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Paleogeodynamics

MINERALOGICAL AND GEOCHEMICAL EVIDENCE FOR MULTI-STAGE FORMATION OF THE CHERTOVO KORYTO DEPOSIT

Yu. I. Tarasova[1,2], O. T. Sotskaya[3], S. Yu. Skuzovatov[1], V. A. Vanin[4], Z. I. Kulikova[1], A. E. Budyak[1,2]

[1] *A.P. Vinogradov Institute of Geochemistry, Siberian Branch of RAS, Irkutsk, Russia*
[2] *Irkutsk Scientific Center, Siberian Branch of RAS, Irkutsk, Russia*
[3] *N.A. Shilo North-East Interdisciplinary Scientific Research Institute, Far East Branch of RAS, Magadan, Russia*
[4] *Institute of the Earth's Crust, Siberian Branch of RAS, Irkutsk, Russia*

Abstract: Introduction. The Lena gold province is one of the largest known gold resources in the world. The history of its exploration is long, but the genesis of gold mineralization hosted in black shales in the Bodaibo synclinorium still remains unclear. The studies face the challenge of discovering sources for the useful component and mechanisms of its redistribution and concentration. This study aims to clarify the time sequence of the ore mineralization in the Chertovo Koryto deposit on the basis of detailed mineralogical and geochemical characteristics of the ore, wallrock metasomatites and the Early Proterozoic host black shales, and to assess the applicability of the Sukhoi Log model for clarifying the Chertovo Koryto origin.

Geological setting. The Lena gold province is located in the junction area of the Siberian platform and the Baikal mountain region (Fig. 1). The main element of its geological structure is the Chuya-Tonoda-Nechera anticline. Its axial segment is marked by horsts composed of the Early Proterozoic rocks with abundant granitoid massifs. The Chertovo Koryto deposit is located within the Kevakta ore complex at the Tonoda uplift, the largest tectonically disturbed block between the Kevakta and Amandrak granitoids massifs. The 150 m thick and 1.5 km long ore zone of the Chertovo Koryto deposit is confined to the hanging wall of the fold-fault zone feathering the Amandrak deep fault (Fig. 2).

Composition. In the ore zone, rocks of the Mikhailovsk Formation include carbonaceous shales of the feldspar-chlorite-sericite-quartz composition with nest-shaped ore accumulations of the pyrite-quartz composition and quartz veinlets. In our study, we distinguish five mineral associations resulting from heterochronous processes that sequentially replaced each other:

- The earliest association related with the quartz-muscovite-sericite metasomatism and the removal of REE and other elements from the rocks and their partial redeposition;
- Metamorphic sulphidization presented by scattered impregnations of pyrrhotite, as evidenced by small lenses of pyrrhotite, which are considerably elongated (axes up to 0.7 cm long) along the foliation planes (Figs 3, *a*, *b*);
- Ore mineralization represented by a superimposed hydrothermal gold association with arsenopyrite (Fig. 3, *d*);
- Late chalcophilic mineralization formed at the final stage of hydrothermal-metasomatic process (Figs 3, *e*, *f*);
- Post-ore silification.

Geochemical characteristics. The geochemical study of rocks and ores from the Chertovo Koryto deposit show that the rocks of the Mikhailovsk Formation are characterized by higher contents of rock-forming elements, such as of Al_2O_3, Fe_2O_{3total}, MgO, K_2O, and P_2O_5, in comparison to the PAAS standards [*Condie, 1993*] and the black shale standard composition (SChS-1) [*Petrov et al., 2004*]. A characteristic feature of the ore zone is that the contents of practically all the oxides, except SiO_2, tend to decrease (Table 1). The distribution of rare elements repeats the pattern established for major elements. The least metamorphosed rocks of the Mikhailovsk Formation have higher contents (up to three times) of Cu, Mo, Ba, W, As, Pb relative to the values in the PAAS and SChS-1 standards. In the ore zone, the contents of almost all rare elements are considerably reduced (Table 2). The contents of elements in the siderophile group (Co, Ni) are clearly correlated with the ore processes and increased more than twice in the area of metamorphic changes. Samples with gold-ore grade contents show the highest concentrations of Co and Ni.

Conclusion. In our opinion, the Chertovo Koryto deposit was formed in five stages, the first two of which were pre-ore, with ore preparation, and probably considerably distant in time from the main ore-generating event. The staged formation of the Chertovo Koryto deposit correlates with the basic stages in the tectono-metamorphic history of the study region and is consistent with the model showing the formation of Sukhoi Log-type deposits [*Nemerov, 1989; Buryak, Khmelevskaya, 1997; Large et al., 2007*].

Key words: gold; black shales; model of metamorphic-metasomatic formation; Chertovo Koryto; the Baikal-Patom Highland (Plateau)

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Минералого-геохимические свидетельства полистадийности формирования месторождения Чертово Корыто

Ю. И. Тарасова[1, 2], О. Т. Соцкая[3], С. Ю. Скузоватов[1], В. А. Ванин[4], З. И. Куликова[1], А. Е. Будяк[1, 2]

[1] *Институт геохимии им. А.П. Виноградова СО РАН, Иркутск, Россия*
[2] *Иркутский научный центр СО РАН, Иркутск, Россия*
[3] *Северо-Восточный комплексный научно-исследовательский институт им. Н.А. Шило ДВО РАН, Магадан, Россия*
[4] *Институт земной коры СО РАН, Иркутск, Россия*

Аннотация: Введение. Ленская золотоносная провинция является одной из крупнейших по запасам золота во всем мире. Несмотря на длительную историю работ на данной территории, генезис месторождений Au, приуроченных к черносланцевым отложениям Бодайбинского синклинория, до сих пор остается открытым. Наиболее дискуссионными являются вопросы, связанные с определением источника полезного компонента и выявлением механизма его перераспределения и концентрирования. Цель настоящей работы – выявление этапности формирования месторождения Чертово Корыто на основании детальной минералого-геохимической характеристики руд, околорудных метасоматитов и вмещающих их черносланцевых отложений раннепротерозойского возраста, а также оценка применимости сухоложской модели для формирования месторождения.

Геологическая позиция. Ленская золотоносная провинция приурочена к зоне сочленения Сибирской платформы и Байкальской горной области (рис. 1). Одним из главных элементов геологического строения рассматриваемой площади является Чуйско-Тонодско-Нечерский антиклинорий. Положение осевой части антиклинория подчеркивают выступы пород раннепротерозойского возраста, в которых значительные площади занимают массивы гранитоидов. Месторождение Чертово Корыто расположено в пределах Кевактинского рудного узла, приуроченного к Тонодскому поднятию и представляющего собой крупный интенсивно тектонически нарушенный блок, заключенный между Кевактинским и Амандракским массивами гранитоидов. Рудная зона месторождения, мощностью 150 м и протяженностью 1.5 км, приурочена к висячему боку складчато-разломной области, оперяющей Амандракский глубинный разлом (рис. 2).

