

Distribution and Formation Conditions of Noble Metal Mineralization in Coal-Bearing Basins

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Abstract—Original data and a survey of the literature indicate that Au and Au–PGE mineralization are abundant in coal measures. Anomalous contents of noble metals have been established in basins with various types of basement, composed of granite, volcanic rocks, schist, and limestone. These basins are located in Au- and PGE-bearing ore districts, as well as at a considerable distance from known ore deposits and occurrences. Ore formation in coal-bearing basins may occur during sedimentation, peat accumulation, and diagenesis of organic matter or may be epigenetic. Noble metals are supplied to sedimentary basins as minerals that are transported by water and air and as ion species migrating along with surface and subsurface in- and exfiltration solutions of various chemical and genetic types. Ore mineralization concentrates in coal seams and host sedimentary beds of various grain size, including conglomerate, sand, and clay, as well as in zones of hydrothermal alteration superimposed on basement rocks and the sedimentary cover. The mode of occurrence of noble metals in coal basins is diverse as well (noble metal minerals, isomorphic admixtures in sulfides, and organic compounds). The data presented allow coal-bearing basins to be regarded as promising for economic noble metal mineralization fit for recovery as by-products in the course of coal mining.

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INTRODUCTION

High contents of noble metals reaching economic levels in coal were detected in the United States even at the end of the 19th century (Jenney, 1903; Stone, 1912), a few decades before the first discoveries of anomalous Au and PGE contents in carbonaceous shales (Noddack, 1936). Nevertheless, the noble metal mineralization in coal measures has turned out to be much less studied than the same mineralization in black shales. While Au and Au–Pt ores hosted in carbonaceous rocks have been mined for a long time in many countries, the similar mineralization hosted in coal measures has been considered until now to be something exotic, with vague prospects for further development. However, the rapid growth of information on anomalous Au and PGE concentrations and/or finds of their minerals in coal measures and Au-bearing cinder dumps of thermal power plants testifies that noble metal mineralization in coal measures is no less abundant than in black shales and is quite permissive for economic development.

Such an evaluation is determined in many respects by possible recovery of noble metals as by-products in the course of dump reprocessing and utilization of coal combustion wastes. Hence, the Au and PGE grades in coal-bearing basins may be lower than in primary ores of traditional types and even in placers.

For example, it has been shown that economically efficient Au recovery from the wastes of the Reft power

plant in the Urals is possible at an average Au grade of 0.1–0.2 g/t in coal combustion products (Leonov et al., 1998). If the chosen combustion regime provides suitable Au and PGE concentrations in ash, as occurs at the Reft and Khabarovsk power plants (Bakulin and Cherepanov, 2003), coal containing only about 50 ppb Au and/or PGE may be considered a specific noble metal ore. Gold may be accumulated in fly ash as well. In this case, by analogy with silver (Shpirt et al., 1986), one may expect that the noble metal content in fly ash, particularly, in its finest fraction, will be ten times higher than in the initial solid fuel. Such a situation was described for Alaska, where the Au content in 12 samples of Cenozoic coal was only 1–18 ppb, whereas, in three samples of ash, it was 76, 120, and 870 ppb (Stricker et al., 1992).

A similar approach that assumes reduced noble metal grades apparently should be extended to the rocks that host and overlie coal seams, as well as over frameworks and basements of coal basins. The development of such mineralized rocks may prolong the lifetime of mines after exhaustion of economic coal reserves.

The widespread occurrence of noble metals in coal measures and the possibility of their recovery as by-products at relatively low grades make coal-bearing basins very promising for economic development as sources of Au and PGE. To evaluate these prospects adequately, the reconstruction of the accumulation conditions of noble metals is of crucial importance because

anomalous Au and PGE concentrations may arise in coal-bearing basins different in geology, at different stages of their evolution, and as a result of different ore-forming processes.

This paper is the first attempt to systematize the information gained on noble metal mineralization in coal-bearing basins in genetic terms. It was not easy to perform such a systematization because many publications only mention high noble metal contents without accompanying comments or necessary data on analytical methods, ash content, the location of enriched samples, and their mineralogy and geochemistry. Therefore, I was obliged to consider the distribution of other metals (U, Ge, etc.) that are thus far better studied as additional background for forecasting noble metal ore localization, orebody morphology, and the scale of noble metal mineralization.

RESEARCH HISTORY AND THE STATE OF THE ART

According to modern estimates, the ordinary contents of noble metals in coal do not exceed their average concentrations in other sedimentary rocks and amount to a few parts per billion (Arbuzov et al., 2003; Yudovich and Ketris, 2003; Seredin, 2004b). Coals that contain these metals in amounts tens, hundreds, or thousands of times greater stand out prominently against this background. The first information on such coals appeared more than 100 years ago. Descriptions of gold and silver mining from coal in Wyoming and South Dakota (Jenney, 1903; Stone, 1912) were cited repeatedly. According to estimation by Yudovich et al. (1985), who recalculated into grams per ton the data in US\$/oz reported by Stone (1912), the Au grade in this coal was 2.8 g/t, or 17.1 g/t Au in ash.

Less well known is the information on anomalous Pt contents (up to 630 ppm in coal and 3.6 wt % in ash) detected at the end of the 19th century in two samples of ultralow-ash ($A^d = 1.7\%$) coal from Australia analyzed in London (USGS..., 1896). On the basis of these analytical results and information on Pt traces in ash of bituminous coal in the vicinity of the city of Mendoza in Argentina, Vysotsky (1923) was the first to suggest that coal may be utilized as a high-grade platinum ore. However, no additional information on the Pt-bearing Australian coal appeared later on, and the location of sampling has remained unknown (Swaine, 1990). Taking into account the low ash content and unusually high vanadium content (up to 25.1% in ash), it seems likely that solid bitumen rather than coal was analyzed. Pt-bearing bitumen has been described from the Boss deposit in Nevada (Jedwab et al., 1998).

The next information on possible enrichment of coal in Au and PGE dates from the early 1930s (Goldschmidt and Peters, 1933). The spectroscopic examination of ash from several bituminous coal samples taken in England and Germany yielded up to 1 ppm Au and

Pt and 0.5 ppm Pd. For a long time, these data remained the sole testimony for high noble metal contents in coal.

Many new publications on noble metals in coal and products of its combustion appeared over the next 70 years; the overwhelming majority of these works were published during the last decade (Fig. 1).

The abrupt intensification of research in this field led to the recognition of three main points.

(1) Gold and PGE occur in coal measures very often. Almost 100 coalfields and particular mines with anomalously high noble metal contents or finds of noble metal minerals are known to date. Such objects are known in 15 countries, but most of them have been revealed in Russia and China, where the study of coalfields with respect to noble metal mineralization has been markedly intensified in recent years.

(2) Gold and PGE concentrate not only in coal seams proper but also in sedimentary rocks of variable grain size (conglomerate, sandstone, and clay) and in quartz and carbonate veins and hydrothermal breccia.

(3) The Au and PGE contents in coalfields may be extremely high and reach tens or even hundreds of grams per ton. However, it must be kept in mind that the overwhelming majority of such anomalous contents were established only in solitary samples and isolated exploration sections.

Some especially high contents reported in the literature are doubtful and may be a result of analytical errors. In many cases, these contents were determined by spectroscopic methods without preliminary concentration of noble metals. For example, the replicate ICP MS analysis of eight of nine coal samples with contents of >1 ppm Pt and Pd obtained by spectroscopy showed that the maximum contents are only 7.7 ppb Pt and 11 ppb Pd in ash (Oman et al., 1997). The older spectral analyses reported by Goldschmidt and Peters (1933) most likely were inaccurate as well (Finkelman and Aruscavage, 1981).

The imperfectness of the existing methods of Au and, especially, PGE determination in organic media predetermines the nonreproducibility of results obtained even with modern methods of analysis and sample preparation. For example, anomalously high Pt and Pd contents (more than 10 and up to 6.1 ppm, respectively) in coal from the Blackburn Mine in Canada were established by spectral analysis of lead beads. The repeated analysis of nickel-sulfide beads from the same samples carried out with INAA revealed no enrichment in PGE (Van der Flier-Keller, 1991). Another typical example is the data on average and maximum concentrations of 1.5 and 4.4 ppm Au, respectively, in Eocene lignite of the Ione Formation in California in the vicinity of the well-known Mother Lode gold deposit. These results were obtained with ICP MS (Finkelman et al., 1994). Check analyses performed at the laboratory of the Placer Dome Company (Finkelman et al., 1995) and the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochem-

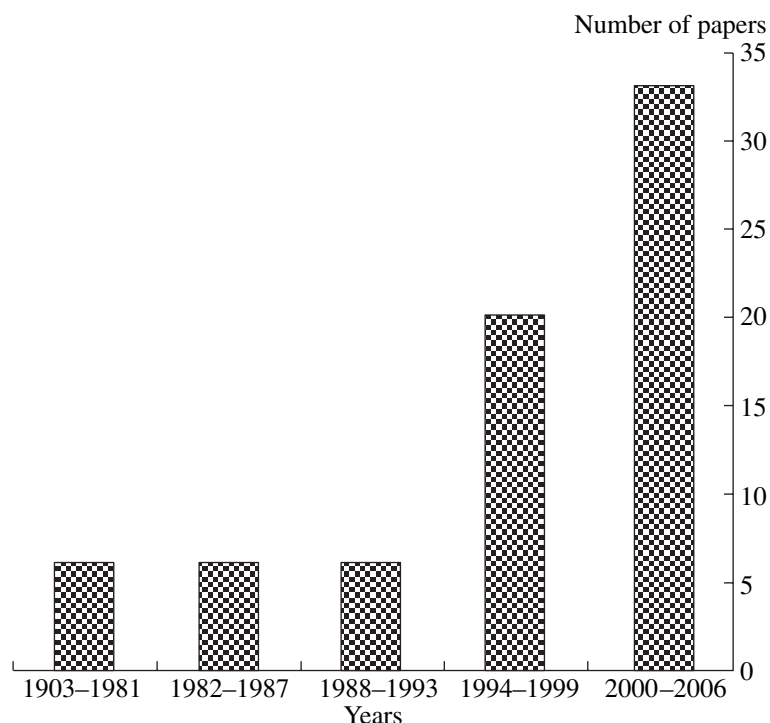


Fig. 1. Distribution of publications on noble metals in coal-bearing basins by years.

istry of the Russian Academy of Sciences (IGEM RAS) in Moscow (spectrochemical analysis and INAA) have shown that the Au contents in this lignite actually are two orders of magnitude lower.

The above examples demonstrate that any analytical information on high Au and, particularly, PGE contents in coal should be regarded with great caution. All such contents, irrespective of the analytical methods used, must be verified with other independent methods. It is necessary to remember that occasional very high results for small coal charges may be obtained as a result of incorporation of noble metal microparticles into a sample. For example, in analyzing a composite sample from coal seam III₂ in the Luzanovsky open-cut mine in Primorye, in the Far East of Russia, I obtained 10.5 ppm Au in ash. The analysis of the seven interval samples that made up this composite sample showed that none of them contained more than 1–2 ppm Au in ash. Finely dispersed gold minerals were identified in this coal seam with SEM-EDS, and most likely this was the cause of the analytical discrepancy.

The experience accumulated at IGEM RAS shows that the choice of a suitable analytical method, although highly important, does not play the key role in determination of noble metals in coal; rather, it is correct sample preparation that is crucial because many compounds of noble metals, e.g., carbonyls, are volatile at a relatively low temperature (300–400°C). Thus, any analytical method that includes high-temperature treatment of samples is insufficiently efficient.

The data presented in Table 1 demonstrate systematic underestimation of Au contents in ashed samples analyzed with ICP MS in comparison with the results of spectrochemical analysis, which is preceded by decomposition of the initial material in acids and Au sorption from solution on Polyorgs-IV sorbent. Depending on the sample composition, such underestimation may vary from 1.5 to 5 times. It should be noted that the results presented in Table 1 pertain to samples with gold that was detected by SEM-EDS. In this regard, it is recommended that cold chemical (wet) ashing of coal samples with the subsequent concentration of noble metals before analysis be used. This approach was efficient in study of Au-bearing coal from Ukraine (Panov et al., 2001).

In regard to the existing analytical problems, only identification of noble metal minerals in coal may serve as unequivocal evidence for its anomalous enrichment in Au or PGE. However, such data are not yet numerous. Au and PGE minerals in coal measures, including coal seams and coal combustion products, have been established with electron microscopy only in 17 coalfields and mines worldwide (Table 2). Only Au minerals have been identified at 9 of 17 deposits, while both Au and PGE minerals have been reported from 6 deposits. Thus, more than 30% of the coal measures studied in this respect contain PGM along with Au, indicating that complex Au–Pt mineralization is widespread in coal-bearing basins, as in black shales. In addition to native gold of variable fineness, the coal-bearing sequences

Table 1. Results of determination of Au contents in coal and coaly rocks from the Pavlovka brown coal field with different methods

Sample	Rock	A ^d , %	Au, ppm		Method
			Ash	Rock	
22	Coaly mudstone	50.4	0.99	0.50*	ICP MS
			1.47*	0.74	SSCA
36	Coaly sandstone	65.60	0.26	0.17*	ICP MS
			1.30*	0.85	SSCA
37	Coal	21.00	0.2	0.04*	ICP MS
			0.95*	0.20	SSCA

Note: SSCA, sorption spectrochemical analysis.

* Calculated data.

Table 2. Composition of noble metal mineral phases in rocks of coalfields

Locality (coalfield)	Rock	Composition of mineral phases	Source
Russia, Primorye (Pavlovka)	Clay	Au, Pd, Pd–Pt	Seredin, 2004a
"	Sand, gravel, and clay of overburden	Au, Au–Ag, Au–Hg, Au–Cu, Au–Cu–Sn, Au–Pb, Pd, Pd–Pt, Pt–Fe	"
"	Fossil wood	Au, Au–Ag, Au–Cu, Pt, Pt–Fe, Pt–Sn–S	Seredin and Magazina, 1999
"	Coal	Au, Au–Ag, Au–Cu, Pt, Pt–Fe, Pt–S	Seredin and Povarennykh, 1995
"	Products of argillic alteration	Au, Au–Ag, Au–Hg, Au–Cu, Au–Cu–Sn, Au–Sn–Pb–Ni, Pd, Pd–Pt	Seredin, 2004a
" (Rettikhovka)	Products of argillic alteration	Au, Au–Ag, Pt	Seredin, 2004b
" (Sinigorsk)	Coal	Au–Ag	Korostylev et al., 2000
" (Lower Bikin)	Coal and cinder-ash wastes	Au, Au–Ag, Pd, Pt	Seredin, 2004b, Bakulin and Cherepanov, 2003
Russia, Amur region (Khurmuli)	Coal and cinder-ash wastes	Au, Pt, Pt–Fe, Pt–Fe–Ir, Os–Ir–Pt	Bakulin and Cherepanov, 2003
Russia, Kansk–Achinsk Basin (Nazarovo)	Power plant cinder dumps	Au, Pd, Pt	Sazonov et al., 1998; Butan et al., 2000
Russia, Kansk–Achinsk Basin (Uryup)	Sand and gravel overburden	Au	Makarov, 1999
Russia, Transbaikalian region (Tarbagatai)	Coal	Au	Meitov, 2001
Russia, Kuzbas (Shevyakov Mine)	Coal	Au–Cu	Seredin, 2004b
Uzbekistan (Angren)	Coal	Au, Pt–S, Pd–S	Klimanov, 2003
"	Sand and gravel overburden	Au	Klimanov, 2003
China, Guizhou	Coal	Au	Belkin, 1998
Bulgaria (Balkan)	Cinder-ash wastes	Au–Ag	Yossifova, 1995
Bulgaria (Vylche Pole)	Fossil wood	Au	Vassilev et al., 1995
United States, Pennsylvania	Coal	Au, Au–Te	Finkelman, 1981
United States, Utah	Coal	Au	Finkelman, 1981
United States, Alaska (Nenana)	Power plant fly ash	Au	Stricker et al., 1992
Great Britain, South Wales	Coal	Au	Gayer and Rickard, 1994

Table 3. Types of noble metal mineralization in coal-bearing basins

		Speciation of supplied material							
		Mineral particles			Ions				
Stages of ore formation	Syngenetic	Cosmic	Pyro-clastic	Alluvial (terrigenous)	Alluvial (ionic)	Ground infiltration	Hydrothermal sedimentary (SEDEX)?	Peat deposition	
	Diagenetic				Alluvial (ionic)	Ground, stratal, and paleovalley infiltration?	Hydrothermal	Humification–gelification of organic matter	
	Epigenetic	Early			Alluvial (ionic)?	Ground, stratal, and paleovalley infiltration	Hydrothermal, contact metasomatic	Lignite–subbituminous	
		Late			Alluvial (ionic)?	Ground infiltration	Hydrothermal, contact metasomatic	Bituminous–anthracite	
			Air flows		Surface water		Infiltration*	Exfiltration**	
							Subsurface water		
Agents of metal transport into coal-forming basins									

* Descending gravity-driven lateral flows.

** Ascending flows of mineral water.

contain küstelite and copper and mercury gold. Native platinum and palladium, Fe- and Pd-bearing platinum, and platinum sulfides are the most abundant PGM. Minerals with high Os and Ir contents ((wt %) 89–90 Os, 10–12 Ir, and 0.5–15 Pt and 50 Ir, 20–25 Os, 15–25 Pt, and 1–3 Fe) have been detected at the Khurmuli coalfield in the Amur region (Bakulin and Cherepanov, 2003).

GENETIC TYPES OF NOBLE METAL MINERALIZATION IN COAL MEASURES

This section contains information on anomalous accumulations of noble metals in peat and coal throughout the world. A critical analysis of these data enabled classification of noble metal occurrences on the basis of relationships between stages of ore formation and coalification, speciation of metals supplied to coal measures, and agents of their transportation (Table 3). Most of the genetic types of metalliferous coal listed in

the table are considered below. Types that might exist but proved occurrences of which are unknown to me are designated by question marks. Information on anomalous noble metal contents of ambiguous genesis is given in Table 4.

Cosmic Type

This type of PGE accumulation has been revealed in New Mexico (United States) as a result of analysis of coal and clay samples taken from the sedimentary sequence that was deposited at the Cretaceous–Paleogene boundary, marked by a global Ir anomaly related to an impact event (Oman et al., 1997). The total PGE content in these samples reached 0.1 ppm, with ~20% Ir in enriched samples. Taking into account the overall abundance of such anomalies, it is evident that they may be of a certain economic interest in the case of cosmic enrichment of low-ash coal seams. The high PGE contents may be expected in the wastes of their combustion.

