

# Au-Pb compounds in nature: A general overview and new evidence from the Inagli Pt–Au placer deposit, the Aldan Shield, Russia



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## ABSTRACT

This study presents a new and first finding of Au-Pb intermetallic compounds in the Inagli Pt–Au placer deposit, the Republic of Sakha (Yakutia), Russia. This is the first time that all three accepted minerals (hunchunite, anyuiite and novodneprite), as well as unnamed Au-Pb intermetallics, corresponding in composition to Au<sub>1.5</sub>Pb and AuPb, are present together in the same locality. We provide chemical compositions of Au-Pb compounds and host gold particles, describe morphology and relationships between different mineral phases. We also present an unexpected finding of unusual inclusion of Pb-Fe-aluminosilicate associated with K-feldspar and anyuiite in the gold grain. The new data together with data from other occurrences of Au-Pb compounds worldwide were reviewed to discuss type localities, mineralogy, conditions and possible mechanisms of formation of Au-Pb intermetallics and to provide an overview of current knowledge about these uniquely rare but naturally occurring minerals.

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## 1. Introduction

Intermetallics of Au and Pb are uniquely rare minerals discovered in the late 1980s, despite the possibility of their finding in nature predicted by experimental studies in the 1950s (Hansen and Anderko, 1958), and the earliest references dating back to 1827 (Voznesenskij and Zolotova, 1986). Nowadays, three intermetallic Au-Pb compounds are discovered: (1) anyuiite AuPb<sub>2</sub> (the Anyui River, Russia; Razin and Sidorenko, 1989), (2) hunchunite Au<sub>2</sub>Pb (the Hunchun River, China; Wu et al., 1992), and (3) novodneprite AuPb<sub>3</sub> (the Novodneprovskoe gold deposit, Kazakhstan; Dyusembaeva et al., 2006). All three minerals are approved by the International Mineralogical Association Commission on new minerals and mineral names.

Cases of findings of Au-Pb intermetallics as well as their chemical compositions are poorly covered in the literature. The first and subsequent records of these compounds reported predominantly from placers (Murzin et al., 1996; Khazov et al., 2010; Sandimirova et al., 2014) have caused to consider these intermetallics as being an exclusively authigenic in origin

(Voznesenskij and Zolotova, 1986; Khazov et al., 2010). However, there are several publications in which Au-Pb compounds are referred from bedrocks, not placers (Nekrasov et al., 1988; Alexandrov and Barannikov, 2012; Ferraris and Lorand, 2015), although Au-Pb minerals are poorly described therein. And only a recent study of Molnár et al. (2016) in which hunchunite is reported from hydrothermal gold-uranium veins at the Rompas deposit, northern Finland, represents a strong evidence for hypogene origin of Au-Pb intermetallics. Nevertheless, after 30 years of active geological investigations (or 190 years including the earliest references to Au-Pb minerals), Au-Pb compounds remain extremely poorly studied and their origin is still unclear.

This paper presents a new and first finding of Au-Pb compounds in the Inagli Pt–Au placer deposit, the Republic of Sakha (Yakutia), Russia. This is the first time that all three accepted minerals (hunchunite, anyuiite and novodneprite), as well as unnamed Au-Pb intermetallics, corresponding in composition to Au<sub>1.5</sub>Pb and AuPb, are present together in the same locality. We provide chemical compositions of Au-Pb compounds and host gold particles, describe morphology and relationships between different mineral phases. We also present an unexpected finding of unusual inclusion of Pb-Fe-aluminosilicate associated with K-feldspar and anyuiite in the gold grain. This indicates that Au-Pb compounds

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may be formed involving potassic fluids. In addition, we are reviewing all available cases of occurrence of Au-Pb intermetallics in nature with the aim to summarize the current knowledge about their type localities, mineralogy, conditions and mechanisms of formation.

## 2. Geological setting

The Inagli platiniferous placer deposit in the upper reaches of the Inagli River is located in the central part of the Aldan Shield, some 30 km west of the town of Aldan (Yakutia, Russia) (Fig. 1). The placer is confined to the Inagli concentrically zoned massif, which is one of the several Uralian–Alaskan-type alkaline-ultramafic complexes in the Aldan Shield, considered to be source of platinum group minerals (mainly Pt-Fe alloys) in the placer (Tolstykh and Krivenko, 1997; Okrugin, 2001; Malitch and Thalhammer, 2002). However, a small amount of native gold (up to 5% of total production, according to Boyarko and Dik (2000)) is also present in the Inagli placer deposit (Litvintsev et al., 2005; Okrugin et al., 2013, 2014; Svetlitskaya et al., 2017).

The Aldan Shield accommodates numerous ore deposits of gold, uranium, platinum group minerals, rare, non-ferrous and ferrous metals. Its geology and metallogeny are considered in numerous studies (Popov and Smelov, 1996; Popov et al., 1999; Parfenov et al., 2003; Shatkov and Volsky, 2004; Smelov and Timofeev, 2007; Goroshko et al., 2010; Khomich and Boriskina, 2010; Khomich et al., 2015; Maximov et al., 2010, etc.). The Aldan Shield consists of the ancient Precambrian crystalline basement comprised of several large tectono-metamorphic units («superterranes») separated by tectonic mélangé zones. The basement is overlain by Vendian (Ediacaran)–Cambrian terrigenous–carbonaceous sequences and locally developed Jurassic and Paleogene–Neogene clastic sedimentary basins. Both the basement and pre-Cenozoic sedimentary cover are intruded by Mesozoic magmatic rocks, which are represented by several Middle Jurassic to Early Cretaceous calc-alkaline to K-alkaline complexes.

The Inagli massif and related Pt–Au placer deposit are situated in the Aldan–Trompton (Central Aldan) area of the Aldan Shield, at the intersection of two deep NW- and NE-trending faults. The

massif is a circular body  $\sim 20 \text{ km}^2$  in area with a concentrically zoned structure (Fig. 1). The core of the massif ( $\sim 16 \text{ km}^2$  in area) consists of dunite, surrounded by a rim of Mesozoic alkaline rocks (shonkinite, pyroxene and alkaline syenite) (Rozhkov et al., 1962; Smirnov, 1977; Korchagin, 1996; Mues-Schumacher et al., 1996; Ibragimova et al., 2015). The host rocks of the Inagli massif are Archean gneisses and amphibolites, Late Neoproterozoic to Cambrian clastic–carbonaceous sequences, and Upper Jurassic to Lower Cretaceous sills and dykes of syenite- and syenite-diorite-porphyrries.

The Inagli Pt–Au placer deposit is hosted by modern alluvial sediments of the Inagli River that drains the area covered mainly by dunite. However, alkaline ring complexes of the Inagli massif as well as the surrounding Cambrian sedimentary and Mesozoic magmatic rocks also contributed to the placer (Fig. 1). Morphology and microchemical signatures of the Inagli placer gold were reported in several studies (Litvintsev et al., 2005; Okrugin et al., 2013, 2014; Svetlitskaya et al., 2017). However, its bedrock source(s) has not yet been identified. As a potential lode gold source, diopside–magnetite skarns developed at the contact of Mesozoic syenite porphyry with Cambrian dolomites south of the Inagli massif has been proposed (Korchagin, 1996). Svetlitskaya et al. (2017) reported three distinct types of gold in the Inagli placer, among them the gold with Au-Pb compounds + K-feldspar inclusions – the main objectives of this study – was classified as the separate type 3 gold. Microchemical characteristics of this gold type have been interpreted as suggestive of an alkaline–magmatic-related fluid. The authors concluded that potential bedrock sources for type 3 gold could be related to the numerous alkaline veins and potassic alteration zones within the dunite core, with the distance from the sampling site to the potential bedrock source of <300 m (Svetlitskaya et al., 2017).

## 3. Sampling and analytical methods

A sample of placer gold for this study was obtained from the heavy mineral fraction extracted from modern alluvial sediments of the Inagli River, within the Inagli Pt–Au placer deposit. The location of the sampling site is shown in Fig. 1. The scanning electron

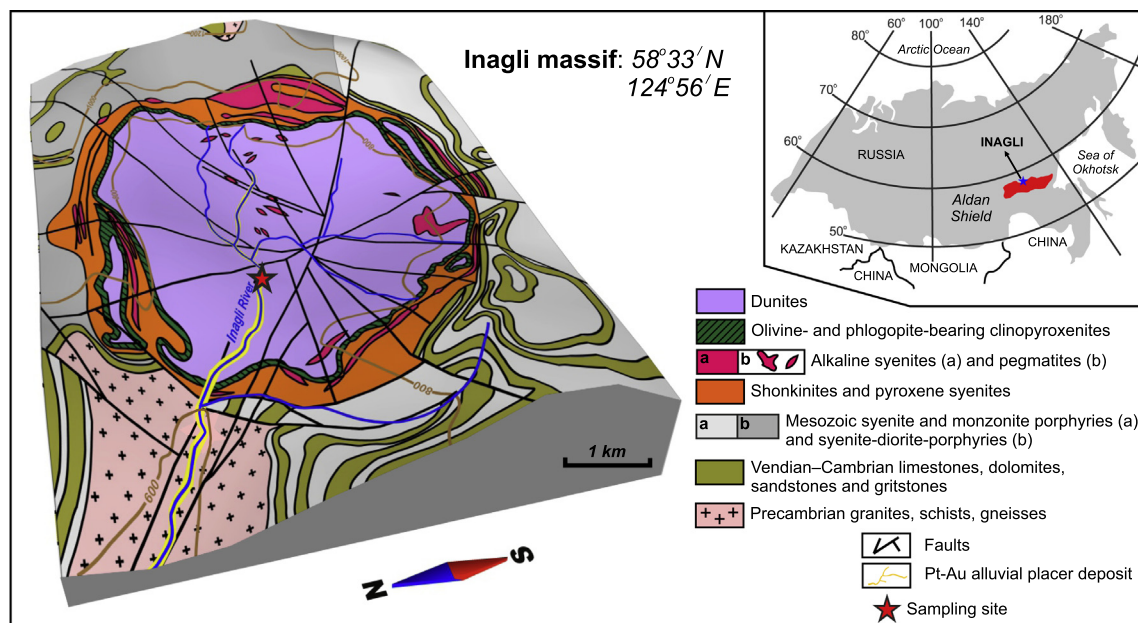


Fig. 1. Simplified geological map of the Inagli massif with the location of the Pt–Au alluvial placer deposit and the sampling site. Modified after Korchagin (1996), with some additions.

microscopic investigation of gold grains revealed 5 of the 70 grains associated with Au–Pb intermetallics or/and Pb-bearing aluminosilicate compounds. These gold grains have been examined in detail.

