Iron oxide Cu-Au (IOCG) mineralizing systems: an example from northeastern Russia

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Synopsis

GIS and multivariate geometric distribution have been used to predict the association of high-level intrusives with hydrothermal alteration related to iron oxide Cu-Au (IOCG) mineralizing systems. Several examples in the Russian northeast are presented in this paper. IOCG ore deposits can have enormous geological resources containing significant reserves of base, precious, and strategic metals, and hence are economically attractive targets for mineral exploration. To date, examples of this type of mineralization have not been reported from the northeastern area of Russia. The Tarinskiy ore cluster, located in Eastern Yakutia, shows brecciated altered rocks with sulphide and iron oxide cement, which is typical for IOCG mineralization of the iron oxide Cu-Au±U type. This cluster was formed near surface and is linked with the Rep-Yuruinskiy pluton. It has potential to host new world-class precious metal deposits in northeastern Russia

Keywords
GIS, multivariate, iron oxide, Au-U-Cu, IOCG, Tarinskiy, Yakutia.

Introduction

A fundamental problem of ore deposit geology is the prediction of and prospecting for new large-scale precious metals deposits. One type of these – the large group of iron oxide copper-gold (IOCG) hydrothermal ore deposits containing Cu, Au, ±Ag, ±U, ±REE, ±Bi, ±Co, ±Nb, ±P – has not yet been recognized in the Russian Far East (Figure 1), and the potential for discovery is currently unknown.

The recognition of IOGC deposit types began with the discovery of the giant Olympic Dam deposit in 1975 in Australia, which contains 2000 Mt at 1.1% Cu, 0.5 g/t Au, 4000 g/t U_3O_8, and 0.24 – 0.45% La + Ce (Roberts. and Hudson, 1983). This was followed in 1987 by La Candelaria in Chile (470 Mt at 0.95% Cu, 0.22 g/t Au, and 3.1 g/t Ag) (Marschik, Leveille, and Martin, 2000). Deposits are often characterized by more than 20 modal per cent of iron oxides and a low content of sulphides. IOCG orebodies are typically linked with large mantle-type granitic intrusions, are breccia-hosted, and are located either proximal or distal to the granitic plutons.

IOCG deposits related to alkali and calc-alkali plutons can also be associated with porphyry-type Cu-Mo or Cu-Au deposits, Cu-Ag 'mantle' deposites, U, haematite, and Au-PGE and polymetallic Pb-Zn-Ag ±Au veins (Corriveau, 2007; Gandhi, 2004).

Since IOCG mineralization is characterized by heterogeneity of both ore and metals, the application of new methods such as multidimensional geometric distribution using GIS and multivariate distribution of deposits should be very promising as a guide to exploration. Classical sub-soil geometry as a method of mathematical mapping spatial distribution of *single* elements can lead, in the case of complex deposits, to a situation where each element has its own geometry, *i.e.* the outlines of anomalies of various indicators do not coincide. This reduces the reliability of any assessment because of errors in determining the type of mineralization and incorrect evaluations of metal inventory. Therefore, it was necessary to develop a multidimensional model of geometric distribution of mineralization, which delineates homogeneous areas of a prospect by all elements simultaneously, thus excluding the ambiguity in the construction of the boundaries (Wedjaev, Wedjaeva, and Rafat, 2009). In addition, this model provides the best estimate of the average values of the parameters of the mineralized bodies (element contents, thickness etc.), which is ensured by a new solution for the statistical problem of multivariate distribution (Rodionov, 1981). This approach allowed the types of precious metal anomalies of East Yakutia, associated with IOCG mineralization, to be assessed with greater confidence.

