Iron Oxide Cu-Au (IOCG) Mineralizing Systems: The Eastern Yakutia (Russia) Perspective

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Abstract. Iron-Oxide-Copper-Gold (IOCG) are the worldwide economically attractive deposits with significant amount of iron oxides, copper minerals, gold and ± silver and REE. In order to obtain more gold resources in Eastern Yakutia (Russia) we provide a descriptive model for IOCG style mineralization for several new prospective sites, which were initially discovered on satellite images and subsequently certified by prospecting. We allocate three basic Fe-oxide-Cu-Au deposit styles in Eastern Yakutia. First is related to Mesozoic hypabyssal intrusions of granodiorites (Kis-Kuel, Kysyltas and Rep-Yure deposits). As follows from the REE behavior in magmatic rocks, the fractionation of the magmatic melt during cooling was extremely insignificant. Due to this, a substantial part of the iron did not fractionate into high-iron melts, and separated into hydrothermal solutions with rich iron oxide mineralization. Second is related to flows of the basaltic and andesitic lavas of the upper Devonian – lower Carboniferous age (Kharat, Rosomakha and Jalkan deposits). Significant accumulations of hematite with copper and gold are associated with calc-alkaline basalts. The appearance of iron oxides in basaltic lavas is a result of decomposition of ilmenite into hematite and pseudorutile. Third style belongs to magnetite rich lavas of upper Jurassic age (Kildyam deposit). Variolithic lava flows saturated with native iron, magnetite, troilite and pyrite, native iron usually spherical in shape. Intrusion related ore bodies are irregular shaped breccias with arrays of variably mineralized veins and veinlets inside intrusives and veins in the host rocks. Associated with basaltic and andesitic lavas deposits occur as massive, tabular bodies, stratified, pyroclastic ores. The gold grade in IOCG ore varies from less than 1 to more than 50 g/t, base metals are optional. Differences in gold' fineness and admixtures characterize the genetic features of ore formation and is represented by a system of alloys: Au-Ag, Au-Ag-Cu and Au-Fe-Pd. Discovered iron-oxide copper gold mineralization in Eastern Yakutia analogous to several World class deposit types. Related to Mesozoic hypabyssal intrusions of granodiorites Kis-Kuel, Kysyltas and Rep-Yure deposits are close to Olympic Dam type. IOCG mineralization in basaltic and andesitic lavas of the Khurat, Rosomakha and Jalkan deposits looks similar to deposits of the Mount-Isa region (Eastern North-West Queensland, Australia). The Kildyam deposit rich iron-oxide ore bodies resemble lava flows and have share many common features with El Laco deposit in High Andes.
1. Introduction
During 2011-2020, geologic investigations of the Diamond and Precious Metal Geology Institute proved the presence of previously unknown iron-oxide copper-gold mineralization in Eastern Yakutia. Economic mineralization is represented with chalcopyrite ± bornite and native gold and localized in iron-oxides. Hematite characterizes low-level, magnetite – deep-level of mineralizing systems. Sulphides-poor deposits with large amount of Fe-oxides and wide hydrothermal alteration make IOCG a good target for regional research. We used ESRI Satellite (ArcGIS/World_Imagery) to detect the areas of iron-oxide potential mineralization. Certification of identified anomalies in the field showed that large magmatic systems with IOCG potential may have three surface types of Fe-oxide mineralization which are used when prospecting: 1 - Bright yellow shades on the surface of the outcrops due to oxidizing veinlets with pyrite, pyrrhotite, sphalerite, chalcopyrite and galena; 2 – Dark brown due to disseminated and lightly oxidized pyrite inclusions in hornfels; 3 – Dark yellow and brown shades on the roof of plutons due to the abundance of partially oxidized hematite (figure 1). This last type is close to IOCG style mineralization. IOCG deposits timing with respect to Earth evolution in Eastern Yakutia is different and does not appear to be critical. Deposits are known to occur from the Devonian age (Khurat, Rossomakha and Dzhalkan), to the Mesozoic (Kis-Kuel, Kysyltas, Rep-Yure and Kildyam) age.