All studies were carried out at the Analytical Center for multi-elemental and isotope research of the Sobolev Institute of Geology and Mineralogy in Novosibirsk, Siberian Branch of the Russian Academy of Sciences, Russia. Back-scattered electron (BSE) images as well as composition of very small (few microns) or complex inclusions were obtained from the polished sections using a scanning electron microscope (SEM) TESCAN MIRA 3 LMU operated at 20 kV equipped with an INCA Energy 450 XMax 80 (Oxford Instruments) microanalysis system. Quantitative chemical analyses (EMPA) were made using a Camebax-micro electron microprobe. Minerals were analyzed by a focused beam in spot mode of 2  $\mu\text{m}$  at an accelerating voltage of 20 kV, counting times of 20 s, and a beam current of 60 nA. For Au–Ag alloys and Au–Pb compounds, the standards used were:  $\text{Au}_{75}\text{Ag}_{25}$  ( $\text{AuM}\alpha$ ;  $\text{AgL}\alpha$ ), Cu–met ( $\text{CuK}\alpha$ ), HgTe ( $\text{HgM}\beta$ ), PbTe ( $\text{PbM}\alpha$ ), and  $\text{Sb}_2\text{S}_3$  ( $\text{SbL}\alpha$ ) (not used in the case of Au–Ag alloys). The detection limits for individual elements were: 0.07 wt% for Au, 0.07 wt% for Ag, 0.06 wt% for Cu, 0.07 wt% for Hg, 0.04 wt% for Pb, and 0.08 wt% for Sb. For Pb–Au–Fe–Ca–Al–Si compounds, the standards used were O-145 (pyrope) ( $\text{FeK}\alpha$ ;  $\text{AlK}\alpha$ ;  $\text{SiK}\alpha$ ;  $\text{CaK}\alpha$ ), PbS ( $\text{PbM}\alpha$ ),  $\text{Au}_{75}\text{Ag}_{25}$  ( $\text{AuM}\alpha$ ;  $\text{AgL}\alpha$ ), ZnS ( $\text{ZnK}\alpha$ ), IGEM (Mn garnet) ( $\text{MnK}\alpha$ ), and GL-6 (glass) ( $\text{TiK}\alpha$ ). Estimated detection limits were: 0.02 wt% for Fe, 0.01 wt% for Al, 0.01 wt% for Si, 0.035 wt% for Pb, 0.03 wt% for Au, 0.04 wt% for Ag, 0.03 wt% for Zn, 0.02 wt% for Mn, 0.01 wt% for Ca, 0.01 wt% for Ti. During Camebax-micro electron-microprobe investigation of Pb–Au–Fe–Ca–Al–Si compounds, we attempted to estimate the concentrations of any other elements using a Kevex Analyst 8000 energy dispersive spectrometer, but only Fe, Al, Si, Pb, Au, Ca, Zn, and Ti were detected.

## 4. Results

### 4.1. Host gold grains

Placer gold particles in association with Au–Pb and Pb–(Au)–Fe–Ca–Al–Si–O compounds are represented by irregularly-shaped grains with dimensions of 0.1–0.3 mm composed of Au–Ag alloys with a fineness ( $\text{Au}^*1000/(\text{Au} + \text{Ag})$ ; Hallbauer and Utter, 1977) of 918–950 (Fig. 2a–e). In respect to the silver distribution, the gold grains are predominantly homogeneous (5–8 wt% Ag in both the cores and margins); only one grain shows a restrictedly developed rim that is richer in gold than the core (6 wt% Ag in the core against 1 wt% Ag in the rim) (Fig. 2c). The concentrations of minor alloying elements in the gold grain cores are 0.55–1.0 wt% for Hg, 0.11–0.22 wt% for Pb and up to 0.1 wt% for Cu. In the gold grain margins, the contents of Hg, Pb and Cu stayed the same or slightly decreased. In the Au-rich rim, the decrease in Ag level is accompanied by a sharp reduction in Hg (from 1.0 wt% Hg in the core to <0.07 wt% in the rim) and Pb (from 0.22 wt% in the core to 0.06 wt% in the rim), but Cu levels (0.07–0.09 wt%) have remained largely constant.

### 4.2. Au–Pb compounds

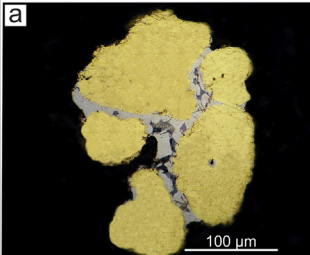
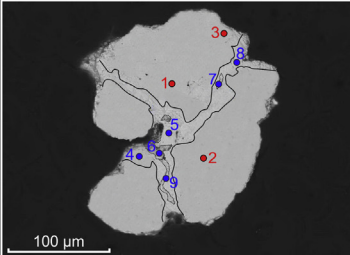
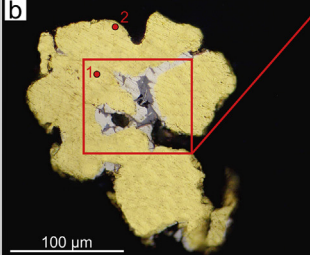
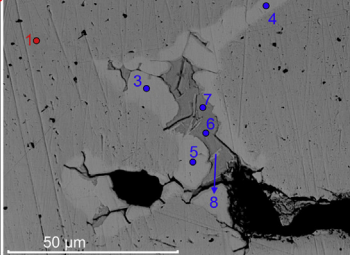
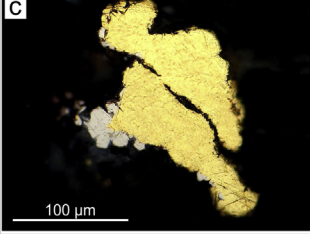
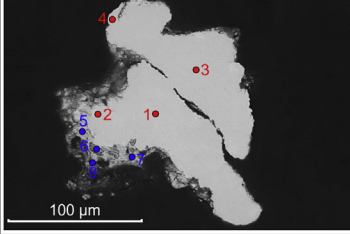
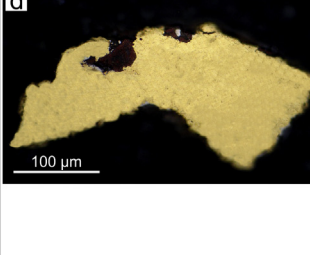
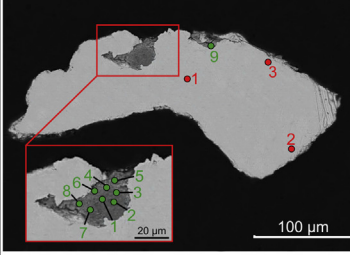
The Au–Pb( $\pm$ Sb) intermetallic compounds occur as veinlets ( $\sim$ 2–55  $\mu\text{m}$  thick) cross-cutting placer gold particles (Fig. 2a, b), partial rims ( $\sim$  10–25  $\mu\text{m}$  thick) on the periphery of ones (Fig. 2c), or as small inclusions (up to 15  $\mu\text{m}$ ) within gold grains (Fig. 2e, f). The results of electron-microprobe and scanning electron microscopic determinations indicate five distinct Au–Pb phases, corresponding to hunchunite ( $\text{Au}_2\text{Pb}$ ), novodneprite ( $\text{AuPb}_3$ ), anyuiite ( $\text{AuPb}_2$ ),  $\text{Au}_{1.5}\text{Pb}$  and AuPb (Fig. 2).

Two types of Au–Pb veinlets in terms of mineralogy and structure are recognized: (i) simple veinlets composed of hunchunite with vein-like inclusions of Sb-bearing anyuiite (0.1–0.5 wt% Sb),  $\text{Au}_{1.5}\text{Pb}$ , and AuPb compounds (Fig. 2a); (ii) complex veinlets with zonal structure, showing a central zone consisting of Sb-bearing novodneprite (0.6–0.7 wt% Sb) with needle-like inclusions of Sb-bearing anyuiite (12.2 wt% Sb) and an outer zone composed of hunchunite (Fig. 2b). In both cases, hunchunite contains from 0.1 to 5.3 wt% Ag, the level of which varies depending on its location within the gold grain and in relation to more Pb-rich phases (Fig. 2a, b). The contact between Au–Pb veinlets and the host gold is gradual to abrupt, irregularly-shaped and, in general, has a replacement habit. Partial rims of Au–Pb compounds on the periphery of gold grains also show zoning: the inner part of the rim consists of hunchunite, and the outer part comprises AuPb with inclusions of anyuiite (Fig. 2c). All Au–Pb phases are Ag- and Sb-free. The contact between the Au–Pb rim and the gold is not clear, but is abrupt and has an irregular shape. Inclusions of Au–Pb compounds, enclosed within the gold grains, are identified as monomineralic and consist of anyuiite, which is Ag-free and contains 0.2 wt% Sb (Fig. 2e). Although the host gold grains contain stable elevated Hg (0.4–1.0 wt%) contents, Au–Pb compounds only occasionally show detectable levels of this element (Fig. 2).

### 4.3. Pb–(Au)–Fe–Ca–Al–Si–O compounds

One gold grain is observed in association with an unusual compound of gold and oxides of lead, silicon, and aluminium, with minor iron and calcium (Fig. 2d). This compound occurs as irregular patches (20–55  $\mu\text{m}$  long and up to 15  $\mu\text{m}$  wide) in the gold grain margins. The contact of Pb–(Au)–Fe–Ca–Al–Si compounds with the host gold is embayed and irregular, but generally abrupt. According to a scanning electron microscopic investigation, Pb–(Au)–Fe–Ca–Al–Si compounds contain 24.18–24.28 wt% Pb, 16.05–17.94 wt% Au, 12.33–13.10 wt% Al, 11.85–12.49 wt% Si, 0.21–0.27 wt% Ca, and 32.08–35.23 wt% O (two compositional determinations). Results of quantitative electron microprobe analyses from 9 points throughout the patches yield the following compositional range: 20.92–29.12 wt% PbO, 8.20–23.64 wt% Au, 23.65–26.52 wt%  $\text{Al}_2\text{O}_3$ , 25.80–33.22 wt%  $\text{SiO}_2$ , 0.33–0.46 wt% CaO, 0.55–0.73 wt% FeO, with occasional ZnO (up to 0.13 wt%) and  $\text{TiO}_2$  (0.23 wt%). There is a constant deficit in the sums (91.81–97.83 wt%) (Fig. 2d), however, no other element has been detected by a Kevex energy dispersive spectrometer. Although a SEM examination did not reveal significant non-homogeneity in the structure of Pb–(Au)–Fe–Ca–Al–Si compounds, we believe they may well be a mixture of several compounds, and Au contents are probably from the host gold matrix. It is also important to note that there is no evidence that Pb is present in form of oxide in these unusual Pb–(Au)–Fe–Ca–Al–Si–O compounds.