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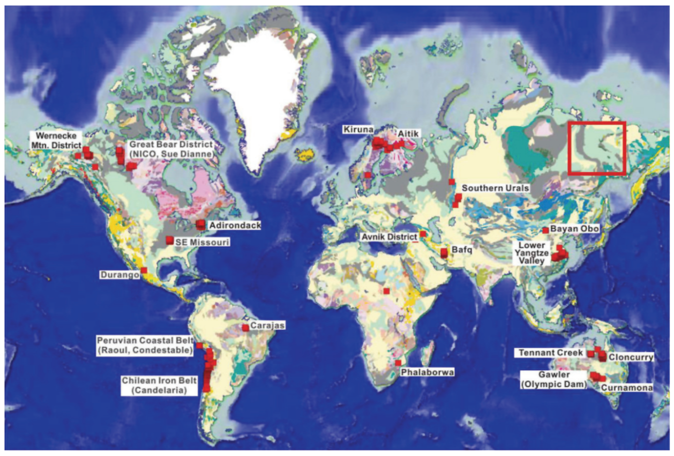

Figure 1—Distribution of IOCG districts and important deposits worldwide (after Corriveau 2007) (red dots) and Eastern Yakutia (Russia) – a new greenfield IOCG area (red rectangle). Australia: Gawler district (Olympic Dam, Acropolis, Moonta, Oak Dam, Prominent Hill, and Wirrda Well), Cloncurry district (Ernest Henry, Eloise, Mount Elliot, Osborne, and Starra), Curnamona district (North Portia and Cu Blow), Tennant Creek district (Gecko, Peko/Juno, and Warrego); Brazil: Carajas district (Cristalino, Alemao/Igarapé Bahia, Sa-lobo, and Sossego); Canada: Great Bear Magmatic Zone (Sue-Dianne and NICO), Wer-necke district (West Coast skarns), Central Mineral Belt, and Kwyjibo deposit; Chile: Chilean Iron Belt district (Candelaria, El Algarrobo, El Romeral, Manto Verde, and Punta del Cobre); China: Bayan Obo (Inner Mongolia), Lower Yangtze Valley district (Meishan and Daye); Iran: Bafq district (Chogust, Chadoo Malu, BS Seh Chahoon); Mauritania: Akjoujt deposit; Mexico: Durango district (Cerro de Mercado); Peru: Peruvian Coastal Belt (Raul, Condestable, Eliana, Monterrosas, and Marcona); Sweden: Kiruna district (Ki-irunavaara, Loussavaara), Aitik deposit (also described as a porphyry Cu deposit); South Africa: Phalaborwa and Vergenoeg deposits; USA: Southeast Missouri district (Pea Ridge and Pilot Knob); Adirondack and Mid-Atlantic Iron Belt (Reading Prong); Zambia: Shimyoka, Kantonga, and Kitumba; Eastern Yakutia (Russia): IOCG greenfield areas with the Nuektaminskiy, Endybalskiy, Kis-Kuelskiy plutons, and Rep-Yuruinskiy district

Main features of known IOCG-type deposits

Hydrothermal features

All regions with IOCG deposits are characterized by large alteration halos, including Na (Ca) and K, ranging from 10 to 100 km^2 or more (Barton and Johnson, 1996, 2004; Hitzman, Oreskes, and Einaudi, 1992). The alteration areas are usually of greater extent than the areas of IOCG mineralization (Gandhi, 2004). A key feature of IOCG deposits is the association with high-K granites (Pollard, 2000).

Mineralization

Economic mineralization is represented by chalcopyrite ± bornite and native gold, hosted by iron oxides. Haematite characterizes upper levels of the mineralizing systems, and magnetite the deeper levels.

Geophysical features

Sulphide-poor deposits with large volumes of Fe oxides and hydrothermal alteration form reasonable targets for regional airborne magnetic and gravity surveys (Kostin *et al.*, 2006; Kostin, 2008). In combination with field geological observations, gravity and magnetic data are very useful, but expensive, tools in IOCG prospecting.

External features on Landsat images

Landsat multispectral data is one of the most powerful tools for exploring and characterizing many aspects of the Earth's surface, and is an inexpensive exploration method (Kostin, 2011, 2012; Kostin and Osipov, 2012). Spectral analysis using red (0.63–0.69 μm), green (0.52–0.60 μm), and blue (0.45–0.52 μm) is a true colour band (3-2-1) combination that allows areas with elevated concentrations of iron oxides to be distinguished (Figure 2).

