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Original article

The geophysical signature of Oyut deposits, Oyu Tolgoi, Mongolia

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ABSTRACT

The well-known Oyu Tolgoi Cu-Au group deposits can be divided into three main deposits: Hugo Dummett deposit (Hugo North and Hugo South), Oyut deposits (South Oyu, Southwest Oyu and Central Oyu), and Heruga deposit in the south. These deposits sit along 26 km long, north-northeast trending belt termed as the Oyu Tolgoi trend. This paper reviews investigations on geophysical signatures of the South Oyu, Southwest Oyu and Central Oyu deposits and compares geophysical models of the mineral deposits with their lithology, alteration, mineralization, and structures. A variety of datasets including induced polarization, ground magnetic, gravity survey are used in the study and generated inversion products of ground magnetic and gravity data with integrated interpretation. Typical responses from the Oyut deposits are: up to 0.1 mGal positive gravity anomaly above background, 100–200 nT low or high magnetic anomaly compared to background depending on the geological situations, and from 12 mV/V to 30 mV/V chargeability anomalies and low resistivity signatures from 100 ohm.m to 400 ohm.m. The interpreted geological -geophysical models of porphyry Cu-Au deposits presents in this study have emphasis on integrated interpretation of geophysical techniques, and inversions of gravity and magnetic data in gold rich porphyry copper system.

Keywords: ground magnetic, induced polarization, gravity, inversion modelling

INTRODUCTION

The Oyu Tolgoi deposits (106.85°E and 43.01° N) are located in Khanbogd soum of the Umnugobi province, Mongolia, approximately 650 km south of Ulaanbaatar, the capital city of Mongolia, and 170 km east of Dalanzadgad, the province center (Fig. 1). Average elevation in the region is 1,160 m and the relief change is less than 50 m.

The well-known Oyu Tolgoi Cu-Au group deposits can be divided into three main deposits: Hugo Dummett deposit (Hugo North and Hugo South), Oyut deposits (South Oyu, Southwest Oyu and Central Oyu), and Heruga deposits in the south. These deposits sit along 26 km long, north-northeast trending belt termed as the Oyu Tolgoi trend (Fig. 2).

The South Oyu, Southwest Oyu and Central Oyu deposits are in production currently by open pit mining, and a development of underground mine construction at Hugo Dummett North deposit is underway. This paper