Of particular interest is the finding of unusual inclusion of Pb–Fe–aluminosilicate associated with K-feldspar within another gold particle (Fig. 2e, f). Unfortunately, although the inclusion has the size suitable for electron microprobe determination ( $\sim$ 40  $\mu\text{m}$  long and up to 17  $\mu\text{m}$  wide), it is polyminerally, and the constituent phases are fine-grained and mixed; for this reason, only a SEM study was carried out. The results show that the inclusion consists of rounded grains of K-feldspar (Point 7 in Fig. 2f, (in wt%): K 14.00, Al 10.96, Si 30.35, O 44.03; Point 8 in Fig. 2f, (in wt%): K 13.47, Al 9.54, Si 29.97, O 45.33) enclosed in matrix of Pb–Fe aluminosilicate (Point 6 in Fig. 2f, (in wt%): Pb 26.20, Fe 11.78, K 1.19, Mg 0.80, Ca 0.68, Al 10.96, Si 14.62, O 32.84) and is rimmed by Sb-bearing (0.35 wt% Sb) anyuiite. Another analysis (Point 9 in Fig. 2f) showed a lower content of Pb (14.76 wt%), Fe (2.16 wt%), Mg (0.56 wt%), Ca (0.38 wt%), and Al (9.95 wt%) and a higher content of K (7.73 wt%) and Si (22.53 wt%) compared to Pb–Fe aluminosilicate from Point 6,

Microphotographs (reflected light)	Back-scattered-electron images	Point	EPMA content, wt. %							Formula / mineral
			Au	Ag	Cu	Hg	Pb	Sb	Total	
		1	90.41	8.04	0.03	0.60	0.19	na	99.27	Gold (core)
		2	90.63	8.07	0.02	0.74	0.27	na	99.73	Gold (middle)
		3	90.31	8.06	0.03	0.60	0.22	na	99.22	Gold (rim)
		4	66.43	0.23	0.00	0.07	33.91	0.00	100.64	Au <sub>2.06</sub> Ag <sub>0.01</sub> Pb / hunchunite
		5	66.70	0.11	0.00	0.09	33.16	0.02	100.08	Au <sub>2.12</sub> Ag <sub>0.01</sub> Pb / hunchunite
		6	32.94	0.04	0.00	0.00	65.56	0.52	99.06	AuPb <sub>1.89</sub> / anyuuite
		7	32.45	0.26	0.00	0.07	66.94	0.12	99.84	AuPb <sub>1.96</sub> / anyuuite
		8	58.09	5.30	0.03	0.21	36.18	0.02	99.83	Au <sub>1.86</sub> Ag <sub>0.23</sub> Hg <sub>0.01</sub> Pb / hunchunite
		9	58.00	1.17	0.01	0.00	40.66	0.08	99.92	Au <sub>1.50</sub> Ag <sub>0.06</sub> Pb / ?
		1	93.77	5.05	0.03	0.55	0.20	na	99.60	Gold (core)
		2	94.44	4.99	0.06	0.46	0.19	na	100.14	Gold (rim)
		3	64.87	0.53	0.00	0.00	34.57	0.00	99.97	Au <sub>1.97</sub> Ag <sub>0.03</sub> Pb / hunchunite
		4	64.18	1.23	0.00	0.00	34.25	0.02	99.68	Au <sub>1.97</sub> Ag <sub>0.07</sub> Pb / hunchunite
		5	65.24	0.58	0.00	0.04	34.06	0.00	99.92	Au <sub>2.01</sub> Ag <sub>0.03</sub> Pb / hunchunite
		6	26.08	0.04	0.00	0.03	72.88	0.59	99.62	AuPb <sub>2.66</sub> Sb <sub>0.04</sub> / novodneprite
		7	27.26	0.00	0.00	0.00	72.03	0.66	99.95	AuPb <sub>2.51</sub> Sb <sub>0.04</sub> / novodneprite
		8	36.37	0.00	0.00	0.00	51.60	12.21	100.18	AuPb <sub>1.35</sub> Sb <sub>0.54</sub> / anyuuite
		1	91.79	6.60	0.05	0.96	0.15	na	99.55	Gold (core)
		2	91.42	6.19	0.09	0.80	0.17	na	98.67	Gold (rim)
		3	91.84	5.97	0.09	1.02	0.22	na	99.14	Gold (core)
		4	98.62	0.96	0.07	0.00	0.06	na	99.71	Gold (rim)
		5	63.68	0.06	0.00	0.12	36.17	0.01	100.04	Au <sub>1.85</sub> Pb / hunchunite
		6	35.01	0.00	0.00	0.00	65.91	0.09	101.01	AuPb <sub>1.79</sub> / anyuuite
		7	50.99	0.00	0.00	0.19	48.95	0.06	100.19	Au <sub>1.10</sub> Pb / ?
		8	53.03	0.09	0.00	0.30	47.12	0.07	100.61	Au <sub>1.18</sub> Hg <sub>0.01</sub> Pb / ?
		1	92.07	5.99	0.11	0.88	0.17	na	99.22	Gold (core)
		2	93.41	5.49	0.06	0.42	0.15	na	99.53	Gold (rim)
		3	93.86	5.34	0.05	0.55	0.12	na	99.92	Gold (rim)
		1	FeO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	PbO	Au	CaO	Total	mixture of several compounds (?)
		1	0.61	26.52	31.32	24.13	13.97	0.42	96.97	
		2	0.68	26.44	28.44	21.04	18.54	0.39	95.53	
		3	0.61	25.35	28.07	26.80	16.60	0.40	97.83	
		4	0.61	24.66	27.90	28.83	13.38	0.36	95.74	
		5	0.65	26.35	27.58	20.92	15.91	0.41	91.81	
		6	0.55	23.65	26.74	25.63	20.45	0.33	97.35	
7	0.65	24.25	25.80	29.12	11.18	0.44	91.84			
8	0.73	25.45	33.22	23.98	8.20	0.36	91.94			
9	0.66	24.78	26.40	21.03	23.64	0.46	97.06			
The following oxides and elements were also looked for: Ag, TiO <sub>2</sub> , MnO, ZnO, but only the components reported in the Table were detected.										

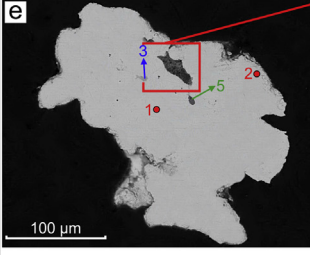
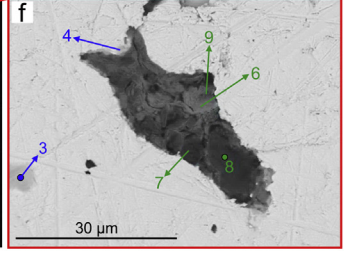
Back-scattered-electron images	Point	EPMA content, wt. %							Formula / mineral		
		Au	Ag	Cu	Hg	Pb	Sb	Total			
		1	93.69	5.56	0.04	0.76	0.13	na	100.18	Gold (core)	
		2	94.05	5.42	0.01	0.37	0.11	na	99.96	Gold (rim)	
		3	33.89	0.00	0.00	0.00	65.28	0.20	99.37	AuPb <sub>1.83</sub> Sb <sub>0.01</sub> / anyuuite	
		SEM content, wt. %									
		4	Au	Ag	Cu	Hg	Pb	Sb	Total		
		4	33.01	0.00	0.00	0.03	65.18	0.35	100.07	anyuuite	
		5	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	FeO	PbO	K <sub>2</sub> O	CaO	MgO	Au	Total
		5	20.22	33.68	14.04	27.74	1.95	0.76	1.34	99.73	Pb-Fe aluminosilicate
		6	20.71	31.27	15.16	28.22	1.43	0.95	1.33	99.07	
7	17.61	64.93	0.00		16.80	0.00	0.00	99.34	K-Fsp		
8	18.03	64.11	0.00		16.17	0.00	0.00	98.31	K-Fsp		
9	18.80	48.20	2.78	15.90	9.28	0.53	0.93	2.95	99.37	K-Fsp + Pb-Fe aluminosilicate(?)	

Fig. 2. The composition of Au-Pb compounds and host gold grains from the Inagli Pt-Au placer deposit, with reflected light photomicrographs and BSE images of the Au-Pb intermetallics in polished sections. Abbreviation: na = not analyzed.

and Au (2.73 wt%) was also identified. This phase apparently is a mixture of K-feldspar and Pb-Fe aluminosilicate, and Au contents are probably from the host gold matrix. Another small ( $\sim 10 \mu\text{m}$ ) inclusion within the same gold particles gives a composition close to that of Pb-Fe aluminosilicate from Point 6 (Point 5 in Fig. 2f, (in wt%): Pb 25.75, Fe 10.91, K 1.63, Mg 0.81, Ca 0.54, Al 10.70, Si 15.74, O 33.65).

## 5. Discussion

### 5.1. Au-Pb compounds from various localities worldwide

#### 5.1.1. Geography and type localities

Scientific records of occurrences of Au-Pb compounds in nature are very rare. Besides the Inagil River placer, intermetallics of gold and lead have been described in no more than 12 localities worldwide (Table 1). They include occurrences of Au-Pb compounds: (i) in bedrocks (the Rompas gold-uranium deposit, Finland (Molnár et al., 2016); the Tetrem gold deposit, Africa (Ramdohr and Evstigneeva, 2011); the Lherz peridotite, France (Ferraris and Lorand, 2015); the Mir kimberlite pipe, Russia (Nekrasov et al., 1988)), (ii) in the oxidized zone of the lode gold deposit (the Novodneprovskoe deposit, Kazakhstan (Dyusembaeva et al., 2006), (iii) in gold-bearing orebodies hosted by weathered volcanic-sedimentary rocks (the Langursko-Alexandrovskaya gold ore zone, Russia (Alexandrov and Barannikov, 2012), and (iv) in gold concentrates from alluvial placers of Russia and China (Voznesenskij and Zolotova, 1986; Razin and Sidorenko, 1989; Wu et al., 1992; Augé et al., 2005; Khazov et al., 2010; Sandimirova et al., 2014).

In bedrock localities, Au-Pb compounds are referred to one of three associations: (1) in gold-bearing hydrothermal calc-silicate veins hosted by metamorphosed mafic rocks – in association with high-fineness gold (up to 1.8 wt% Ag), sulfides (galena, pyrite, pyrrhotite, chalcopyrite, molybdenite), altaite, nickeline, cobaltite, and Pb-bearing maldonite (Molnár et al., 2016), (2) in gold-bearing quartz veins within a shear zone-related fracture at the contact between greenstone and basalt sequences and granitoids – in assemblage with native gold (Ag up to 7.2 wt%; Hg up to 5.7 wt%), electrum, aurostibite, altaite, unnamed  $\text{Au}_6\text{Pb}_5\text{Sb}_3$  ( $\text{Au}_3(\text{Pb}, \text{Sb})_4$ ) mineral, arsenopyrite, and base-metal sulfides (pyrite, galena, sphalerite, chalcopyrite, pyrrhotite, molybdenite) (Ramdohr and Evstigneeva, 2011), and (3) in modified (deformed, serpentized, carbonatized) ultramafic rocks as micrometric inclusions in olivines from orogenic lherzolites (Ferraris and Lorand, 2015) or in gold particles from kimberlites (Nekrasov et al., 1988). In weathering localities, Au-Pb compounds are also related to gold mineralization and occur: (1) in the oxidation zone of the gold deposit within unusual spheroidal aggregates – together with native lead, native gold and auricupride (Dyusembaeva et al., 2006), and (2) in disseminated gold mineralization within weathered volcanic-sedimentary rocks – in association with native gold, tetraauricupride, pyrite, chalcopyrite, galena and sphalerite (Alexandrov and Barannikov, 2012). In placer localities, intermetallics of gold and lead are found in gold (Voznesenskij and Zolotova, 1986; Razin and Sidorenko, 1989; Wu et al., 1992) and PGM (platinum group minerals) – gold deposits (Augé et al., 2005; Khazov et al., 2010; Sandimirova et al., 2014).