Table 4. Anomalous noble metal contents (≥ 0.2 ppm total in ash) of ambiguous origin in coal and products of its dressing and combustion

Country	Region, coal basin, underground mine, open-cut mine	Coalfield, underground mine, open-cut mine	Content, ppm coal/ash (concentrate)			Source
			Au	Pd	Pt	
United States	Wyoming		2.8/17.1*	—	—	Stone, 1912
"	Kentucky		—	—	<0.2/<2	Chyi, 1982
"	Alaska	Nenana	/<4	—	—	Rao, 1968
"	Alaska	Nenana	/<0.9	—	—	Stricker et al., 1992
"	West Virginia	Power plant fly ash	/11	—	—	Finkelman, 1981
Czech Republic			/35	—	—	Bouška, 1977
Germany	Westphalia		/0.5–1	—	—	Goldschmidt, Peters, 1933
FYRO Macedonia		Timok	/0.1–0.6	—	—	Popovich, 1954
India	Assam	Makum	22.8–32/	—	—	Baruah et al., 1998
China		Cinder dumps of Khabarovsk thermal power plants	/0.2–1.1	—	—	Bakulin and Cherepanov, 2003
"	Ningxia	Shizuishan, Mine 1 ¹	—	/0.9–1.2*	/0.4–0.6*	Dai et al., 2003
"	"	Shitanjing, Mine 1 ²	—	/0.2–1.3*	/0.02–0.3*	
"	"	Shitanjing, Mine 2 ³	—	/0.9–1.1*	/0.2*	"
"	"	Shitanjing, Wulan Mine	—	/0.8*	—	"
"	"	Weizhou, Taiyangch Mine	—	/0.7*	/0.3*	"
"	Shanxi	Liulin Mine	—	0.07/0.7*	0.01/0.1*	"
"	"	Linxian Mine	—	0.09/0.4*	0.01/0.04*	"
"	"	Xequ Mine	—	0.1/0.7*	0.01/0.06*	"
"	"	Xinxian Mine	—	/0.2*	/0.07*	"
"	"	Pianguan Mine	—	/0.3*	/0.07*	"
"	Inner Mongolia	Zhunger ⁴	—	0.1–0.6/0.8–2.3*	<0.2/<0.8*	"
"	Guizhou	Zhijin	—	0.24/0.96	0.11/0.44	"
"	"	Zhengfeng, Musang Mine	—	0.54/1.7	—	"
"	"	Qinglong, Gaoling Mine	—	0.1–1.2/0.9–4.9*	0.02–0.04/0.06–0.2*	"
"	"	Xingren	0.1–0.4/0.3–1.4*	0.3/0.9*	0.01/0.03*	"
"	"	Langdai Mine	—	0.06/0.5*	0.07/0.6*	"
"	"	Puan Mine	0.1/0.8*	0.08/0.2*	0.04/0.1*	"
"	"	Libo Mine	0.1/1.2*	—	—	"
Kazakhstan		Shubarkol	<0.13/	—	—	Belyaev and Pedash, 1989
"		Eqibastuz cinder dump of Reft power plant	/0.1–0.6 (1000–1500)	—	—	Leonov et al., 1998
"		Lower Ili	<0.4/<1.7	—	—	Ratynsky et al., 1982
"		Qaraghandy	/2–10***	—	—	"
Russia	Urals, Chelyabinsk Basin	Pervomaisky, Greater Chelyabinsk open-cut mine	0.1–0.8/	—	—	Yurovsky, 1968
"	Urals, Kizel Basin	Klyuchevsky Mine**	0.2/0.5	—	—	Zharov et al., 1996
"	"	"	—	—	0.1/	Torikova et al., 1996
"	Moscow Basin	Lipkovsky Mine no. 9**	0.2/0.5	—	—	Zharov et al., 1996
"	"	Power plant cinder dumps	/0.1–1.1	—	—	Pavlova and Timofeev, 2000

Table 4. (Contd.)

Country	Region, coal basin, underground mine, open-cut mine	Coalfield, underground mine, open-cut mine	Content, ppm coal/ash (concentrate)			Source
			Au	Pd	Pt	
Russia	Kansk–Achinsk Basin	Power plant cinder dumps Nazarovo	(0.5–6)	–	(<1)	Butan et al., 2000
"	"	Sayan-Partizansk	/0.2	–	–	Arbuzov, 2005
"	"	Bol'shoi Syr	/0.3	–	–	"
"	"	Stepanovo	/0.2	–	–	"
"	West Siberian Basin	Luginets, Kolpashevo	/0.2	–	–	Arbuzov et al., 2004
"	"	Trassovy, Gerasimovsky, South Tabagan	/0.3	–	–	"
"	"	Lower Tabagan	/0.8	–	–	"
"	"	Shirotny	/0.9	–	–	"
"	"	Stupenchaty	/1.2	–	–	"
"	"	North Kalinovskiy	/1.7	–	–	"
"	"	Upper Tromegan	/1.9	–	–	"
"	Kuznetsk Basin	Ol'zheras	0.8–1.2/	–	–	Arbuzov et al., 2000
"	"	Sibirga	0.7/	–	–	"
"	"	Krasny Uglekop Mine	/2.4	–	–	Nifantov et al., 2003
"	"	Kirov Mine	3.2/27.2	–	–	"
"	"	Zav'yalovo Mine	/0.6	/1.1	/0.1	Data of the author
"	Minusa Basin	Chernogorsk, Beisk	/1.4	–	–	Arbuzov et al., 2003
"	Transbaikalian region	Mordoi	0.2/0.6	–	–	Meitov, 2001
"	"	Kharanor	0.9/	–	–	"
"	"	Kharanor	/0.6	–	–	Bakulin and Cherepanov, 2003
"	"	Urtui	/0.6	–	–	"
"	"	Apsat		0.005/	0.025/	Meitov, 2001
"	"	Chitkanda		0.04/	0.01/	"
"	Irkutsk Basin	Azei	/0.3	–	–	Bakulin and Cherepanov, 2003
"	Tunguska Basin	Zhigansk	/0.4	–	–	Seredin, 2004b
"	South Yakutia Basin	Neryungri	/0.2	–	–	Bakulin and Cherepanov, 2003
"	Primorye	Ushumun	/0.4	–	–	"
"	"	Ushumun	/8.0	–	–	Krapiventseva, 2005
"	"	Khurmuli	/0.8–1.2 (850)	/<0.1	/<0.1	Bakulin and Cherepanov, 2003
"	"	Urgal	/0.2–0.7	/0.1–0.3	/0.04–0.1	Data of the author
"	Primorye	Tavrichanka	/0.2	/0.08	/0.62	"
"	"	Artem	/0.09	/0.03	/0.14	"
"	"	Middle Bikin	/1.8	/0.9	–	"
"	"	Chernyshevka	/0.9	/0.4	–	"
"	"	Luzanovsky	/<3.1	/<1.2	–	"
"	"	Luzanovsky	–	–	/0.7**	Zharov et al., 1996
"	"	Ash dump of Vladivostok thermal power plant no. 2	/1.5 (126)	(28)	/2.5 (80)	Cherepanov, 2005

Note: (1–4) Coal with additional high concentrations of other PGEs: ¹ up to 0.26 ppm Ru; ² up to 0.2 ppm Ru; ³ up to 0.17 ppm Ru in ash; ⁴ up to 0.31 ppm Rh in coal and 1.23 ppm in ash (Dai et al., 2003).

* Recalculated contents.

** ROM samples.

*** Ash of light coal fraction.

Table 5. Gold content in rocks of the Morozovsky open-cut mine, after Panov et al. (2004)

Material	n	Au, ppm		
		min	max	average
Coal	41	0.04	0.63	0.11
Ash 1	42	0.04	8.9	0.65
Ash 2	12	0.3	3.6	1.3
Coaly sand	6	0.08	1.8	0.53
Coaly clay	13	0.02	0.36	0.11

Note: The results of fire assay are presented. Ash 1 was prepared by standard ashing of coal samples; ash 2 is the product of wet ashing; n, number of samples.

Pyroclastic Type

Noble metal accumulations of pyroclastic origin in coal measures remain poorly studied. It is suggested that an interbed of volcanic ash within a coal seam could be a probable source of platinum in the Tulameen field, Canada (Van der Flier-Keller, 1991). The Pt content in the interbed that underlies the uppermost coal unit reaches 52 ppb (32 ppb, on average).

Extremely high PGE contents presumably related to the fallout of basic and intermediate tephra enriched in these elements into a peat bog were established in the province of Guizhou in southern China. The PGE contents in Upper Permian coal seam no. 9 (thickness, 0.9 m; ash content, 35%) in the Zhijin coalfield are (ppm) 4.24 Pd, 0.82 Pt, 0.064 Ir, 0.052 Ru, and 0.03 Rh, with 5.21 ppm PGE in total (Dai et al., 2003). The recalculation to ash yielded (ppm) 12.11 Pd, 2.24 Pt, 0.18 Ir, 0.15 Ru, and 0.09 Rh, with 14.64 ppm PGE in total.

Particles of volcanic ash impregnated with organic matter and admixtures of α -cristobalite, augite, quartz, kaolinite, and anatase were revealed in this coal in the course of its thorough examination. No sulfides were detected in coal despite the high Fe and Cu contents (4.24 wt % and 370 ppm, respectively). The PGE-bearing coal is enriched in Ti (3.5 wt %) and Cr (113 ppm), largely concentrated in basic pyroclastic material (Dai et al., 2003).

By analogy with accumulations of other trace elements gained with volcanic tephra (Seredin, 2004b), the maximum enrichment in noble metals may be expected in tonstein and the adjacent coal seams, which concentrate the metals removed from tonstein. The thickness of such metalliferous units usually does not exceed a few decimeters; however, they may cover tens or hundreds of square kilometers.

Alluvial Type

This type, related to the activity of surface streams, may be subdivided into clastic and ionic subtypes, depending on the form of transport of noble metals. Both subtypes are related to the erosion of primary and placer deposits located in close proximity to sedimen-

tary basins. If deposits that are resistant to weathering, e.g., gold-quartz veins, occur in the framework of a coal basin, noble metals are transported largely as mineral particles. If noble metals are contained in ores that are unstable in the supergene zone, e.g., in gold-sulfide ore, the metals are involved in transport mainly as soluble species. Both mechanisms of noble metal migration often operate simultaneously.

Clastic subtype. This mechanism of contamination of coal seams with Au is commonly considered first of all. However, as was sensibly mentioned by Yudovich and Ketris (2003), "...native gold is a characteristic component of placers, which are formed in the setting of active hydrodynamics. This setting is quite unlike the still-water or even stagnant facies of peat deposition." Hence, this interpretation of anomalous accumulations of noble metals in coal should be regarded with caution. Only minerals with indications of transport by flows of water may serve as direct evidence for such an origin of enrichment of coal in noble metals. Primary deposits exposed at the walls of coal-bearing basins at the time of peat deposition may be used as indirect evidence. However, such evidences remain rare. In this regard, anomalous accumulations of noble metals interpreted as clastic may actually be products of more complicated formation mechanisms rather than simply terrigenous supply.

The clastic nature of anomalous Au contents in coal measures has been established in the Aleksandriya district of the Dnieper brown coal field (Panov et al., 2001, 2004). The Paleogene coal measures of this district fill depressions in the Neoproterozoic crystalline basement and are surrounded by numerous Precambrian gold deposits and occurrences. As follows from sampling of three open-cut and one underground mines, the maximum Au contents in coal reach 9.8 ppm. Combustion wastes of Au-bearing coal of the Dnieper Basin at the Aleksandriya thermal power plant contain 0.32 ppm Au. Anomalous Au contents are characteristic not only of coal but also of the host coaly sand and clay.

The Au contents in sedimentary lithotypes in the thoroughly studied Morozovsky open-cut mine vary widely (Table 5), demonstrating a nonuniform distribution of ore mineralization in both the vertical and lateral directions. Two stratigraphic levels of gold accumulation are recognized: (1) the lower seam I with 2.8 ppm Au in ash and (2) the middle seam II with 1.7–4.8 ppm Au in ash and the overlying unit of coaly sand with 1.8 ppm Au. The Au content in the middle seam increases eastward from 0.14 to 1.85 ppm in ash. The enrichment of the eastern area is related to its erosion during peat deposition.

The Au reserves in the Morozovsky open-cut mine amount to 1.36 t at a grade of 0.5 g/t Au. This estimate indicates a limited scale of clastic gold accumulation; however, in the opinion of the authors, the Au reserves may be of some interest for recovery as by-products.

The clastic accumulation of gold was established in coal-bearing basins of the Upper Amur region. The well-known Nagimino gold placer is located in a Cen-

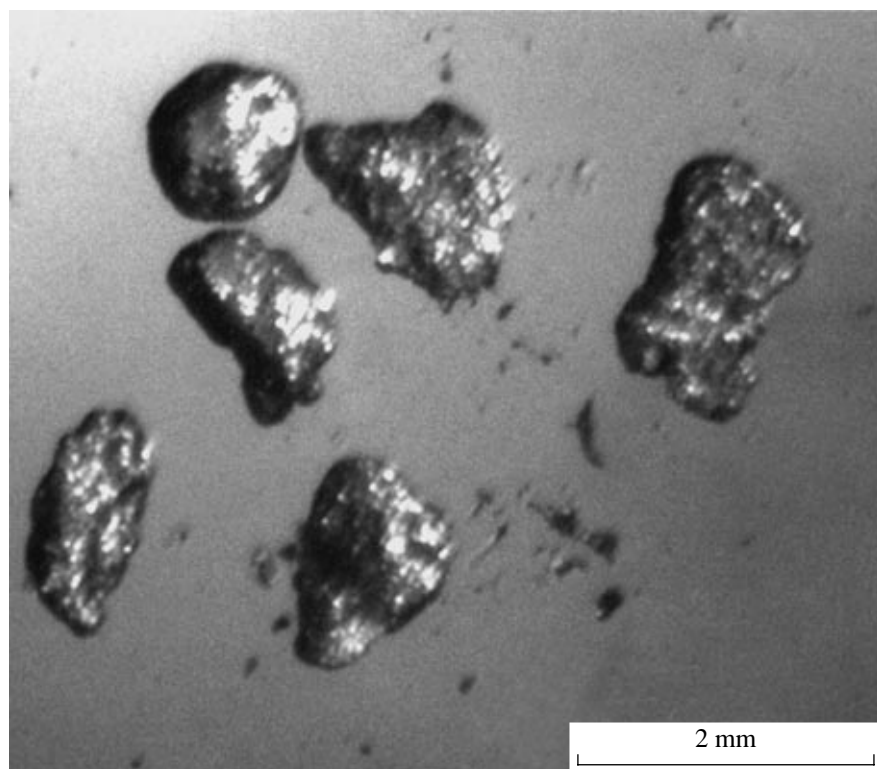


Fig. 2. Rounded placer gold grains from sand of the overburden, the Pavlovka 2 open-cut mine, Primorye.

ozoic graben filled with coal-bearing sandshale sediments more than 50 m thick (Kuz'minykh and Sorokin, 2004).

In the Kansk–Achinsk Basin, gravity concentrates from sandshale overburden in the Achinsk open-cut mine of the Nazarovo coalfield and from sand and gravel of the Uryup coalfield contain 12.5 and 9.8 ppm Au, respectively (Butan et al., 2000; Makarov, 1999). In addition, the first concentrate contains 1 ppm Rh.

In the Pavlovka brown coal field of Primorye, rounded gold grains were found in the Pliocene alluvial sediments of the Suifun Formation that overlie the eroded Miocene coal measures (Fig. 2). Gold accumulated in the basal alluvial unit and at the levels of local intraformational breaks in sedimentation.

In Alaska, particles of placer gold incorporated into a shell of Ca-glass were found in fly ash left from the combustion of Cenozoic coal of the Nenana field. The close correlation of Au and ash contents indicates the prevalence of terrigenous supply of gold (Stricker et al., 1992).

It is suggested that the marked accumulation of gold in the Jurassic bituminous coal of Tajikistan (up to 0.3 ppm in coal and up to 7.7 ppm in ash) and in conglomerate units (from 2–5 to 50–250 ppm) within the coal-bearing terrigenous sequence is of clastic origin as well. The scouring of Late Carboniferous–Permian hydrothermal sulfide deposits during peat deposition is considered to be the crucial factor in gold accumulation (Valiev et al., 2002). Very high contents of Ag (up to

112 ppm in coal and 663 ppm in ash) and many other elements are noted. In the Zuddy open-cut mine, the ash of Au-bearing coal contains up to 2.02 wt % Sb; 0.40–0.71 wt % Ba, Zn, and Ni; and 0.07–0.10 wt % Pb, Cu, As, and Hg.

The anomalous concentrations of Au (up to 0.25 ppm in ash), Ba (up to 2.98 wt %), Zn (up to 1.78 wt %), Br (up to 2333 ppm), As (up to 2255 ppm), Sb (up to 947 ppm), Hg (up to 254 ppm), and Ag (up to 50 ppm in ash) previously established in the Jurassic anthracite of the Nazar-Ailok coalfield in Tajikistan were considered products of hydrothermal activity resulting in the formation of Sb–Hg ore mineralization hosted in coal measures (Valiev et al., 1993).

A clastic origin of anomalous Au and PGE contents (up to 0.1 ppm Au, 0.04 ppm Pt, and 0.25 ppm Pd in ash) is accepted for the Paleogene lignite of the Mattagami Formation in Canada (Kronberg et al., 1987). It should be mentioned, however, that this lignite is obviously characterized by anomalous geochemistry. The maximum V, Sr, Ba, REE, and Zr contents reach 0.15–0.5 wt % in ash of this coal, together with 135–230 ppm Ge, Ga, and Nb and 60–80 ppm Hf, Th, and U. The highly anomalous Zr contents (up to 3 wt %) in clay may testify to the occurrence of volcanic material in coal measures and, hence, to an additional source of noble metals.

Data on very high Au and Ir contents in anthracite of the eastern Donets Basin were published by Kizilshtein (2002). If these data, obtained with INAA, are valid, the

Table 6. Au and Ir contents, ppm, in coal seam i_3^u at the Kapital'ny West Mine, after Kizilshtein (2002)

Parameter	Area 1					Area 2			
	6	7	8	9	10	41	4	5	40
A^d , %	22.4	25.9	33.4	25.7	17.6	18.3	25.1	26.7	13.5
Au	0.8(3.6)	0.95(3.7)	1.2(3.6)	1.1(4.3)	0.95(5.4)	0.03(0.16)	1.4(5.6)	0.8(3.0)	0.02(0.15)
Ir	0.1(0.45)	0.45(1.7)	0.6(1.8)	0.65(2.5)	0.33(1.8)	0.1(0.55)	0.3(1.2)	3.8(14.2)	0.4(3.0)
n	29	17	24	27	26	21	19	27	19

Note: INAA results are presented. Numbers designate sections, spaced at 10–15 m. Numerals in parentheses are contents recalculated to ash; n , number of samples.

average Au and Ir contents in coal of seam i_3^u , 1.0–1.5 m thick, in the Kapital'ny West Mine reach 1.4 and 3.8 ppm in separate sections (Table 6). The recalculation to ash yields 5.6 and 14.2 ppm, respectively. This coal is distinguished by anomalous contents of other trace elements, especially as concerns coal from the first area, where 220 ppm As, 90.6 ppm Mo, 47.5 ppm Hg, 26.3 ppm Cs, and 10.9 ppm W have been detected.