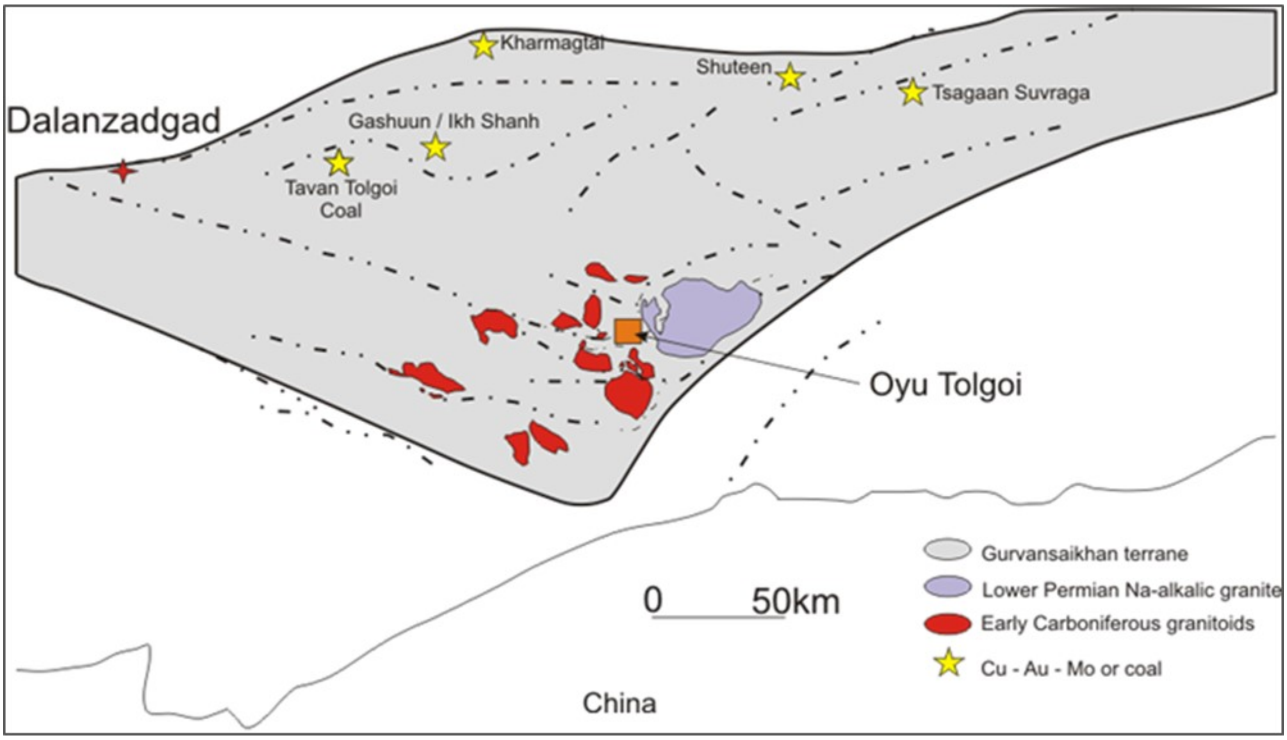


Fig. 1. The location of Oyu Tolgoi deposits in Gurvansaikhan Island Arc terrain

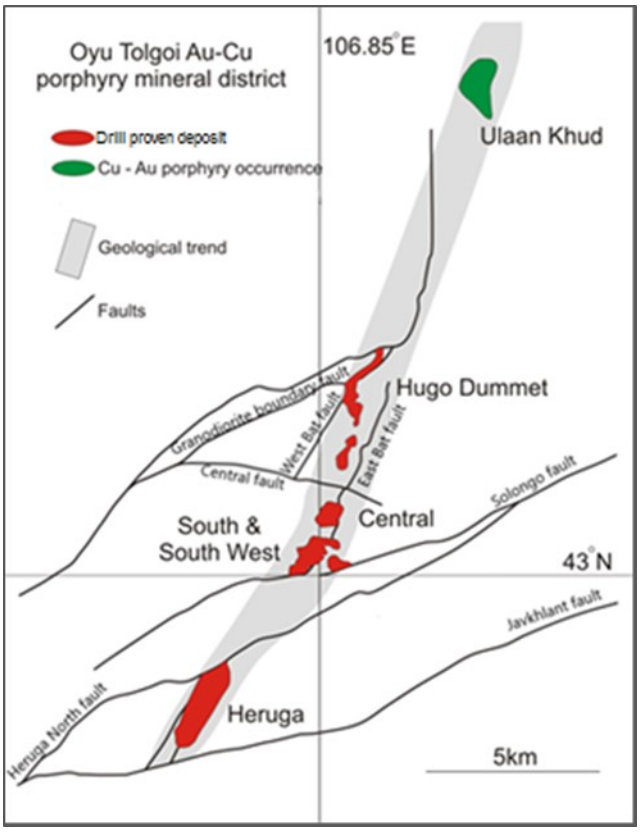


Fig. 2. The Oyu Tolgoi group deposits and main faults

presents results on the review of geophysical signatures from South Oyu, Southwest Oyu and Central Oyu deposits, and compares the geophysical models generated in the frame of this study. The geophysical data used in the study were collected during exploration programmes during 2001-2009 and the mineral deposits, and faults structures were constructed during exploration and mine processing stages.

GEOLOGICAL BACKGROUND

The Oyu Tolgoi deposits are situated in the Gurvansaikhan island-arc terrane. The Gurvansaikhan island-arc is a part of the Central Asian Orogenic Belt, a zone of arc-continent collision, which was active from the Silurian to Early Carboniferous.