It is quite possible that Au-Pb minerals are much more common in nature, and not all cases of finding of these intermetallics were reported and documented in literature properly. For instance, there are some references to Au-Pb compounds in concentrates from the Eastern Shishim River (Central Urals, Russia) (Murzin et al., 1996), in the Nizhne-Tagil'skoye Cu deposit (Urals, Russia), the Dongping Au-Te deposit (Hebei Province, China), the Sandaogou Au deposit

(Jilin Province, China), the Lubin (the Lubin–Sieroszowice ore zone, Lower Silesia (Dolnośląskie), Poland) (data from MINDAT.org (<http://www.mindat.org/min-1949.html>; <http://www.mindat.org/min-271.html>) and WEBMINERAL.COM (<http://www.webmineral.com/data/Hunchunite.shtml>)).

#### 5.1.2. Mineralogy of Au-Pb compounds

Today, only hunchunite is reliably defined in bedrock mineralization as individual grains (the Rompas and Tetrem deposits) (Fig. 3), whereas anyuiite and novodneprite are reported as submicron-sized particles, too small for EMPA examination (the Lherz peridotite, the Mir kimberlite pipe). In gold-bearing oxidized and weathering zones, hunchunite in the form of separate crystals and crystal intergrowths as well as anyuiite and novodneprite as intergrowths with each other are found separately (the Langursko-Alexandrovskaya zone and the Novodneprovskoe deposit, respectively). In placers, Au-Pb compounds are distinguished by a wide range of compositions (Table 1; Fig. 3). Thus, Au-Pb intermetallics from the Hunchun River placer (Jilin province, China) are represented by hunchunite in intergrowth with gold, anyuiite, and native lead. Au-Pb compounds from a placer gold deposit of North-East Russia are characterized by a mixed composition within which anyuiite and novodneprite in association with native Pb can be identified. Au-Pb intermetallics from the Bolshoi Anyui River placer (Chukotka, Russia) correspond in composition to anyuiite occurring in complex intergrowths with native Pb. Among Au-Pb compounds referred from the Ol'khovaya-1 River placer (Kamchatka, Russia), anyuiite and novodneprite are identified reliably in association with native Pb and oxides of Pb. Among intermetallics of Au and Pb from placer gold deposits of the Uralian rivers (Russia), hunchunite can be defined (Augé et al., 2005; Khazov et al., 2010).

As can be seen in Fig. 3, chemical compositions of Au-Pb compounds from different placer localities cluster in two discrete areas: (i) around the composition of hunchunite  $\text{Au}_2\text{Pb}$  and (ii) around the compositional field of anyuiite  $\text{AuPb}_2$  – novodneprite  $\text{AuPb}_3$ , with a displacement of compositions in the Pb-rich region, implying the presence of native Pb. Thus, the following mineral assemblages of Au-Pb compounds can be distinguished based on available literary sources:

- 1) hunchunite (bedrock and weathering localities) (the Rompas and Tetrem deposits; the Langursko-Alexandrovskaya gold ore zone);
- 2) hunchunite + anyuiite + native Pb (placer localities) (the Hunchun River);
- 3) anyuiite + native Pb (placer localities) (the Bolshoi Anyui River);
- 4) anyuiite + novodneprite + native Pb (weathering and placer localities) (the Novodneprovskoe deposit; placers of North-East Russia and the Ol'khovaya-1 River).

A literature review of the compositions of Au-Pb compounds from various localities suggests that there are some relationships between Au–Bi–Pb and Au–Sb–Pb mineral systems. Compositions of Pb-rich maldonite (or Bi-rich hunchunite?) reported by Molnár et al. (2016) from the Rompas Au-U deposit in northern Finland plot on a projected  $\text{Au}_2\text{Pb}$ – $\text{Au}_2\text{Bi}$  tie-line, suggesting that some miscibility can exist between maldonite and hunchunite in the system Au–Bi–Pb (Fig. 4). Compositions of  $\text{Au}(\pm\text{Ag})$ -Pb-Sb compounds from the Ol'khovaya-1 River placer in eastern Kamchatka presented in Sandimirova et al. (2014) include non-stoichiometric (?) anyuiite  $\text{AuPb}_{1.1-1.2}\text{Sb}_{0.5}$ ,  $\text{Au}(\pm\text{Ag})$ -Pb-Sb compounds, depicting Pb– $\text{AuSb}_2$  tie-line (that strongly resemble a mechanical mixture of several mineral phases), and an Au-Pb-Sb compound, corresponding in composition to  $\text{AuPb}_{0.4}\text{Sb}_{1.6}$ , that lies

**Table 1**  
Occurrences of Au-Pb compounds from various localities worldwide.

Mineral	Locality	Type locality	General geological setting	Appearance and associated minerals	Composition (wt. %)	Composition of associated gold	Ref
Hunchunite Au <sub>2</sub> Pb	Rompas Au-U deposit, Peräpohja Schist Belt, Northern Finland	Bedrock	Disseminated Au-U mineralization hosted by deformed calcsilicate veins in amphibolites (metamorphosed mafic rocks).	Discrete grains (1–20 µm large) or tens of microns long ribbon-like, elongated precipitations within the native gold fillings of fractures in uraninite. Associated minerals: galena, altaite, native gold, nickeline, cobaltite, Pb-bearing maldonite, pyrite, pyrrhotite, chalcocopyrite, molybdenite and titanite.	Au 64.78–67.04, Pb 29.72–31.64, Ag 0.0–0.29%; S, Cu, Fe, Mn, Ni, Co, Zn, Sb, Bi, Sn, Te, Cd, Se, As, V, Mo, Hg – b.d.l.	Ag 0.29–1.76 wt%, Cu 0.07–0.97 wt%; Hg – b.d.l.	1
Hunchunite Au <sub>2</sub> Pb	Tetrem gold deposit, Tarkwa area, SW Ghana, West Africa	Bedrock	Disseminated Au mineralization hosted by a quartz vein at the contact between the greenstone and basalt and the granitoids.	In close intergrowths with native gold (contain tiny, <5–10 µm, grains of austrobitite and altaite) and unnamed Au <sub>6</sub> Pb <sub>5</sub> Sb <sub>3</sub> (Au <sub>3</sub> (Pb,Sb) <sub>4</sub> ) mineral. Gold is associated with pyrite, galena, sphalerite, chalcocopyrite, arsenopyrite, pyrrhotite, molybdenite.	No data available	Ag up to 7.2 wt%; Hg up to 5.7 wt%	2
Novodneprite AuPb <sub>3</sub> and anyuiite Au(Pb, Sb) <sub>2</sub>	Lherz peridotite, Eastern Pyrenees, France	Bedrock	Within plastically deformed mantle-derived olivine grains separated from orogenic lherzolite.	Micrometric inclusions in olivine together with nanometric clusters of metallic gold.	Both minerals have been identified through selected area electron diffraction and energy dispersive spectroscopy analyses		3
Au-Pb compounds (a mixture of Au and AuPb <sub>2</sub> ?)	Mir («Peace») kimberlite pipe, Yakutia, Russia	Bedrock	In concentrates separated from serpentized and carbonatized kimberlite.	Inclusions in native gold. Together with inclusions of Au-Pb compounds, inclusions rich in Ni (native nickel or carbide, boride or nitride of Ni) are also present within gold grains.	Au 41.2–58.98, Pb 38.53–56.93, Ni up to 0.55, Ti up to 0.19, Cu – traces, Zn – b.d.t. to trace, Ag – b. d.l.	Gold grains with dimensions 0.05–1.8 mm contain <10 wt% Ag	4; 5
Novodneprite AuPb <sub>3</sub> and anyuiite Au(Pb, Sb) <sub>2</sub>	Novodneprovskoe gold deposit, Kazakhstan	Oxidized zone of bedrock gold deposit	Within spheroidal aggregates from an oxidized zone of gold-arsenic-polymetallic deposit.	In intergrowths with anyuiite (±native lead) fills the free spaces between the crystals of gold (± auricupride) inside the spheroidal aggregates hosted by jacobsonite–mimetite aggregates. Crystals and intergrown crystals up to 0.02–0.05 mm in size with inclusions of sn-bearing gold and rims of high-fineness Sb-bearing gold.	Au 20.73–25.29, Pb 73.74–77.33, Cu 0–0.18, Ag 0–0.13	No data available	6
Hunchunite Au <sub>2</sub> Pb	Langursko-Alexandrovskaya gold ore zone, Ekateriniskiy lode-placer cluster, North Urals	Gold mineralized zones in weathering crust	In concentrates from zones of disseminated gold mineralization in weathered Devonian volcanic-sedimentary rocks intersected by monzodiorites.	Crystals and intergrown crystals up to 0.02–0.05 mm in size with inclusions of sn-bearing gold and rims of high-fineness Sb-bearing gold. Associated minerals in concentrates: native gold, tetraauricupride, Cu- and Hg-, Sb- and sn-bearing gold, pyrite, chalcocopyrite, galena, sphalerite.	Au 66.49–68.49, Pb 30.07–31.84, Ag 0.5–1.02, Sn 0.32–0.71, Fe 0.1–0.46	sn-bearing gold (wt%): Au 78.0–96.2, Sn 1.2–10.2, Ag 0.6–6.3, Cu up to 4.1, Pb 0.5–0.8, Sb 0.4–1.7; Sb-bearing gold (wt%): Au 95.6–99.3, Sb 0.4–2.0, Cu 0.1–0.2, Pd up to 0.4.	7
Anyuiite Au(Pb,Sb) <sub>2</sub>	Bolshoi Anyui River, Chukotka, Russia	Placer	Concentrates from the Bolshoi Anyui River placer gold deposit. Bedrock sources for the placer are believed to be small Hercynian dunite-harzburgite and gabbroid massifs of the Koryak-Kamchatka fold province.	Platy aggregates and prismatic crystals (1–50 × 100–900 µm) in complex intergrowths of three types with native lead within weakly rounded to angular polymineralic grains containing Au-Pb compounds, native Au, and native Pb. Anyuiite contains inclusions of native Au and Pb, Cr-spinel, ilmenite, Ti-magnetite, and hematite. Associated minerals in concentrates: gold, PGM, Cr-spinel, ilmenite, hematite, pyrite, chalcocopyrite.	Au 32.6–36.7, Pb 52.9–64.8, Sb 0.3–10.2, Ag up to 0.3	Gold in intergrowths with anyuiite: Au 54.5–84.2 wt%, Ag 6.31–42.4 wt%, Cu up to 15.9 wt%	8; 9
Au-Pb compounds (which are completely miscible with one another over the entire range of	Urals, Russia	Placer	Concentrates from Au-Pt alluvial placers of the Uralian rivers.	(1) Irregular submicron-sized particles with mixed Au-Pb composition in films of spongy gold coating placer gold grains together with native Cu, Au-bearing galena, and Au-Ag-Pb-Fe hydroxybromides.	An outer zone of kelyphitic rims: Au 55.30, Pb 42.62, Ag 0.61, Sn 0.21, Fe 0.64, Sb 0.1,	Placer gold grains with kelyphitic rims contain ~ 3.76 wt% Ag. An inner zone of kelyphitic rims (wt%): Au 83.73,	10