Geological age

Geological age does not appear to be critical (Nisbet *et al.*, 2000). IOCG deposits are known to occur from the Archean (Salobo and Igarapé Bahia) to the Mesozoic (Chilean Iron Belt, Russian Far East) (Requia *et al.*, 2003; Sillitoe, 2003; Tallarico *et al.*, 2004).

Prerequisites for IOCG-style mineralization in East Yakutia

A review of samples resulted in the identification of ore types that could be assigned to IOCG mineralization, but which were previously considered as a product of oxidation of sul-phidic ores.

The Pozolota' zone (65.799669°N 129.596191°E) in the Nuektaminskiy cluster (Kostin *et al.*, 2006) includes a 50 × 26 m stock-like body of milky drusy quartz with haematite cement and a gold content ranging from 1.2 to 19.8 g/t (Figure 3A). The field of the eruptive breccias of the

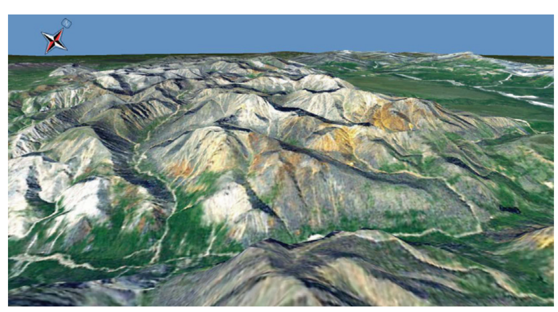

Figure 2—Example of elevated concentrations of iron oxide on surface – draped Landsat geo-image (colour band 3-2-1 combination) over to DTM

Endybalskiy cluster (65.673781°N 130.132772°E) includes large bodies of breccia with goethite as cement. These were not analysed for copper and gold, but have a strong visual resemblance to IOCG mineralization (Figure 3B). The Kis-Kuelskiy diorite-granodiorite intrusive (65.501242°N 130.280125°E) includes different types of IOCG-like mineralization (Kostin, 2010): brecciated granodiorite with iron oxide cement (Figure 3C) and brecciated hornfels with iron oxide and sulphide cement (Figure 3D). In the 2011 field season, one of the iron oxide anomalies identified in Landsat TM imagery was confirmed as IOCG-style mineralization. This anomaly is situated in the Rep-Yuruinskiy district (Tarynskiy cluster, 63.574957°N 143.275846°E) and is hosted by brecciated and metasomatized rocks. The Rep-Yuruinskiy sub-type of IOCG mineralization consists of granodiorite-associated, breccia-hosted bodies in which arsenopyrite mineralization is associated with iron oxide alteration of breccias (Figures 3E, 3F). The breccias include thick lenses of quartz-chlorite metasomatic lithologies with disseminated Cu sulphide mineralization. Breccia colour depends on the saturation of iron oxides, and changes in the supergene zone from 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 area of brecciation covers some 5 km^2, while density varies from 2.41 to 3.23 (average = 2.76 t/m^3). Hence, the resource potential could be about 712 Mt applying a depth of 50 m. The grab samples assay results are presented in Table I.