Two major stratigraphic sequences such as Upper Devonian Alagbayan Group and Carboniferous Sainshandkhudag Formation are recognized in the Oyu Tolgoi district. Two formations were classified within the Alagbayan Group, and each of these divisions comprises several members and beds. The lowest unit, Bulagbayan formation is often strongly altered and mineralized, while the upper units including

Khalzan-Ovoo formation lacks significant alteration and mineralization.

The Carboniferous Sainshandkhudag Formation, the part of the Gurvankharaat Group intersected in the Oyut deposits does not host mineralization. The Sainshandkhudag Formation is divided into three major units at Oyu Tolgoi including a lowermost tuffaceous sequence; an intermediate clastic package, and an uppermost volcanic/volcaniclastic sequence (Sersmaa and Minjin 2005, Minjin et al. 2006, Wainwright et al., 2011, Uranbileg et al., 2019). The unit post-dates porphyry mineralization and is separated from the underlying Devonian rocks by a regional unconformity.

Intrusive rocks are widely distributed through the Oyu Tolgoi district and range from large batholithic intrusions to narrow discontinuous sills and dykes (Jargaljav, 2009).

- Late Devonian Quartz-monzodiorite intrusions are varied in texture and composition. Typically phenocryst-crowded with >40% plagioclase phenocrysts up to 5 mm long, and 10-15% biotite and hornblende. It is oldest intrusive within area, and is related to copper–gold porphyry mineralization that occur in all of the deposit areas.
- Post-mineralization late Devonian Biotite granodiorite intrusions are usually intruded into the Oyut deposits as dykes and along the contact fault as sills. At Hugo Dummett deposits, it flares upward above the contact fault. The granodioritic intrusions are strongly porphyritic with feldspar, hornblende, and biotite phenocrysts. Quartz