Table 1 (continued)

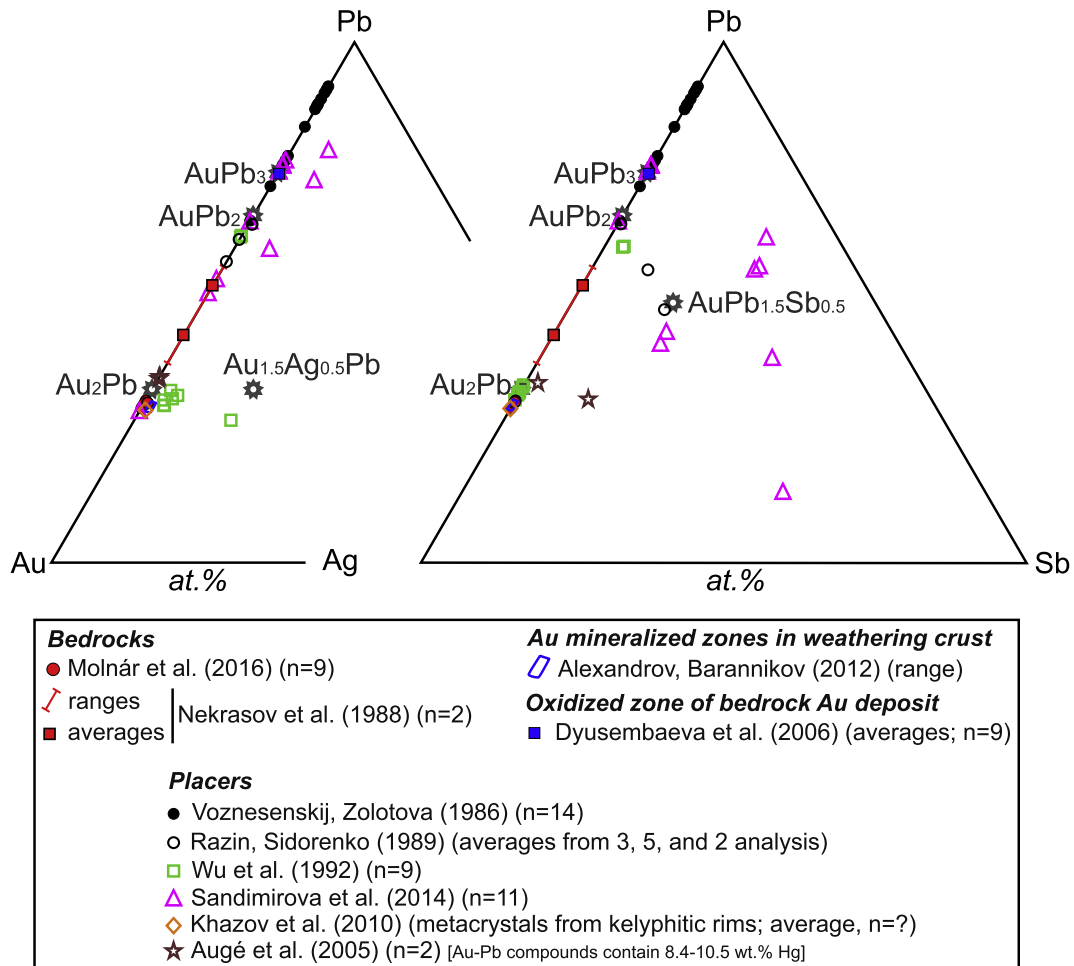
Mineral	Locality	Type locality	General geological setting	Appearance and associated minerals	Composition (wt. %)	Composition of associated gold	Ref
<i>possible compositions)</i>				(2) As kelyphitic rims up to 50–100 µm width on placer gold grains. Rims consist of an inner Au–Ag–Pb zone and an outer Pb–Au–Ag zone which enclose small (10 µm to 50 µm) euhedral metacrystals of Au–Pb compounds.	As 0.33 (average). Metacrystals: Au 68.82, Pb 30.5, Ag 0.61.	Ag 15.43, Pb 0.83 (average).	
Au–Pb compounds (~Sb-bearing novodneptite Au(Pb, Sb) <sub>3</sub> and anyuuite AuPb <sub>2</sub> ?)	Ol'khovaya-1 River, Eastern Kamchatka, Russia	Placer	Concentrates from Pt–Au placer deposits of the Ol'khovaya-1 River, whose tributaries drain the Soldatskaya Mountain ultramafic massif of the Karaginskiy ophiolite complex.	(1) Individual well-rounded grains 1–3 mm in size consisting of graphic intergrowths of native Pb and Au–Pb(±Sb) compounds. (2) Aggregates of irregular grains of (i) native Au, electrum, and native Pb with inclusions of Au–Pb compounds, or (ii) electrum and native Pb with inclusions of AuPb <sub>3</sub> . In the last case, peripheral parts of complex Pb–Au–Pb grains have rims in which native Pb is replaced by lead oxide. Associated minerals in concentrates: native Au, PGM, auricupride, tetraauricupride, native Pb, Sn, and Bi and their oxides, cuprostibite, galena, (Pb,Sb)O <sub>2</sub> ; Pb–Sb, Pb–Sn, Au–Ag–Sn, Au–Sn, and Au–Ag–Pb–Sn compounds	Au 12.12–41.88, Pb 18.18–77.40, Sb up to 41.51, Ag up to 2.95	Gold in intergrowth with Au–Pb compounds: native gold (10–30 wt% Ag), electrum (30–70 wt% Ag), küstelite (70–80 wt% Ag). The gold grains are zonal with an Au–Ag phase in core and Au–Cu phases at the margins.	11
Hunchunite Au <sub>2</sub> Pb, anyuuite Au(Pb,Sb) <sub>2</sub>	Hunchun River, Jilin province, China	Placer	Concentrates from Quaternary gold alluvial placers along the Hunchun River	Anhedral granular aggregates 170–500 × 3–30 µm in size in intergrowth with gold, anyuuite, and native lead.	Hunchunite: Au 63.38–66.26, Pb 31.60–34.64, Ag 1.68–2.96. Anyuuite: Au 35.31–35.62, Pb 62.5–62.73, Sb 1.88–1.97, Ag – b.d.l. Au 8.2–33.1, Pb 66.5–91.8	Gold in intergrowth with Au–Pb compounds contains 91.2–93.2 wt% Au and 6.8–8.8 wt% Ag.	12; 13
Unnamed Au–Pb compounds (AuPb <sub>2</sub> , AuPb <sub>3</sub> , or their intergrowths with native gold ?)	North-East Russia	Placer	Concentrates from an alluvial gold deposit of North-East Russia.	(1) Individual segregations (up to 12 mm), (2) a cement among grains of gold, pyrite, ilmenite, garnet, quartz, zircon, (3) coatings on rounded gold grains in association with native Pb. Associated minerals in concentrates: native Au, pyrite, ilmenite, garnet, zircon, marcasite, pyrrhotite, tourmaline.	Au 8.2–33.1, Pb 66.5–91.8	Well-rounded gold grains with Ag up to 15–19 wt% and Hg up to 0.5–4 wt%.	14; 15
Au–Pb compounds	Chaush River, Urals, Russia	Placer	Concentrates from the Pt–Au placer of the Chaush River, derived from the Nizhny Tagil Uralian–Alaskan-type complex	As matrix mineral to beads composed of an Au–Sn alloy in association with gold. Associated minerals in concentrates: native Au, PGM, chromite.	Au 52.2–57.3, Pb 30.6–33.1, Hg 8.4–10.5, Sb 1.1–6.7, Ag and Cu–b.d.l.	Gold in association with Au–Pb compounds: Ag 7.9–48.5 wt%, Cu 0.5–1.1 wt%, Pb up to 0.24 wt%, Hg and Sb–b.d.l.	16

b.d.l. – below detection limit.

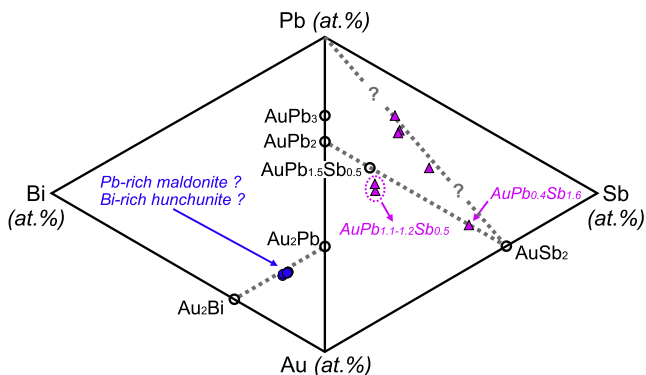
Fineness = Au\*1000/(Au + Ag) (Hallbauer and Utter, 1977).

PGM – platinum group minerals.

Ref – References: (1) Molnár et al. (2016); (2) Ramdohr and Evstigneeva (2011); (3) Ferraris and Lorand (2015); (4) Nekrasov et al. (1988); (5) Jambor and Grew (1990); (6) Dyusembaeva et al. (2006); (7) Alexandrov and Barannikov (2012); (8) Razin and Sidorenko (1989); (9) Jambor and Grew (1991); (10) Khazov et al. (2010); (11) Sandimirova et al. (2014); (12) Wu et al. (1992); (13) Jambor et al. (1994); (14) Voznesenskij and Zolotova (1986); (15) Hawthorne et al. (1988); (16) Augé et al. (2005).



**Fig. 3.** Compositions (in atomic percent, at%) of Au-Pb compounds from various localities worldwide. The theoretical compositions of  $\text{Au}_2\text{Pb}$  (hunchunite),  $\text{AuPb}_2$  (anyuinite), and  $\text{AuPb}_3$  (novodneprite) are from Okamoto and Massalski (1984). The empirical composition of hunchunite  $\text{Au}_{1.5}\text{Ag}_{0.5}\text{Pb}$  and anyuinite  $\text{AuPb}_{1.5}\text{Sb}_{0.5}$  are from Webmineral Mineralogy Database (WEBMINERAL.COM).



**Fig. 4.** Bi-Pb-Sb-Au compositional diagram illustrating relationships between Au-Bi-Pb and Au-Sb-Pb mineral systems. Compositions of Pb-rich maldonite (or Bi-rich hunchunite ?) reported in Molnár et al. (2016) plot on a projected  $\text{Au}_2\text{Pb}$ - $\text{Au}_2\text{Bi}$  tie-line, suggesting that some miscibility can exist between maldonite and hunchunite in the system Au-Bi-Pb. Compositions of  $\text{Au}(\pm\text{Ag})$ -Pb-Sb compounds presented in Sandimirova et al. (2014) include non-stoichiometric (?) anyuinite  $\text{AuPb}_{1.1-1.2}\text{Sb}_{0.5}$ ,  $\text{Au}(\pm\text{Ag})$ -Pb-Sb compounds depicting Pb-AuSb<sub>2</sub> tie-line (that strongly resemble a mechanical mixture of several mineral phases), and an Au-Pb-Sb compound corresponding in composition to  $\text{AuPb}_{0.4}\text{Sb}_{1.6}$ , that lies on the  $\text{AuPb}_2$ -( $\text{AuPb}_{1.5}\text{Sb}_{0.5}$ )- $\text{AuSb}_2$  tie-line. The last compositional case may indicate that some miscibility can exist between aurostibite and anyuinite in the system Au-Sb-Pb.