Вещественный состав. В пределах рудной зоны месторождения породы михайловской свиты представлены углеродсодержащими сланцами полевошпат-хлорит-серицит-кварцевого состава с гнездообразными рудными скоплениями пирит-кварцевого состава и прожилками кварца. Установлено пять минеральных ассоциаций, сформированных в результате разновременных процессов, поэтапно сменяющих друг друга:

- наиболее ранняя ассоциация связана с кварц-мусковит-серицитовым метасоматозом и выносом РЗЭ и ряда других элементов из пород с их частичным переотложением;
- метаморфическая сульфидизация представлена рассеянной вкрапленностью пирротина с образованием мелких, значительно вытянутых (до 0.7 см по длинной оси) вдоль рассланцевания линзочек пирротина (рис. 3, *a*, *b*);
- рудная минерализация представлена наложенной гидротермальной ассоциацией золота с арсенопиритом (рис. 3, *d*);
- поздняя халькофильная минерализация, образовавшаяся на завершающем этапе гидротермально-метасоматического процесса (рис. 3, *e*, *f*);
- пострудное окварцевание.

Геохимическая характеристика. В результате геохимического изучения пород и руд месторождения Чертово Корыто установлено, что отложения михайловской свиты характеризуются повышенными содержаниями, относительно стандартов PAAS [*Condie, 1993*] и СЧС-1 [*Petrov et al., 2004*], таких породообразующих элементов как Al_2O_3, $Fe_2O_{3общ}$, MgO, K_2O, и P_2O_5. Характерно то, что содержание практически всех оксидов в рудной зоне имеет тенденцию к снижению. Исключением является SiO_2 (табл. 1). Распределение редких элементов повторяет закономерность, установленную для петрогенных элементов. Наименее измененные породы михайловской свиты характеризуются повышением содержания (до трех раз) Cu, Mo, Ba, W, As, Pb относительно значений PAAS и СЧС-1, в то время как в рудной зоне содержание практически всех редких элементов заметно снижается (табл. 2). Содержание ряда элементов сидерофильной группы (Co, Ni) имеет четкую корреляцию с рудными процессами, проявляя увеличение в два раза и более в зоне околорудных изменений. Максимальные концентрации Co и Ni отмечены в пробах с рудными содержаниями золота.

Выводы. Формирование месторождения Чертово Корыто происходило в пять этапов, первые два из которых являются дорудными, носят рудоподготовительный характер и, вероятно, значительно оторваны по времени от основного рудоформирующего события. Установленная стадийность формирования месторождений Чертово Корыто коррелирует с основными стадиями тектонометаморфической истории региона и согласуется с моделью формирования месторождений сухоложского типа [*Nemerov, 1989; Buryak, Khmelevskaya, 1997; Large et al., 2007*].

Ключевые слова: золото; черные сланцы; модель метаморфогенно-метасоматического формирования; Чертово Корыто; Байкало-Патомское нагорье

1. Introduction

The potential gold resources of the Lena gold province, one of the largest gold provinces of the world, are currently estimated at several thousands of tonnes. All gold deposits in this region are black shale hosted [*Buryak, Khmelevskaya, 1997*]. Over 90 % of the gold reserves of the Baikal-Patom Highland are located in the Khomolkho and Aunakit Formations of the Neoproterozic Dal'nyaya Taiga–Zhuya stratigraphic horizon [*Development..., 1998*]. The major object of the Lena gold province is the Sukhoi Log deposit. The concept of its formation is much debated, and a number of genetic models has been proposed [*Nemerov, 1989; Distler et al., 1996; Large et al., 2007.; Meffre et al., 2008*]. The model of the metamorphogenic-metasomatic origin of the black-shale hosted gold mineralization [*Buryak, Khmelevskaya, 1997*] is currently most recognized. This model assumes gold extraction from the initially siderite-chalcophilic host rocks and refers to a common source of the veinlet-impregnated and quartz-vein types of the gold mineralization, which jointly occur in the ore bodies in Sukhoi Log-type deposits in the Baikal-Patom Highland. According to the geochronological studies conducted in the most studied field of Sukhoi Log, these types of gold mineralization occurred in significantly distant time intervals dated 447±5 and 321±14 Ma, respectively [*Laverov et al., 2007*]. The first dating is consistent with the occurrence of granitoids in the Mama formation (421±15 Ma, U-Pb dating, SHRIMP-II) [*Zorin et al., 2008*], and the second dating corresponds to the age of the Barguzin formation composing the Angara-Vitim batholith (330–310 Ma) [*Tsygankov et al., 2007; 2010*].

New gold deposits and occurrences have been recently discovered in the Lena province. In terms of their geological structures and conditions of formation, these are gold-ore objects of the Sukhoi Log type, which are either hosted in the Paleoproterozoic black shales or confined to the contact of black shales and the overlying sediments of the ancient weathering crust (Chertovo Koryto, Zheltukta-Mikhailovskoye, Verkhne-Kevakta, Khadokan, Istanakh and others) [*Ivanov, 2014; Geological Report..., 2014*]. The genesis of these new gold deposits and occurrences and their relations to specific geological and geodynamic processes are still highly debatable.

This study aims to clarify the time sequence of the ore mineralization in the Chertovo Koryto deposit on the basis of detailed mineralogical and geochemical characteristics of the ore, wallrock metasomatites and the Early Proterozoic host black shales, and to assess the applicability of the Sukhoi Log model for clarifying the Chertovo Koryto origin.

2. The geological setting of the Chertovo Koryto deposit

The Lena gold province is located in the junction area of the Siberian platform and Baikal mountain region (Fig. 1). In this province, spatial positions of the main gold-bearing areas and complexes are controlled by the Chuya-Tonoda-Nechera uplift (Fig. 1) [*Nemerov, 1989; Distler et al., 1996; Buryak, Khmelevskaya, 1997; Perevalov, Sryvtsev, 2013; Ivanov, 2014; Yudovskaya et al., 2016*].

The Chertovo Koryto deposit is a part of the Kevakta ore complex that is promising for gold and uranium resources. This complex is confined to the Early Precambrian Formations of the Tonoda uplift composed mainly of the Paleoproterozoic carbonaceous rocks of the Kevakta series (Albazinsk and Mikhailovsk Formations) and granitoids of the Kevakta complex represented by S-type Late Karelian-type granites (1846±8 Ma) [*Larin et al., 2006*].

This deposit is confined to the EW-trending linear syncline of the second order, which wings dip at angles of 10–20° [*Gold..., 2007*]. This deposit is represented by a 1.5 km long and up to 150 m thick linear ore zone (Fig. 2) that is controlled by a gently dipping fault zone complicated by numerous smaller strike-slip faults, folding zones, fractures and boudinage structures. The ore zone is confined to the major tectonic

