A new mineral assemblage from the diorite complex in the Fe-Oxide-Cu-Au ores of the Kis-Kuel deposit (Eastern Yakutia, Russia)

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Abstract. This research continues our investigations of the iron-oxide copper-gold deposits in the Western Verkhoyansk region, where recent years efforts of the IGABM SB RAS led to the discovery of a new gold Kiskuel deposit. The Kis-Kuel intrusion-related IOCG deposit in Eastern Yakutia (Russia) with a wide range of mineral styles has a direct genetic link with a cooling intrusion during its formation. The IOCG worldwide and the Kis-Kuel deposit have common features for this style - the abundance of iron oxides and low of sulfides. Magmatic contribution to the Kis-Kuel deposit is significant. Intrusive rocks range from diorite to granodiorite in composition. The Kiskuel deposit hosted in diorites and granodiorites; xenoliths confirming deep mineralization represented by pyrrhotite (main), pyrite, chalcopyrite, and clinosafflorite (Co,Fe,Ni)As₂, chromite, pentlandite. Clinosafflorite localized at the contact of pyrrhotite and chalcopyrite and at the contact of pyrrhotite and biotite. Chalcopyrite is found in intergrowth with pyrrhotite, were it forms bands and lenses. Parallel to the biotite cleavage, the thinnest layers of chalcopyrite are common. Clinosafflorite is rare and discovered in hydrothermal cobalt-nickel ores of the Bou-Azzer (Morocco), Cobalt (Canada), Glassberg (Germany), Silver Mine (England) and several others. Mineralization of rich mica processes occur in connection with the chromite, pentlandite, chalcopyrite, pyrite, and pyrrhotite; a common feature of the mineralized dark-colored rock is phlogopite abundance, ilmenite, potassium feldspar, calcite, rarely quartz; clinosterilite metasomaticaly replaced with phlogopite and dolomite. This new evidence supports a magmatic-hydrothermal model for the formation of IOCG deposit in the Kis-Kuel, where iron-oxide mineralization sourced from intermediate magmas. The deep complex predominantly composed of chromite, ilmenite, magnetite, pentlandite, and clinocafflorite; less of galena and sphalerite. Many diverse mineralization systems from Kis-Kuel classified together as iron oxide copper-gold (IOCG) deposits. The obtained data suggest deep ore-bearing structure of the Kis-Kuel ore-magmatic cluster with the potential for discovering of a new mineral ores style. All of this help in developing a new robust prospecting model.

1. Introduction
The brief geology: region correspond to a fold-and-thrust belt forms part of a major orogenic system separating the Siberian North Asian Craton to the west from the immense expanse of accreted terranes that form most of Far East Russia. The Verkhoynansk belt extends for 2,000 km from the Laptev Sea to the Sea of Okhotsk. It is comprised of a greater than 7 km thick sequence of Late Precambrian to Triassic rocks deposited along the Palaeo-Pacific margin of the Siberian Craton, which developed due to rifting events during the Late Precambrian period and again during the Late Devonian to Early Mississippian periods. Deformation during the Late Jurassic to Early Cretaceous occurred with low-grade
metamorphism in the internal parts of the belt and in the emplacements of high-level granitic bodies. In 2008 and 2009 Diamond and Precious Metal Geology Institute, Siberian Branch of the Russian Academy of Sciences discovered the new Kis-Kuel mineralization, located at the East Part of Russia, about 400 km north of Yakutsk and within the Verkhoyansk mobile belt of northeastern Yakutia. Fieldworks in 2018 led to the discovery of high Fe and Au grades in IOCG and Cu-Au porphyry style ores of the Kis-Kuel Breccia Complex (KKBC). After 2018, Kis-Kuel site identified as an important Fe-Cu-Au with additional Ag, Pb, Bi and Mo mineralization. In 2020, we documented occurrences of additional significant Cr, Ni, and Cu mineralization, collected from xenoliths in diorites and granodiorites; this confirm ore mineralization at a deep level. Our analyses reveal the complex textural relationships between xenoliths in diorites and granodiorites; chemical analysis in%: SiO$_2$ – 40.46; TiO$_2$ – 1.48; Al$_2$O$_3$ – 22.83; FeO$_{total}$ – 17.0; MgO – 2.43; CaO – 6.99; Na$_2$O – 3.34; K$_2$O – 1.9; Cr$_2$O$_3$ – 0.44; Cu – 0.69. The obtained composition determine the paragenetic sequence of the ultrabasic group. More than 1000 minerals performed along the mineralized zones across the Kis-Kuel intrusion. Mineral composition of the rock: Mg-biotite, phlogopite, pyroxenes (augite, enstatite and ferrosilite), plagioclase (labrador), ilmenite. Compositions of biotite and feldspar of sulfide-saturated nodule and diorite are identical in composition; this indicates that sulfide nodules are most likely a product of liquid faction of the diorite melt (Figure 1).

