikan zone of tectonic melange. *Otechestvennaya Geol.* **2002**, *4*, 45–49. (In Russian)
35. Cabri, L.J.; Feather, C.Z. Platinum-iron alloys: A nomenclature based on studi of natural end sinthetic alloys. *Can. Mineral.* **1975**, *13*, 117–126.
36. Dmitrenko, G.G. *Platinum-Group Minerals of Alpine-Type Ultramafites*; Publishing House SVKNII: Magadan, Russia, 1994. (In Russian)
37. Balmasova, E.A.; Smol'skaya, L.S.; Lopatin, G.G.; Lazarenkov, V.G.; Malitch, K.N. Native osmium and iridosmine in the Gulinsky massif. *Trans. Russ. Acad. Sci. Earth Sci. Sect.* **1992**, *325*, 154–157.
38. Likhachev, A.P.; Kirichenko, V.T.; Lopatin, G.G.; Kirichenko, A.A.; Deryagina, G.G.; Rudashevskiy, N.S.; Botova, M.L. Distinctive features of platinum occurrences in the massifs of alkali ultrabasic formations. *Zap. Vses. Mineral. Obsh.* **1987**, *1*, 122–125. (In Russian)
39. Sazonov, A.M.; Romanovskii, A.E.; Grinev, O.M.; Lavrent'ev, Y.G.; Maiorova, O.N.; Pospelova, L.N. Precious-metal mineralization of the Gulinskaya intrusion. *Russ. Geol. Geophys.* **1994**, *9*, 51–65.
40. Malitch, K.N.; Rudashevsky, N.S. Bedrock platinum-metal mineralization in chromitite of the Guli massif. *Trans. Russ. Acad. Sciences. Earth Sci. Sect.* **1992**, *327*, 165–169.
41. Malitch, K.N.; Kogarko, L.N. Chemical composition of platinum-group minerals from the Bor-Uryakh massif (Maimecha-Kotui Province, Russia). *Dokl. Earth Sci.* **2011**, *440*, 1455–1459. [CrossRef]
42. Harris, D.C.; Cabri, L.J. Nomenclature of platinum-group-element alloys: Review and revision. *Can. Mineral.* **1991**, *29*, 231–237.
43. Razin, L.V. Minerals—Natural alloys of gold and copper in ores of copper-nickel deposits of the Norilsk type. *Proc. Fersman Mineral. Mus.* **1975**, *24*, 93–106. (In Russian)

44. Holwell, D.A.; Blanks, D.E. Emplacement of magmatic Cu-Au-Te(-Ni-PGE) sulfide blebs in alkaline mafic rocks of the Mordor Complex, Northern Territory, Australia. *Miner. Depos.* **2020**, *56*, 789–803. [CrossRef]
45. Bukhanova, D.S.; Kutyrev, A.V.; Sidorov, E.G.; Chubarov, V.M. The first finding of platinum group minerals in the Malmyzh gold-copper porphyry deposit, Khabarovsk region, Russia. *Zapiski RMO Proc. Russian Miner. Soc.* **2020**, *149*, 54–64. (In Russian)