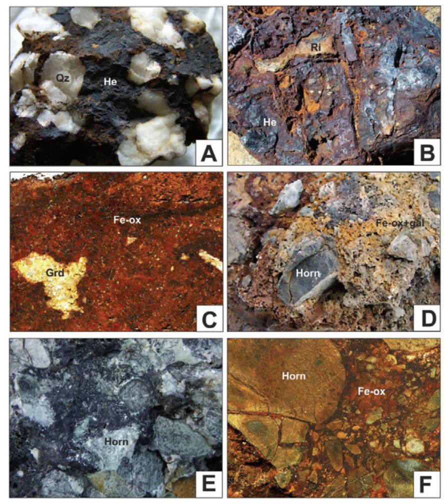

Figure 3—Typical samples and outcrops of mineralized material. (A) Sample 5214 – gold-bearing mineralization from the Pozolota showing (Nuektaminskiy cluster) of milky drusy quartz with haematite cement; (B) sample 5307 – eruptive breccia from the of Endybalskiy cluster with haematite cement; (C) sample 6279 – Kis-Kuelskiy pluton: brecciated granodiorite with iron oxide cement; (D) sample 6246-1 – Kis-Kuelskiy pluton exocontact zone: brecciated hornfels with iron oxide and sulphide cement; E sample 7117 – brecciated hornfels from Rep-Yuruinskiy pluton exocontact zone with gold-bearing cement; (F) sample 7127 – brecciated hornfels from Rep-Yuruinskiy plutone exocontact zone with Au-and U-bearing iron oxide cement. Qz – quartz; He – haematite; horn – hornfels; Ri – rhyolite; Grd – granodiorite; Fe-ox – iron oxide cement; Fe-ox+gal – iron-oxide + galena cement

Table I

Assay results of rock grab samples from the Rep-Yuruinskiy cluster

No	Sample ID	Density g/cm^3	Au (g/t)	Fe (%)	Cu (%)	Bi (g/t)	Mo (g/t)	W (g/t)
Chlorite-quartz metasomatite								
1	3021	3.2	1.3	4.9	0.1	1000	NSR	490
2	7108	2.8	0.1	13.7	0.1	520	NSR	NSR
3	7143	2.7	0.7	48.5	0.6	890	NSR	280
4	7154	2.8	0.4	3.9	1.1	180	NSR	NSR
5	7157	2.7	3.7	7.7	0.2	890	NSR	NSR
	Average:	2.8	1.2	15.74	0.4	696	0	154
Hornfels breccias with Fe oxide cement								
1	3022	2.8	7.5	7.7	1.6	890	26	8250
2	3024-1	3.5	0.2	9.6	0.4	110	26	NSR
3	3058-3	2.8	6.4	4.4	0.0	110	26	NSR
4	7112	2.5	0.3	20.1	0.2	300	94	2800
5	7115	2.6	0.4	13.7	0.4	940	120	8250
6	7116	2.5	2.2	6.5	0.0	160	150	NSR
7	7117a	2.9	0.0	4.3	0.0	NSR	99	NSR
8	7117b	2.9	0.2	10.7	0.8	890	160	NSR
9	7118	2.6	1.7	7.9	0.2	99	37	160
10	7124c	2.5	0.4	30.2	0.2	890	26	490
11	7127	2.6	0.0	38.7	0.6	850	43	7000
12	7128	2.7	1.4	33.6	0.8	890	51	NSR
13	7129	2.4	0.1	6.2	4.2	890	NSR	NSR
14	7137	2.7	0.5	6.1	0.4	890	NSR	NSR
15	7139	2.7	0.0	13.7	0.2	NSR	NSR	NSR
16	7141	2.8	0.0	34.9	0.7	410	63	NSR
17	7142	2.9	0.6	4.8	0.9	760	NSR	NSR
18	7156	2.8	0.1	18.5	0.4	650	31	NSR
19	7159	2.6	2.9	56.4	0.1	890	36	NSR
20	7161	3.2	0.8	6.3	0.4	890	NSR	3800
21	7169	3.0	0.5	5.6	0.0	230	NSR	1900
22	7170	2.9	0.4	10.7	0.0	NSR	NSR	2200
23	7174	2.5	0.0	17.9	0.0	NSR	24	NSR
	Average:	2.8	1.16	16.0	0.5	510	44	1515

Note: NSR – no significant result

Table II compares the Rep-Yuruinskiy occurrence with major worldwide IOCG-type deposits in terms of the resource and grade of mineralization.

Application of multivariate geometric distribution to enhance the reliability of assessment using the Rep-Yuruinskiy anomaly

The area of mineralization associated with the Verkhne-Chubukhulakhsky intrusive has been rock-chip sampled on a regular grid. The samples were crushed, pulverized, and analysed by atomic absorption spectrometry (AAS) for Au and by atomic emission spectrometry (AES) for Cu.

The results of geochemical sampling were tabulated in a Microsoft Access™ database, which is connected by the function *Join* to the layer of geochemical sampling points. The key field for the connection is the geological number of the sample. The result is a system that uses the geostatistical analyst module for the interpolation of the surface by any element of the connected tables. Ordinary kriging is usually used for the interpolation method, by which means a surface for each element can be constructed.