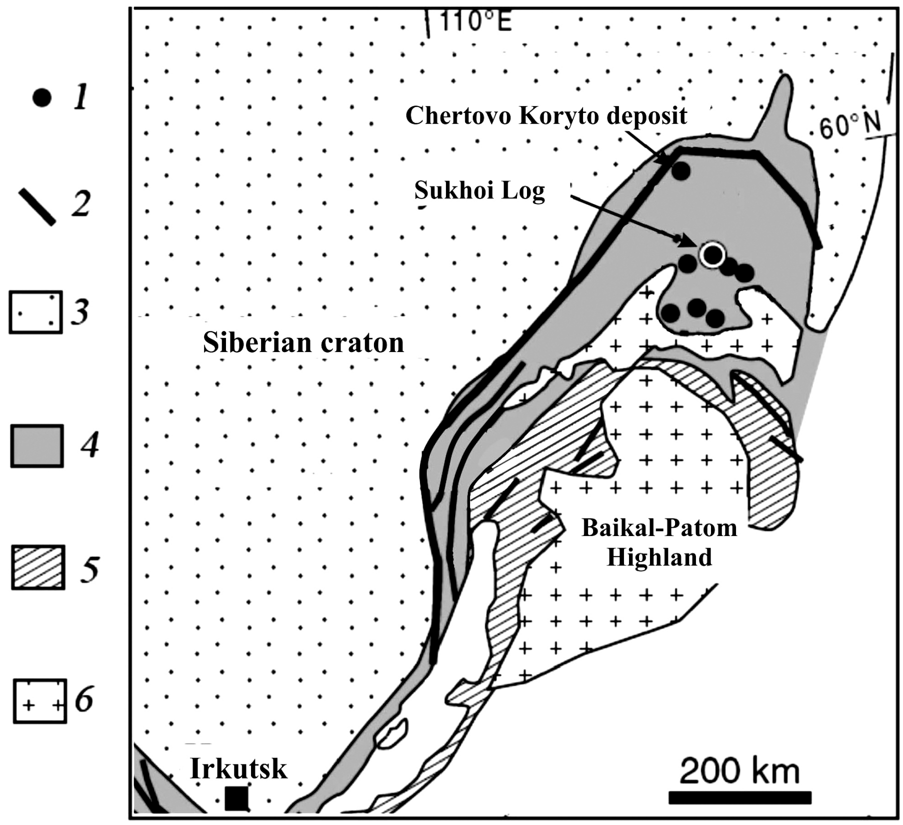

Fig. 1. Setting of the Chertovo Koryto and Sukhoi Log deposits in the Lena gold province on the eastern margin of the Siberian craton (modified after [*Large et al., 2007*]). *1* – black-shale hosted gold ore deposits hosted; *2* – main faults (thrusts); *3* – Siberian craton; *4* – Paleoproterozoic passive margins; *5* – Middle and Late Proterozoic accretionary edifices; *6* – Late Proterozoic and Paleozoic granites.

Рис. 1. Схематическое расположение месторождения Чертово Корыто [*Large et al., 2007*] с незначительными изменениями. *1* – золоторудные месторождения, приуроченные к черным сланцам; *2* – основные разломы (надвиги); *3* – Сибирский кратон; *4* – палеопротерозойские пассивные окраины; *5* – средне- и позднепротерозойские аккреционные образования; *6* – позднепротерозойские и палеозойские граниты.

zone composed of the Early Proterozoic Mikhailovsk host rocks (i.e. the second pack of the upper sub-suite) that were strongly metasomatically transformed.

The ore zone is a stockwork-type body including a system of branching and intersecting quartz veins and veinlets, with the low-sulphide veinlet-impregnated mineralization of the pyrite-pyrrhotite-arsenopyrite composition. The quartz veinlets have complex morphology due to their confinement to the various structural elements and weakened zones impacted by deformation processes. Geological boundaries of the currently known industrial ore body have not been constrained yet and are determined with respect to the cut-off grade of 0.8 gram per tonne, as accepted for the reserve evaluations. Gold concentrations are extremely randomly scattered, and intervals of ore and barren rocks alternate within the ore body [*Gold…, 2007*]. Evaluated gold reserves of the Chertovo Koryto deposit in categories C_1 и C_2 amount to 84 tonnes [*Gold…, 2007*].

3. Rock composition. Brief description of the host rocks

Metasedimenaty rocks. In the Chertovo Koryto deposit, host rock are interbedded metasandstone, metaaleurolite and metaargillite of the Mikhailovsk Formation which underwent the regional metamorphism mainly at the level of sericite-chlorite subfacies of the greenschist and lower epidote-amphibolite facies, as evidenced by low-temperature-resistant quartz-albite-sericite-chlorite and quartz-albite-muscovite-biotite-amphibole mineral associations. In the host rocks, pervasive are relict structures of primary foliation, which is consistent with the limited low-temperature metamorphism of the primary sedimentary substrate. All the rocks are considerably schistose and contain carbonaceous material. A distinctive feature of the Mikhailovsk Formation is the lack of interlayers composed of sedimentary carbonate rocks.

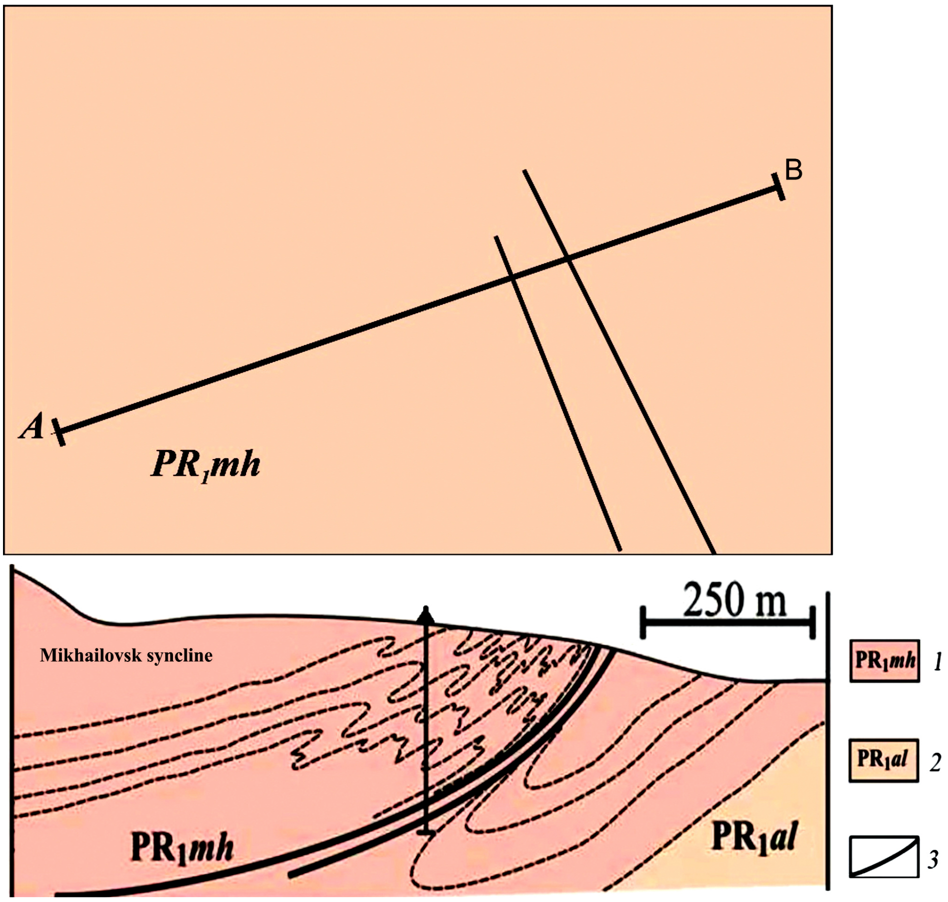

Fig. 2. Schematic geological section across the Chertovo Koryto deposit [*Yudovskaya et al., 2016*]. *1* – Mikhailovsk Formation (carbonaceous shale and sandstone); *2* – Albaza formation (terrigenous rocks); *3* – fault.

Рис. 2. Схематический геологический разрез через рудное тело месторождения Чертово Корыто [*Yudovskaya et al., 2016*]. *1* – отложения михайловской свиты, представленные карбонатными сланцами и песчаниками; *2* – отложения албазинской свиты, представленные терригенными породами; *3* – разлом.