Such a high degree of enrichment in noble metals has been established in zones of syngenetic scouring resulting in replacement of the central zone of the seam with siltstone and mudstone and complication of the peatland structure owing to the appearance of partings composed of coaly siltstone. In the opinion of Kizilshtein, these features indicate the clastic nature of enrichment of coal seams in trace elements, including noble metals. However, the assemblage of chemical elements, typical of hydrothermal deposits, can hardly be purely terrigenous in origin. This is supported by high (0.4 ppm in coal and 2.4 ppm in ash) Ir contents in section 39, 1 km from the second area, where the coal seam retains a simple structure. The anomalous REE pattern should be mentioned as well. The metalliferous coal of the first area is appreciably enriched in HREE (up to 4.7 ppm Lu) and Eu (up to 4.8 ppm), whereas coal from the second area is enriched in Ce (up to 183.4 ppm).

Taking into account that Ir content in most Au–PGE deposits is lower by at least an order of magnitude than Pt and Pd contents, extremely high contents of other PGEs should be expected in this coal. Thus, if the reported analytical data are valid, Kizilshtein discovered a high-grade Au–PGE mineralization in a coal seam of the eastern Donets Basin. It is regrettable that he did not attach the significance to this discovery that it undoubtedly merits.

The study of ore mineralization known to be clastic in Late Cenozoic coal measures (Ruppert et al., 1997) has shown that orebodies of this type hosted in coal seams are localized in marginal zones of sedimentary basins close to the emptying of small streams that drain deposits containing ore minerals resistant to weathering in the nearest framework of the basin. The metal contents in enriched sedimentary units abruptly decrease toward the central zones. The ash content of coal decreases in the same direction.

The discovery of clastic-type coal that is enriched in noble metals automatically makes the host sedimentary units promising for Au and PGE. Taking into account the unfavorable conditions for terrigenous ore formation in the hydrologically passive lacustrine–swamp setting, it may be expected that relatively high-grade ore material will be revealed in coarse clastic sediments. Finds of clastic gold in coal measures stimulate prospecting for its sources at the walls of basins, even in the case where such sources were previously unknown in the region.

Ionic subtype. The hydrochemical data on the Upper Amur region, with numerous primary and placer gold deposits, indicate the possibility of significant accumulation of noble metals in surface water. The Au concentration in river water here reaches 4–12 $\mu\text{g/l}$; i.e., it is three to four orders higher than the background level (Kuz'minykh and Sorokin, 2004). Therefore, it is not surprising that a considerable amount of newly formed gold is detected in many placers (Shilo, 2000).

Finds of nodular PGM segregations (coreless nodules, stalactites and their bunchy intergrowths, and crusts with a concentrically shelly structure) in some placer deposits testify to the migration of PGE in surface water as ionic and colloidal species. Such segregations, typical of Pt, Pd, and even osmiridium, were described in Brazil and other countries as early as at the beginning of the 20th century (Hussak, 1904; Vysotsky, 1923). Much importance was attached to PGE precipitation from solutions by Chukhrov (1955).

On entering sedimentary sequences saturated with organic matter, dissolved Au and PGE may be reduced to the native state (Baranger et al., 1991) or taken up by organic matter, clay particles, or iron hydroxides. These processes proceed during both peat deposition and the late stages of coal basin evolution, when coal measures are scoured by surface streams.

The study of present-day peatlands testifies to the possible formation of high noble metal contents during peat deposition. For example, the enrichment of peat in Au up to 0.10–0.13 ppm was noted in Indonesia (Palmer and Cameron, 1989) and Wales (Andrews and Fuge, 1986). In the first case, peat was also enriched in As (up to 0.22%), and, in the second case, Au anomalies were established in a Cu-bearing peat bog (up to

5.14% Cu) fed by water draining the geochemical halo around a porphyry copper deposit located nearby.

In peatlands of Western Siberia, the Au content reaches 0.48 ppm in ash. Humic acids are the major carriers of gold in this peat; the Au content in their ash varies from 1.8 to 26.4 ppm (Arbuzov et al., 2004). It is suggested that gold was supplied to peat bogs in ionic form as chloride and organic complexes and afterward absorbed by organic matter. The occurrence of organic Au species is confirmed by an inverse correlation between Au and ash contents. Gold deposits and rocks enriched in Au, which are abundant in the southeastern, southern, and southwestern frameworks of the peatland, are regarded as Au sources. This is supported by localization of Au-rich peat at the basin margins and basement uplifts with hydrothermal Au–Sb, Au–Ag, and Au–As–Ag ore occurrences and deposits and by a systematic decrease in Au contents toward the center of the vast basin of peat deposition.

Gold may occur in peat bogs not only as organic compounds. Microparticles of native gold in association with sulfides, sulfates, and carbonates were detected in peat from Altai, Salair, and Kuznetsk Alatau (Matukhina et al., 1996).

The highest noble metal contents have been established in the Muthurajawela peatland, Sri Lanka's largest (Dissanayake and Kritsotakis, 1984). The average Au content calculated taking into account the thickness of the sampled intervals in three studied sections (4.2–6.0 m), including the underlying clay, is 0.42 ppm (the maximum concentration is 0.88 ppm Au; Pt, 1.24 and 7.9 ppm in peat). In the most representative section, the noble metal contents increase from the roof of the peat layer to the underlying clay unit; this trend is especially distinct for Pt (Fig. 3). Au is correlated with Fe, Mn, Co, Na, K, and Mg and does not show a significant correlation with organic matter. Pt is not correlated with any other element or organic matter. It is suggested that noble metals are supplied to peat bogs in a soluble form, being removed from surrounding laterites, and taken up by clay particles and Fe and Mn oxides and hydroxides.

Anomalous Au concentrations chronologically related to peat formation in paleovalleys were recently established in coal of four coalfields in the Upper Amur region (Kuz'minykh and Sorokin, 2004). Having applied fire assay and an original technique of sample preparation that rules out Au loss by ashing, the authors concluded that Au contents in 120 samples taken from one bituminous coal and three brown coal fields varied from 5 to 100 ppm Au (!). In the Miocene brown coal from the Svobodny and Sergeevsky fields, the average Au contents are 15 and 17 ppm; in the Lower Cretaceous bituminous coal, the Au content increases to 30 ppm, and in the Paleocene brown coal of the Raichikhinsk field, to 53 ppm.

It is difficult to believe in such high average Au grades in the coalfields of the Upper Amur region because, if this is actually the case, then the coal seams

of the fields listed above should be classed with high-grade gold ore, with reserves—taking into account the coal resources—comparable with the world's largest gold deposits. Nevertheless, an anomalous, though not such a high, Au grade of the Raichikhinsk coalfield is confirmed by the fact that, among coals from ten fields combusted at the Khabarovsk thermal power plant, the highest Au content (1.78 ppm) has been established in the ash of the Raichikhinsk coal (Bakulin and Cherepanov, 2003).

It is suggested that surface water draining primary and placer gold deposits carried dissolved Au to basins of peat deposition during the entire Cenozoic. The concentration of gold in coal is related with chemical sorption of Au by humic acids of peat bogs and the subsequent compaction of organic matter in the course of coalification. However, this mechanism is hardly applicable to the Au mineralization of the Ogodzha coalfield, which was formed in the pre-Cenozoic in the Seledzha volcanotectonic depression of Cretaceous age and later affected by hydrothermal activity and contact metamorphism.

As the study of metalliferous peatlands shows, the ore mineralization formed as a result of supply of dissolved compounds of various metals by surface drainage at the peat stage of coal deposition is also localized in marginal zones near the emptying streams. The entire peat layer may be metalliferous at the bog periphery. Toward the peatland center, the ore mineralization pinches out and concentrates only at the bottom of the peat (Fig. 4a). Such an apronlike morphology of orebodies is typical of some U-bearing peat deposits (Kochenov et al., 1965) and of peat that bears base metal mineralization (Cannon, 1955) formed by entry of ore components into peatlands in a soluble form. The extent of these orebodies is commonly no more than a few hundred meters.

Another situation may be observed when metalliferous surface streams erode already formed coal measures (Fig. 4b). In this case, the ore mineralization concentrates in the areas where the channels downcut the beds of buried peat and coal. Such a situation is characteristic, in particular, of some uranium–coal deposits (Danchev and Strelyanov, 1979; Kislyakov and Shchetochkin, 2000). The gold accumulation in areas of coal seam scouring in the Pavlovka field (Seredin, 2002) is probably of the same origin. Here Miocene coal coming into contact with Pliocene sand contains native gold microparticles of clearly authigenic nature, while the sand contains clastic gold.

The thickness of the subchannel zone of coal enrichment is apparently controlled by the rate of coalification of organic matter during the scouring. The maximum thickness is observed when the buried peat is eroded, and the minimum thickness is related to the scouring of bituminous coal. This is caused by a decrease in the absorption capacity of organic matter with respect to ions of different metals and its permeability for water solutions with increasing rank of coal. However, in any case, the permeability of organic matter does not exceed a few decimeters.

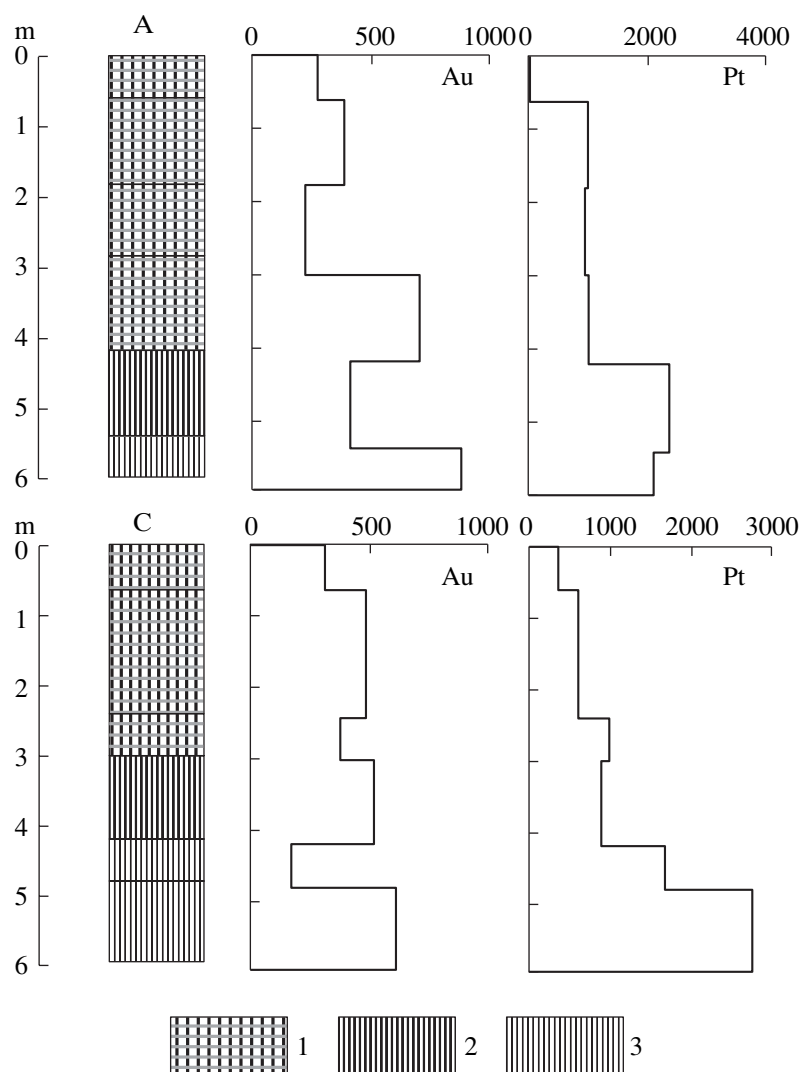


Fig. 3. Distribution of Au and Pt contents, ppb, in sections A and C of the Muthurajawela peatland, Sri Lanka, after data reported by Dissanayake and Kritsotakis (1984). (1) High-ash peat; (2) peat clay; (3) clay.

Infiltration Type

This type comprises noble metal accumulations that were formed as a result of supply of dissolved Au and PGE compounds to coal measures along with subsurface meteoric water migrating under the effect of gravity from the framework of sedimentary basins to their central portions. Unconfined groundwater circulating near the surface in the zone of free water exchange and confined formation water penetrating along coarse clastic units deep into sedimentary basins are distinguished (Kislyakov and Shchetochkin, 2000).

Buried channels filled with coarse clastic sediments often serve as conduits of migration. The infiltration uranium deposits of paleovalley type are formed in such settings. The localization of orebodies in this case is similar to that described above (Fig. 4b).

Infiltration accumulations of noble metals formed at the stage of early epigenesis are known in coal-bearing

basins of central Asia and Kazakhstan, including basins that host uranium–coal deposits. In the Apartak area of the Angren coalfield, anomalous Au, Pt, and Pd contents were detected in pyrite and marcasite in epigenetically altered coaly clay (Klimanov, 2003).

Very high Au contents (up to 14.5 g/t of coal) were established at the Kol'zhat U-bearing coalfield. Gold is localized here largely in authigenic pyrite and to a lesser extent in organic matter (Deep..., 2002).

Anomalous PGE contents of (ppm) 0.05 Pt, 0.22 Pd, and 0.082 Ir (0.31 ppm in total) related to a zone of stratal oxidation were detected in lignite from Tomsk oblast (Shor et al., 1996). Such high Ir contents had not been reported previously even in accumulations of the cosmic type. Later, it was established that, in halos at pinches of stratal oxidation zones in Western Siberia, the Pt content in brown coal and fossil wood buried in

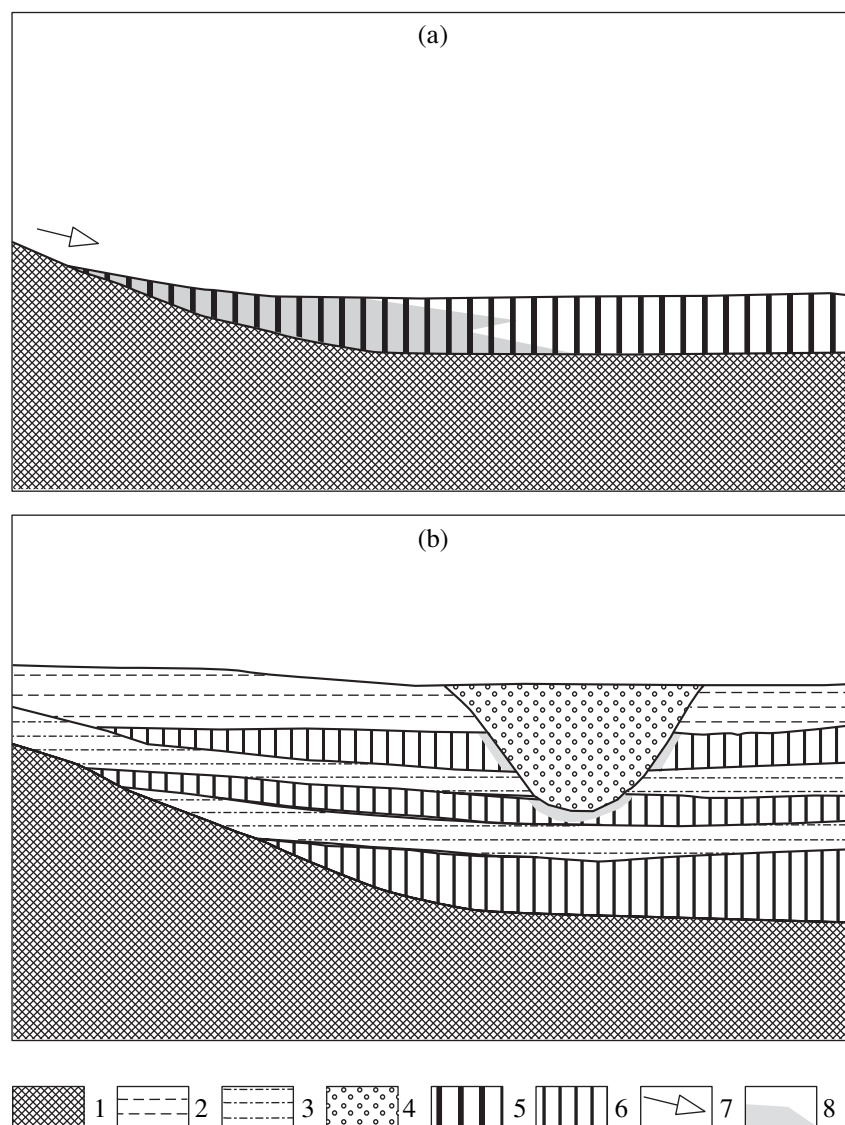


Fig. 4. Alluvial ore mineralization of ionic subtype developing (a) at the stage of peat deposition and (b) during scouring of coal measures by surface streams (a conceptual scheme). (1) Bedrock; (2) clay; (3) siltstone and mudstone; (4) pebbles; (5) peat; (6) coal; (7) direction of stream; (8) ore mineralization.

sedimentary sequences may reach 0.57 ppm (Shor et al., 2004).

High PGE contents, presumably controlled by infiltration, have been reported from two coalfields in British Columbia, Canada (Van der Flier-Keller, 1991). In the Quinette field, the roof of a coal seam overlapped by a conglomerate unit is marked by 1.7 ppm Pt and 0.18 ppm Rh in coal. Still higher concentrations: >10 ppm Pt, 6.1 ppm Pd, 80 ppb Ru, 61 ppb Rh, 24 ppb Os, and 22 ppb Ir (unproved by check analyses, however) were established in samples taken from tectonized coal in the Tulameen field, Blackburn Mine. As Van der Flier-Keller suggested, these concentrations are related to a gain in PGE with groundwater enriched in these elements as a result of circulation in the nearby ultramafic massif with high PGE contents.

These data indicate that noble metals may be transported by oxygen-bearing subsurface water of meteoric origin. The concentration of ore elements probably occurs similarly to the accumulation of other metals studied at infiltration uranium deposits.

Exfiltration Type

Gold and PGE mineralization related to the injection of hydrothermal solutions into the sedimentary cover of coal-bearing basins has been found in South Wales, China, Uzbekistan, and Primorye. Minerals of noble metals were revealed in enriched coal in almost all these provinces. Judging from the available information, the metalliferous solutions had variable temperature and chemical composition and entered coal measures at different stages of coal basin evolution.