Figure 1. A – Kis-Kuel global placement on the ArcGIS Earth. B – Location of the Kis-Kuel cluster [130.2771693E 65.5039993N] in the Verkhoyansk Range. C – A Cox-Bell-Pankhurst SiO$_2$ –
K₂O+Na₂O variation diagram [1] for Kis-Kuel intrusive rocks; (1) xenolith with high sulfidation in ijolite series rock, (2) diorite with Cu mineralization, (3) granodiorite with Fe-Cu-Au-Ag-Mo-REE mineralization (legend for the diagram: 1 – granite, 2 – granodiorite, 3 – diorite, 4 – gabbro, 5 – monzonite, 6 – syenite, 7 – syenite nepheline, 8 – ijolite) associated with IOCG mineralization. D – Map showing the basic geology of Kis-Kuel iron oxide-copper-gold (IOCG) deposit, spatially associated with granodiorite magmatic system (modified from Kostin, [2]); the trenches tr-9003, tr-9004, sr-008, and sr-009 showing xenolith location.

2. Materials and Methods

Four trenches from Kis-Kuel selected for sampling: two from the northern section (tr-9003, and tr-9004), and two from the central area (sr-008, and sr-009). Fifty polished thin sections studied using reflected and transmitted light microscopy in order to characterize mineralogy of the deposit and to determine the paragenetic sequence. Further mineral identification and characterization performed by using scanning electron microscopy JSM6480LV with an INCA-Energy with 20 kV of accelerating voltage at the cathode; samples were prepared from polished sections with a sprayed thin conductive layer of carbon. All analyses performed in the Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences (DPMGI SB RAS).

3. Mineralization

Known before 2008 as a greenfield project, after field works of 2008-2009 and 2018, Kis-Kuel Breccia Complex (KKBC) discovered as a new prospective area with IOCG mineralization. Economic mineralization of KKBC localized within the apical zone of a granodiorite-diorite stock and represented by hematite, goethite, quartz, rare chalcopyrite, arsenopyrite, pyrite, native gold and bismuth; no signs of any mineralization found outside the Kis-Kuel intrusive. KKBC consists of a manto-type irregular shaped breccia body with arrays of variably mineralized veins and veinlets inside. The KKBC has a complete gradation from hematite-goethite altered granodiorites and more locally diorites, to intensely brecciated hematite-goethite breccias [3], [4].