In the highest carbon metasedimentary rocks of the metapelitic composition, contents of C_{org} range from 1.0 to 2.0 %. A characteristic feature of clay interlayers of the Mikhailovsk Formation is siderophilic specialization with evidently increased contents of Au (0.0n gpt) and As (>100 gpt) relative to more sandy varieties. Within the ore zone, the Mikhailovsk rocks are significantly depleted in carbonaceous material (0.5 %), with minimum contents of organic material in the ore bodies and halos of metasomatically altered rocks (0–0.2 %).

Mineralogical mapping by a QemScan hardware set shows that the gold quartz veinlets in the ore zone are always accompanied by quartz-muscovite (sericite) metasomatic halos near the veins. In the compositions of metasomatites, constantly present are albite, carbonates (siderite and ankerite) and chlorite. In this case, the metasomatite halo contains fluoro-apatite (up to 7.5 % fluorine) and tissonite (oxyfluoride of cerium-lanthanum) in the close association with quartz, sericite and albite, as well as carbonate of light REE (mainly cerium-lanthanum-neodymium) and cerium oxide, that form minute isometric inclusion in the metasomatite matrix. Noticeably less abundant in the metasomatites are other silicate and oxide phases (rutile, magnetite, and baddeleyite), some of which may be relics of the primary paragenesis of the metasedimentary rocks.

Mineralogy of ores. In the Chertovo Koryto deposit, the ore mineralization is imposed and developed in zones of metasomatically transformed rocks. The main ore mineral is arsenopyrite; widespread are pyrrhotite and pyrite, and to a lesser extent, galena, chalcopyrite and sphalerite.

Based on the detailed mineralogical study of the ores, we distinguish three heterochronous mineral associations: pyrite-pyrrhotite, pyrite-pyrrhotite-arsenopyrite (with placer gold), and galena-sphalerite-chalcopyrite.

Pyrite-pyrrhotite association is represented by scattered inclusions of pyrite-I and pyrrhotite-I (Fig. 3, *a*, *b*). This association is the earliest.

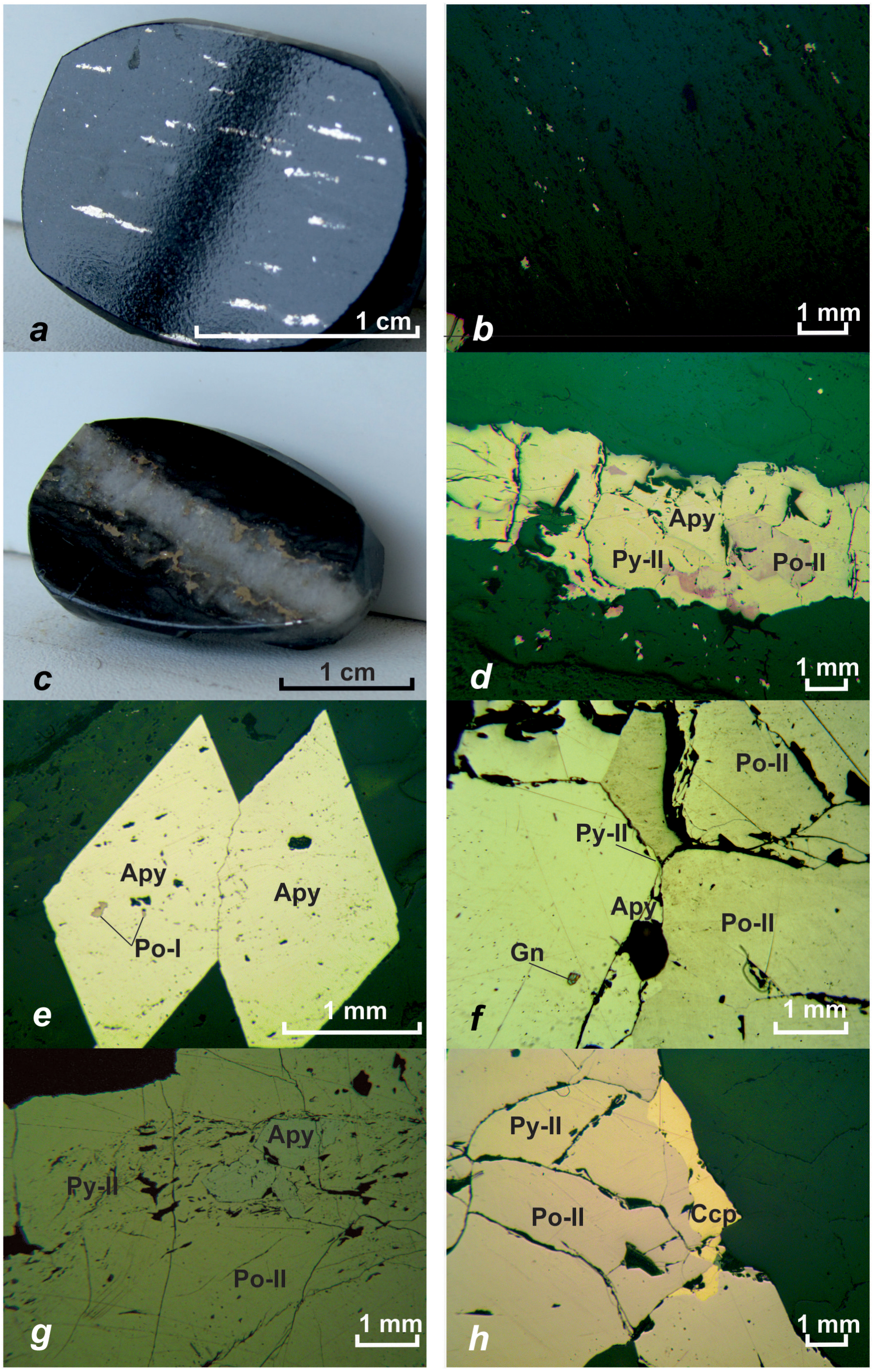

Fig. 3. Sulfide minerals in the ore mineral associations of the Chertovo Koryto deposit.

Pyrite-pyrrhotite association: (*a*) lenses of metamorphic pyrrhotite in the host black shale; (*b*) scattered fine pyrite and pyrrhotite in black shale; pyrite-pyrrhotite-arsenopyrite association: (*c*) quartz-sulphide veins in black shale; (*d*) vein-disseminated pyrite-II, pyrrhotite-II and arsenopyrite in quartz aggregate; (*e*) twins of arsenopyrite with inclusions of pyrrhotite-I; (*f*) cataclastic arsenopyrite with an inclusion of galena in association with pyrrhotite-II and pyrite-II; (*g*) arsenopyrite in the large joint aggregate of cellular pyrrhotite-II and uniform pyrite-II; (*h*) chalcopyrite developing at the periphery of the aggregate of pyrite-II and pyrrhotite-II. Images in the reflected light.

Рис. 3. Формы выделений и характер взаимоотношений сульфидных минералов в рудных минеральных ассоциациях месторождения Чертово Корыто.

Пирит-пирротиновая ассоциация: *a* – линзовидные выделения метаморфического пирротина во вмещающих черных сланцах; *b* – рассеянные скопления тонкодисперсных пирита, пирротина в черных сланцах; пирит-пирротин-арсенопиритовая ассоциация: *c* – кварц-сульфидный прожилок в черных сланцах; *d* – прожилковидное обособление пирита-II, пирротина-II и арсенопирита в кварцевом агрегате; *e* – двойники арсенопирита с включениями пирротина-I; *f* – катаклазированный арсенопирит с включением галенита в ассоциации с пирротином-II, пиритом-II; *g* – выделение арсенопирита в крупном совместном агрегате ячеистого пирротина-II и однородного пирита-II; *h* – халькопирит, развивающийся по периферии агрегата пирита-II и пирротина-II. Снимки в отраженном свете.