It should be noted, however, that a single element may belong to various types of mineralization that may make up a deposit and determine its geological and industrial type. It is therefore difficult to characterize a deposit by the spatial distribution of a certain element. On the other hand, an attempt to divide a deposit into homogeneous areas in order to characterize its geometry also entails considerable difficulties, since the boundaries delineated by a single element may conflict with the boundaries built with the help of other elements (Rudenko and Vedyaev, 2009).

By contrast, the geometric distribution utilizes the full range of elements simultaneously, based on a probabilistic model of the mineralization and the new aggregated solution of the statistical problem by multivariate distribution (Rudenko nd Vedyaev, 2009). This eliminates not only the conflict between boundaries, but also allows, on the basis of the statistical characteristics of the homogeneous groups of observations obtained, the use of mineralogical and techno-logical mapping to establish types of mineralization. This makes it possible, even at early stages of exploration, to recognize the geological-mining type of the prospect.

Table II

Comparison of the potential of the Rep-Yuruinskiy occurrence with major worldwide IOCG-type deposits [according to Corriveau, 2009]

Deposit	Country	Resource (Mt)	Cu (%)	Au (g/t)
Aitic	Sweden	226	0.37	0.20
Manto Verde	Chile	580	0.52	0.11
Candelaria	Chile	470	0.95	0.22
Cristallino	Brazil	500	1.00	0.30
Rep-Yuruinskiy	Russia (Yakutia)	716	0.53	1.17
Sossego	Brazil	355	1.10	0.28
Salobo	Brazil	789	0.96	0.52
Ernest Henry	Australia	167	1.10	0.50
Olympic Dam	Australia	3810	1.10	0.50
Raul Condestable	Peru	32	1.70	0.30
Igarape Bahia	Brazil	170	1.50	0.80

The multidimensional geometric distribution of mineral-ization of the Verkhne-Chubukhulakhsky intrusive was mapped with 19 elements using the software package AGATA (Figure 4). The average element contents of the main mineralization types are shown in Table III. The orientation of these types coincides with a series of small granitic intrusions.

The following is a brief description of the mineralization types:

- ➤ Type 1 corresponds to the highest grades associated with Fe oxide breccia at the exocontact zone. In addition, this zone contains late-stage veins composed of arsenopyrite, wolframite, chalcopyrite, and sphalerite

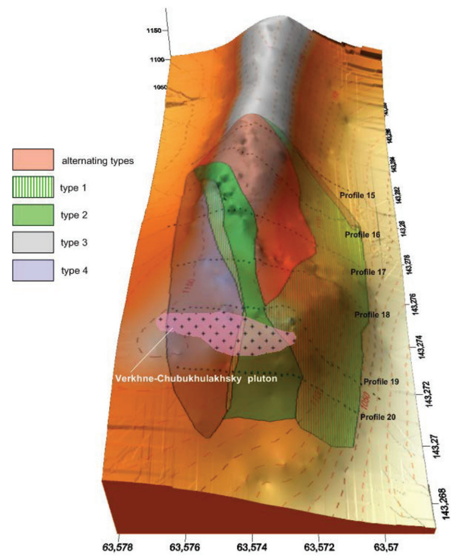

Figure 4—Multidimensional geometric distribution of endo- and exocontact zones of the Verkhne-Chubukhulakhsky intrusive using 19 elements simultaneously

Table III

Average contents of selected elements (conven-tional units) from samples of the Verkhne-Chubukhulakhsky intrusive for the main types of Au-U mineralization

Element	Type 1	Type 2	Type 4
Fe	101293	32735	16108
Co	24889	7297	5583
Cr	8444	4002	3188
V	5144	2599	1917
Pt	5720	4455	932
W	3744	2852	696
Hg	3276	2442	602
Cu	2524	1957	574
Zn	2269	1603	457
Sc	632	642	1075
Au	334	92	148
U	157	36	199
Zr	144	129	140
Sr	86	39	86
As	4182	4869	759
Se	640	1.067	295
Th	535	1.039	180
Pb	694	804	231
Ag	13	15	0

- Type 2 is located in the mass of the brecciated hornfels and is characterized by initially low permeability to hydrothermal solutions, leading to low concentrations of Au and U
- Type 3 is associated with the outermost zone of the exocontact of the intrusive massif, passing into unaltered sandstone
- Type 4 corresponds to the outer brecciated zone of the exocontact, where Fe hydroxide cement is weakly developed and veins are absent. This type is characterized by the highest content of U.