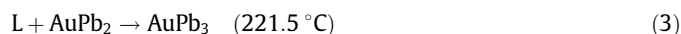
on the  $\text{AuPb}_2$ -( $\text{AuPb}_{1.5}\text{Sb}_{0.5}$ )- $\text{AuSb}_2$  tie-line (Fig. 4). The last compositional case may indicate that some miscibility can exist between aurostibite and anyuinite in the system Au-Sb-Pb. This suggestion is supported by at least one other case of finding of Au-Pb-Sb compound reported from the Tetrem gold deposit in West Africa, where hunchunite has been described in intergrowths with unnamed  $\text{Au}_6\text{Pb}_5\text{Sb}_3$  ( $\text{Au}_3(\text{Pb,Sb})_4$ ) mineral (Ramdohr and Evstigneeva, 2011).

#### 5.1.3. Conditions and mechanisms of formation of Au-Pb compounds

There is only one case of bedrock occurrence, in which formation conditions for the hunchunite-bearing mineral assemblage have been interpreted. According to Molnár et al. (2016), in the Rompas deposit, hunchunite was precipitated from neutral-alkaline fluids at  $\sim 300^\circ\text{C}$  ( $270$ – $340^\circ\text{C}$ ), under  $\log f_{\text{S}_2}$  and  $\log f_{\text{Te}_2}$  conditions to around  $-17$  and between  $-13.8$  and  $-11.3$ , respectively. The radiogenic lead derived from the earlier formed uraninite-bearing assemblage was considered as the dominant source of lead for Pb-bearing minerals (galena, hunchunite, and altaite), and deposition of ore minerals was linked to a hydrothermal event caused by intrusion of pegmatitic and tourmaline-rich granites (Molnár et al., 2016). In all other cases of both bedrock and weathered localities, conditions of formation of Au-Pb minerals and often mineralization styles are unclear. However, a review of the available literature would suggest that Au-Pb minerals are

spatially and apparently genetically linked to gold mineralization. Au-Pb intermetallics are associated with gold of different composition in different mineralogical assemblages (Table 1), thus, they may possibly be formed through different gold mineralization types.

A comparison of the Au-Pb mineral assemblages (see subsection 5.1.2. «Mineralogy of Au-Pb compounds») with experimental data (Prince, 1980, 1980a; Okamoto and Massalski, 1984; Okamoto, 1993; Hassam et al., 1995; Wang et al., 2010) which provide for three peritectic reactions



and the eutectic reaction



for the formation of Au-Pb intermetallics shows clearly that native Pb observed in nature Au-Pb mineral assemblages cannot be explained by peritectic reactions (1) to (3). However, the Pb excess can be successfully described by eutectic (and possibly successive) reactions  $\text{Au}_2\text{Pb} \rightarrow \text{AuPb}_2 + \text{Pb}$  and  $\text{AuPb}_2 \rightarrow \text{AuPb}_3 + \text{Pb}$  during which the primary hunchunite  $\text{Au}_2\text{Pb}(\pm\text{Ag}, \text{Sb})$  is presumed to have broken down to yield the eutectoid-type textures. Such textures represented by complex intergrowths of  $\text{AuPb}_2 + \text{Pb}$ ,  $\text{Au}_2\text{Pb} + \text{AuPb}_2 + \text{Pb}$ , and  $\text{AuPb}_2 + \text{AuPb}_3 + \text{Pb}$  are referred from some localities (Razin and Sidorenko, 1989; Wu et al., 1992; Dyusembaeva et al., 2006; Sandimirova et al., 2014). Thus, myrmekitic intergrowths of  $\text{AuPb}_2 (\pm\text{AuPb}_3)$  and Pb probably represent decomposed hunchunite  $\text{Au}_2\text{Pb}(\pm\text{Ag}, \text{Sb})$ .

Experimental studies suggest that  $\text{Au}_2\text{Pb}$  (as well as  $\text{AuPb}_2$  and  $\text{AuPb}_3$ ) can be formed by the interaction of a liquid *L* (corresponds to potential Pb-bearing fluids in nature?) with a solid solution *Au* (corresponds to potential native Au-Ag alloys in nature?). This mechanism in nature appears to be coming true through metasomatic processes. However, it should be taken into account that the formation of Au-Pb compounds may occur during some local metasomatic reactions under excess of lead and extremely low *fS*<sub>2</sub> and *fTe*<sub>2</sub> conditions to effectively stabilize Pb in intermetallic form. Another mechanism involving an Au-bearing fluid and lead ions ( $\text{Pb}^{2+}$ ) through the equation of the precipitation process  $2\text{Au}(\text{HS})_2 + 2\text{H}_2 + \text{Pb}^{2+} \rightarrow \text{Au}_2\text{Pb} + 4\text{H}_2\text{S}$  has been proposed to explain the formation of hunchunite at the Rompas Au-U deposit, where it is a common mineral associated with native gold (Molnár et al., 2016). In this way, a general consensus that Au and Pb will be separated during the magmatic-hydrothermal processes (Au goes in vapor, Pb stays in brine) (e.g., Heinrich et al., 1999) requires different sources for gold and lead.

By contrast to the bedrock localities, origin of Au-Pb compounds from the placer occurrences is controversial. In some cases, there are clear indications that Au-Pb minerals have passed into the placer by erosion of mineralized bedrocks. This empirical evidence includes the outer appearance (i.e., size and morphology) of Au-Pb compounds, features of their relationship with associated gold, the existence of eutectoid-type textures (myrmekitically intergrowths of  $\text{AuPb}_2 (\pm\text{AuPb}_3)$  and Pb), the presence of mineral inclusions enclosed in Au-Pb compounds, and the impurity in Au-Pb minerals of other elements such as Sb and Bi (the Bolshoi Anyui River (Razin and Sidorenko, 1989), the Hunchun River (Wu et al., 1992)). In other cases, namely when Au-Pb compounds occur as kelyphitic rims on placer (often well-rounded) gold grains or as submicron-sized particles in films of spongy gold coating placer gold grains (Khazov et al., 2010), this should be regarded as a major evidence of formation *in situ* in the placer environment. But in fact,

the mechanisms of formation of such Au-Pb compounds are unclear. Formation of authigenic Au-Pb compounds is suggested to be the result of cathodic reduction of metallic Pb on the gold grain surface in weakly mineralized Pb-bearing water solutions filtered through porous gold-bearing alluvial sediments (Voznesenskij and Zolotova, 1986; Khazov et al., 2010). Alternately, Au-Pb compounds may grow within placers by microbially assisted dissolution, precipitation and aggregation, in the same way as it is suggested for supergene gold (Reith and McPhail, 2006; Reith et al., 2005, 2006, 2007, 2009, 2010; Kamenov et al., 2013; Shuster et al., 2017). There are also unclear cases where Au-Pb compounds, with or without eutectoid-type textures, occur as a cement among grains of various other minerals (Voznesenskij and Zolotova, 1986; Augé et al., 2005) or gold grains of different composition (the Ol'khovaya-1 River placer; Sandimirova et al., 2014).

## 5.2. Au-Pb compounds from the Inagli Pt-Au placer

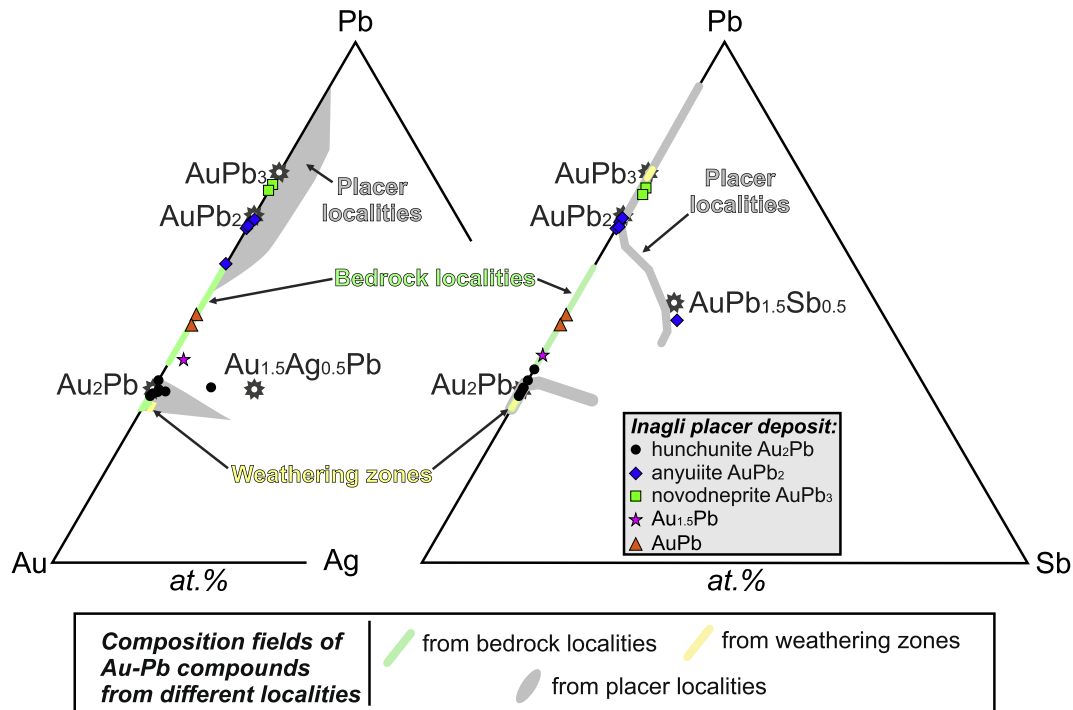
The occurrence of Au-Pb compounds in the Inagli Au-Pt placer deposit is the first known locality of Au-Pb compounds in the Aldan Shield, Russia. In this locality, Au-Pb compounds are associated with homogeneous gold grains, containing 5.0–8.1 wt% Ag, 0.3–1.0 wt% Hg, 0.11–0.22 wt% Pb, and up to 0.1 wt% Cu (Fig. 2). The morphology of gold particles (angular to slightly elongated shapes, irregular surface topography, grain embayments, relatively regular outline with rare evidence of folding, lack of coating and biofilm-like forms) indicates that gold (and apparently associated Au-Pb compounds) derives from a local source situated probably less than 300 m from the sampling site (according to Townley et al., 2003; see Svetlitskaya et al., 2017). However, a thin partial Au-rich rim depicted by one single gold grain (Fig. 2c) may come from the presence of gold particles in weathering zone over a relatively short period of time. The lower Hg level in the rim compared to the grain core indicates a loss of mercury in the supergene weathering environment and, thus, the elevated Hg content in gold is a feature of primary deposition rather than a consequence of the amalgamation processes used by local inhabitants to recover the panned gold (Litvintsev et al., 2005).