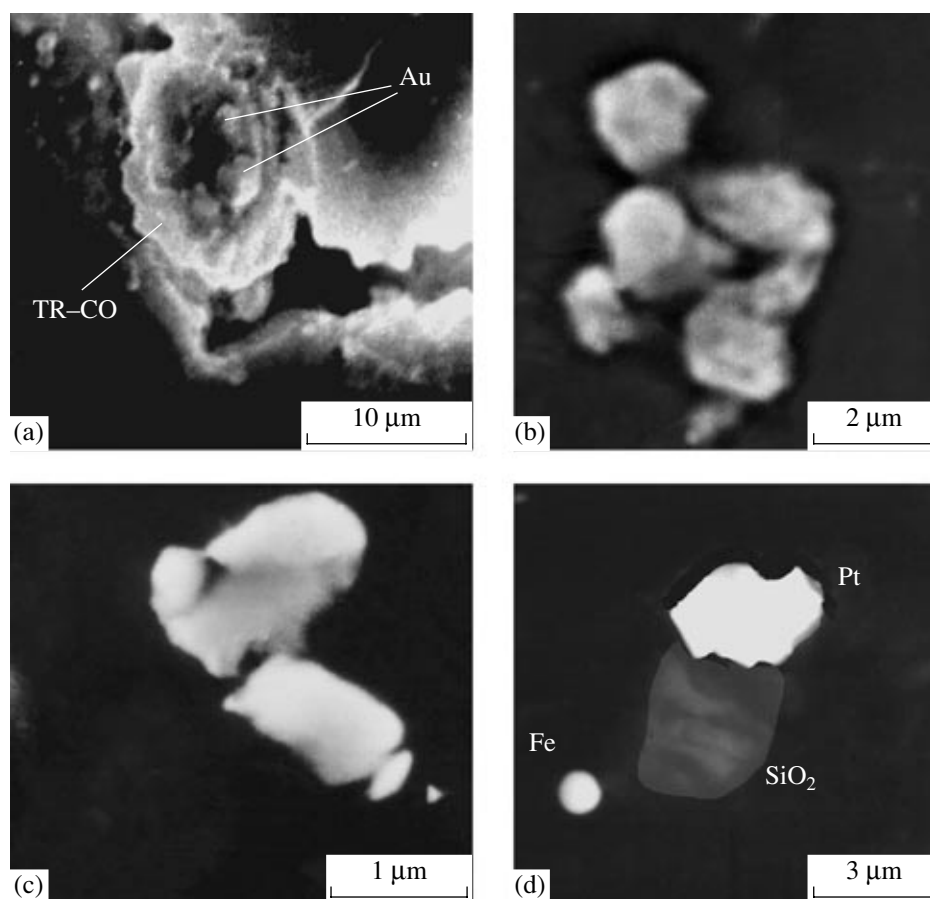


Fig. 5. Au and Pt minerals in coal seam I in the Pavlovka field formed at the stage of diagenesis of organic matter. (a) Gold micronodules on the surface of a bastnaesite grain TR-CO; (b) aggregate of copper gold microcrystals; (c) aggregate of native platinum microcrystals; (d) native platinum near a silica segregation and a globule of native iron. (a) Back-scattered electron (BSE) image; (b–d) images in reflected electrons.

Syngenetic mineralization. No data on exfiltration concentrations of noble metals are known to date in the literature. However, the high Au contents (up to 15 µg/l) in the vapor-saturated hydrothermal systems of Kamchatka (Karpov, 2004) and finds of Au, Pt, and Pd minerals in the exhalation ore on the Kuril Islands (Korzhinsky et al., 1998; Distler et al., 2003; Rybin et al., 2003; Yudovskaya et al., 2003) definitely indicate a possibility of hydrothermal contamination with Au and PGE of peatlands located in zones of current volcanic activity. The Ge-bearing peat of Kamchatka (Ivanov et al., 1984) shows that orebodies formed near gas-saturated mineral springs discharging into a peat layer are commonly oval in plan and dome-shaped in section. The maximum metal contents are related to the lower portions of these domes, where metalliferous fluids spread out within peat.

Diagenetic mineralization. The accumulation of noble metals after burial of organic matter in peatlands but before its coalification was established in some coalfields of Primorye, including Ge-bearing fields. It can be considered proven that these coalfields were formed at the diagenetic stage as a result of circulation

of high-pressure vapor-saturated hydrothermal solutions through the basement (Seredin, 2004b).

In the Pavlovka coalfield, the best studied in this respect, anomalous Au and PGE concentrations were detected in the lowermost coal seam I, which lies close to the basement surface (Seredin, 2004a). The total noble metal contents in seam I vary from $n \times 0.01$ to $n \times 0.1$ ppm in coal, or from $n \times 0.1$ to $n \times 1$ ppm in ash.

The diagenetic hydrothermal nature of this mineralization is indicated by (i) local enrichment of a thick (2–5 m) coal seam in noble metal; (ii) accumulation of noble metals in the overlying sedimentary rocks; (iii) occurrence of some noble metal minerals in vitrinite lenses, as well as beyond microfractures and pores in organic matter of coal; and (iv) association of noble metals with sulfides, halogenides, carbonates, native metals, and intermetallic compounds. All these indications are direct evidence for the formation of noble metal mineralization as a result of circulation of high-pressure sulfate–chloride hydrothermal solutions after the burial of peat but before coalification of organic matter.

Table 7. Au, Pt, and Pd contents, ppm, and their yield in fractions of various density and ash content obtained by gravity separation of metalliferous coal from the Pavlovka brown coal field

Density, g/cm ³	Fraction yield, %	A ^d , %	Au, coal (ash)	Pt, coal (ash)	Pd, coal (ash)	Yield in fraction, %		
						Au	Pt	Pd
–1.4	80.3	5.6	0.08(1.42)	0.17(3.0)	0.03(0.54)	66.5	58.7	73.7
1.4–1.6	15.7	14.0	0.13(0.93)	0.32(2.29)	0.04(0.29)	21.2	21.9	19.7
+1.6	4.0	49.1	0.30(0.6)	1.11(2.26)	0.05(0.11)	12.3	19.3	6.6
Total	100.0	8.7	0.10(1.11)	0.23(2.65)	0.03(0.38)	100.0	100.0	100.0

Note: Results of sorption spectrochemical analysis are presented.

The coal of seam I enriched in noble metals in various areas of the Pavlovka field pertains to two geochemical types: Ge–Sb–W–Au and REE–Au–PGE. The Au–Sb–W assemblage is characteristic of some hydrothermal gold deposits, including of the volcanic type (Berger, 1978). The REE–Au–PGE assemblage is noted at some hydrothermal Au–PGE deposits: the Boss deposit in the United States (Jedwab et al., 1999), the Chudny deposit in the Urals (Moralev et al., 2005), and the Serra Pelada deposit in Brazil (Moroni et al., 2001; Cabral et al., 2002). These geochemical features serve as additional evidence for exfiltration hydrothermal origin of noble metal mineralization in coal of the Pavlovka field.

Minerals of noble metals comprise copper and mercury gold, native platinum, isoferroplatinum, and cooperite. The grains of all identified Au and Pt minerals vary from 1 to 5–7 μm in size and occasionally comprise intergrowths of several microparticles (Fig. 5). The gold and platinum grains either are hosted in an organic matrix or grow over authigenic minerals. One native platinum grain was observed near an amorphous silica segregation in coal, thus indicating a siliceous composition of the metalliferous solution and its low temperature.

The distribution of noble metals in specific-gravity fractions demonstrates that relative Au and PGE amounts increase with the ash content of fractions and the percentage of mineral particles contained therein (Table 7, Fig. 6). At the same time, the maximum yield of noble metals is characteristic of the low-density and low-ash fractions, probably, owing to localization of noble metals largely in organic matrix of coal. It may also be suggested that organic compounds of noble metals occur in this coal together with finely dispersed mineral carriers.

Such a possibility is supported by experimental data (Varshal et al., 1995; Lakatos et al., 1997) and by the appreciable accumulation of Au in humic substance extracted from metalliferous coal of the Luzanovsky open-cut mine in the Pavlovka field by alkaline leaching (Table 8). The percentage of “organic” gold in this coal is 52.4% of its total amount.

The anomalous concentrations of noble metals established in other Ge-bearing coalfields in Primorye likely are of diagenetic exfiltration nature as well.

In the Lower Bikin Basin, Au–PGE mineralization was found in the Eocene coal seams of the Cheremshovy and Fedos’evsky Ge-bearing coalfields. In the Fedos’evsky field, coal is enriched in not only Ge but also contains up to 35 ppm Ag. The noble metal contents are comparable with those in the Pavlovka field and are even higher in some samples of Ge-bearing coal.

The gold distribution in products of gravity separation of Ge-bearing coal from the Fedos’evsky field is opposite the distribution of germanium, an element contained in the organic component of coal (Table 9, Fig. 7). This and a small yield of Au in the fraction with the lowest ash content clearly indicate that mineral species of gold are predominant in this coal.

The Ag distribution by fractions is unlike the distribution of Au and Ge. Silver accumulates in both the lightest and the heaviest fractions with marked variations in the Ag/Au ratio, which abruptly falls in heavy fractions against light fractions. The Ag content in ash of the lightest fraction is 198 ppm, i.e., close to the Ag grade of traditional ores. Such a distribution may testify to the occurrence of both organic and mineral Ag species in coal. The first are probably prevalent because the light fraction contains 57% and the heavy fraction only 17% of the total silver. Experiments conducted by Eskenazy (1974) indicate the ability of Ag to form organic compounds with organic matter of coal.

Au and Pt minerals were identified in cinder-ash wastes of the Luchegorsk thermal power station, which operates on coal of the Lower Bikin field (Bakulin and Cherepanov, 2003); a fused grain of native palladium was found therein (V.M. Li, oral communication). In ash of a coal sample with ordinary Ge grade taken from the Luchegorsk open-cut mine, the Au content was 0.45 ppm (Bakulin and Cherepanov, 2003).

In the Shkotovo coalfield, anomalous concentrations of Pt (up to 0.22 ppm in coal and 0.92 ppm in ash) and Pd (up to 0.01 ppm in coal and 0.04 ppm in ash) were established in ROM samples from the Artem Mine and the Smolyaninovo open-cut mine (Zharov et al., 1996).

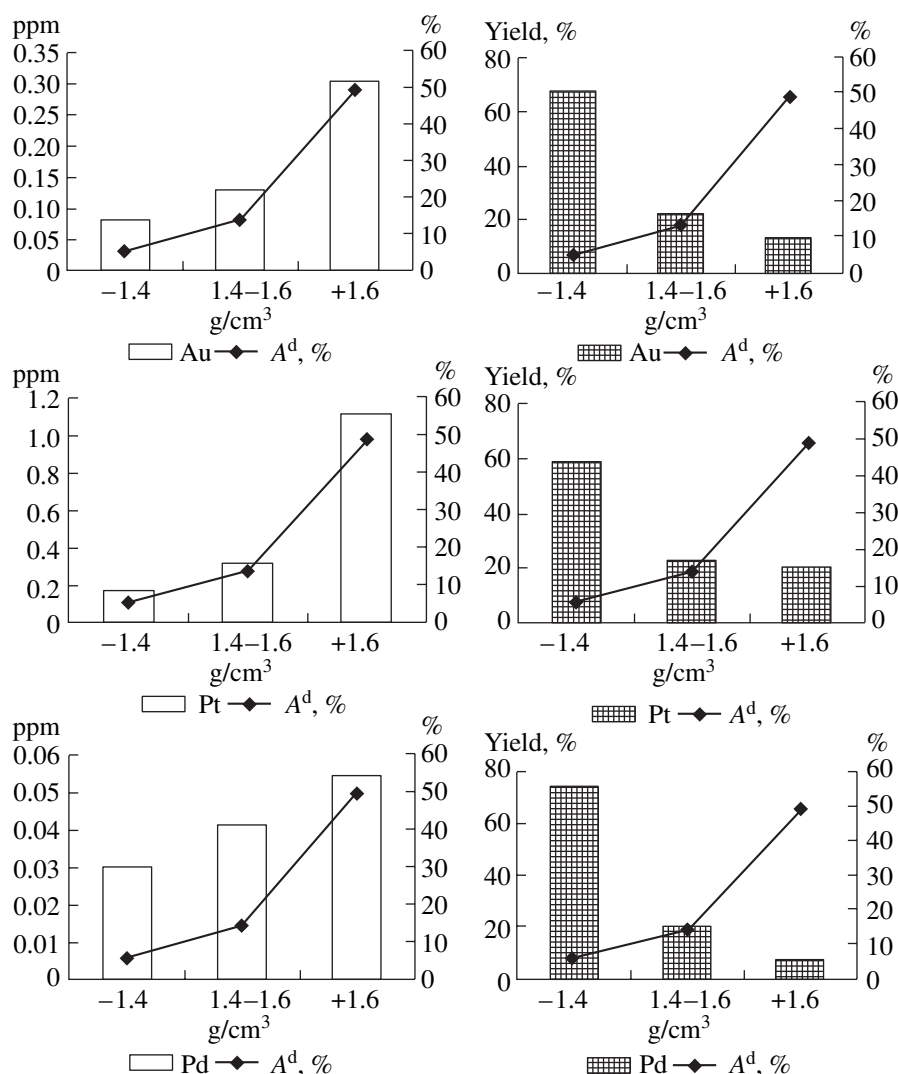


Fig. 6. Distribution of ash content (A^d , %) and Au, Pt, and Pd contents in products of gravity separation of metalliferous coal in the Pavlovka field and yields of metals in fractions of various densities.

It cannot be ruled out that still higher noble metal contents may be detected in Ge-bearing coal of this field, as attested by very high Sb and As contents (up to 1000 and 180 ppm, respectively). Sb and As are common companion elements of noble metals at hydrothermal deposits. The appreciable enrichment

of host siltstone and sandstone in Sb (0.1–1.0 wt %) indicates that the ore formation occurred after burial of peat. The anomalous Hg content in coal of this field is also a favorable criterion. The Hg content in coal near faults reaches 40 ppm (Dvornikov et al., 1991).

Table 8. Au content and distribution in metalliferous coal of the Luzanovsky open-cut mine before and after its treatment with 1% NaOH and calculated Au concentration in humic matter

Product	A^d , %	Product yield, %	Au, ppm		Au yield, %
			coal	ash	
Initial coal	17.6	100	0.1	0.57	100
Residual coal	23.2	79.3	0.06	0.26	47.6
Humic matter	4.7	20.7	0.25	5.39	52.4

Note: INAA results are presented.

Table 9. Au and Ag contents, ppm, their yield, and distribution of the Ag/Au ratio in products of gravity separation of metalliferous coal from the Fedos'evsky high-Ge coal deposit, the Lower Bikin brown coal field

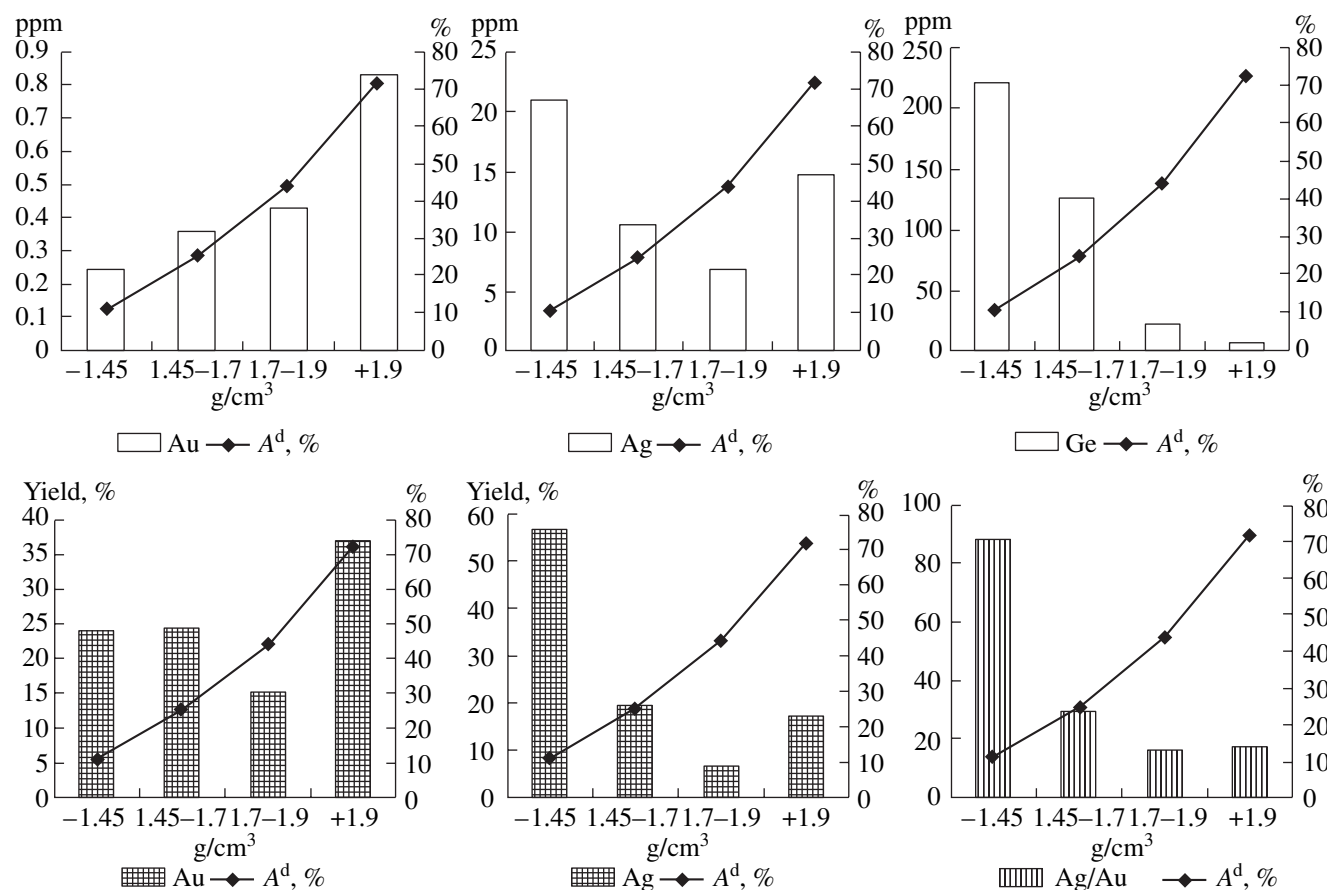
Density, g/cm ³	Fraction yield, %	A ^d , %	Au, coal (ash)	Ag, coal (ash)	Yield in fraction, %		Ag/Au
					Au	Ag	
-1.45	40.5	11.0	0.24(2.18)	20.9(198)	23.9	56.8	88.4
1.45–1.7	27.6	25.0	0.35(1.4)	10.4(41.6)	24.3	19.3	29.5
1.7–1.9	14.2	44.0	0.43(0.98)	6.8(15.5)	15.0	6.5	16.0
+1.9	17.7	72.0	0.84(1.17)	14.7(20.4)	36.8	17.4	17.6
Total	100	30.3	0.40(1.32)	14.9(49.2)	100.0	100.0	49.3

Note: Au contents were determined with SSCA; Ag contents are average values after INAA and AAS results.