Exploration model for Arc GIS analysis

IOCG-type deposits usually occur in the vicinity of porphyry Cu-Au or Cu-Mo deposits, associated with alkali and calc-alcali plutons from A (anorogenic) to I (igneous) types, enriched with U, F, Mo, and REE (Corriveau, 2007). A-type granitoids are greatly enriched with Fe and comprise ferroan calc-alkali and alkali types, most of them being metaluminous. I-type granitoids are mostly calc-alkali or calcic and are of the magnesian type, while A-type granitoids are metaluminous, less often peraluminous (Frost *et al.*, 2001).

The use of GIS to assess the potential of plutons plays an important role in the development of exploration models. Many deposits show a spatial relationship with plutons and this stimulates attempts to assess their potential for economic mineralization.

To date no exploration for IOCG deposits has been carried out in the territory of Eastern Yakutia, and the potential for this type of mineralization has not been discussed in the public domain. This paper represents the first attempt to assess the potential of the territory for IOCG-type mineralization.

For this purpose a GIS project was created, which includes:

- Basic geology with the location of plutons and their simplified geometry
- Geodatabase of major-element compositions of samples from the plutons (more than 4000 analyses)
- ArcGIS online service with 15 m eSAT images;
- Airborne magnetic data using a line spacing of 1 km.

The interpretation of Landsat images near plutons yielded a large number of areas with conspicuous colors indicating Fe oxides – from dark orange to reddish-brown (Kostin, 2011, 2012).

In the first phase of the investigation the prospective A- and I-type granitoids with Fe, Cu, Au, and U mineralization are recognized. These are then compared with the magnetic anomalies to guide further exploration.

In the second phase, the areas with elevated concentrations of Fe oxides are tested for their possible association with IOCG-type mineralization. Using the geodatabase of major-element compositions, samples from these areas are evaluated for their prospectivity for Fe, Cu, Au, and U mineralization.

Uranium

As exemplified by Australian deposits (Schofield, 2009), the major-element composition of rocks plays an important role in the behaviour of uranium. The highest uranium concentrations match to:

- ASI – U diagram: ASI index from 0.9 to 1.2
- $(Na_2O + K_2O) / Al_2O_3$ – U diagram: agpaicity index from 0.6 to 1.0.

Copper and gold

For the assessment of the potential of plutons for Au-Cu and Cu-Mo mineralization, data from Mongolian copper-porphyry deposits (Gerel, 1995) was used. A K_2O/Na_2O ratio ranging from 0.3 to 0.7 was established for Cu-Mo magmatic systems, while for Au-Cu systems the range increases to 0.7–1.3.

From the geodatabase, samples with Au-Cu mineralization were selected based on ratios of K_2O/Na_2O from 0.7 to 1.3 using the inquiry function of the database. Therefore, classification of the GIS band was made based on the feature pluton area, and the selected groups characterized by the extent of their erosional level.

In order to rank the number of prospects for Au-Cu mineralization, a filter has been used that selects plutons belonging to the high-potassium calc-alkaline and shoshonitic series.

The algorithm of the filter is based on formulae for the curves that describe the series of magmatic rocks in the diagram SiO_2–K_2O. The general form of the equation is $K_2O=k \times SiO_2 - b$, and inquiries take the form of, *e.g.*:

- For rocks of the tholeiite series: $K_2O < (0.033462 \times [SiO_2] - 1.5)$
- For rocks of the calc-alkaline series: K_2O between $(0.033462 \times [SiO_2] - 1.5)$ and $(0.066507 \times [SiO_2] - 2.5)$
- For rocks of the high-potassium calc-alkaline series: K_2O between $(0.066507 \times [SiO_2] - 2.5)$ and $(0.169054 \times [SiO_2] - 7.12)$
- For rocks of the shoshonite series: $K_2O > (0.169054 \times [SiO_2] - 7.12)$.