3.1 IOCG and associated mineralization

Main brecciation event of high hematitic-goethite–altered rocks often contains different size fragments of host granodiorites; rare sulfides partly oxidized, and small cracks filled with scorodite, malachite and azurite (IOCG grades Fe₁₀X – 13.58-63.24%; Cu – 0-3.57%; Au – 12.93-64.48 g/t; Ag – 2.7-830 g/t). The most significant feature of Kis-Kuel IOCG deposit is strong correlation between Au and Fe₂O₃ grades. The gold grade increases with Fe₂O₃ (oxidized iron), and FeO (reduced iron) stay low and do not correlate with gold. High-grade gold and copper mineralization strongly oxidized, we identified arthusite CuFe₃((H₄O)₄(OH)₂(AsO₄)₂), jarosite (K₀.9(H₂O)₀.05)Fe₄(SO₄)₂(OH)₆ and scorodite FeAsO₄(H₂O)₂ by x-ray phase analysis on D2 PHASER diffractometer. Some of quartz veins include clusters of arsenopyrite with native gold, bismuth, bismite and neyite. Native bismuth contains a small amount of silver and gold. The admixture of gold and rare tellurium also found in neyite – a typical primary sulfide mineral in a porphyry molybdenum deposits and in many of intrusions related gold deposits after [5]–[7].

Lead-silver veins and breccias with additional IOCG mineralization located both in diorites and in granodiorites. Diorites close to galena veins usually mineralized with disseminated copper, and thin fractures filled with malachite and azurite.

Porphyry copper-gold mineralization hold quartz-gold-bismuth-copper veins; disseminated copper minerals, veins and breccias, associate with quartz-molybdenite and REE. In porphyry environment intrusion-hosted sheeted quartz veins with gold-bismuth mineralization linked to the apex of the Kis-Kuel pluton; commonly 0.1 to 5 cm in width and typically makes up less than 1-5 volume percent of mineralization. Veins of light yellow single stage quartz with minor sulphides and mica are parallel to the north–south elongate direction of the structural elements, as dikes and shears.
3.2 Mineralized xenoliths and phenocrysts

Host rocks carry xenoliths and phenocrystal from different horizons of intrusive; some of them discovered in (1) trenches tr-9003 and tr-9004 from diorites close to granodiorites; (2) another samples gathered from trenches sr-008 and sr-009 in granodiorites.

(1) Diorites host a small nodular releases saturated with sulfides by 10-15%. The nodular texture in diorite represented by sulfides separation of oval shape; size of the nodule is about one cm across. Sulfide nodules characterized by a stratified structure, were bottom enriched in heavier sulfides, and sulfides-free on top. Nodules consists of copper, iron, cobalt and nickel sulfides. The origin of the nodules is due to the elimination of the ore-bearing melt and division into immiscible sulfide and ilmenite + silicate phases before crystallization. A common feature of mineralized xenolith are pyrrhotite, pyrite, chalcopyrite and clinosafflorite (Co,Fe,Ni)As₂ in Pt-containing pyrrhotite. Chalcopyrite and pyrrhotite (prevail) form stripes and lenses; biotite cleaved and filled of finest chalcopyrite layers (Figure 2). It is believed that some Fe and Ni can replace Co as part of the mineral. Occurrence of clinosafflorite documented in pyrrhotite, in the contacts of pyrrhotite and chalcopyrite, and pyrrhotite and biotite. Clinosafflorite is a rare arsenide Co from the group of lellingite (FeAs₂), first described in cobalt-nickel ores in silver deposit Cobalt (Ontario, Canada).

Figure 2. Photomicrograph (a) and back-scattered electron images of ore minerals in the sulfidized nodule (b – f) from diorite, close to granodiorite border. A – Due to liquation sulfides sink and
accumulate in thin layers. B – Intergrowth of pyrrhotite and chalcopyrite with clinosafflorite on the border, surrounded with biotite. C – A grain of pyrrhotite and cristal of Co-Ni-clinosafflorite; immiscible texture developed in plagioclase and liquid pyrrhotite micro-spherules. D – Plagioclase matrix within an ilmenite-pyrrhotite-chalcopyrite intergrowth. E – Apatite and monazite in pyrrhotite. F – Monazite in biotite. Abbreviations: Ap – apatite, Bi – biotite, Ccp – chalcopyrite, Csf – clinosafflorite, Ilm – ilmenite, Mnz – monazite, Po – pyrrhotite (main), Pl – pyrite, Pl – plagioclase, Px – pyroxene.