![Image 1](https://example.com/image1.png)

Figure 1. IOCG-potential mineralizing system in Eastern Yakutia at Levo-Jolakagskiy, Burgaliyskiy and Verkhne-Burgaliyskiy plutons as an example of satellite imagery analysis. Mineralization style: 1 – Oxidized veinlets with pyrite, pyrrhotite, sphalerite, chalcopyrite and galena showing bright yellow shades on the surface of the outcrops. 2 – Pyrite inclusions in hornfels with light oxidation form dark brown colors. 3 – Partially oxidized breccia with hematite cement showing dark yellow to brown shades.

Field data made it possible to combine the discovered IOCG manifestations (figure 2) in two groups: 1. IOCG manifestations Associated with hypabyssal Late Cretaceous intrusions of granodiorites (Kis-Kyuel, Kysyltas and Rep-Yure); 2. IOCG manifestations in the lava flows of Devonian age basaltic lavas (Khurat, Rossomakha and Dzhalkan) and Upper Jurassic andesite-dacite magnetite rich lavas (Kildyam).

2. IOCG mineralization in hypabyssal Mesozoic intrusions
The intrusion solidification depth and the degree of the melt fractionation importantly influence the formation of IOCG mineralization. At great depths magma-fluid systems cannot generate enough mechanical energy to crush the host rocks and form ore breccias. As follows from the REE behavior in Kis-Kuel magmatic rocks [1, 2], the fractionation of the magmatic melt during cooling was extremely insignificant. Due to this, a most part of the iron did not fractionate into high-iron melts and separated
into hydrothermal solutions with rich iron oxide mineralization. At shallow depths of solidification,
ore breccias with hematite and goethite cement are formed in the roof bearing additionally disseminated sulfide mineralization. Ores consisting of more than 20% iron oxides sulfides are deficient. Moreover, Fe-oxide mineralization can cover significant volumes of altered intrusive rocks,
while copper and gold minerals are disseminated and streaked-disseminated in nature, forming stockwork bodies with stable parameters to a depth. The basic ore styles related to Mesozoic intrusions are shown on figure 3.

Figure 2. Regional geologic map of the Eastern Yakutia, Russia. The IOCG, Au, Ag, Sn and Hg deposits lies in the Carboniferous – Jurassic sedimentary units of the Verkhoyansk fold-and-thrust belt.

Figure 3. Main mineral IOCG ore styles related to Mesozoic intrusions. A – The Kis-Kuel breccia,
were granodiorite fragments cemented with hematite and pyrite, grades FeOtot - 50.8%, Cu - 0.094%,
Au - 37.17 g/t. B – The Kysiltas iron-oxide breccia with Cu - 0.33%, Au - 18.2 g/t; Ag - 754 g/t. C –
The Kysiltas quartz breccia with hematite cement and malachite + azurite staining. D – The Rep-Yure
breccia consist of sub-angular and rounded fragments of hornstone and granite with Au-bearing arsenopyrite-cement Cu - 3.2%, Au 12 g/t.
**Kis-Kuel** is intrusion-related IOCG deposit with a wide range of mineral styles. Economic mineralization discovered at the top of small Kis-Kuel pluton include Iron Oxide Copper-Gold and Cu-Au-porphyry ore breccia in hornfelsed aureole. Ore grades FeOX – 13.58-63.24%; Cu – 0-3.57%; Au – 12.93-64.48 g/t; Ag – 2.7-830 g/t. Associated arrays of sheeted auriferous quartz veins with arsenopyrite, native gold and bismuth and Ag-Bi sulphosalts with Au – 0.15-4.6 g/t; Ag – 20.6-196 g/t; Cu – 0.048-0.24%; Pb – 0.3-3.73%, gold fineness varies from 719 to 760 [1, 2]. Magmatic contribution to the Kis-Kuel deposit is significant. Intrusive rocks range from diorite to granodiorite in composition. Rare-earth geochemical system of igneous rocks of the Kis-Kuel intrusive is characterized by behavior close to the CHArge-and-RAdius-Controlled CHARAC-system (26<Zr/Hf<46 и 24<Y/Ho<34) in which the H/Ho – Zr/Hf ratios of the pair show a distribution close to chondrite (Zr/Hf ~ 36.6 and Y/Ho ~ 27.7). After M. Bau [3] we suppose that minor deviations of the Kis-Kuel rocks from the CHARAC intervals indicate an unevolved magmatic system [1].