The morphology and composition features of gold particles as well as the general outward look and composition of Au-Pb compounds, including exsolutions of  $\text{Au}_{1.5}\text{Pb}$  and Sb-bearing anyuinite in hunchunite, Sb-bearing anyuinite in Sb-bearing novodneprite, and anyuinite in AuPb (Fig. 2), clearly support the hypogene origin of Au-Pb minerals from the Inagli placer. Five distinct Au-Pb phases identified in the Inagli placer locality (Fig. 5) occur in four assemblages:

- 1) hunchunite + anyuinite +  $\text{Au}_{1.5}\text{Pb}$ ;
- 2) hunchunite + anyuinite + AuPb;
- 3) hunchunite + anyuinite + novodneprite;
- 4) anyuinite.

In contrast to mineral assemblages distinguished based on available literature sources (see subsection 5.1.2. «Mineralogy of Au-Pb compounds»), ones from the Inagli placer do not involve native Pb. This fact suggests that these Au-Pb mineral assemblages probably could not be formed though eutectic reactions describing the decomposition of hunchunite, but is consistent with peritectic reactions (1) to (3) indicating the interaction between Pb-bearing fluids and Au-Ag alloys. Sustained elevated contents of Pb in gold associated with Au-Pb compounds are in good agreement with this conclusion.

These are some observations on Au-Pb compounds from the Inagli placer: (i) the general outward look of Au-Pb minerals (veinlets, partial rims, small inclusions within gold grains), (ii) the mineralogical and compositional zoning within veinlets and partial



**Fig. 5.** Compositions (in atomic percent, at.%) of Au-Pb compounds from the Inagli Au-Pt placer deposit. Compositional fields of Au-Pb compounds from different various localities worldwide were defined based on published analyses summarized in Fig. 3 and included (1) Au-Pb compounds from *bedrock localities* (Nekrasov et al., 1988; Molnár et al., 2016), (2) Au-Pb compounds from *weathering zones* (Dyusembaeva et al., 2006; Alexandrov and Barannikov, 2012), and (3) Au-Pb compounds from *placer localities* (Voznesenskij and Zolotova, 1986; Razin and Sidorenko, 1989; Wu et al., 1992; Khazov et al., 2010; Sandimirova et al., 2014).

rims, in which Au-Pb phases change with increasing Au and decreasing Pb contents from the central to outer parts (anyuiite +  $Au_{1.5}Pb$  → hunchunite; novodneprite + anyuiite → hunchunite;  $AuPb$  + anyuiite → hunchunite), (iii) the general replacement look of the contact between the Au-Pb veinlets, rims/the hosting gold and between different Au-Pb phases within the veinlets and rims, and (iv) the variable content of Ag in hunchunite. These observations support formation of Au-Pb compounds via metasomatic replacement of host gold through Pb-bearing fluids – Au-Ag alloys interaction. The presence of individual inclusions of anyuiite in native gold indicates that anyuiite can be formed not only by decomposing of hunchunite, but also as a separate mineral phase.

The very unusual inclusion within the gold grain, consisting of Pb-Fe-aluminosilicate + K-feldspar with a reaction rim of anyuiite, is a clear indication that: (1) it is precisely that Pb-bearing fluid containing Fe, Si, Al, and K was responsible for the formation of Au-Pb minerals in the bedrock source, and (2) the Pb-bearing fluid interacting with gold was potassic in composition. Based on the above, we suggest that pre-existing gold grains have undergone *in situ* hydrothermal overprint by K-rich Pb-bearing solutions, which produced the formation of Au-Pb compounds.

## 6. Concluding remarks

A synthesis of the available data on Au-Pb compounds from various localities worldwide, including reported in this study for the Inagli placer, can result in the followings:

1) Au-Pb compounds include hunchunite  $Au_2Pb$ , anyuiite  $AuPb_2$ , novodneprite  $AuPb_3$ , and unnamed  $Au_{1.5}Pb$  and  $AuPb$  phases and are observed as minor minerals in bedrock, weathering and placer gold deposits in at least twelve localities worldwide.

2) The following natural mineral assemblages of Au-Pb compounds are distinguished:

- 1) hunchunite (bedrock and weathering localities);
- 2) hunchunite + anyuiite + native Pb (placer localities);
- 3) hunchunite + anyuiite +  $Au_{1.5}Pb$  or  $AuPb$  (placer localities; this study);
- 4) hunchunite + anyuiite + novodneprite (placer localities; this study);
- 5) anyuiite (placer localities; this study);
- 6) anyuiite + native Pb (placer localities);
- 7) anyuiite + novodneprite + native Pb (weathering and placer localities).

The occasional cases of Pb-rich maldonite (or Bi-rich hunchunite?) (Molnár et al., 2016) and Au-Pb-Sb compounds (Ramdohr and Evstigneeva, 2011; Sandimirova et al., 2014) indicate that some miscibility can exist between maldonite and hunchunite in the system Au–Bi–Pb and between aurostibite and anyuiite in the system Au–Sb–Pb.

3) The more plausible natural mechanisms of formation of Au-Pb compounds include: (1) metasomatic interaction between Pb-bearing fluids and Au-Ag alloys, with or without subsequent decomposition of the primary hunchunite  $Au_2Pb$  ( $\pm Ag, Sb$ ) to anyuiite ( $\pm$  novodneprite) and native Pb/ $Au_{1.5}Pb$ / $AuPb$ , (2) precipitation of hunchunite from hydrothermal Au- and Pb-bearing fluids, and (3) formation *in situ* in the placer environment through biological or geochemical growth. In the first case, the formation of Au-Pb compounds could have occurred during some local metasomatic reactions under an excess of lead and extremely low  $f_{S_2}$  and  $f_{Te_2}$  conditions to effectively stabilize Pb in intermetallic form. In the second case, different sources for gold and lead,

contributing to the complex Au- and Pb-bearing hydrothermal solution, are a decisive factor. As Au-Pb intermetallic forming reactions are temperature-related, the composition of observed mineral assemblages of Au-Pb compounds would be directly influenced by initial temperature of Pb-bearing or Au-, Pb-bearing fluids.

- 4) Everything that is known about formation conditions of Au-Pb minerals today is restricted to one case of the Rompas deposit (Molnár et al., 2016). It includes the temperature about 300 °C, log  $fS_2$  around -17, and the log  $fTe_2$  values between -13.8 and -11.3. According to Molnár et al. (2016), hunchunite from the Rompas deposit precipitated from neutral-alkaline fluids. In the Inagli placer deposit (this study), the formation of Au-Pb minerals is likely linked to potassic alkaline fluids.
- 5) The following features can be useful to distinguish the hypogene origin of Au-Pb compounds: the outer appearance (i.e., size and morphology) of Au-Pb compounds, features of their relationship with associated gold, the existence of eutectoid-type textures (intergrowths of different Au-Pb minerals, with or without Pb), the presence of primary mineral inclusions enclosed in / associated with Au-Pb compounds, and the impurity in Au-Pb minerals of other elements such as Sb and Bi. The phenomenon of supergene Au-Pb compounds forming *in situ* in the placer environment is confirmed by kelyphitic rims of Au-Pb intermetallics on placer gold grains as well as submicron-sized Au-Pb intermetallic particles in films of spongy gold coating placer gold grains.