Pyrrhotite-I is earlier and more abundant as compared with pyrite-I. Pyrrhotite-I and pyrite-I are closely interrelated and occur in the form of individual lenses extended along foliation planes of the host rocks (see Fig. 3, *a*, *b*). Generally, such aggregates are up to 0.7 mm long, rarely less than 2 mm or longer.

The chemical composition of pyrrhotite-I is characterized by a varying ratio of Fe and S. The contents of these elements range from 56.2 to 60.1 wt % and 40.2 to 43.8 wt %, respectively.

Pyrite-I is represented by abundant idiomorphic single cubic grains (up to 0.4 mm) and xenomorphic splices (up to 5–10 mm). The occurrences of the aggregates and complexs of pyrite-I follow the rock foliation. The chemical composition of pyrite-I is quite consistent and characterized by the stable stoichiometry of Fe and S.

The pyrite-pyrrhotite-arsenopyrite association is represented by quartz veins with vein-disseminated aggregates of arsenopyrite, pyrrhotite-II and pyrite-II (Fig. 3, *c*, *d*). In the Chertovo Koryto deposit, this association is closely related to the main part of the native gold occurrences.

Arsenopyrite, the main ore mineral in the Chertovo Koryto deposit, occurs in carbonaceous metasediments and at the contact of shales and quartz veinlets (see Fig. 3, *c*). It is most typically found in the form of lense- and nest-shaped occurrences, as well as scattered inclusions of individual idiomorphic prismatic crystals and their twins (Fig. 3, *e*). In the host rocks, arsenopyrite is often found in pressure fringes of hydrothermal quartz. Dimensions of the individual crystals are highly variable, mainly from 0.02 to 0.1 mm, and reach 1.0 cm in rare cases. Arsenopyrite aggregates are strongly cataclastic and covered with networks of cracks, along which pyrrhotite, rarely pyrite and galena, as well as gold are developed (Fig. 3, *f*, *g*). Arsenopyrite shows a consistent composition, with an almost unchanged S/As ratio; only a specific admixture of Co is noted, which amounts to 2 wt % in rare cases.

Pyrite-II and pyrrhotite-II, that are less common as compared with arsenopyrite and are later in relation to it, form complex aggregates. *Pyrite-II* is represented by scattered inclusions of hypidiomorphic cubic grains or nest-shaped impregnated aggregates. Dimensions of individual crystals amount to 0.2 mm, and the aggregates are as large as 3.0 cm. The chemical compositions are quite consistent, with stable contents of Fe (46.9–47.3 wt %) and S (52.3–53.5 wt %).

Pyrrhotite-II occurs in elongated nest-shaped forms and individual grains, the size of which varies within a wide range and reaches 3.0 cm. The chemical composition of pyrrhotite-II relative to that of pyrrhotite-I is characterized by an admixture of Ni (to 0.73 wt %).

The pyrite-pyrrhotite-arsenopyrite association is overlaid by the later galena-sphalerite-chalcopyrite association.

Chalcopyrite is one of the latest ore minerals, as evidenced by chalcopyrite fringes, veinlets and inclusions in arsenopyrite, pyrite-II and pyrrhotite-II (Fig. 3, *h*). The chemical composition of chalcopyrite is close to the average content accepted in the literature.

Galenite occurs in the form of fine inclusions in arsenopyrite and rare joint fusions with gold. The X-ray microstructural analysis method shows submicrons of placer silver in galenite.

In the studied samples, *sphalerite* is very rarely observed in the form of single microscopic aggregates in chalcopyrite and pyrrhotite. An elevated Cd concentration of Cd (4–7 %) is a characteristic feature of the composition of sphalerite.

In the Chertovo Koryto deposit, *Greenockite-CdS* has been discovered for the first time. In all the studied samples, greenockite is associated with sphalerite and chalcopyrite and occurs in elongated drop-shaped forms as long as a few dozens of microns (Fig. 4). The composition of the studied greenockite is close theoretical, with a specific admixture of Zn. Similar forms of greenockite were described previously in the Krasnoe [*Palenova, 2015*] and Sukhoi Log [*Distler et al., 1996*] gold fields located in the study region. The presence of submicron inclusions of greenockite in sphalerite may explains the increased content of cadmium in the latter.

Native gold of the Chertovo Koryto deposit is represented by allotriomorphic inclusions developing along the zones wherein large grains of arsenopyrite together with pyrrhotite-II and pyrite-II (Fig. 5), more rarely galena, are subject to cataclasis. In rare cases, native gold is observed in large (to 1.0 cm) idiomorphic pyrite crystals. Gold nuggets are mainly isometric, flattened, branching and irregularly shaped with interstitial-splintery extensions. The gold nuggets are light yellow and, in rare cases, have a distinctive reddish color shade due to a significant admixture of copper.

Chemical compositions of the native gold vary in a wide range. Admixtures of Ag are common in the native gold, and its concentrations vary from 8 to 16 wt %. Much less frequently observed are admixtures of Cu, reaching 30 wt % in rare cases. In the samples from the Chertovo Koryto deposit, an average purity of gold in parts per 1000 (i.e. fineness) amounts to 860–880, with higher values in quartz veins (900–920) and lower values in complex multiphase sulfide aggregates (780–800).

4. Geochemical characteristics

In the Chertovo Koryto deposit, the Mikhailovsk host rocks show high contents of Al_2O_3, FeO, MgO, K_2O and P_2O_5 relative to the post-Archean shale in PAAS

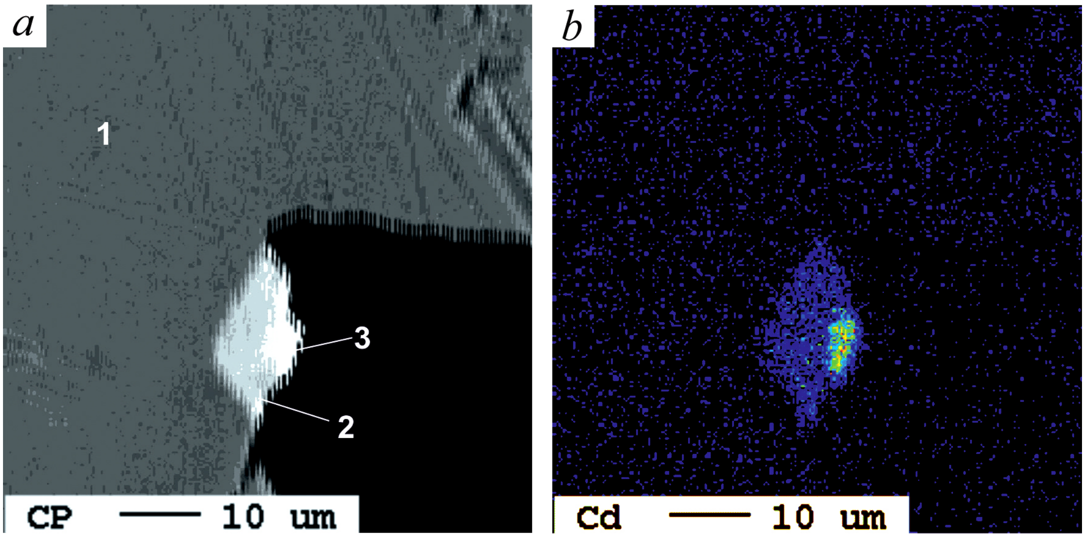

Fig. 4. Sphalerite (1) with a drop-shaped occurrence of chalcopyrite (2) and a small inclusion of greenockite (cadmium blende) (3): *a* – an image in backscattered electrons; *b* – Cd distribution map. An X-ray microanalyzer JCXA-733 (JEOL Ltd, Tokyo, Japan) was used (L.A. Pavlova).