Au–PGE mineralization was found recently in Ge-bearing coal and underlying clayey products of weathering in the Angren field, Uzbekistan (Klimanov, 2003). The coal seams contain micrometer-sized gold segregations in pyrite (Fig. 8), as well as Pd and Pt sulfides and intermetallic compounds and Au-bearing (up to 400 ppm) pyrite–marcasite nodules in clay. Visible gold was noted by A.V. Vnukov during exploration of Ge-bearing coal in the Tarbagatai field of the Transbaikalian region (Meitov, 2001). In addition, anomalous

Au and Ir contents (up to 26 and 51 ppb, respectively) have been established at the Ulan Tug high-Ge coal deposit in northeastern China. According to SEM examination, gold is incorporated here into the finest (1–2 μm) particles of Ge oxide (Zhuang et al., 2006).

The large exfiltration Ge deposits commonly are made up of a series of closely spaced dome-shaped or columnar orebodies that may cross several coal seams overlying one another (Seredin, 2004b). The zones

**Fig. 7.** Distribution of ash content (A^d, %); Au, Ag, and Ge contents; and Ag/Au ratio in specific-gravity fractions of Ge-bearing coal of the Lower Bikin field and yields of Au and Ag in fractions of various densities.

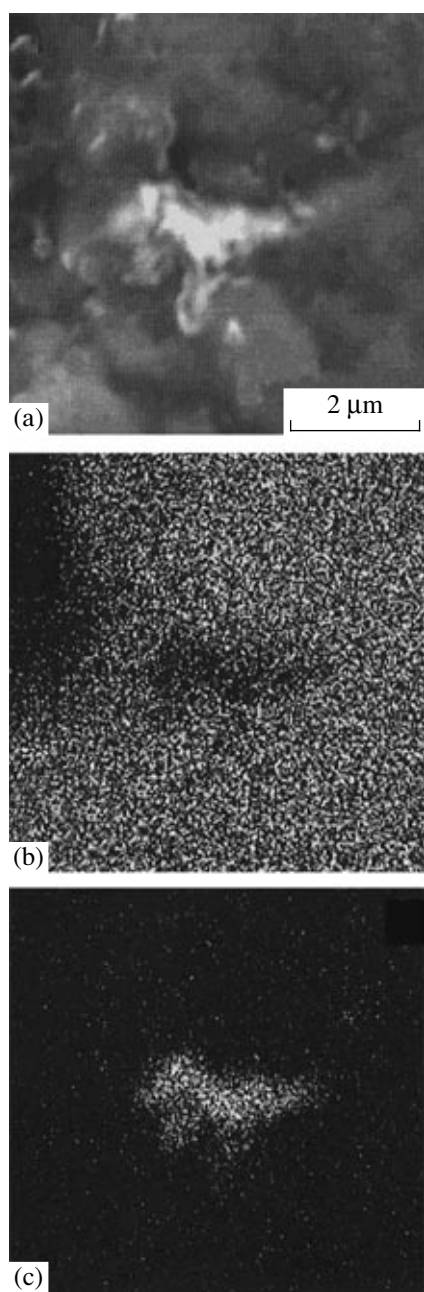


Fig. 8. (a) Gold microinclusion in pyrite from coal of the Angren field and (b, c) distribution of (b) Fe and (c) Au in characteristic X-ray irradiation. Photomicrograph by E.V. Klimanov.

enriched in Au and PGE probably have the same morphology, as indicated by contamination of all Ge-bearing coal seams with gold at the Spetsugli (Special Coal) deposit (Table 10). Almost all samples taken from cores of two boreholes drilled in the central area of this deposit in 2000 are marked by anomalous Pd contents (up to 0.1 ppm in coal and up to 0.26 ppm in ash). High Au contents at this deposit were detected not only in coal seams and their host rocks but also in the lowermost unit of the rewashed weathering mantle (sam-

ple 25d-75). This unit occurs 5.5 m below the bottom of coal measures and, in addition to gold, is enriched in REE (up to 0.2 wt %).

Thus, the high concentrations of noble metals and/or their minerals at many high-Ge coal deposits allow them to be considered as highly promising with respect to noble metal mineralization suitable for recovery as a by-product. The finding of Pd–Pt germanate $[(\text{Pd,Pt})_2\text{Ge}]$ in a hydrothermal noble metal ore (Armitage et al., 2002) indicates that these metals may be transported jointly by ascending metalliferous solutions.

Judging by the enrichment of both high- and low-S coals in noble metals, these solutions could have been of different compositions.

Sulfate hydrothermal solutions apparently were responsible for the formation of Au–PGE mineralization in high-S (1.35–2.38% S) coal of the Angren field in Uzbekistan (Klimanov, 2003) and the Makum field in India (Baruah et al., 1998). In these fields, the noble metals either concentrate in sulfides (Angren) or enter into organic compounds (Makum). According to the results of selective leaching of coal in three samples with anomalous Au contents (22.8, 24.9, and 32.0 ppm), the “organic” gold in the Indian coal may reach 100% (Table 11). It is suggested that gold was supplied to coal as thiosulfate complexes during the breakdown of plant organic matter.

The formation of Au–PGE mineralization in most coalfields of Primorye and probably in the Lower Ili field in Kazakhstan was related to the circulation of low-S chloride solutions, as follows from an insignificant (<0.5%) sulfur content in coal and a prevalence of Cl over S in most studied fluid inclusions in metalliferous quartz and carbonate veinlets at the flanks and in the basement of the Pavlovka coalfield (Seredin, 2004a).

In the Lower Ili field, anomalous Au contents (0.004–0.44 ppm in coal and 0.02–1.67 ppm in ash) were determined in coal with an elevated S content (reaching 0.4–9.9%) (Ratynsky et al., 1982). However, a detailed examination of the Au-bearing samples showed that Au correlates with finely dispersed authigenic quartz rather than with sulfur: the samples richest in Au turned out to be low-sulfur. It is suggested that gold was introduced along with deep siliceous solutions. The absence of quartz veinlets in coal indicates that these solutions were supplied before coalification of organic matter.

Epigenetic mineralization. The epigenetic exfiltration concentrations of noble metals in coal measures pertain to two different types. The first type comprises Au and PGE accumulations resulting from circulation of relatively low-temperature metalliferous fluids, while the second type is related to the high-temperature impact of magmatic bodies upon coal seams.

The first type may be exemplified by anomalous Au accumulations (up to 0.18 ppm Au in coal and 4.4 ppm Au in ash) in the Carboniferous anthracite seams of Wales mines (Gayer and Rickard, 1994). Gold is dis-

Table 10. Au and Ge contents, ppm, in samples taken from Ge-bearing coal seams of the Spetsugli deposit, the Pavlovka brown coal field, Primorye

Borehole-sample	Coal seam	Rock	Thickness, m	A ^d , %	Ge	Au		Analytical method (for Au)
						ash	rock	
25d-22	III-lower	2	0.60	50.4	1728	1.47*	0.74	SSCA
4-37	III-lower	1	0.45	16.0	1632	0.23	0.037*	ICP MS
25d-24	II-upper	1	0.60	10.7	1117	0.40	0.043*	INAA
25d-27	II-lower	1	0.30	38.0	994	2.63*	1.0	SSCA
4-48	II-lower	1	0.35	29.6	2013	0.35	0.10*	ICP MS
25d-36	I	3	0.40	65.60	223	1.30*	0.85	SSCA
25d-37	I	1	0.80	21.00	1552	0.95*	0.20	SSCA
25d-40	I	1	0.20	34.00	755	3.82*	1.3	SSCA
25d-75		4	1.00		<1		1.1	ICP MS

Note: Rocks: (1) coal, (2) coaly mudstone, (3) coaly sandstone from seam roof, (4) clayey material of reworked weathered granite. Analytical methods: INAA, instrumental neutron activation analysis; ICP MS, inductively coupled plasma mass spectrometry; SSCA, sorption spectrochemical analysis. * Calculated data. The Au contents determined with INAA and SSCA in the coal and coaly rock samples reduced to ash may be underestimated because of Au loss during ashing (Table 1).

Table 11. Gold distribution in products of chemical separation of Au-bearing coal from the Makum field, India, after Baruah et al. (1998)

Product (Au mode of occurrence)	Au, ppm		
	Tirap Mine	Tikak Mine	Baragolai Mine
Extract of ammonium acetate (ion-exchange)	<	<	<
Extract of 1M HCl (organic + mineral)	26.0	10.0	<
Extract of RuCl ₃ after treatment of coal with 1M HCl (organic + mineral)	6.0	12.0	<
Extract of RuCl ₃ after treatment of the light demineralized fraction with 1M HCl (organic)	<	12.8	24.9
Baragolai Mine	32.0	22.8	24.9

Note: AAS results are presented.

tributed through coal measures extremely nonuniformly. For example, at the East Pit Mine, only four of ten sampled seams showed high Au contents (>1 ppm Au in ash). No correlation of Au with ash content was established. The increase in Au content is related to the increasing number of desiccation cleats. This correlation may serve as evidence for early epigenetic enrichment.

Colloform bedded gold overgrowths no more than 100 µm in length on the walls of cleats oriented normally to the bedding were identified in this coal with SEM. The coal has a high fineness and contains less than 5% Pd, Ag, Bi, and Cu as microadmixture. Gold in fractures is associated with quartz, carbonates, and clay minerals; sulfates (gypsum, barite); sulfides of Fe, Co, Ni, Cu, Zn, Mo, Cd, and Pb; clausthalite (PbSe); oxides; and phosphates. It is suggested that gold precipitated from a low-temperature (<100°C) solution after formation of quartz, carbonate, and clay minerals but before crystallization of sulfides and selenides. Thus,

this mineral assemblage is epigenetic and related to the circulation of metalliferous solutions through microfractures formed during coalification. It is important to note that no primary or placer gold deposits are known close to this basin.

Epigenetic noble metal mineralization, along with diagenetic mineralization, is developed in coal and overburden in the Pavlovka coalfield in Primorye (Seregin, 2004a). As in South Wales, epigenetic Au minerals concentrate here in microfractures within coal seams. The maximum number of Au minerals is observed in zones of tectonic crushing of coal, near the roofs of seams, and in zones of their scouring at the bottom of the Pliocene alluvium that overlaps the Miocene coal measures. The Au minerals often reach 1–2 mm in size. Their morphology is diverse: perfect crystals, dendrites, needles, and plates combined into multilayer packets are observed (Fig. 9).

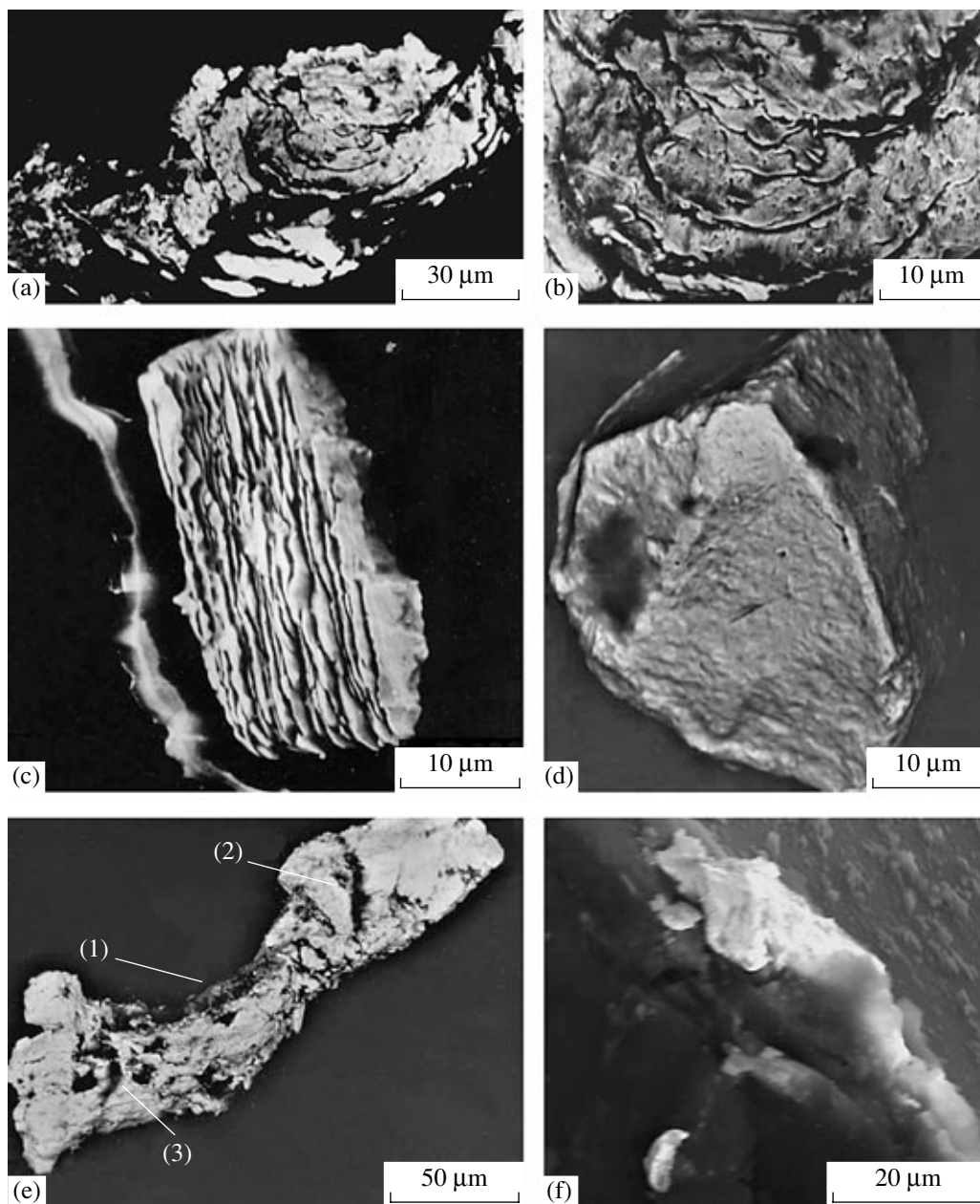


Fig. 9. BSE images of epigenetic gold minerals located in microfractures within coal seams. (a–c) Lamellar gold, (b) close-up of grain (a); (d) crystalline gold; (e) large grain of copper gold of irregular shape associated with (1) Cu carbonates on the surface, (2) a chrome-ferrite veinlet, and (3) inclusions of Ca-aluminosilicates, presumably zeolites; (f) microfracture wall overgrown with copper gold. (a–e) Coal seam III₂ in the Luzanovsky open-cut mine of the Pavlovka coalfield, Primorye; (f) coal seam XI, Shevyakov Mine, southern Kuzbas.

The epigenetic character of such mineralization is confirmed by the occurrence of Au and PGE minerals in sediments of the overburden, including the Pliocene alluvium, the fossil wood buried therein, and the bottom of the lower Pleistocene clay. The noble metal mineralization in the sediments that overlie coal measures comprises angular grains of copper and mercury gold, native platinum and palladium, and Pd- and Fe-bearing platinum (Fig. 10); copper and mercury gold with a microadmixture of Pt, as well as Sn-bearing cooperite, are contained in fossil wood (Fig. 11).

The epigenetic noble metal mineralization in the Pavlovka coalfield is related to the hydrothermal activity conjugated with Pliocene and early Pleistocene volcanism. This conclusion is based on the identical composition and mineral morphology of noble metal mineralization hosted in the Late Cenozoic basic dikes and hydrothermal breccia located in the basement of the coalfield (Fig. 12); the dikes and breccia bodies were affected by argillic alteration. The mineral assemblages in coal and hydrothermally altered rock consisting of sulfides, halogenides, carbonates, native metals, and

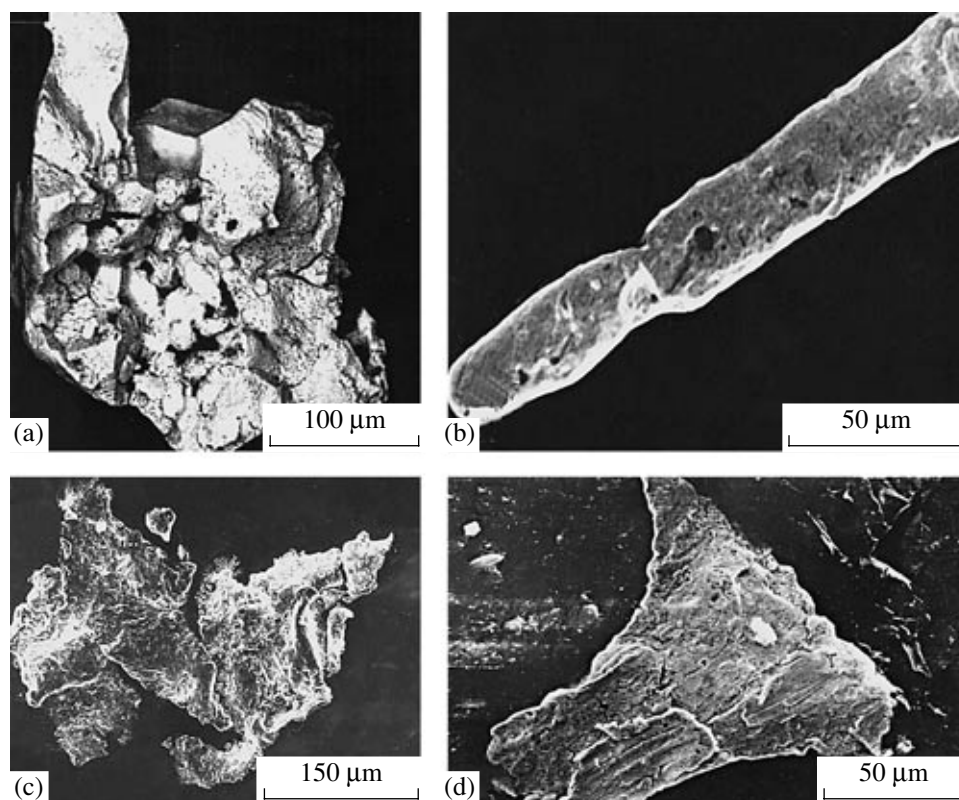


Fig. 10. BSE images of angular grains of noble metal minerals from limonitized sediments of overburden in the Pavlovka coalfield. (a) Aggregate of mercury gold crystals; (b) tubular gold; (c, d) lamellar Pd-bearing platinum. (a, c) Roof of sand and pebbles of the Pliocene Suifun Formation; (b, d) bottom of lower Pleistocene clay. (a, b, d) Pavlovka 2 open-cut mine; (c) Luzanovsky open-cut mine.

intermetallic compounds are close to each other. The breccia bodies that cut through coal measures in the Pavlovka coalfield contain up to 150.5 ppm Au, 72 ppm Ag, 0.57% Hg, and 3.17% As (Seredin et al., 2007).