**Kysylta**s is intrusion-related gold and silver deposit with additional IOCG features. Prior to the formation of the bulk of the gold-silver ore veins, formed significant accumulations of hematite and goethite with inclusions and nests of tetrahedrite, galena and native gold. Gold is mostly thin and disintegrated, gold grades vary from 0.7 to 18.2 g/t, silver - from 24.2 to 1891 g/t. Native gold contain admixture of iron, gold fineness varies from 629 to 673.

**Rep-Yure** deposit consists of granit-granodiorite-monzonite-associated, breccia-hosted bodies, where arsenopyrite mineralization is associated with iron-oxide alteration of breccias. Hematite-rich breccias host the bulk of the ore. The dominant alteration assemblage at Rep-Yure is hematite± quartz±chlorite with disseminated chalcopyrite, arsenopyrite native gold, bismuth and copper. Breccia color depends on the saturation of iron-oxides and is changing in the supergene zone from brown and dark brown to different shades of brown and yellow-brown. The breccias are commonly heterolithic and composed of sub-angular to rarely rounded lithic clasts or fine-grained massive material. The ore body is of MANTO type. The area of brecciating covers some 5 km². Ore grades: Fe – 7.75-56.43%; Cu – 0.01-4.2%; Au – 0-7.55 g/t; Ag – 5.02-859 g/t, gold fineness varies from 800 to 844 [4].

### 3. IOCG mineralization in basaltic and andesitic lava flows

Toleitic or calc-alkaline evolutionary trends of Devonian age basaltic lavas of the Sette-Daban ridge affect the dispersion or accumulation of iron, which is critical for the formation of IOCG ores. Rich low- sulfide copper ores, where native copper is widespread, are associated with tholeiitic basalts. Significant accumulations of hematite with copper and gold, which are of the Fe-oxide-Cu-Au style, are associated with calc-alkaline basalts. The appearance of iron oxides in basaltic lavas is a result of decomposition of ilmenite into hematite and pseudorutile (figure 4). The Upper Jurassic fine-bubble variolite andesite-basalts near Yakutsk are composed of radially radiant intergrowths of needle-shaped clinopyroxene and labrador crystals, with unfolded glass in between. Variolitic lavas are enriched in magnetite, less native iron, troilite, chalcopyrite and pyrite.

**Khurat** promising site is located in the outsole of basaltic flow and include abundant hematite breccia with sparse pyrite and chalcopyrite mineralization. Breccia fragments ranging in size from fractions of cm to 1.5 m are composed of light brown dolomite, impregnated with a hematite. The main mineral-concentrator of gold is hematite. The pillow-lavas in the roof of the basalt flows cemented with silica and hematite have low-grade gold content. Native gold contains admixture of iron and palladium and does not contain any silver at all. Ore is economically attractive - the content of FeOtot – 15.11-43.29%; Cu – 0.023-0.083%; Au – 0.1-17.5 g/t and gold fineness varies from 878 to 936 [5].
Figure 4. Backscattered electron images showing decomposition structure of ilmenite solid solution. A – ilmenite (IL) with Ti-hematite (HMT) growths; B – decomposition of ilmenite (IL) grain into pseudorutil (PRT) with hematite (HMT) growths.