Рис. 4. Сфалерит (1) с каплевидным выделением халькопирита (2) и мелким включением гринокита (3): *a* – изображение в обратнорассеянных электронах; *b* – карта распределения Cd. Изображения получены на рентгеновском микроанализаторе JCXA-733 (JEOL Ltd, Tokyo, Japan) (Л.А. Павлова).

[*Condie, 1993*] and black shale in SChS-1 [*Petrov et al., 2004*]. In the ore zone, contents of almost all major oxides tend to decrease. The higher content of SiO_2 in the ore zone (up to 90 %, Table 1) is due to the fact that all the elements, without any exception, were significantly diluted during silicification and quartz-muscovite-sericite metasomatism. In terms of geochemistry, this process is evidenced by a sharp negative correlation between the contents of quarts and other rock-forming oxides and trace elements in the samples of rocks affected by the imposed ore process (Table 1).

In the ore zone, average concentrations of the main components, Au and Ag, amount to 12.5 gpt and 3.5 gpt, respectively. The analysis of the distribution of trace elements in the rock and ore samples shows that the ore-formation process was accompanied by the concentration of elements in the ore group (Au, Ag, Co, Ni, and As) and the removal of lithophilic elements.

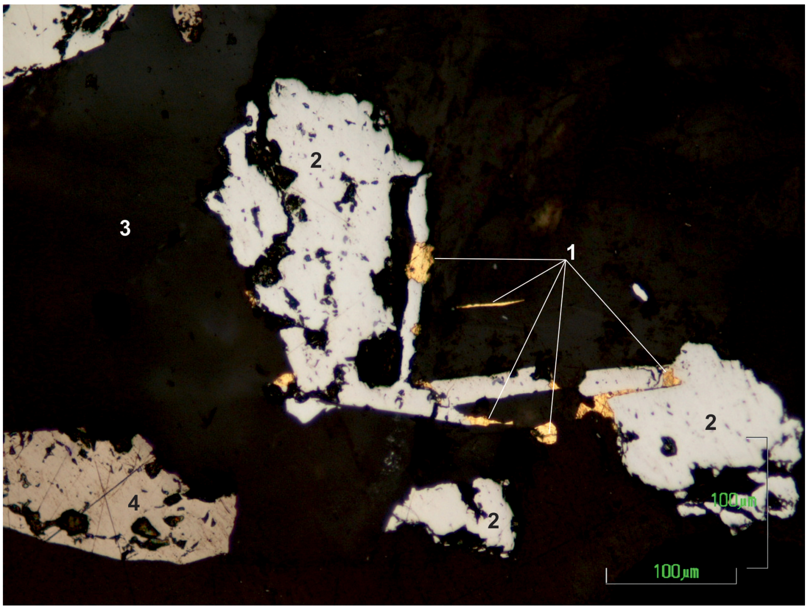

Fig. 5. The image in the reflected light [*Gold Ore Deposit…, 2007*]. 1 – native gold / gold nuggets; 2 – arsenopyrite; 3 – large blastogenic sericite-chlorite aggregate; 4 – pyrrhotite.

Рис. 5. Самородное золото (1) в ассоциации с арсенопиритом (2) в крупнобластическом серицит-хлоритовом агрегате (3), коричневатое зерно – пирротин (4). Изображение в отраженном свете [*Gold Ore Deposit…, 2007*].

Т a b l e 1. **Variations and average contents (wt %) of components in the host rocks and ores sampled from the Chertovo Koryto deposit**

Т а б л и ц а 1. **Вариации и средние содержания компонентов в породах и рудах месторождения Чертово Корыто, мас. %**

Components	Host rocks mh PR_1 (34 estimates)	Metasomatic rocks $mhPR_1$ (37 estimates)
SiO_2	56.7 50.3–60.7	73.20 61.5–97.5
TiO_2	0.87 0.69–1.23	0.52 0.04–0.79
Al_2O_3	20.4 17.5–31.7	12.40 1.10–20.1
Fe_2O_3	7.86 5.24–9.32	5.62 3.90–7.10
MgO	2.90 2.59–3.30	2.04 0.14–3.11
CaO	0.11 0.06–0.17	0.13 0.10–0.21
Na_2O	0.30 0.20–0.90	0.84 0.20–1.54
K_2O	5.52 4.60–6.60	2.90 0.30–5.30

N o t e. RFA estimates (Institute of Geochemistry SB RAS, Irkutsk).

П р и м е ч а н и е. Определение проводилось методом РФА (ИГХ СО РАН).

Samples from the Mikhailovsk Formation show higher concentrations (up to 3 times) of Cu, Mo, Ba, W, As, and Pb relative to the PAAS [*Condie, 1993*] and SChS-1 values [*Petrov et al., 2004*], while the contents of practically all trace elements are markedly reduced in the ore zone (Table 2). Exceptions are As, Ni and Co. In the ore zone, concentrations of As are increased by more than an order of magnitude, and an average content of As amounts to 1000 gpt in the samples with industrial gold contents. Contents of Ni and Co also show a clear relationship of these elements with the ore formation process – at the transition from the host rocks to the ore zone, concentrations of Ni and Co are doubled.

In terms of the rare element composition, metasedimentary host rocks of the Mikhailovsk Formation are close to the post-Archean clay shale (Fig. 6, *A*). The distribution of rare earth elements is characterized by a steep slope, from light REE to medium REE, with a

Т a b l e 2. **Average contents (gpt) of trace elements in host deposits and ores sampled from Chertovo Koryto deposit**

Т а б л и ц а 2. **Средние содержания микроэлементов во вмещающих отложениях и в руде месторождения Чертово Корыто, г/т**

Elements	Host rocks mh PR_1 (34 estimates)	Metasomatic rocks $mhPR_1$ (37 estimates)
Au	0.02	12.50
Co	6.13	16.46 (23)
Ni	19.51	30.96 (55)
Cu	53.90	13.24
Zn	90.40	65.70
Mo	2.03	0.46
Sb	1.57	1.03
Ba	882	484
Pb	13.68	9.84
As	88	>>>1000
Th	13.04	7.01
U	3.99	2.54

N o t e. ICP-MS estimates (Institute of Geochemistry SB RAS, Irkutsk).

П р и м е ч а н и е. Определения проводилось методом ICP-MS (ИГХ СО РАН).