Like the diagenetic mineralization, the Late Cenozoic epigenetic Au–PGE mineralization pertains to different geochemical types: REE–Au–PGE, Au–Ag–As–Hg, and Mo–As–Ni–Co. The first assemblage is similar to that mentioned above for the diagenetic accumulations of noble metals in coal of this field. The second assemblage is characteristic of postvolcanic epithermal deposits, and the third assemblage resembles the deposits hosted in the Lower Cambrian PGE-bearing carbonaceous shales of southern China (Lott et al., 1999) and some Polish cupriferous black shales enriched in Au and PGE (Kucha and Przybylowich, 1999). Lower Cambrian black shales anomalously enriched in Au and PGE (up to 0.1–0.2 ppm) are widespread in the Pavlovka coalfield. Noble metals may be leached from these rocks and redeposited by ascending flows of aggressive hydrothermal fluids related to volcanic activity (Seredin et al., 1997).

At the Angren high-Ge coalfield in Uzbekistan, as in the Pavlovka coalfield in Primorye, not only diagenetic but also epigenetic hydrothermal Au–PGE mineralization has been revealed (Klimanov, 2003). This mineral-

ization is related to an outburst of Late Jurassic–Early Cretaceous volcanic activity with eruptions of alkali basalts and is composed of sulfides with noble metal inclusions that fill microfractures in coal seams and slightly auriferous (up to 0.3–0.7 ppm Au) carbonate–kaolinite metasomatic rocks and barite veins in the weathered rhyolite that underlies coal measures (Koldaev, 2004).

In the southern Kuzbas (Kuznetsk Basin), epigenetic hydrothermal Au mineralization was found at the Shevyakov Mine in coal seam XI. Copper gold overgrows here the walls of microfractures (Fig. 9f) in association with native Fe, Cu, Pb, Zn, and Ag and intermetallic compounds, sulfides, halogenides, and carbonates of these metals. This assemblage is typical of hydrothermal activity related to basic and intermediate magmatism. The occurrence of diorite intrusions that cut through the coal measures allow this Au mineralization to be considered as a product of postmagmatic hydrothermal activity.

The high gold concentrations (10.3 ppm Au in ash) in the Gorely Verkhny (Upper Burnt) coal seam in the Shestaki I open-cut mine (Nifantov, 2003; Nifantov et al., 2003) probably have a similar nature. The anomalous Au concentrations (up to 1.1 ppm) in zones of

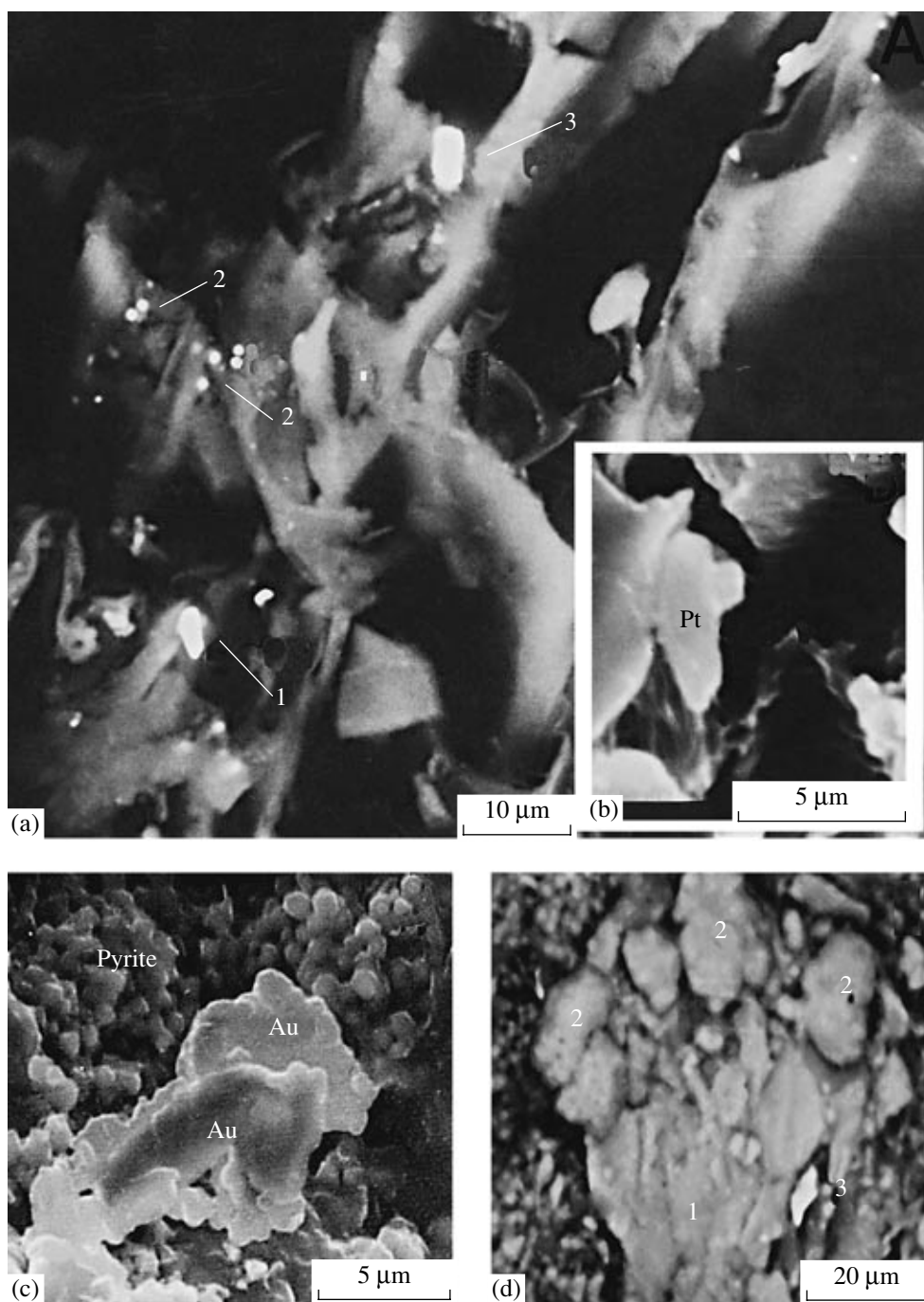


Fig. 11. Noble metal minerals in fossil wood from Pliocene sand of overburden in the Pavlovka coalfield. (a, d) Images in reflected electrons; (b, c) BSE images. (a) Sn-bearing cooperite (1), stannite (2), and native bismuth (3); (b) close-up of the Sn-bearing cooperite; (c) plates of copper gold containing 2.0–2.5 wt % Pt on a substrate of framboidal pyrite; (d) native copper (1) with overgrowths of Cu sulfides (2) and gold microinclusions (3).

argillic alteration superimposed on coal measures and described by E.G. Peskov and O.O. Minko testify to the hydrothermal origin of gold mineralization. In the neighboring Shestaki II open-cut mine, these researchers revealed coal seams with Au contents reaching 1.2 ppm (Arbuzov et al., 1999).

Anomalous Au concentrations (up to 0.57 ppm Au in coal) have been established in Upper Permian anthracite in southwestern Guizhou, southern China (Belkin, 1998). This coal is enriched sporadically in As (up to 3.5%), Sb (up to 370 ppm), and Hg (up to 55 ppm). A similar geochemistry is characteristic of the low-

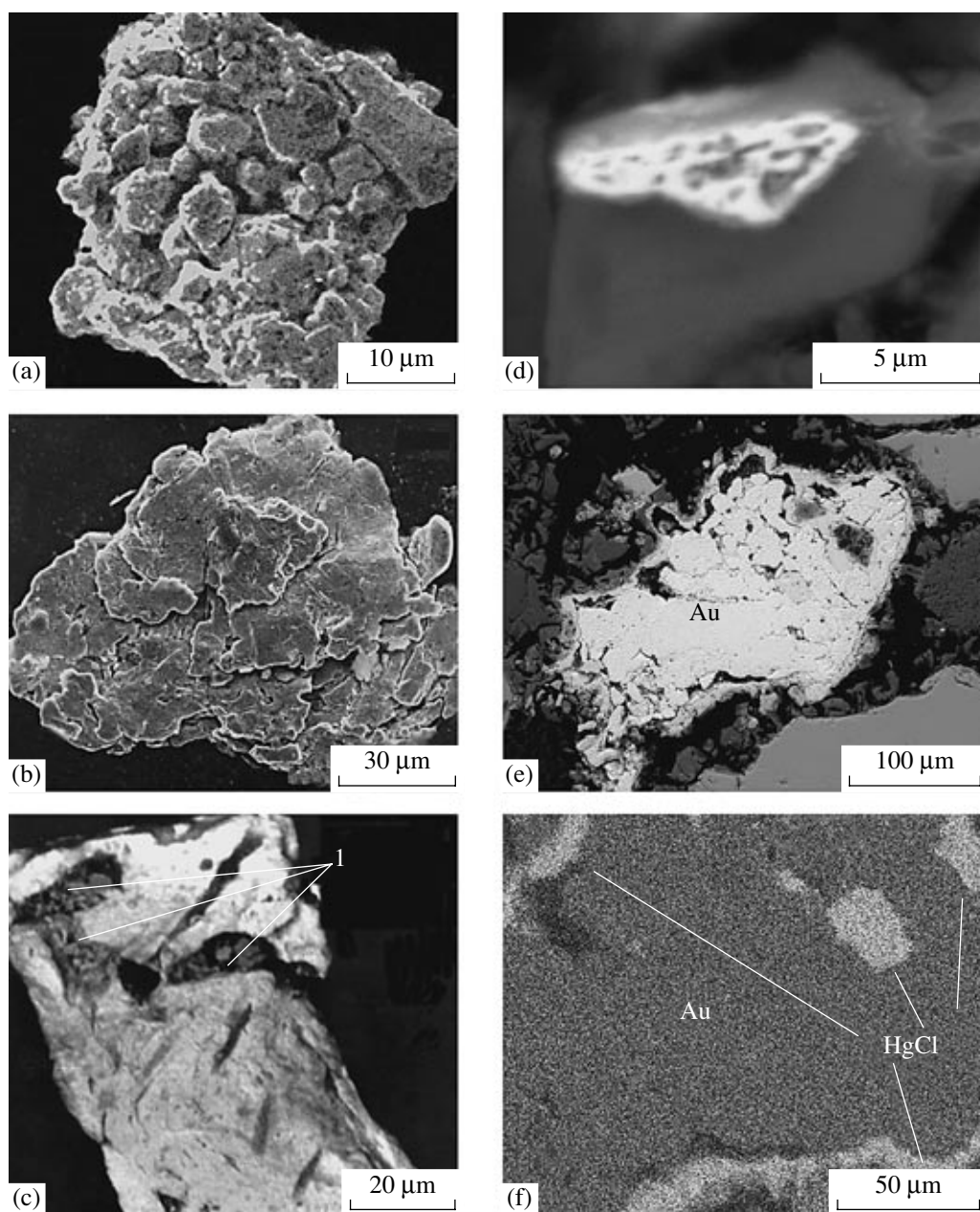


Fig. 12. Noble metal minerals from hydrothermal breccia in basement rocks and coal measures of the Pavlovka field. (a, b) BSE images; (c–e) images in reflected electrons; (f) image in characteristic X-ray irradiation. (a) High-fineness gold; (b) lamellar Pd-bearing platinum; (c) gold with inclusions of K bromides of lead and silver (1); (d) porous Au and Ag amalgam; (e) brecciated gold segregation with mercury chloride rims and inclusions; (f) close-up of grain (e).

temperature ($T_{\text{hom}} = 140\text{--}250^{\circ}\text{C}$) Carlin-type gold deposits in carbonaceous shales that occur nearby.

According to data obtained by S. Dai (written communication, 2005), elevated gold contents (0.10–0.37 ppm Au in coal and 0.3–1.4 ppm Au in ash) have been established in the province of Guizhou in five anthracite seams in the Xingren, Libo, and Puan coalfields. Along with gold, these seams are enriched in silver (0.6–3.1 ppm Ag in coal and 1.9–20.4 ppm Ag in ash).

In five coalfields of this province, including the Xingren field, large epigenetic PGE accumulations were found in stockworks of quartz and carbonate microveinlets hosted in coal seams (Dai et al., 2003, 2004, 2005). The PGE contents in coal are extremely high; in the veinlets themselves (1–5 mm thick), they are much higher than the average grades in most types of platinum ores (Table 12).

The progressive six-step chemical separation of two PGE-enriched samples of coal cut by quartz and anker-

Table 12. Pd and Pt contents, ppm, in coal seams of fields with hydrothermal quartz–carbonate mineralization, Guizhou Province, China, after Dai et al. (2004, 2005)

Coalfield	Sample	Rock	A ^d , %	Rock			Coal ash*		
				Pd	Pt	Pd + Pt	Pd	Pt	Pd + Pt
Zhengfeng	ZM02	1	38.9	1.24	0.02	1.3	3.19	0.05	3.2
Zhengfeng	ZM06	1	36.3	1.32	0.03	1.4	3.64	0.08	3.7
Zhengfeng	ZM031	1	38.2	1.35	0.02	1.4	3.54	0.05	3.6
Zhengfeng	ZM051	4		0.39	63.00	63.4			
Xingren	XD10	4		0.53	0.22	0.8			
Qinglong	QG031	1	21.5	1.93	0.37	2.3	8.98	1.72	10.7
Qinglong	QG02	1	50.0	2.71	0.07	2.8	5.42	0.14	5.6
Qinglong	QG07	1	28.6	5.18	0.42	5.6	18.09	1.47	19.6
Dafang	#11	2	25.8	1.57	0.15	1.7	6.09	0.58	6.7
Dafang	#11	3		9.60	1.08	10.7			
Zhijin	ZJ-30	1	15.8	2.10	2.43	4.5	13.29	15.38	28.7
Zhijin	ZJ-30	3		24.10	18.40	42.5			

Note: High-resolution ICP MS data are presented. Rocks: (1) coal with quartz veinlets; (2) coal with quartz and carbonate veinlets; (3) quartz veinlets; (4) calcite veinlets. * Calculated values.

Table 13. Presumable PGE speciation in metalliferous coal from the Zhijin field, seam 30 (ZJ-30), and the Dafang field, seam 11 (no. 11), that bears epigenetic hydrothermal quartz and quartz–carbonate mineralization, after Dai et al. (2004, 2005)

Mode of occurrence	PGE content, ppm									
	Pt		Pd		Ir		Rh		Ru	
	ZJ-30	No. 11	ZJ-30	No. 11	ZJ-30	No. 11	ZJ-30	No. 11	ZJ-30	No. 11
Water-soluble	<	<	<	<	<	<	<	<	<	<
Ion-exchange	<	<	<	<	<	<	<	<	<	<
Carbonate	<	0.002	<	0.002	<	<	<	0.001	<	<
Organic	<	<	<	0.003	<	0.002	<	<	0.002	<
Sulfide	<	<	<	<	<	<	<	<	<	<
Silicate	20.4	1.23	18.2	10.4	0.05	0.05	0.005	<	<	0.003
Quartz veinlets	18.4	1.08	24.1	9.6	0.04	0.07	0.007	0.001	<	0.003
Ankerite veinlets	–	0.001	–	0.004	–	<	–	<	<	<

Note: High-resolution ICP MS data are presented. The symbol < denotes that contents are below the detection limit.

ite veinlets from the adjacent Zhijin (seam 30, 0.67 m thick) and Dafang (seam 11, 0.9 m thick) coalfields has shown that the quartz veinlets are the main PGE carriers (Table 13). The homogenization temperature of fluid inclusions in platiniferous quartz is estimated at 160–220°C (Zhijin field) and 175–210°C (Dafang field).

In the Zhengfeng and Qinglong coalfields, not only coal but also coaly clay and clayey partings are enriched in PGE (2.7 ppm Pd and 1.8 ppm Pt, respectively).

High PGE concentrations were established in coal seams of Guizhou Province in both quartz and calcite veinlets. A calcite veinlet with an anomalous Pt content of 63 ppm was formed from a solution heated to 145–172°C (Dai et al., 2003).

These data demonstrate that PGE may enter coal seams with both siliceous and carbonate low-temperature fluids, as follows from high concentrations of noble metals and occurrence of their minerals in carbonate veins at the margins of sedimentary basins elsewhere.

For example, gold and Pt and Pd minerals are known from carbonate veins ($T_{\text{hom}} < 150^{\circ}\text{C}$) at Hope's Nose in England (Stanley et al., 1990). In Primorye, high noble metal contents (5.8 ppm Au, 3.0 ppm Pt, and 0.4 ppm Pd) were detected in calcite veinlets ($T_{\text{hom}} = 140–170^{\circ}\text{C}$) that cut Lower Paleozoic dolomite in the framework of the Pavlovka brown coal field (data of the author).

The epigenetic accumulation of noble metals in coal seams affected by thermal metamorphism is known in Russia and China. However, the anomalous concentrations of noble metals in zones of natural coking are not always related to the direct effect of magma emplacement. In some cases, the enrichment is caused by precipitation from subsequent low-temperature hydrothermal fluids that circulate in porous and fractured thermally metamorphosed coal.

In China, very high PGE concentrations (0.77 ppm Pt and 2.51 ppm Pd in coal or 5.5 ppm Pt and 17.8 ppm Pd in ash) were established in such a geological setting in the Fengfeng coalfield, Hebei Province. The mineralization is related to the emplacement of Cretaceous intermediate and basic intrusions into the Paleozoic coal measures (Dai et al., 2003). In Guizhou Province, anomalous PGE concentrations (0.035 ppm Pt and 0.12 ppm Pd) were determined in pyrite from a coal seam at a contact with dolerite. In addition, pyrite is enriched in As (260 ppm) and Se (200 ppm) and, according to the isotopic data, is of hydrothermal origin.

In Russia, high contents of noble metals in coal measures affected by thermal metamorphism were established in the Noril'sk district, well-known owing to its magmatic PGE–Cu–Ni deposits, and in Primorye. The noble metal contents in the Kaerkan coalfield reach (ppm) 0.018 Au, 0.80 Pt, 0.24 Pd, and up to 0.80 Os in coal (1.86 ppm in total) (Koshcheeva, 2002). The ash content in coal is 32.2%; thus, as a minimum, threefold enrichment of ash wastes in these metals may be

Table 14. Au content in coal and host rocks of the Sinegorsk coalfield, after Korostylev et al. (2000)

Rock	n	Au, ppm		
		min	max	average
Sandstone	2	0.8	1.35	1.075
Conglomerate	3	1	1.7	1.31
Siderite rock	7	0.34	9.0	2.71
Coal with quartz veinlets	1	–	–	1.1
Quartz vein in coal	1	–	–	2.4
Clay	2	1.7	2.2	1.95
Coal ash	3	0.3	5.9	3.75

Note: Results of fire assay are presented; n, number of samples.

expected. In addition to PGE, coal is highly enriched in Cr, Zn, Ni, and Cu (6800, 570, 470, and 250 ppm, respectively). Although no evidence for metamorphism of PGE-enriched coal has been reported, the abundant dikes and sills in the coalfield indicate a possible contribution of ore-bearing basic intrusions to the enrichment of coal in noble metals.