In addition to the inquiry using high-potassium calc-alkaline series plutons, further conditions have been applied:

- Size of area < 5 km^2
- K_2O/Na_2O ratio 0.3–0.7 (for Cu-Mo systems) and 0.7–1.3 (for Au-Cu systems).

GIS query results

The pluton analysis using three algorithms: ASI – U; $(Na_2O + K_2O) / Al_2O_3$ – U; and K_2O / Na_2O for U and Au-Cu mineralizing systems defined a common group of plutons with potential for Cu-Au-U mineralization, *viz*. Burgaliyskiy, Verkhne-Burgaliyskiy, Levo-Jolakagskiy, Verkhne-Tirekhtyakhskiy, Vostochno-Polousniy, Gornoe Ozero, Druza, Ilnimanskiy, Levo-Alaseiskiy, Magan-Tasskiy, Pravo-Tuostakhskiy, Takalkanskiy, Tarbagannakhskiy, Tommotskiy, and Elikchanskiy.

Using ArcGisOnline, the *i*-cubed 15 m eSAT images showed the presence of elevated concentrations of iron oxides in the vicinity of the Burgaliyskiy, Verkhne-Burgaliyskiy, Levo-Jolakagskiy, Verkhne-Tirekhtyakhskiy, Druza, Pravo-Tuostakhskiy, and Takalkanskiy plutons.

Large magmatic systems with IOCG potential may have three types of Fe oxide minerali-zation – directly at the contacts with the intrusive rocks (bright yellow shades), along the edge of plutons (dark yellow and brown tints), and in hornfels (dark brown) – this is seen at Levo-Jolakagskiy, Burgaliyskiy, and Verkhne-Burgaliyskiy plutons as an example (Figure 5).

Conclusions

- The data obtained suggests that mineralization ascribed to IOCG-type deposits is widely manifested in Eastern Yakutia (northeast of Russia), but its economic potential and geological features are unknown
- An exploration model for IOCG mineralization has been developed using GIS methodology to define plutons with higher prospectivity and associated mineralization
- The potential for IOCG mineralization is estimated to be very high. For example, the Verkhne-Burgaliyskiy pluton contains several areas of iron oxide mineralization. The largest is about 135 km^2, which may yield an inventory of several billion tons of iron oxides. Even at low Au grades, this type of mineralization may be of economic interest
- A review of historic samples confirms the IOCG potential and a regional exploration model can be built. This may differ somewhat from the known analogues because of the geological history of Eastern Yakutia
- Based on the classification of IOCG mineralization the first discovery in Eastern Yakutia is an iron-oxide-rich breccia with Au-U-Cu(±Bi±Mo±W) mineralization. It is located at the roof of the calc-alkali/alkaline plutons, and is interpreted to correspond to a subtype of Olympic Dam (Australia)
- The use of multidimensional geometric distribution enhances the reliability of the assessment of mineralization type even at early stages of exploration with limited detailed data.

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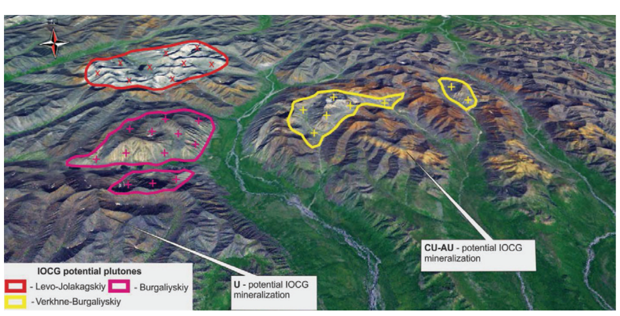

Figure 5—Potential IOCG- mineralizing system at Levo-Jolakagskiy, Burgaliyskiy, and Verkhne- Burgaliyskiy plutons as an example of GIS query for U and Au-Cu mineralization

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