(2) Mineralization of rich mica processes occur in connection with the chromite, Pt-bearing pentlandite, chalcopyrite, pyrite, and pyrrhotite and totally composed of SiO$_2$ – 50.37; TiO$_2$ – 0.98; Al$_2$O$_3$ – 11.52; Fe$_2$O$_3$ – 1.93; FeO – 4.18; MnO – 0.08; MgO – 7.66; CaO – 6.92; Na$_2$O – 1.59; K$_2$O – 4.58; H$_2$O – 0.3; H$_2$O$^+$ – 0.99; P$_2$O$_5$ – 0.6; CO$_2$ – 7.32; S – 0.51; F – 0.26; LOI – 0. A common feature of the mineralized dark-colored rock (sample 88085) is phlogopite abundance, ilmenite, potassium feldspar, calcite, rarely quartz; clinoenstatite metasomatically replaced with phlogopite and dolomite [8] (Figure 3).

Figure 3. Photograph (a) and back-scattered electron images of ore phenocrysts in the phlogopite-rich rock (b – f); numerous euhedral forms with zoning and late dissolving are typical structures among Kis-Kuel phenocrysts, and originally brought from the different depth levels. A – phlogopit. B –  

![Figure 3](image-url)
Inclusion of polycrystalline Ti-Fe-Cu-Zn spinel in ilmenite. C – Pyrite phenocryst differs in Co, Ni and Co concentrations. D – Pentlandite inclusion in chromite grain. E – Chromite phenocryst considered as the evidence of a long-time forming magmatic structure. F – Grains with inclusion-rich chromite cores and inclusion-poor rims of calcite (Cc), and clinoenstatite (Cen-1) and (Cen-2).

Abbreviations: Cc – calcite, Ccp – chalcopyrite, Cen – clinoenstatite, Chr – chromite, Phl – phlogopit, Pn – pentlandite, Po – pyrrhotite, Py – pyrite.

4. Results and discussions

Recent hypotheses for the formation of Kis-Kuel presented hematite breccias as the end member IOCG mineral system [2]; this research expands deposit model with a new discovery of mineralized xenoliths [9]–[12]. Mineral sequences and spatial association of breccia from top of Kis-Kuel (a) iron (hematite) oxide copper-gold and associated silver-led veins, copper-porphyry with quartz-gold-bismuth-copper veins and sheeted quartz vein arrays in the apex of the Kis-Kuel pluton; (b) porphyry copper-gold mineralization in granodiorite were disseminated copper minerals, veins and breccias associate with quartz, molybdenite, monazite, and xenotime. At deep levels (c), magnetite is dominant close to the IOCG breccias; significant element group of Fe-Cu-Co-Ni-Cr continues IOCG succession Table 1 and Table 2.

Hematite, pyrite and chalcopyrite occur throughout the paragenesis but are most abundant in breccia. Mineralization of chrome, ilmenite, magnetite, pentlandite, and clinocafflorite [13]. Mineralization occupies stratiform position, and looks similar to many of word class stratified intrusives: sulfide mineral in gabbroic rocks from the southwest Indian ridge [14]; Cu-Ni-PGE Dzhaltul microgabbroic intrusion [15]; sulfides, and native metals of the Skaergaard intrusion, Greenland [16]; Kis-Kuel xenoliths with high sulfidation correspond to ijolite series rock [17].