In Primorye, high Au contents were revealed in the Sinegorsk coalfield in seams of Triassic anthracite locally transformed into semicoke and in their host rocks (Korostylev et al., 2000). The metalliferous coal is hosted in siltstone, sandstone, and conglomerate con-

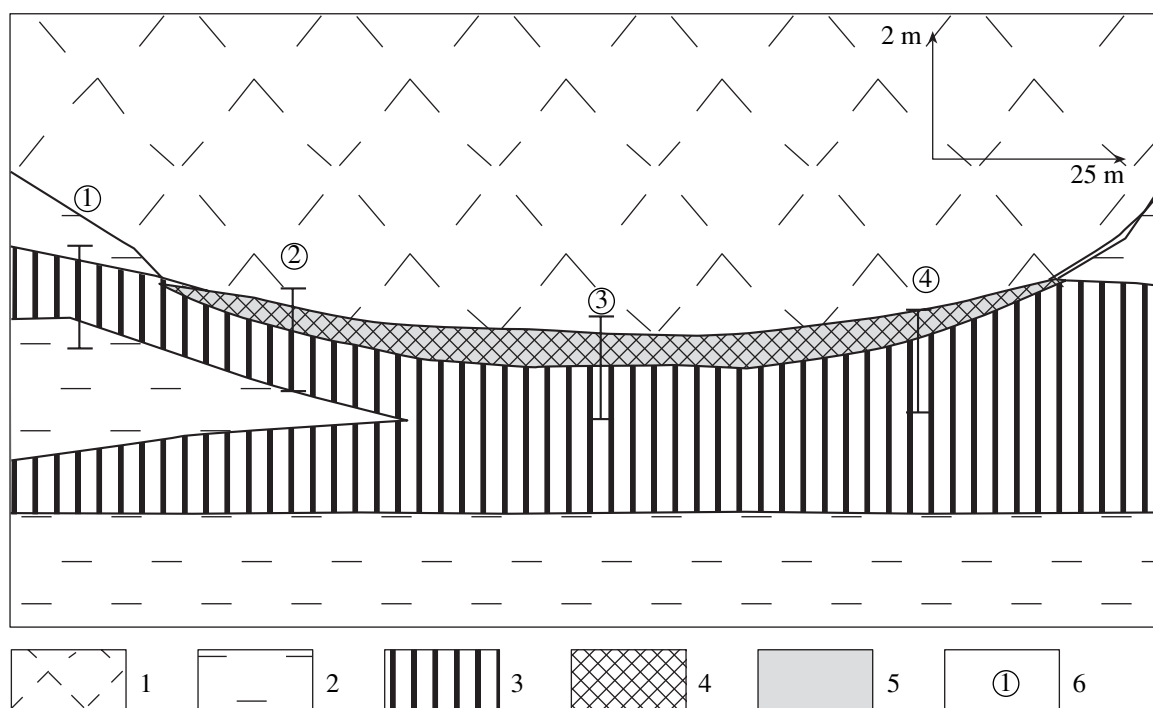


Fig. 13. Zone of natural coking enriched in noble metals in the Rettikhovka open-cut mine (coal seam III). Sketch of the open pit bench drawn by the author in August 1995. (1) Dacitic lava affected by argillic alteration; (2) siltstone; (3) coal; (4) coke; (5) Au–PGE–REE mineralization; (6) studied sections 1–4.

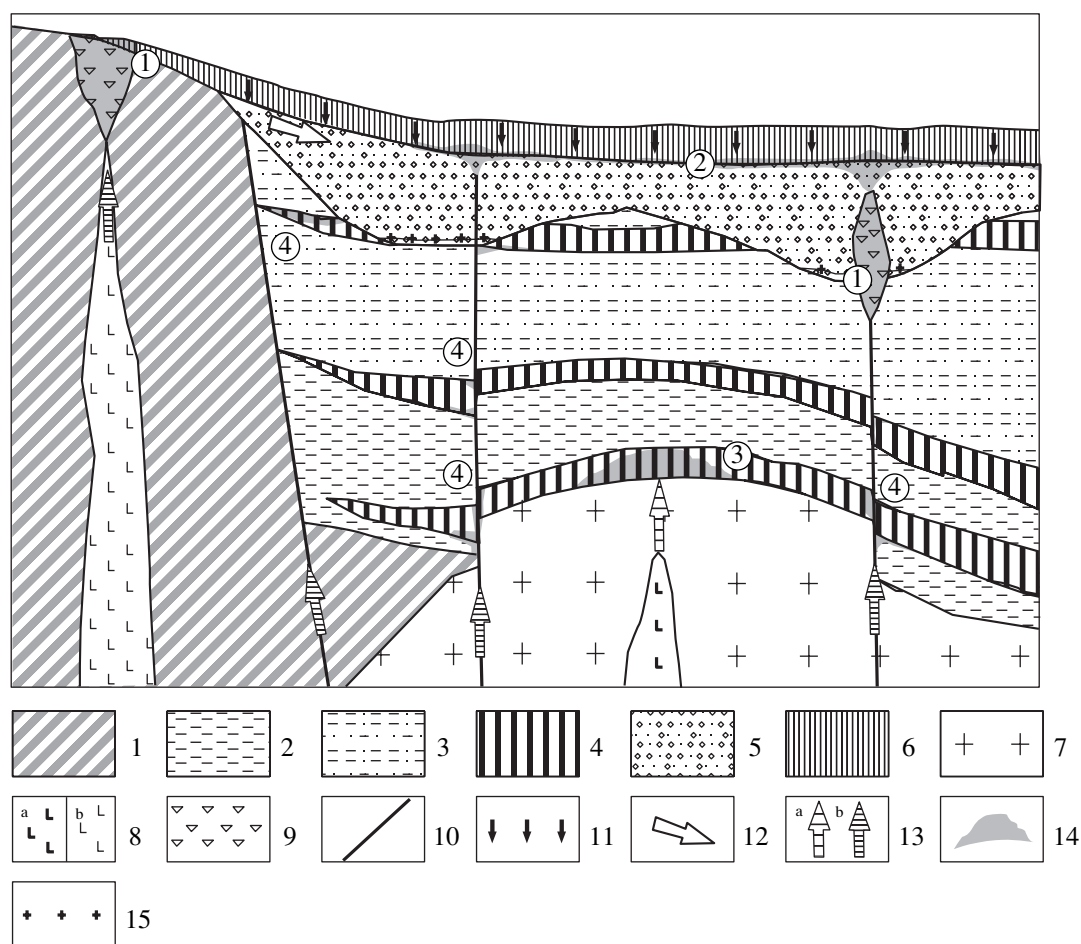


Fig. 14. Formation of polygenetic and multistage Au-PGE mineralization in the Pavlovka brown coal field (a conceptual model). (1) Lower Cambrian carbonaceous chert; (2, 3) Miocene terrigenous rocks: (2) siltstone and mudstone and (3) silty sandstone; (4) coal; (5) Pliocene sand and pebbles; (6) Pliocene-Quaternary clay; (7) Middle Paleozoic granite; (8) basalts: (a) Miocene, (b) late Pliocene-early Pleistocene; (9) explosion breccia; (10) faults; (11-13) flow directions: (11) groundwater, (12) formation water, (13) hydrothermal solutions: (a) Miocene and (b) late Pliocene-early Pleistocene; (14) hydrothermal Au-PGE mineralization (numerals in circles): (1) in breccia bodies and overlapping clay, (2) in limonitized sand and clay enriched in manganese, (3) diagenetic and (4) epigenetic in coal seams; (15) placer gold.

taining siderite lenses and pockets. The sedimentary rocks are silicified and severely pyritized. Pyrite is associated with Cu, Zn, and As sulfides. Coal and host rocks are cut through by quartz-adularia and younger calcite veinlets. As follows from fire assay results, the maximum Au content in ash reaches 5.9 ppm (Table 14).

Still higher Au contents are characteristic of silicified and pyritized siderite rocks largely occurring at the bottom of coal seams. A gold grain 20 μm in size and containing 74.8% Au and 24.7% Ag was recovered from the ash. The wide temperature range (175–485°C) of the gold mineralization presumably indicates a change of high-temperature, substantially pneumatolytic processes to low-temperature hydrothermal ore deposition. Hidden silicic intrusions of Cretaceous age similar to those exposed at some distance from outcrops of coal likely were a source of metalliferous fluids.

The Partizansk Basin, filled with Lower Cretaceous bituminous coal measures, is distinguished from other coal-bearing basins of the Far East by a great number of sill-like intrusions varying from silicic to basic rocks emplaced into coal-bearing sequences. The coal at contacts with intrusions is occasionally enriched in Au and PGE. For example, at the Central Mine, their contents in zones of natural coking are (ppm) 0.3 Au, 0.17 Pt, and 0.22 Pd (in total, 0.69 ppm) in ash.

Similar PGE contents (ppm)—0.18 Pt and 0.13 Pd in ash—were determined by I.G. Sharova in ROM samples from some mines in this basin (Zharov et al., 1996). Anomalous Pt contents were established in products of coal cleaning at the Partizansk Central Mill. The Pt content in concentrate (0.12 ppm, or 0.6 ppm Pt in ash) is higher than in middlings (0.07 ppm, or 0.18 ppm Pt in ash). This difference may testify to the ionic nature of PGE accumulation in coal. Taking into

account the insignificant contribution of coked coal to the bulk of commodity production, there are sufficient grounds to suggest that the noble metal mineralization in coal of this basin is not only of contact-metamorphic origin. The siderite, pyrite, and amethyst-like quartz veinlets in coal seams at some mines, as well as stibnite and galena disseminations in coal and host rocks situated at a distance from intrusive bodies, count in favor of this suggestion (G.V. Kuznetsov and V.B. Morozov, oral communications). In addition, a unit of Au-bearing conglomerate about 15 m thick with 10–15 ppm Au is known at the base of coal measures in the Partizansk Basin. Numerous primary Au occurrences hosted in gabbroic rocks at the eastern margin of the coal basin are a probable source of clastic gold. The above data testify to the polygenetic accumulation of noble metals in this coal-mining district, Primorye's oldest.

In the Rettikhovka coalfield, Au–PGE mineralization was found at the coked roof of coal seam III, which underlies a thick (20–30 m) flow of argillized dacitic lava (Fig. 13). The lava is cut through by pipelike and mushroom-shaped bodies of hematite–martite ore and explosion breccia. The latter contains globular inclusions of iron ore and a porous volcanic glass. The Au and Pt contents in the ash of coked coal are 0.46 and 0.78 ppm, respectively. In addition to noble metals, the zone of natural coking is enriched in REE and Ba (1.0–1.7% in ash); Mo, Zn, and V (up to 1000 ppm); As, Sb, and Cd (up to 100–400 ppm); and Ag, Se, and Cs (up to 10–50 ppm in ash).

According to analytical results reported by Sharova, the Pt content in ROM samples from this open-cut mine sampled in 1988 at a distance from the lava flow reaches 0.25 ppm (1.52 ppm in ash). These estimates, finds of native platinum in the pipelike bodies of hematite–martite ore, and the Au contents in explosion breccia that cuts through argillized dacite having a thermal effect upon coal show that the ore mineralization here may be related to the late hydrothermal process (Seredin, 2004b). The zone of fractured coked coal beneath the lava screen is a favorable medium for circulation of postvolcanic solutions.

CONCLUSIONS

The data presented in this paper indicate that noble metal mineralization is widespread in coal-bearing basins. Irrespective of the genetic type of anomalous accumulations of noble metals, coal-bearing basins that are framed by Au- and PGE-specialized rocks, e.g., black shales or ultramafic plutonic rocks, and overlap a basement composed of these rocks should be regarded as the most promising. The basins where the coal formation was synchronized with hydrothermal activity are especially attractive. In such a situation, noble metals may be supplied to coal measures not only from magma chambers but also as products of leaching of the metalliferous basement rocks by aggressive solutions.

In some coalfields, e.g., in the Pavlovka field in Primorye (Fig. 14) and the Angren field in Uzbekistan, the Au–PGE mineralization is polygenetic and multistage. As is known, a combination of several genetic types and stages of ore mineralization is a characteristic attribute of large deposits. Hence, coal-bearing basins with several stages of ore mineralization are particularly promising for discovery of economic noble metal ore. It cannot be ruled out that the list of such basins will be considerably expanded owing to the further exploration of coalfields with anomalous concentrations of noble metals. Thus, there are sufficient grounds to regard coal-bearing basins as structural units highly promising for noble metal mineralization of different genetic types. This conclusion is supported by the abrupt increase in the number of publications on gold and PGE in coalfields over the last 12 years. It is quite realistic to suppose that targeted metallogenic research will lead to the discovery of economic ore mineralization in the upcoming years.

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REFERENCES

1. M. J. Andrews and R. Fuge, "Cupriferous Bogs of the Coed y Brenin Area, North Wales and Their Significance in Mineral Exploration," *Appl. Geochem.* **1**, 519–525 (1986).
2. S. I. Arbuzov, "Geochemistry of Rare Elements in Coals of Central Siberia," Doctoral Dissertation in Geology and Mineralogy (Tomsk, 2005).
3. S. I. Arbuzov, V. V. Ershov, A. A. Potseluev, and L. P. Rikhvanov, *Rare Elements in Coals of the Kuznetsk Basin* (Kemerovo, 2000) [in Russian].
4. S. I. Arbuzov, V. V. Ershov, L. P. Rikhvanov, et al., *Rare-Metal Potential of Coals in the Minusa Basin* (Siberian Division, Russ. Acad. Sci., Novosibirsk, 2003) [in Russian].
5. S. I. Arbuzov, L. P. Rikhvanov, and V. M. Levitskii, "Gold in Coals of Siberia," in *Gold in Siberia and Far East* (Buryat. Sci. Center, Siberian Division, Russ. Acad. Sci., Ulan-Ude, 2004), pp. 16–18 [in Russian].
6. S. I. Arbuzov, L. P. Rikhvanov, S. G. Maslov, et al., "Anomalous Gold Concentrations in Lignite and Peat of Southeastern West Siberian Plateau," *Izv. Tomsk. Politekh. Univ.* **307** (7), 25–30 (2004).
7. P. E. B. Armitage, I. McDonald, S. J. Edwards, and G. M. Manby, "Platinum-Group Element Mineralization in the Platreef and Calc-Silicate Footwall at Sand-

- sloot, Potgietersrus District, South Africa," *Trans. Inst. Min. Metall. Sect. B* **111**, 36–45 (2002).
8. Yu. I. Bakulin and A. A. Cherepanov, "Gold and Platinum in Cinder Wastes of Thermal Power Station in the City of Khabarovsk," *Rudy Met.*, No. 1, 60–67 (2003).
 9. P. Baranger, J. R. Disnar, J. P. Gatellier, and G. Ouzounian, "Metal Reduction by Sedimentary Organic Materials: Influence of Medium Parameters on Reaction Rate," in *Source, Transport and Deposition of Metals* (Balkema, Rotterdam, 1991), pp. 511–514.
 10. M. K. Baruah, P. Kotoky, and G. C. Borah, "Gold in High Sulphur Indian Coals," *Fuel* **77** (15), 1867–1868 (1998).
 11. H. E. Belkin, "Mineralogy and Speciation of Arsenic in Coals of the Upper Permian Longtan Formation, Guizhou Province, P.R. China," in *GSA Abstract* (Toronto, 1998).
 12. V. K. Belyaev and E. T. Pedash, "Minor Elements in Coals and Host Rocks of the Shubarkol Deposit," *Razved. Okhr. Nedr*, No. 11, 12–16 (1989).
 13. V. I. Berger, *Antimony Deposits* (Nedra, Leningrad, 1978) [in Russian].
 14. V. Bouška, *Coal Geochemistry* (Academia, Praha, 1977).
 15. V. A. Butan, A. M. Sazonov, V. P. Shorokhov, and V. V. Kosarev, "Coals from the Kansk–Achinsk Basin and Their Combustion Products as Nontraditional Mineral Resources," *Ugol*, No. 6, 55–57 (2000).
 16. A. R. Cabral, B. Lehmann, R. Kwitko, and C. H. Cravo Costa, "The Serra Pelada Au–Pd–Pt Deposit, Carajas Mineral Province, Northern Brazil: Reconnaissance Mineralogy and Geochemistry of Very High Grade Palladian Gold Mineralization," *Econ. Geol.* **97** (5), 1127–1138 (2002).
 17. H. L. Cannon, "Geochemical Relations of Zinc-Bearing Peat to the Lockport Dolomite, Orleans County, New York," *US Geol. Surv. Bull.*, No. 1000-D, 109–185 (1955).
 18. F. V. Chukhrov, *Colloids in the Earth's Crust* (Acad. Sci. USSR, Moscow, 1955) [in Russian].
 19. L. L. Chyi, "The Distribution of Gold and Platinum in Bituminous Coals," *Econ. Geol.* **77** (6), 1592–1597 (1982).
 20. S. Dai, C.-L. Chou, M. Yue, et al., "Mineralogy and Geochemistry of a Late Permian Coal in the Dafang Coalfield, Guizhou, China: Influence from Siliceous and Iron-Rich Calcic Hydrothermal Fluids," *Int. J. Coal. Geol.* **61**, 241–258 (2005).
 21. S. Dai, D. Li, D. Ren, et al., "Geochemistry of the Late Permian No 30 Coal Seam, Zhijin Coalfield of Southwest China: Influence of a Siliceous Low-Temperature Hydrothermal Fluid," *Appl. Geochem.* **16**, 1315–1330 (2004).
 22. S. Dai, D. Ren, J. Zhang, and X. Hou, "Concentrations and Origins of Platinum Group Elements in Late Paleozoic Coals of China," *Int. J. Coal. Geol.* **55**, 59–70 (2003).
 23. V. I. Danchev and N. P. Strelyanov, *Exogenic Uranium Deposits* (Atomizdat, Moscow, 1979) [in Russian].
 24. *Deep Structure and Mineral Resources of Kazakhstan* (Almaty, 2002), Vol. 2. Metallogeny [in Russian].
 25. C. B. Dissanayake and K. Kritsotakis, "The Geochemistry of Au and Pt in Peat and Algal Mats: A Case Study from Sri Lanka," *Chem. Geol.* **42**, 61–76 (1984).
 26. V. V. Distler, M. A. Yudovskaya, V. S. Znamenskii, and I. V. Chaplygin, "Platinum Group Elements in Recent Fumaroles of Kudryavy Volcano (Iturup Island, Kuril Island Arc)," in *Proceedings of All-Russia Scientific Conference on Geology, Geochemistry, and Geophysics on the Turn of the XX and XXI Centuries* (Svyaz-Print, Moscow, 2002), Vol. 2, pp. 258–260 [in Russian].
 27. A. G. Dvornikov, N. A. Ol'khova, L. B. Anoshko, et al., "Some Tendencies in Localization of Mercury Anomalies in Coals," in *New Techniques of the Integrated Studies and Utilization of Coals, Pyroschists, and Associated Mineral Resources during Geological Exploration* (Moscow, 1991), pp. 98–105 [in Russian].
 28. G. M. Eskenazy, "Studies on the Binding Form of Silver in Coals," *Godishn. Sofiisk. Univ. Geol.* **66**, 279–284 (1973/1974).
 29. T. Evstigneeva and M. Tarkian, "Synthesis of Pt and Pd Sulfides in Low-Temperature Solutions," in *Mineral Deposits: from Their Origin to Their Environmental Impacts* (Balkema, Rotterdam, 1995), pp. 731–734.
 30. R. B. Finkelman, "Modes of Occurrences of Trace Elements in Coal," in *US Geol. Surv. Open-File Report* (1981), pp. 81–99.
 31. R. B. Finkelman and P. J. Aruscavage, "Concentration of Platinum-Group Metals in Coal," *Int. J. Coal. Geol.* **1**, 95–96 (1981).
 32. R. B. Finkelman, N. H. Bostick, and R. D. Congdon, "Inorganic Geochemistry of Lignite in the Ione Formation from the Vicinity of the Mother Lode Gold Deposit, Amador County, California," in *Proceedings of the 11th Ann. Meet. Soc. Organic Petrol.* (1994), Vol. 11, pp. 25–27.
 33. R. B. Finkelman, N. H. Bostick, W. M. Martin, and N. W. Kirshenbaum, "Inorganic Geochemistry of Lignite in the Ione Formation, California, USA," *Soc. Organic Petrol. Newsletter* **13** (3), 4–7 (1996).
 34. R. Gayer and D. Rickard, "Colloform Gold in Coal from Southern Wales," *Geology* **22** (1), 35–38 (1994).
 35. V. M. Goldschmidt and C. Peters, "Über die Anreicherung Seltener Elemente in Steinkohlen," *Nachr. Ges. Wiss. Gottingen. Math.-Phys. Kl., Fach. IV*, No. 4, 371–387 (1933).
 36. A. G. Gunn and M. T. Styles, "Platinum-Group Element Occurrences in Britain: Magmatic, Hydrothermal and Supergene," *Trans. Inst. Min. Metal.* (2002), Sect. B, **111**, 2–14 (2002).
 37. E. Hussak, *Über das Vorkommen von Palladium und Platinum in Brasilien* (Sitzb. Akad. Wiss., Wein, 1904).
 38. P. A. Ignatov, A. G. Lykhin, A. D. Zhizhin, et al., "Specific Ecogeochemical Features of Coal Deposits in Mosbass," *Rudy Met.*, No. 4, 107–117 (1995).
 39. V. V. Ivanov, A. Ya. Katz, Yu. P. Kostin, et al., *Economic Types of Natural Germanium Concentrations* (Nedra, Moscow, 1984) [in Russian].
 40. J. Jedwab, D. Badaut, and P. Beaunier, "Discovery of Palladium–Platinum–Gold–Mercury Bitumen in the Boss Mine, Clark County, Nevada," *Econ. Geol.* **94** (7), 1163–1172 (1999).