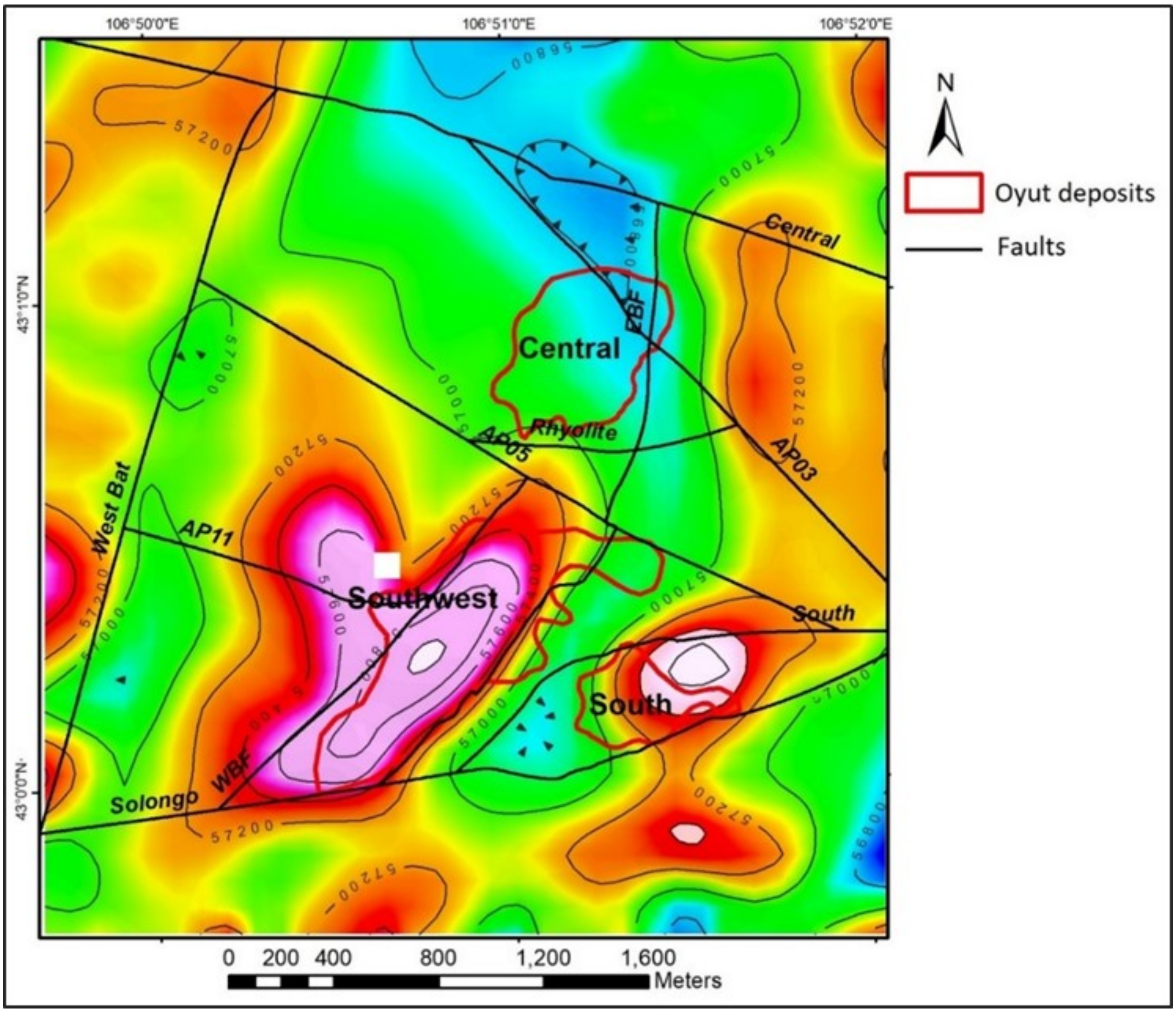


Fig. 3. Oyut deposits and faults on the ground magnetic Reduced To Pole map (legend in Fig. 6): WBF – West Bounding Fault, EBF – East Bounding Fault, AP- Assumed local faults;

Table 1. Faults in the Oyu Tolgoi group deposits area (Figs. 2 and 3)

Structure	Setting	Description
Main NE trending faults within the Oyu Tolgoi group deposits, described from north to south		
Granodiorite boundary fault	A corridor of subparallel faults, located to the NW of Hugo North	This fault zone juxtaposes the Carboniferous granitic complex to the NW over the Devonian and Carboniferous sequences, hosting and overlying the Oyu Tolgoi deposits to the SE (Porter, 2015).
Solongo Fault	East to northeast-striking, sub-vertical structure; cuts across the Oyu Tolgoi deposits just south of the Southwest Oyu and South Oyu deposit	Typically occurs as a strongly foliated zone up to several tens of meters wide. Forms a major structural break; a minimum of approximately 1,600 m of south side down offset where it juxtaposes mineralized basalt in the South Oyu deposit against sediments correlated with the upper Alagbayan group to the south. It is reflected by a strong linear anomaly in ground magnetic data (Porter, 2015).
Heruga North fault	It separates the Heruga North and Heruga zones and strikes ENE to NE.	It dips moderately to the north. To the NE it coalesces with the Solongo fault, and to the SW with the Javkhlant fault (Peters et al., 2012; Porter, 2015).
Javkhlant fault	It crosses the Heruga trend	It has apparent south side down and dextral offset (Porter, 2015).
Other faults, described from north to south		
West Bat, East Bat Faults	North–northeast-trending, bounding Hugo Dummett deposit.	Control the structural high which hosts Hugo Dummett deposit. Offsets of post-mineral contacts, measure at least 1 km (east side up) for the West Bat Fault, and 200–300 m (west side up) for the East Bat Fault
Central Fault	West–northwest-striking, moderately north-dipping structure that lies between the Hugo South and Central Oyu deposits	Fault consists of several splays and may have experienced multiple periods of displacement. Early fault displacement resulted in north-side-down apparent offset, followed by a later apparent reverse displacement of lesser magnitude. Visible as linear magnetic feature cutting the overlying Sainshandkhudag Formation.
Rhyolite fault	It juxtaposes the Central and Southwest deposits	A curved, east-west structure, occupied by a rhyolite dyke swarm.
East Bounding Fault (EBF) and West Bounding Fault (WBF)	North–northeast-trending; bound the Southwest Oyu deposit	Form a primary control on the distribution of copper and gold mineralization. Presence of mineralized clasts within the fault zones implies faults were active post-mineralization.
South fault	It forms the NW and northern boundary to the South Oyu deposit.	A curvilinear NE to EW striking fault, it is interpreted to branch from the Solongo fault in the southwest.