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## References

- Alexandrov, V.V., Barannikov, A.G., 2012. Unconventional type of gold ore-forming process in Ekaterinskii ore-alluvial cluster (North Urals). *Litosfera* 1, 161–165 (in Russian with English abstract).
- Augé, T., Genna, A., Legendre, O., Ivanov, K.S., Volchenko, Y.A., 2005. Primary platinum mineralization in the Nizhny Tagil and Kachkanar Ultramafic Complexes, Urals, Russia: a genetic model for PGE concentration in chromite-rich zones. *Econ. Geol.* 100, 707–732.
- Boyarko, G.Y., Dik, I.P., 2000. The Inagli gold-platinum placer deposit. In: Korobeynikov, A.F. (Ed.), *Proceedings of Prospecting and Exploration of Mineral Deposits in Siberia*. TPU, Tomsk, pp. 257–267 (in Russian).
- Dyusembaeva, K.S., Levin, V.L., Kotel'nikov, P.E., Bekeanova, G.K., 2006. Novodneprite AuPb<sub>3</sub> – a new mineral from Novodneprovsk deposit (Northern Kazakhstan). *Dokl. Akad. Nauk Resp. Kaz.* 5, 46–50 (in Russian with English summary).
- Ferraris, C., Lorand, J.-P., 2015. Novodneprite (AuPb<sub>3</sub>), anyuuite [Au(Pb, Sb)<sub>2</sub>] and gold micro- and nano-inclusions within plastically deformed mantle-derived olivine from the Lherz peridotite (Pyrenees, France): a HRTEM-AEM-EELS study. *Phys. Chem. Miner.* 42 (2), 143–150.
- Goroshko, M.V., Kaplun, V.B., Malyshev, Y.F., Romanovskiy, N.P., Gurovich, V.G., 2010. The deep structure, magmatism, and metallogeny of the Central Aldan block, Aldan-Stanovoy shield. *Russ. J. Pac. Geol.* 4, 275–288.
- Hallbauer, D.K., Utter, T., 1977. Geochemical and morphological characteristics of gold particles from recent river deposits and the fossil placer of the Witwatersrand. *Miner. Deposita* 12, 293–306.
- Hansen, M., Anderko, K., 1958. *Constitution of Binary Alloys*. McGraw-Hill, New York.
- Hassam, S., Gambino, M., Bros, J.P., 1995. The Ag + Au + Pb system: determination of the liquidus surface. *Thermochim. Acta* 257, 83–82.
- Hawthorne, F.C., Burke, E.A.J., Ercit, T.S., Grew, E.S., Grice, J.D., Jambor, J.L., Puziewicz, J., Roberts, A.C., Vanko, D.A., 1988. New mineral names. *Am. Mineral.* 73, 189–199.
- Heinrich, C.A., Günther, D., Audétat, A., Ulrich, T., Frischknecht, R., 1999. Metal fractionation between magmatic brine and vapor, determined by microanalysis of fluid inclusions. *Geology* 27, 755–758.
- Ibragimova, E.K., Radkov, A.V., Molchanov, A.V., Shatova, N.V., Shatov, V.V., Lepekina, E.N., Antonov, A.V., Tolmachova, E.V., Soloviev, O.L., Terekhov, A. V., Horohorina, E.I., 2015. The results of U-Pb (SRIMP II) dating of zircons from dunites of the Inagli massif (the Aldan Shield) and the problem of the genesis of concentrically-zoned complexes. *Regionalnaya Geologiya i Metallogeniya* 62, 64–78 (in Russian with English abstract).
- Jambor, J.L., Grew, E.S., 1990. New mineral names. *Am. Mineral.* 75, 931–937.
- Jambor, J.L., Grew, E.S., 1991. New mineral names. *Am. Mineral.* 76, 299–305.
- Jambor, J.L., Grew, E.S., Roberts, A.C., 1994. New mineral names. *Am. Mineral.* 79, 1210–1214.
- Kamenov, G.K., Melchiorre, E.B., Ricker, F.N., DeWitt, E., 2013. Insights from Pb isotopes for native gold formation during hypogene and supergene processes at Rich Hill, Arizona. *Econ. Geol.* 108, 577–589.
- Khazov, A.F., Silaev, V.I., Filippov, V.N., 2010. Autigenic mineralization in river placers as a natural scientific phenomenon. In: *Proceedings of the Komi Science Centre of the Uralian Division of the Russian Academy of Sciences* 2, 54–60 (in Russian with English abstract). <[http://www.izvestia.komisc.ru/Archive/i02\\_ann.files/hasov.pdf](http://www.izvestia.komisc.ru/Archive/i02_ann.files/hasov.pdf)>.
- Khomich, V.G., Boriskina, N.G., 2010. Structural position of large gold ore districts in the Central Aldan (Yakutia) and Argun (Transbaikalia) superterrane. *Russ. Geol. Geophys.* 51, 661–671.
- Khomich, V.G., Boriskina, N.G., Santosh, M., 2015. Geodynamics of late Mesozoic PGE, Au, and U mineralization in the Aldan shield, North Asian Craton. *Ore Geol. Rev.* 68, 30–42.
- Korchagin, A.M., 1996. Inagli Pluton and Its Mineral Resources. Nedra, Moscow (in Russian).
- Litvintsev, V.S., Ponomarchuk, G.P., Bانشchikova, T.S., 2005. Morphological characteristic of gold of legacy placers of the Dzhalsinda River and Inagli River and problems of its extraction. *Mining Inf. Anal. Bull.* 3, 318–326 (in Russian).
- Malitch, K.N., Thalhammer, O.A.R., 2002. Pt-Fe nuggets derived from clinopyroxenite-dunite massifs, Russia: a structural, compositional and osmium-isotope study. *Can. Mineral.* 40, 395–418.
- Maximov, E.P., Uytov, V.I., Nikitin, V.M., 2010. The Central Aldan gold-uranium ore magmatogenic system, Aldan-Stanovoy Shield, Russia. *Russ. J. Pac. Geol.* 4, 95–115.
- Molnár, F., Odoro, H., Cook, N.D.J., Pohjolainen, E., Takács, Á., O'Brien, H., Pakkanen, L., Johanson, B., Wirth, R., 2016. Association of gold with uraninite and pyrobitumen in the metavolcanic rock hosted hydrothermal Au-U mineralisation at Rompas, Peräpohja Schist Belt, northern Finland. *Miner. Deposita* 51, 681–702.
- Mues-Schumacher, U., Keller, J., Kononova, V.A., Suddaby, P.J., 1996. Mineral chemistry and geochronology of the potassic alkaline ultramafic Inagli complex, Aldan Shield, eastern Siberia. *Mineral. Mag.* 60, 711–730.
- Murzin, V.V., Bushmakina, A.F., Sustavov, S.G., 1996. Hunchunite Au<sub>2</sub>Pb from placer of the Eastern Shishim River (Central Urals). *Ural. Mineral. Sb.* 6, 96–103 (in Russian).
- Nekrasov, I.Ya., Yakovlev, Ya.V., Pavlova, L.A., Gotovtsev, V.V., 1988. Unusual inclusions in native gold from kimberlites of the Mir pipe. *Dokl. Akad. Nauk SSSR* 303(5), 1209–1213 (in Russian).
- Okamoto, H., 1993. Au-Pb (Gold-Lead). *J. Phase Equilib.* 14, 648–649.
- Okamoto, H., Massalski, T.B., 1984. The Au-Pb (Gold-Lead) system. *Bull. Alloy Phase Diagr.* 5, 276–284.
- Okrugin, A.V., 2001. Mineral parageneses and the origin of isoferroplatinum nuggets from the Inagli placer deposit (Siberian Platform). *Geol. Ore Deposits* 43, 239–250.
- Okrugin, A.V., Zhuravlev, A.I., Mokhnachevsky, G.V., 2013. Mineralogical, geochemical and morphological features of placer gold of the southeastern Siberian platform. *Otechestvennaya Geol.* 5, 19–27 (in Russian with English abstract).
- Okrugin, A.V., Zhuravlev, A.I., Mokhnachevsky, G.V., Ibragimov, K.Z., 2014. Topomineralogical projection of the precious metals, rare and radioactive elements endogenetic mineralization in the Central Aldan magmatogenic system (Aldan Shield, Russia). *Geol. Miner. Resour. Siberia* 3, 23–27 (in Russian with English abstract).
- Parfenov, L.M., Berzin, N.A., Khanchuk, A.I., Badarch, G., Belichenko, V.G., Bulgatov, A.N., Drii', S.I., Kirillova, G.L., Kuzmin, M.I., Nokleberg, U., Prokopyev, A.V., Timofeev, V.F., Tomurtogoo, O., Yan, H., 2003. Model of formation of orogenic belts of Central and North-East Asia. *Tikhookean. Geol.* 22, 7–41 (in Russian).
- Prince, A., 1980. The Ag-Au-Pb system (Silver-Gold-Lead). *Bull. Alloy Phase Diagr.* 1, 54–56.
- Prince, A., 1980a. The Au-Pb (Gold-Lead) system. *Bull. Alloy Phase Diagr.* 1, 59–62.
- Popov, N.V., Shaporina, M.N., Amuzinsky, V.A., Smelov, A.P., Zedgenizov, A.N., 1999. Metallogeny of gold of Aldan province. *Geol. Geofiz.* 40, 716–728 (in Russian).
- Popov, N.V., Smelov, A.P., 1996. Metamorphic formations of the Aldan Shield. *Geol. Geofiz.* 40, 716–728 (in Russian).
- Ramdohr, R.P., Evstigneeva, T.L., 2011. Au<sub>3</sub>(Pb, Sb)<sub>4</sub> mineral phase from Tetrem gold deposits, Ghana, West Africa. *Goldschmidt Conference Abstracts. Mineral. Mag.* 75 (3), 1691 <http://goldschmidt.info/2011/abstracts/finalPDFs/1691.pdf>.
- Razin, L.V., Sidorenko, G.A., 1989. Anyuuite AuPb<sub>2</sub> – a new intermetallic of gold and lead. *Mineral. Zh.* 11 (4), 88–92 (in Russian with English summary).

- Reith, F., McPhail, D.C., 2006. Effect of resident microbiota on the solubilization of gold in soil from the Tomakin Park gold mine, New South Wales, Australia. *Geochim. Cosmochim. Acta* 70 (6), 1421–1438.
- Reith, F., McPhail, D.C., Christy, A.G., 2005. *Bacillus cereus*, gold and associated elements in soil and other regolith samples from Tomakin Park gold mine in southeastern New South Wales, Australia. *J. Geochem. Explor.* 85 (2), 81–98.
- Reith, F., Rogers, S.L., McPhail, D.C., Webb, D., 2006. Biomineralization of gold: biofilms on bacterioform gold. *Science* 313, 233–236.
- Reith, F., Lengke, M.F., Falconer, D., Craw, D., Southam, G., 2007. The geomicrobiology of gold. *ISME J.* 1 (7), 567–584.
- Reith, F., Etschmann, B., Grosse, C., Moors, H., Benotmane, M.A., Monsieurs, P., Grass, G., Doonan, C., Vogt, S., Lai, B., Martinez-Criado, G., George, G.N., Nies, D.H., Mergeay, M., Pring, A., Southam, G., Brugger, J., 2009. Mechanisms of gold biomineralization in the bacterium *Cupriavidus metallidurans*. *Proc. Natl. Acad. Sci. U.S.A.* 106 (42), 17757–17762.
- Reith, F., Fairbrother, L., Nolze, G., Wilhelmi, O., Clode, P.L., Gregg, A., Parsons, J.E., Wakelin, S.A., Pring, A., Hough, R., Southam, G., Brugger, J., 2010. Nanoparticle factories: biofilms hold the key to gold dispersion and nugget formation. *Geology* 38 (9), 843–846.
- Rozhkov, I.S., Kitsul, V.I., Razin, L.V., Borishanskaya, S.S., 1962. *Platinum of Aldan Shield*. Academy of Sciences of the USSR Press, Moscow (in Russian).
- Sandimirova, E.I., Sidorov, E.G., Chubarov, V.M., Ibragimova, E.K., Antonov, A.V., 2014. Native metals and intermetallic compounds in heavy concentrate Halos of the Ol'khovaya-1 River, Kamchatsky Mys Peninsula, Eastern Kamchatka. *Geol. Ore Deposits* 56, 657–664.
- Shatkov, G.A., Volsky, A.S., 2004. *Tectonics, Deep Structure, and Minerageny of the Amur River Region and Neighboring Areas*. Izdatelstvo VSEGEI, St. Petersburg (in Russian).
- Shuster, J., Reith, F., Cornelis, G., Parsons, J.E., Parsons, J.M., Southam, G., 2017. Secondary gold structures: relicts of past biogeochemical transformations and implications for colloidal gold dispersion in subtropical environments. *Chem. Geol.* 450, 154–164.
- Smelov, A.P., Timofeev, V.F., 2007. The age of the North Asian Cratonic basement: an overview. *Gondwana Res.* 12, 279–288.
- Smirnov, V.I., 1977. *Ore deposits of the U.S.S.R. Vol. II. Deposits of the Platinum Metals*. Pitman Publishing, London, pp. 100–110.
- Svetlitskaya, T.V., Nevolko, P.A., Kolpakov, V.V., Tolstykh, N.D., 2017. Native gold from the Inagli Pt-Au placer deposit (the Aldan Shield, Russia): geochemical characteristics and implications for possible bedrock sources. *Miner. Deposita*. <http://dx.doi.org/10.1007/s00126-017-0744-6>.
- Tolstykh, N.D., Krivenko, A.P., 1997. Platinum-group minerals in the Inagli placer (Aldan Shield). *Russ. Geol. Geophys.* 38, 808–817.
- Townley, B.K., Héral, G., Maskaev, V., Palacios, C., de Parseval, P., Sepulveda, F., Orellana, R., Rivas, P., Ulloa, C., 2003. Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. *Geochem. Explor. Environ. A* 3, 29–38.
- Voznesenskij, S.D., Zolotova, N.G., 1986. Contemporary mineral-forming processes in a gold placer. *Zapiski Vses. Mineralog. Obshch.* 115, 301–310 (in Russian with English abstract).
- Wang, J., Meng, F.G., Rong, M.H., Liu, L.B., Jin, Z.P., 2010. Thermodynamic description of the Au–Ag–Pb ternary system. *Thermochim. Acta* 505, 79–85.
- Wu, S., Yi, Y., Song, Q., 1992. A new gold mineral – Hunchunite ( $Au_2Pb$ ). *Acta Mineral. Sin.* 12 (4), 319–322 (in Chinese with English abstract).