Figure 5. Main mineral IOCG ores styles related to Devonian age basaltic lavas. A – Hematite ore in the bottom of the basalt flow at the contact with dolomite contains Fe – 15.11-43.29%; Cu – 0.023-0.083%; Au – 0.1-17.5 g/t; Ag – 5.9-43.3 g/t (Khurat ore style); B – Hematitized basalt; C – Concentrically-zoned mineralized tonsil in andesite-basalt: light bands are less saturated with bornite than dark (Rosomakha ore style); D – Fragment of basalt outcrop with malachite staining on the right side of the river Jalkan; E – Hematized basalt with native copper (Jalkan ore style).

Rosomakha promising site is located in the central part of basalt flows were the big volumes of lava are a common feature and they are occupied with one or more meter flattened tonsils and tubes made of jasper, native copper, bornite and cuprite. Most of basalt outcrops contain malachite and azurite.
staining. Ore content is Fe – 8.37-11.09%; Cu – 8.09-18.24%, gold fineness varies from 865 to 895 [5].

_Jalkan_ promising site is related to epidote, calcite, and chlorite alteration zones in different parts of the multi-stage basalt flows and is accompanied by relatively uniform dissemination of native copper. The main minerals in the ore body are hematite, goethite, chalcopyrite, covelin, chalcosine, bornite, native copper and gold. The bulk of IOCG mineralization at Jalkan is intergrown or in shapeless volume bodies within the basalts. Ore contains Fe – 9.95-20.16%; Cu – 0.011-3.98%, gold fineness is 862 [5].

_Kildyam_ promising site discovered in the natural outcrops and quarries of the Kangalassky terrace. The manifestations of volcanism are represented by magnetite rich lava flows, agglomerate, pyroclastic breccia and tuff of andesites and dacites [6]. In andesitic variolitic lavas the Pt content determined by the ICP-MS method - 0.11 g/t. A mineral phase enriched in Au (6.85%) and Hg (2.94%) was diagnosed in the Fe₂TiO₄ - MgAl₂O₄ spinelide (figure 6, table 1). Lava flows saturated with native iron, magnetite, troilite and pyrite, native iron usually spherical in shape. According to microprobe analysis native iron contains Co – 0.04-2.89%; Ni – 0.01-1.09%; Pt – up to 1.45%; Ir – up to 2.97%; Pyrite contains Au – 0.11-2.25%; Pt – 0.57-2.88%; Ag – 0-1.18%; Troilite contains Au – 0-3.15%; Pt – 0-2.02%; Ag – 0-1.68%. In some parts of lava flows the amount of the magnetic fraction reaches 25-37% of the total volume. On the flanks of the volcanic field, alluvial gold is known in the Zolotinka stream (Cape Kangalassky) and in Paleogene sediments, discovered by the Khatyn-Yuryakh quarry 8 km from the center of Yakutsk by A. P. Smelov and A. A. Surmin [7]. Most of the analyzed gold fineness varies from 846 to 996. Among high- fineness gold there is an Ag alloy – electrum which is typical for gold-silver mineralization [8].

![Figure 6. Backscattered electron image of ulvospinel in Kildyam andesitic variolitic lavas. Mineral phases: Sa – sanidine, Usp – ulvospinel (table 1, assay 1030-1), Usp+Au-Hg (table 1, assay 1030-2) – gold and mercury bearing ulvospinel.](image)

| Assay    | TiO₂ | Al₂O₃ | FeO₄ tot | MgO | Au | Hg | Total |
|----------|------|-------|----------|-----|----|----|-------|
| 1030-1   | 68.83| 7.28  | 16.44    | 5.57| -  | -  | 98,12 |
| 1030-2   | 76.36| 3.26  | 7.46     | 1.29| 6.85| 2.91| 98,13 |

4. Results and discussions
The magmatism and volcanism of East Yakutia with associated IOCG mineralization has attracted a lot of attention due to compositional variability of magmas (figure 7). Magma ranges from mafic to felsic and varies in calc-alkaline – high-K calc-alkaline and potassic – sodic series [1, 2, 4, 5, 6]. The
main feature of IOCG mineralization is the lack of a clear link with any particular type of igneous rock. There is one main component at the IOCG ore style – significant volumes of low sulfide and rich iron oxide ore breccias and accompanied alteration. A likely source of the high iron oxide content of IOCG deposits is low fractionation of the magmatic melt during cooling. Due to this, a significant part of the iron separated into hydrothermal solutions with rich iron oxide mineralization.