phenocrysts are common.

- Hornblende-biotite andesite and dacite dykes range from meters to a few tens of meters in width. Typically, strongly porphyritic with feldspar, hornblende, and biotite. Quartz phenocrysts are common.
- Rhyolite dykes range from meters to a few tens of meters in width and aphanitic and aphyric in texture. Intrusive breccia's are common along dyke contacts, commonly incorporating both rhyolitic and wall rock fragments within a flow-banded groundmass.
- Basalt/dolerite bodies in southwest part of the deposit area can occur as large, sill-like intrusive, in range from meters to a few tens of meters wide, and intrude all stratified units. Typical aphanitic to fine-grained, locally vesicular, and contain variable amounts of plagioclase phenocrysts.

The Oyu Tolgoi deposit area is underlain by complex networks of faults, folds and shear zones. Most of these structures are poorly exposed at surface and have been defined through integration of detailed exploration data (primarily drill-hole data), property-scale geological mapping, and geophysical data. There is an evidence for several phases of deformation and reactivation of the early faults during later deformational events. Structural elements of major faults are summarized in the Table 1 (Figs. 2 and 3).

All Oyu tolgoi deposits are related to phenocryst -crowded quartz-monzodiorite intrusions. The Oyut deposits include the Southwest Oyu, South Oyu, and Central Oyu orebodies. There are some differences in the mineralization and alteration styles. Boundaries between individual blocks coincide with major fault zones (Crane and Kavalieris, 2012; Porter, 2015).

The Southwest Oyu deposit

The Southwest Oyu (SWO) deposit is a gold-rich porphyry system characterized by a southwest-plunging, pipe-like geometry that has a vertical extent of as much as 700 m. The high-grade core of the deposit is about 250 m in diameter; the low-grade shell extends for about 600 m x 2 km (Fig. 3). Over 80% of the deposit is hosted by massive to fragmental augite porphyritic basalt of the Upper Devonian Bulagbayan formation, the remainder hosted by Late Devonian quartz–monzodiorite intrusions.

Several types of post-mineralization dykes cut the SWO deposit. Dykes are rhyolite, hornblende–biotite andesite, or biotite granodiorites. Dykes commonly have steep dips and invade fault zones.

Most of the SWO deposit, and the entire high-grade, gold-rich core of the deposit, lies between two northeast-striking faults, the West Bounding Fault and the East Bounding Fault.

The high-grade core is characterized by 1-50 cm wide contorted milky white quartz veins in sericite, albite, minor tourmaline-altered quartz-monzodiorite, and biotite–magnetite-altered augite basalt, overprinted by chlorite and sericite. Chalcopyrite with subordinate pyrite, bornite, and molybdenite occur as late veinlets filling fractures in quartz veins and disseminated through wall rocks.

Low-grade copper mineralization peripheral to the high-grade core is characterized by lower vein densities, and is hosted in chlorite and epidote altered basalt and lesser sericite and albite altered quartz-monzodiorite. Magnetite veinlets post-date the quartz veins but predate the main sulphide event. Chalcopyrite, bornite, and pyrite are mainly disseminated, with fracture or vein controlled sulphides being less prominent.

The SWO deposit is capped by an oxidized zone that varies from 50-60 m thick, and consists of black copper oxide (neotocite or tenorite), or copper carbonate (malachite) as fracture coatings, and speckled throughout the oxidized limonite-stained basalt.