**Table 1.** Representative values of sulfides from xenoliths in Kis-Kuel

| Sample          | Fe  | As  | Co  | Ni  | Cr  | Cu  | S  | Total   |
|-----------------|-----|-----|-----|-----|-----|-----|----|---------|
| **Clinocafflorite** |     |     |     |     |     |     |    |         |
| 9009-218/4-1    | 19.79 | 71.82 | 5.28 | 2.46 | -   | -   | -  | 99.35   |
| 9009-218/4-2    | 20.54 | 71.55 | 5.79 | 2.18 | -   | -   | -  | 100.06  |
| 9009-218/4-3    | 20.24 | 71.54 | 5.19 | 2.64 | -   | -   | -  | 99.61   |
| 9009-218/7      | 18.64 | 70.40 | 7.63 | 3.21 | -   | -   | -  | 99.88   |
| 9009-218/14     | 20.02 | 70.86 | 5.97 | 2.53 | -   | -   | -  | 99.38   |
| 9009-218/15-1   | 19.25 | 71.60 | 7.12 | 2.82 | -   | -   | -  | 100.79  |
| 9009-218/15-2   | 20.55 | 70.68 | 6.55 | 2.07 | -   | -   | -  | 99.85   |
| 9009-218/17-1   | 19.54 | 70.92 | 6.72 | 2.72 | -   | -   | -  | 99.90   |
| 9009-218/17-2   | 19.53 | 70.90 | 6.28 | 2.74 | -   | -   | -  | 99.45   |
| 9009-218/17-3   | 19.72 | 68.92 | 6.3 | 2.03 | -   | -   | -  | 96.97   |
| 9009-218/17-4   | 19.13 | 68.77 | 7.58 | 2.23 | -   | -   | -  | 97.71   |
| 9009-218/17-5   | 19.58 | 71.22 | 6.92 | 2.79 | -   | -   | -  | 100.51  |
| 9009-218/25     | 20.22 | 70.99 | 6.00 | 2.43 | -   | -   | -  | 99.64   |

| Pentlandite     |     |     |     |     |     |     |    |         |
| 88085-7(1)      | 25.58 | -  | -  | 31.59 | 1.87 | 0.32 | 38.69 | 98.06   |
| 88085-7(2)      | 24.85 | -  | -  | 29.84 | 2.45 | 0.01 | 41.67 | 98.82   |
| 88085-7(3)      | 23.69 | -  | -  | 31.78 | 3.28 | 0.09 | 39.69 | 98.54   |

| Chalcopyrite    |     |     |     |     |     |     |    |         |

6
Table 2. Representative values of oxides from xenoliths in Kis-Kuel

| Sample       | MgO | MnO | Al₂O₃ | TiO₂ | Cr₂O₃ | FeO₄² | Total     |
|--------------|-----|-----|-------|------|-------|-------|-----------|
| Chromite     |     |     |       |      |       |       |           |
| 88085-7/(1)  | 10.66| -   | 13.37 | -    | 50.20 | 25.16 | 99.40     |
| 88085-7/(2)  | 12.44| -   | 12.09 | 0.99 | 50.95 | 21.30 | 97.76     |
| 88085-7/(3)  | 11.75| -   | 12.11 | 0.74 | 50.82 | 22.39 | 97.82     |
| 88085-7/(4)  | 11.42| -   | 13.58 | 0.29 | 49.35 | 20.73 | 95.37     |
| 88085-7/(5)  | 11.74| -   | 10.40 | 1.14 | 54.84 | 21.76 | 99.89     |
| Ilmenite     |     |     |       |      |       |       |           |
| 9003-218/2-1 | -   | 1.68| -     | 53.17| 0.28  | 44.92 | 100.05    |
| 9003-218/2-2 | -   | 1.32| -     | 51.05| 0.20  | 47.02 | 100.04    |
| 9003-218/2-3 | -   | 1.30| -     | 52.21| 0.23  | 45.33 | 99.07     |
| 9003-218/18-1| -   | 2.05| -     | 51.57| -     | 45.28 | 98.90     |
| 9003-218/18-2| -   | 1.59| -     | 52.01| -     | 44.64 | 98.25     |

5. Conclusions
Kis-Kuel new promising target in Eastern Yakutia (Russia), still under-exploration. This new evidence supports a magmatic-hydrothermal model for the formation of IOCG deposit in the Kis-Kuel, where iron-oxide mineralization sourced from intermediate magmas. The deep complex predominantly composed of chromite, ilmenite, magnetite, pentlandite, and clinocafflorite; less of galena and sphalerite.

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