41. W. P. Jenney, "The Chemistry of Ore Deposition," *Am. Inst. Miner. Eng. Trans.* **33**, 445–498 (1903).
42. Ya. M. Kislyakov and V. N. Shchetochkin, *Hydrogenic Ore Formation* (Geoinformmark, Moscow, 2000) [in Russian].
43. L. Ya. Kizilshtein, *Ecogeochemistry of Trace Elements in Coals* (North Caucasus Sci. Center, Rostov-on-Don, 2002) [in Russian].
44. V. R. Kler, V. F. Nenakhova, F. Ya. Saprykin, et al., *Metallogeny and Geochemistry of Coal-Bearing and Pyroschist-Bearing Sequences. Concentration of Elements and Methods of Their Study* (Nauka, Moscow, 1988) [in Russian].
45. V. R. Kler, G. A. Volkova, E. M. Gurvich, et al., *Metallogeny and Geochemistry of Coal-Bearing and Pyroschist-Bearing Sequences. Geochemistry of Elements* (Nauka, Moscow, 1987) [in Russian].
46. E. V. Klimanov, "Gold and PGE in the Angren Kaolin-Lignite Deposit: Speciation, Deposition Conditions, and Outlooks for Development," in *Problems of Ore Deposits and Increase in Efficiency of Geological Exploration* (Tashkent, 2003), pp. 308–310 [in Russian].
47. A. A. Koldaev, "Gold in Metasomatic Rocks from the Angren Kaolin and Lignite Deposit," in *Gold in Siberia and Far East* (Buryat. Sci. Center, Siberian Division, Russ. Acad. Sci., Ulan-Ude, 2004), pp. 104–106 [in Russian].
48. I. A. Kondrat'eva, G. V. Komarova, and A. K. Lisitsyn, "Uranium Mineralization in Peat," in *Hydrogenic Uranium Deposits. Principles of Formation Theory* (Atomizdat, Moscow, 1980), pp. 138–143 [in Russian].
49. P. G. Korostylev, G. V. Andrienko, S. V. Andrienko, et al., "Metallic Mineralization of the Sinegorsk Coal Field," in *Geology and Mining of Primorye in the Past, Present, and Future* (Dal'nauka, Vladivostok, 2000), pp. 45–47 [in Russian].
50. M. A. Korzhinsky, S. I. Tkachenko, R. E. Bocharnikov, and K. I. Shmulovich, "Magmatic Degassing and Mineral Formation on the Kudryavy Volcano (Iturup Island, Kuril Islands)," in *Experimental and Numerical Modeling of Mineral Formation* (Nauka, Moscow, 1998), pp. 143–168 [in Russian].
51. V. V. Krapivnetseva, "Metalliferous in Coals of the Amur Region," *Tikhookean. Geol.* **24** (1), 73–84 (2005).
52. B. I. Kronberg, F. H. Murray, C. G. Fyfe, et al., "Geochemistry and Petrography of the Mattagami Formation Lignites (Northern Ontario)," in *Coal Science and Chemistry* (Elsevier, Amsterdam, 1987), pp. 245–263.
53. H. Kucha and W. Przybylowich, "Noble Metals in Organic Matter and Clay–Organic Matrices, Kupferschiefer, Poland," *Econ. Geol.* **94** (7), 1137–1162 (1999).
54. V. M. Kuz'minykh and A. P. Sorokin, "Gold Migration and Accumulation during Supergene Processes," *Vestn. Dal'nevost. Otd. Ross. Akad. Nauk*, No. 2, 113–119 (2004).
55. J. Lakatos, S. D. Brown, and C. E. Snape, "Unexpectedly High Uptake of Palladium by Bituminous Coals," in *Proceedings of ICCS'97* (DGMK, Essen, 1997), Vol. 1, pp. 247–250.
56. S. B. Leonov, K. V. Fedotov, and A. E. Senchenko, "Economic Gold Recovery from Cinder Dumps of Thermal Power Plants," *Gorn. Zhurn*, No. 5, 67–68 (1998).
57. D. A. Lott, R. M. Coveney, and J. B. Murowchick, "Sedimentary Exhalative Nickel–Molybdenum Ores in South China," *Econ. Geol.* **94** (7), 1051–1066 (1999).
58. V. A. Makarov, "Gold from Sand and Gravel Deposits of the Yenisei and Chulym River Basins: Results of Technical Feasibility Study and Prospects for the Integrated Exploration of Objects," in *Geology and Mineral Resources in Krasnoyarsk Krai* (KNIIGiMS, Krasnoyarsk, 1999), pp. 99–105 [in Russian].
59. V. G. Matukhina, M. V. Popova, and L. D. Malyushko, "Secondary Mineral Formation in Peat Deposits in the Territories Adjacent to Mountainous Framework," *Otech. Geol.*, No. 5, 65–71 (1996).
60. E. S. Meitov, "Metalliferous in Coals," in *Coal Resources of Russia* (Geoinformmark, Moscow, 2001), Vol. IV, pp. 293–301 [in Russian].
61. G. V. Moralev, A. V. Borisov, S. V. Surenkov, et al., "Distribution and Speciation of Rare Earth Elements in the Chudny and Nesterovsky Au–Pd–REE Ore Occurrences (Maldynyrd Range, Subpolar Urals)," *Geokhimiya* **43** (5), 65–71 (2005). [*Geochem. Intern.* **43** (5) (2005)].
62. M. Moroni, V. A. V. Girardi, and A. Ferrario, "The Serra Pelada Au–PGE Deposit, Serra dos Carajas, (Para State, Brazil): Geological and Geochemical Indications for a Composite Mineralizing Process," *Miner. Deposita* **36**, 768–785 (2001).
63. B. F. Nifantov, "Valuable and Toxic Elements in Coals," in *Coal Resources of Russia* (Geoinformmark, Moscow, 2003), Vol. II, pp. 77–91 [in Russian].
64. B. F. Nifantov, V. P. Potapov, and N. V. Mitina, *Geochemistry and Evaluation of Rare Earth and Radioactive Elements in Kuznetsk Coals. Outlooks of Recovery* (Kemerovo, 2003) [in Russian].
65. I. Noddack, "Über die Allgegenwart der Chemischen Elemente," *Angew. Chemie* **49** (47), 809–816 (1936).
66. C. L. Oman, R. B. Finkelman, and S. J. Tewlot, "Concentrations of Platinum Group Elements in 122 US Coal Samples," *US Geol. Surv. Open-File Report* 97–53 (1997).
67. C. A. Palmer and C. C. Cameron, "The Occurrence of Gold and Arsenic in a Sumatra, Indonesia, Peat Deposit (Abstract)," *J. Coal Qual.* **8** (3/4), 122 (1989).
68. B. S. Panov, V. I. Alekhin, and A. A. Yushin, "Gold Mineralization in Coals of the Dnieper Brown Coal Basin," in *Geology of Coal Deposits* (UGGGA, Yekaterinburg, 2001), No. 11, pp. 248–252 [in Russian].
69. B. S. Panov, V. I. Alekhin, and A. A. Yushin, "Gold in the Dnieper Brown Coal Basin," in *Geology of Coal Deposits* (UGGGA, Yekaterinburg, 2004), No. 14, pp. 222–228 [in Russian].
70. A. Popovich, "Plemeniti metali u pepelima nekikh ugl'eva Timochkog bazena," *Glasnik Khem. Dr-va* **19** (5), 305–307 (1954).
71. P. D. Rao, *Distribution of Certain Minor Elements in Alaskan Coal* (Miner. Industry Res. Labor., Univ. Alaska, 1968), Report 15.

72. V. M. Ratynsky, M. Ya. Shpirt, S. A. Musyal, and M. A. Beloshapko, "Gold in Fossil Coals," *Khim. Tverd. Topl.*, No. 4, 88–90 (1982).
73. L. Ruppert, R. Finkelman, E. Boti, et al., "Origin and Significance of High Nickel and Chromium in Pliocene Kosovo Basin Lignite, Central Yugoslavia," *Int. J. Coal Geol.* **29**, 235–258 (1996).
74. A. V. Rybin, V. B. Gur'yanov, M. V. Chibisova, and R. V. Zharkov, "Rhenium Exploration Prospects on Sakhalin and the Kuril Islands," in *Geodynamics, Magmatism, and Minerageny of the North Pacific Ocean* (Magadan, 2003), Vol. 3, pp. 180–183 [in Russian].
75. A. M. Sazonov, N. K. Algebraistova, and V. I. Sotnikov, *Platinum Mineralization in Ore Deposits of Central Siberia* (Geoinformmark, Moscow, 1998) [in Russian].
76. V. V. Seredin, "New Types of REE and Au–PGE Mineralization of the Russian Coal-Bearing Depressions," in *Mineral Deposits* (Balkema, Rotterdam, 1995), pp. 799–801.
77. V. V. Seredin, "Native Metals in Metalliferous Coal-Bearing Strata," in *Proceedings of ICCS'97* (DGMK, Essen, 1997), Vol. 1, pp. 405–408.
78. V. V. Seredin, "Gold and PGM Mineralization in Germanium-Bearing Coal Deposits of Primorye: Speciation, Deposition Conditions, and Outlooks for Development," in *Proceedings of All-Russia Symposium on Geology, Genesis, and Development of Multicomponent Noble Metal Deposits* (Svyaz-Print, Moscow, 2002), pp. 374–379 [in Russian].
79. V. V. Seredin, "Hydrothermal Mineralization of Cenozoic Rifts in Primorye," in *Geodynamics, Magmatism, and Minerageny of the North Pacific Ocean* (Magadan, 2003), Vol. 3, pp. 159–162 [in Russian].
80. V. V. Seredin, "Au–PGE Mineralization on the Pavlovka Brown Coal Field, Primorye," *Geol. Rudn. Mestorozhd.* **46** (1), 40–71 (2004a) [*Geol. Ore. Deposits* **46** (1), 36–63 (2004a)].
81. V. V. Seredin, "Metalliferous in Coals: Formation Conditions and Outlooks for Development" in *Coal Resources of Russia* (Geoinformmark, Moscow, 2004b), Vol. VI, pp. 452–519 [in Russian].
82. V. V. Seredin and L. O. Magazina, "Mineralogy and Geochemistry of Fossil Wood from the Pavlovka Brown Coal Field, Primorye," *Litol. Polezn. Iskop.* **34** (2), 158–173 (1999) [*Lithol. Miner. Resour.* **34** (2), 134–148 (1999)].
83. V. V. Seredin and M. Yu. Povarennykh, "First Finding of Platinum Minerals in Coals," *Dokl. Akad. Nauk* **342** (6), 801–803 (1995).
84. V. V. Seredin, M. G. Dobrovol'skaya, and A. V. Mokhov, "Unique Multicomponent Ore Mineralization in Breccia Bodies in the Pavlovka Brown Coal Field," *Dokl. Akad. Nauk* (2007, in press).
85. V. V. Seredin, T. L. Evstigneeva, and M. E. Generalov, "Au–PGE Mineralization in Cenozoic Coal-Bearing Strata of the Pavlovka Deposit, Russian Far East: Mineralogical Evidence for Hydrothermal Origin," in *Mineral Deposits* (Balkema, Rotterdam, 1997), pp. 107–110.
86. N. A. Shilo, *Theory of Placers* (Acad. Mining Sci., Moscow, 2000) [in Russian].
87. G. M. Shor, V. D. Alekseenko, O. V. Golikova, and R. V. Shipov, "Specific Features of the Radiogeochemical Section of the Cover in the West Siberian Platform and Their Implications for Forecasting Uranium Mineralization," in *Radioactivity and Radioactive Elements in the Human Habitat* (Tandem-Art, Tomsk, 2004), pp. 670–672 [in Russian].
88. G. M. Shor, G. V. Ditmar, N. I. Komarova, and O. V. Golikova, "Formation of the Infiltration-Type PGE Mineralization in the Cover of the West Siberian Platform," *Dokl. Akad. Nauk* **351** (4), 525–527 (1996) [*Dokl. Earth Sci.* **351A** (9), 1385–1387 (1996)].
89. C. J. Stanley, R. F. Symes, and C. G. Jones, "Precious and Base Metal Selenide Mineralization at Hope's Nose, Torquay, Devon.," *Miner. Mag.* **54**, 485–493 (1990).
90. R. W. Stone, "Coal near the Black Hills Wyoming-South Dakota," *US Geol. Surv. Bull.*, No. 499, (1912).
91. G. D. Stricker, R. B. Tripp, J. B. McHugh, et al., "Gold in the Usibelli Group Coals, Nenana Coal Field, Alaska," *US. Geol. Surv. Bull.*, No. 2041, 93–97 (1992).
92. D. J. Swaine, *Trace Elements in Coal* (Butterworths, London, 1990).
93. M. V. Torikova, Yu. A. Kudinov, and P. V. Timofeev, "Rare Metals in Oils, Fossil Coals, Products of Their Processing, and Mineralized Waters," *Razved. Okhr. Nedr.*, No. 8, 21–23 (1996).
94. *USGS 17th Ann. Rep.* (1896). Part III, pp. 282–283.
95. Yu. Ya. Valiev, G. I. Gofen, and D. N. Pachadzhannov, "Trace Elements in Jurassic Anthracite of the Nazar-Ailok Field (Central Tadzhikistan)," *Geokhimiya* **31** 2, 243–251 (1993).
96. Yu. Ya. Valiev, B. A. Vol'nov, D. N. Pachadzhannov, and G. I. Gofen, "Gold in Jurassic Coals in the Mountainous Framing of the Tajik Basin and Its Prospecting Significance," *Geokhimiya* **40** (1), 105–108 (2002) [*Geochem. Int.* **49** (1), 96–99 (2002)].
97. E. Van der Flier-Keller, "Platinum Group Elements in Tulameen Coal, British Columbia, Canada," *Econ. Geol.* **86** (2), 387–395 (1991).
98. G. M. Varshal, T. K. Velyukhanova, D. N. Chkhietiya, et al., "Sorption on Humic Acids as a Basis for the Mechanism of Primary Accumulation of Gold and Platinum Group Elements in Black Shales," *Litol. Polezn. Iskop.* **35** (6), 605–612 (2000) [*Lithol. Miner. Resour.* **35** (6), 538–545 (2000)].
99. N. K. Vysotsky, *Platinum and Regions of Its Mining* (Petrograd, 1923) [in Russian].
100. Ya. E. Yudovich and M. P. Ketris, "Gold in Coals," in *Lithogenesis and Geochemistry of Sedimentary Formations in the Timan-Uralian Region* (Syktyvkar, 2003), No. 5, pp. 80–109 [in Russian].
101. M. A. Yudovskaya, V. V. Distler, I. V. Chaplygin, et al., "Gold Speciation in Crystallization Products of High-Temperature Gas Fluids of the Kudryavy Volcano, the Kuril Islands," *Dokl. Akad. Nauk* **391** (4), 535–539 (2003) [*Dokl. Earth Sci.* **391A** (6), 874–878 (2003)].
102. Yu. N. Zharov, E. S. Meitov, and I. G. Sharova, *Valuable and Toxic Elements in Commodity Coals of Russia. Reference Book* (Nedra, Moscow, 1996) [in Russian].
103. X. Zhuang, X. Querol, A. Alastuey, et al., "Geochemistry and Mineralogy of Cretaceous Wulantuga High-Germanium Coal Deposit in Shengli Coal Field, Inner Mongolia, Northeastern China," *Int. J. Coal Geol.* **66**, 119–136 (2006).