![Image](image_url)

**Figure 7.** SiO$_2$ – K$_2$O+Na$_2$O diagram [9] showing intrusive rocks associated with IOCG mineralization: 1 – Kis-Kuel, 2 – Kysyltas, 3 – Rep-Yure, 4 – Khurat, 5 – Jalkan, 6 – Rosomakha, 7 – Kildyam.

The potential of magmas to produce Cu and Au mineralization appears to be mainly a function of K$_2$O/Na$_2$O ratio, and it has been proven by O. Gerel [10] on the example of porphyry copper deposits in Mongolia. This model expanded for tin ore deposits in East Yakutia were cassiterite-quartz deposits occupy the range of K$_2$O/Na$_2$O values from 1.3 to 2.0; cassiterite-silicate – from 1.5 to 2.0; cassiterite sulfide – from 1.7 to 2.0; gold-copper – from 0.7 to 1.3 and copper-molybdenum – from 0.3 to 0.7. The location of the IOCG deposits of East Yakutia in this model is shown in figure 8. Kis-Kuel rocks cover Cu-Mo, Au-Cu and cassiterite-quartz specialization with Au-Cu prevailing. Kysyltas shows a gold-copper and tin orientation that is confirmed by the joint presence of gold and stannite in the ore. Rep-Yure rocks occupies the boundary between copper-molybdenum and gold-copper position. Khurat basalts belong to the gold-copper trend and this is confirmed by the mineral composition of the ore, where hematite, chalcopirite and gold are the main components. Jalkan and Rosomakha basalts carry gold-copper mineralization but are outside of the model. It is most likely that not all basalt flows were studied here, it is assumed that some of them can carry more hematite. The most of Kildyam volcanic rock composition points falls into the field of gold-copper specialization.

![Image](image_url)

**Figure 8.** The metallogenic specialization of igneous rocks for porphyry copper deposits of Mongolia [10] and tin ore systems of East Yakutia. Site: 1 – Kis-Kuel, 2 – Kysyltas, 3 – Rep-Yure, 4 – Khurat, 5 – Jalkan, 6 – Rosomakha, 7 – Kildyam.
The presence of native gold in ores is an important factor for all IOCG deposit style. We believe that the composition of gold characterizes the genetic features of ore formation. Usually differences in gold fineness and admixtures characterize the genetic features of ore formation and is represented by a system of alloys: Au-Ag, Au-Ag-Cu and Au-Fe-Pd (table 2).

Table 2. Representative microprobe analyses of gold (wt. %)