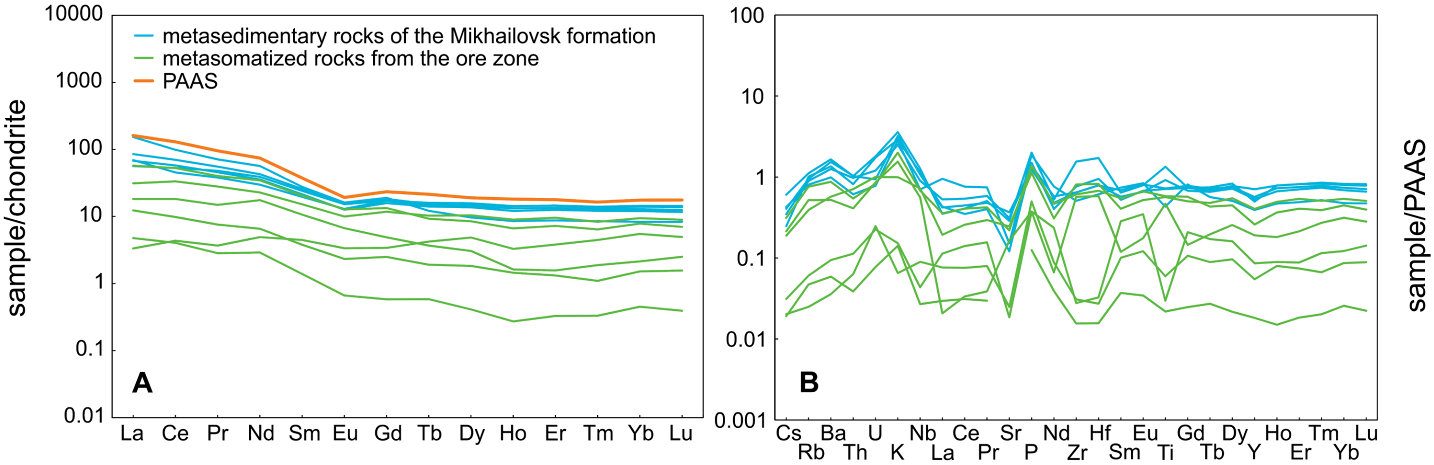

Fig. 6. Distribution spectra of REE (*A*), and multi-element spectra (*B*) for the host sediments of the Mikhailovsk Formation and metasomatically altered rocks in the Chertovo Koryto ore zone.

Рис. 6. Спектры распределения REE (*А*) и мультиэлементные спектры (*В*) для вмещающих отложений Михайловской свиты и метасоматически измененных пород в рудной зоне месторождения Чертово Корыто.

small negative angle in the area of heavy REE, the La/Yb_N ration in the range from 4.8 to 18.4, a clearly manifested negative anomaly of Eu (Eu/Eu* in a range of 0.68–0.74), and a weak (to 0) minimum of cerium (Ce/Ce* in a range of 0.84–1.02).

Multi-element spectra of the distribution of trace elements in the host rocks show a more complex picture, although being similar with respect to PAAS and differing mainly in the total contents of the trace elements (Fig. 6, *B*). The distribution spectra are characterized by minimum concentrations of Sr, maximum concentrations of P, and variable contents of light REE, Nb, Ta and Ti. Variations in the contents of light REE, Nb, Ta and Ti are most likely due to the different content of accessory phase-concentrators of these elements. The content of LILE correlates with the concentration of K and may thus be controlled by the concentration of primary muscovite/biotite.

A contrasting pattern is revealed for the trace-element compositions of the rocks that were, to varying degrees, metasomaticly transformed in the zone of metamorphic changed rocks. In the least altered rocks, concentrations of rare elements and the general distribution patterns remain practically unchanged (La/Yb_N in a range of 3.3–7.3, and Eu/Eu* in a range of 0.74–0.75), and only a more fractionated spectrum is noted, with reduced contents of the lightest REE (especially La) and a clear low maximum of Ce (Ce/Ce* from 1.08–1.13) (Fig. 6). For some of the rare elements, contents of LILE and K relative to Th and U, as well as light REE, are considerably reduced, while other rare-element characteristics (particularly, the content of HFSE and heavy REE) remain the same.

Based on results of our geochemical studies of the rock and ore samples from the Chertovo Koryto deposit, the following regularities in the behavior of elements in the ore process are revealed: (1) concentrations of trace elements are generally reduced (in particular, the content of ΣREE relative to the host rocks is reduced up to five times); (2) the rocks and the ores are depleted in LILE cations (mainly, K, Rb, and Ba), light REE, and HFSE elements (in particular, Zr and Hf with significant variations in the content of Ti).

5. Discussion of results

Based on results of the mineralogical-petrographic and geochemical studies of the host rocks and the ores sampled from the Chertovo Koryto deposit, the following mineral associations resulting from the sequences of heterochronous processes are revealed:

1. The earliest association is related to the processes of pre-ore metasomatosis of the metasedimentary rocks and expressed in the formation of quartz-muscovite-sericite veinlets, as well as the extraction and removal of REE from the host rocks, with the partial redislocation in the form of tiny inclusions of separate carbonate and oxide minerals. On the sites showing metamorphic changes around the quartz-mica veinlets, no newly formed quartz is observed, in contrast to the studied ore zone with abundant silicification. Moreover, samples from frames of the veinlets with higher contents of gold show significantly decreased contents of SiO_2 и Na_2O and increased contents of

Al_2O_3, Fe_2O_5, K_2O,Ba, Mo, U, Th, CO_2, and REE (see Tables 1 and 2).

In general, the observed variations in the composition, which result from metasomatic changes of the rocks of the Mikhailovsk Formation in the Chertovo Koryto ore zone, reflect the process of the dissolution of quartz and feldspar by the carbon-dioxide fluid and the replacement of the muscovite-sericite mineral assemblage with the carbonate material. In the course of transformations, alkalis were redistributed in favor of a stronger base of K_2O, and Na_2O was considerably removed. Dissolved silicon oxide, jointly with Na, migrated to the lowest pressure zones to form the metasomatic silicification halos, and the subsequent ore mineralization developed along such halos. The spatial relationship between the zones of metasomatic changes and the ore associations can be explained by the fact that these ore associations were more permeable than the host black shales and, consequently, more apt for the development of subsequent ore-forming processes.

The rear zone of the metasomatic changes shows depositions of mobile fluid elements (K, Rb, and Ba) and some other elements (light REE, and HFSE). The behavior of these elements in fluids is debatable. The recently published data from simulations and estimates suggest that these elements can be successfully extracted from the rock by dissolving the corresponding accessory phases (monazite) [*Wood, Williams-Jones 1994; Wood, 2005*] and transferred by aggressive carbon dioxide fluids with a significant content of fluorine [*Keppler, 1993; Haas et al., 1995; Gammons et al., 2002; Migdisov, Williams-Jones, 2008; Migdisov et al., 2009; Yudovskaya et al., 2011; Linnen et al., 2014*].

2. The early sulphide mineralization, that was unrelated to the formation of the gold mineralization, developed in the metasomatically altered rocks. This association has no regional distribution and occurs only within the ore field. Presumably, the pre-mineral sulphidization occurred similar to the initial stage of the formation of the Sukhoi Log deposit [*Distler et al., 1996; Large et al., 2007*], which, according to [*Nemerov et al., 2005*], was associated with the catagenetic transformation of ore-productive carbon strata at the low-temperature metamorphic phase of the Baikal stage of folding [*Yudovskaya et al., 2011*].

3. The ore deposition stage, represented by the association of arsenopirite with pyrite-II and pyrrhotite-II, was related to the subsequent hydrothermal-metasomatic processes. The sulphide mineralization of the ore stage was accompanied by the formation of quartz-vein-veinlet bodies. Ore minerals are often accompanied by pressure rims, which is similar to the mineralization in other fields of the Bodaibo synclinorium. The minerals differ from the pre-ore sulphides in the high degree of idiomorphism and larger sizes, which is characteristic of the hydrothermal-metasomatic stage.