| Sample | Au  | Ag  | Fe  | Cu  | Pd  | Hg  | Total |
|--------|-----|-----|-----|-----|-----|-----|-------|
| Kis-Kuel                                    |
| 880093 | 73.87 | 23.32 | -  | -  | -  | -  | 97.19 |
| 880093 | 76.07 | 22.88 | -  | -  | -  | -  | 98.95 |
| 880093 | 71.91 | 25.31 | -  | -  | -  | -  | 97.22 |
| 880093 | 72.36 | 24.77 | -  | -  | -  | -  | 97.13 |
| Kysyltas                                   |
| K-950  | 62.97 | 35.03 | 2.88 | -  | -  | -  | 100.88 |
| K-950  | 63.67 | 33.82 | 1.98 | -  | -  | -  | 99.47  |
| K-950  | 65.18 | 32.18 | 2.59 | -  | -  | -  | 99.95  |
| K-950  | 67.31 | 30.23 | 2.74 | -  | -  | -  | 100.28 |
| Rep-Yure                                    |
| 7159   | 80.05 | 19.65 | -  | -  | -  | -  | 99.7   |
| 7159   | 81.78 | 17.01 | -  | -  | -  | -  | 98.79  |
| 7159   | 83.51 | 16.09 | -  | -  | -  | -  | 99.6   |
| 7159   | 83.35 | 16.28 | -  | -  | -  | -  | 99.63  |
| 7159   | 84.4  | 15.44 | -  | -  | -  | -  | 99.84  |
| Khurat                                       |
| 10012  | 93.68 | 5.99  | 0.59 | -  | 0.58 | -  | 100.25 |
| 10012  | 92.87 | 5.96  | 0.89 | -  | 0.89 | -  | 99.72  |
| 10012  | 87.85 | 10.13 | 1.20 | -  | 1.20 | -  | 99.18  |
| Jalkan                                        |
| 10195  | 86.24 | 8.85  | 3.23 | -  | -  | -  | 98.32  |
| Rosomakha                                    |
| 27     | 89.52 | 11.02 | -  | -  | -  | -  | 100.54 |
| 27     | 88.66 | 10.34 | -  | -  | -  | -  | 99.00  |
| 27     | 87.31 | 8.62  | 2.96 | -  | -  | -  | 98.89  |
| 27     | 86.57 | 10.04 | 1.39 | -  | -  | -  | 98.00  |
| 27     | 87.03 | 8.81  | 2.21 | -  | -  | -  | 98.05  |
| Kildyam [8]                                  |
| K-Y    | 99.64 | 0.11  | 0.04 | -  | 0.57 | -  | 100.36 |
| K-Y    | 97.04 | 0.03  | 0.44 | -  | 0.07 | -  | 97.58  |
| K-Y    | 96.64 | 0.01  | 0.5  | -  | 0.13 | -  | 97.28  |
| K-Y    | 87.28 | 9.31  | 0.05 | -  | 0.22 | -  | 96.86  |
| K-Y    | 84.64 | 13.01 | 0.01 | -  | -  | -  | 97.66  |
| K-Y    | 59.86 | 40.54 | -  | -  | 0.03 | -  | 100.43 |

Ore minerals were identified by scanning electron microscope JSM-6480LV with energy spectrometer INCA-Energy with accelerating voltage at the cathode 20 kV. Samples were prepared from polished sections with a sprayed thin conductive layer of carbon.

5. Conclusions
Due to its economic importance, the Iron Oxide Copper Gold (IOCG or FeOx-Cu-Au) class of deposits has become a prime target for exploration in many countries. Overall, the Eastern Yakutia
(Russia) looks promising for discovering different styles of IOCG mineralization. A revise of mineral types of ores associated with the Devonian basalts and prospecting at the Sette-Daban ridge made it possible to establish the genetic type of Fe-oxide-Cu-Au (IOCG) ores previously unknown for Northeast Russia. The difficulty is that there are many basaltic flows and each can have its own style of ore mineralization. The placement of ore in a basalt flow is difficult to predict. The good news for the project’ economics is the proximity to the city of Yakutsk of the discovered iron-oxide ores and gold in Mesozoic andesite-dacite lava flows. Mesozoic magmatism in Eastern Yakutia is extensive and its metallogenic potential is not fully understood. This is confirmed by the findings of previously unknown IOCG ores in Kis-Kuel, Kysyltas and Rep-Yure intrusions.

This is only a beginning and there is much work to do. The occurrence of IOCG deposit in Eastern Yakutia (Russia) requires further research and should be associated with a detailed study of satellite imagery and characterization of the alteration of facies at regional to deposit scale, characterization of the magmatism and associated ores, mineralogy of gold, silver, copper, iron, molybdenum and REE.

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