Further, admixtures of Co and Ni are revealed in arsenopyrite and pyrrhotite-II, respectively, as shown by the detailed study of the chemical compositions of sulphide in the ore association. It is noteworthy that the samples with the highest gold contents show the highest concentrations of Co and Ni. Despite this fact, contents of Co and Ni are below the PAAS values in the unaltered sediments and sediments that were subject to metasomatosis, and the concentration coefficients are 0.25 and 0.72 for Co, and 0.35 and 0.56 for Ni, respectively. This suggests borrowing of gold and associated components from the host rocks, without an involvement of any additional deep sources.

A.V. Chugaev and co-authors conducted the study focused on isotopic compositions of Pb in sulfides from the Verninskoye deposit [*Chugaev et al., 2014*]. Their results show that the crustal sources of Pb played the major role in the formation of the mineralization in this field. By comparing the points of the Pb-isotopic compositions in the Verninskoye and Sukhoi Log deposits, the compositions were found similar, which is indicative of the geochemical similarity of the source materials that were involved in the formation of these deposits. The same research team compared the model Pb-Pb datings for the Chertovo Koryto and Sukhoi Log deposits [*Chugaev et al., 2010*] and suggested an upper crust source for the gold mineralization in the studied fields, without any involvement of substances from larger depths. In their study, differences in the isotopic characteristics of the analyzed rocks are explained by differences in the characteristics of the heterochronous host rocks that accumulated in different geodynamic settings. According to [*Chernyshev et al., 2009*], the source of Pb in the Bodaibo synclinorium was the terrigenous-carbonate strata. The potential of the host black shale strata was thus sufficient for the formation of the deposits in the Baikal–Patom Highland.

4. The ore-formation stage was completed with the formation of the galena-sphalerite-chalcopyrite mineral association, most probably, due to the decay of the hydrothermal process. For the ore-forming process, changes at that stage were critical – specifically, such changes were related to the redeposition, consolidation and refining of the earlier native gold.

The above-mentioned ore associations, including the formation of the first pyrite-pyrrhotite association without ore gold, occupy the same area, but are separated in time. The later associations overlied the earlier ones, and the components of the ore and the majority of both the elements of the rock-forming components and the trace elements were redistributed and transported. An important feature of the sulphide mineralization in the studied zone is the repeated occurrence of the mineral associations, which is determined by the oscillating development of tectonic deformations, with the preferential formation of quartz-sulphide veins and veinlet inclusions in the areas prepared during the pre-ore stage.

5. The formation of the Chertovo Koryto deposit was completed with the formation of post-ore quartz veins and veinlets that are not auriferous. The post-ore silicification was associated with the repeated redeposition of gold, which resulted in the higher grade of gold in the study deposit and higher concentrations of gold in the above-mentioned veinlets that are observed only in the places where they intersect the ore zone.

Summarizing our findings concerning the mineralogical, petrographical and geochemical characteristics of the Chertovo Koryto deposit, and comparing these data with the isotopic study results and the concepts on conditions providing for the redistribution and removal of REE, we can conclude that the Chertovo Koryto deposit formed in the host black shales without an involvement of any additional magma source, and thus disagree with the conclusion stated in [*Kucherenko et al., 2008; Vagina, 2012*].

6. Conclusion

This study shows that the formation of the Chertovo Koryto deposit was multi-staged. In the first two pre-mineral stages, ore preparation processes took place discontinuously, and these two stages were considerably distant in time. The multi-stage origin of this deposit is related to the main regional geodynamic processes. This conclusion is generally consistent with the metamorphogenic-hydrothermal model showing the development of the Sukhoi Log-type deposits [*Nemerov, 1989; Buryak, Khmelevskaya, 1997; Large et al., 2007*].

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Tarasova, Yulia I., Candidate of Geology and Mineralogy
A.P. Vinogradov Institute of Geochemistry, Siberian Branch of RAS
1A Favorsky street, Irkutsk 664033, Russia
Irkutsk Scientific Center, Siberian Branch of RAS, Irkutsk, Russia
134 Lermontov street, Irkutsk 664033, Russia
e-mail: j.tarasova84@yandex.ru

Тарасова Юлия Игоревна, канд. геол.-мин. наук
Институт геохимии им. А.П. Виноградова СО РАН
664033, Иркутск, ул. Фаворского, 1А, Россия
Иркутский научный центр СО РАН
664033, Иркутск, ул. Лермонтова, 134, Россия
e-mail: j.tarasova84@yandex.ru

Sotskaya, Olga T., Candidate of Geology and Mineralogy
N.A. Shilo North-East Interdisciplinary Scientific Research Institute, Far East Branch of RAS
6 Portovaya street, Magadan 685000, Russia
e-mail: sotskaya@neisri.ru

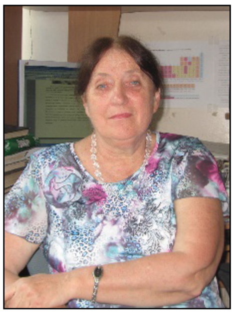
Соцкая Ольга Тарасовна, канд. геол.-мин. наук
Северо-Восточный комплексный научно-исследовательский институт им. Н.А. Шило ДВО РАН
685000, Магадан, ул. Портовая, 6, Россия
e-mail: sotskaya@neisri.ru

Skuzovatov, Sergei Yu., Candidate of Geology and Mineralogy
A.P. Vinogradov Institute of Geochemistry, Siberian Branch of RAS
1A Favorsky street, Irkutsk 664033, Russia
e-mail: skuzovatov@igc.irk.ru

Скузоватов Сергей Юрьевич, канд. геол.-мин. наук
Институт геохимии им. А.П. Виноградова СО РАН
664033, Иркутск, ул. Фаворского, 1А, Россия
e-mail: skuzovatov@igc.irk.ru

Vanin, Vadim A., Candidate of Geology and Mineralogy
Institute of the Earth's Crust, Siberian Branch of RAS
128 Lermontov street, Irkutsk 664033, Russia
e-mail: vanin_geo@mail.ru

Ванин Вадим Александрович, канд. геол.-мин. наук
Институт земной коры СО РАН
664033, Иркутск, ул. Лермонтова, 128, Россия
e-mail: vanin_geo@mail.ru



Kulikova, Zoya I.
A.P. Vinogradov Institute of Geochemistry, Siberian Branch of RAS
1A Favorsky street, Irkutsk 664033, Russia
e-mail: kulikova@igc.irk.ru

Куликова Зоя Ивановна
Институт геохимии им. А.П. Виноградова СО РАН
664033, Иркутск, ул. Фаворского, 1А, Россия
e-mail: kulikova@igc.irk.ru

Budyak, Aleksander E., Candidate of Geology and Mineralogy
A.P. Vinogradov Institute of Geochemistry, Siberian Branch of RAS
1A Favorsky street, Irkutsk 664033, Russia
Irkutsk Scientific Center, Siberian Branch of RAS, Irkutsk, Russia
134 Lermontov street, Irkutsk 664033, Russia
e-mail: budyak@igc.irk.ru

Будяк Александр Евгеньевич, канд. геол.-мин. наук
Институт геохимии им. А.П. Виноградова СО РАН
664033, Иркутск, ул. Фаворского, 1А, Россия
Иркутский научный центр СО РАН
664033, Иркутск, ул. Лермонтова, 134, Россия
e-mail: budyak@igc.irk.ru