Biotite and patchy magnetite alteration occur pervasively in the core of the deposit within the augite basalt. This grades outwards to selvages contained within a broad sericite zone, in turn grading out to a late overprinting of pervasive chlorite and epidote alteration. Minor albite alteration occurs as selvages along veins or fractures. Locally, brown carbonate alteration is present in the basalt.

Vein-rich quartz-monzodiorite in the high-grade core contains sericite-biotite-albite alteration with minor tourmaline and montmorillonite. Pink albite alteration commonly occurs as selvages on veins or fractures, and sericite overprints biotite and albite.

In the low-grade peripheral portions of the deposit, augite basalt is pervasively chlorite-magnetite altered, with epidote occurring in patches and sericite and pink albite on vein or fracture selvages. Late calcite or ankerite veins crosscut the assemblage. Quartz-monzodiorite within the low-grade margin contains pervasive sericite alteration, with albite occurring along quartz vein or fracture margins. Spotty biotite alteration also occurs locally.

The South Oyu deposit

The South Oyu (SO) deposit is a porphyry-copper deposit, developed mainly in basaltic volcanic rocks and related to small, strongly-sericite altered quartz-monzodiorite dykes. Deposit dimensions are about 400 m x 300 m in area, and vertically extended from surface down to 500 m depths.

The deposit occurs within an east to northeast-dipping sequence basalt and basaltic tuff of Alagbayan group, intruded to the southwest by an irregular quartz-monzodiorite body. Ore body is mostly overlain by basaltic tuff sequence and it has been affected by advanced argillic alteration. To the northeast, the altered and mineralized rocks are overlain by barren mudstones and conglomerates of the upper Alagbayan group.

The deposit area is intersected by numerous barren dykes, most of which belong to the post-mineral rhyolite and basalt subvolcanics. Dykes typically have widths of only a few meters, with the exception of one major, east–west rhyolite dyke that cuts through the middle of the SO deposit and attains widths of up to a few tens of meters.

The SO deposit lies within a faulted block bound on the northwest by the northeast-striking South Fault, and on the south by the east northeast-striking Solongo Fault. The Solongo Fault cuts the southern edge of the SO deposit, forming a wide, strong fault-fracture zone.

Fracture-controlled sulphide veins are minor, and sulphides occur dominantly as disseminated chalcopyrite, bornite, and molybdenite. Chalcopyrite is the principal copper sulphide, but in higher-grade areas, bornite locally exceeds chalcopyrite in abundance. Magnetite occurs as disseminations and as veins.

A small zone of high-sulphide mineralization occurs within a quartz-monzodiorite breccia in the western part of the deposit, adjacent to the South Fault. Mineralization here consists of pyrite, chalcopyrite, bornite, covellite, and primary chalcocite in quartz-sericite-kaolinite alteration, with late dickite veins.

An oxide zone approximately 60 m thick overlies the South deposit, and consists of malachite, azurite, cuprite, chrysocolla, neotocite or tenorite hosted within basalt and quartz-monzodiorite.

Alteration within the basaltic rocks at SO consists of moderate chlorite, biotite, hematite-magnetite, weak sericite and pink albite fracture and vein selvages. Hematite overprints magnetite. Quartz-monzodiorite is typically pervasively altered with quartz, sericite, and pyrite, as well as albite within vein selvages, small radiating clusters of tourmaline, and fluorite in quartz veins. Advanced argillic alteration, consisting of quartz, sericite and kaolinite with late dickite veins, is associated with the high-sulphidation in the quartz-monzodiorite breccia.

The Central Oyu deposit

The Central Oyu (CO) deposit is a porphyry-copper deposit, its dimensions are about 600 m in diameter and about 600 m depth in the form of inverted cone. The CO deposit is hosted within a feldspar-quartz-monzodiorite intrusions, emplaced into porphyritic augite basalt and overlying basaltic tuff of the Alagbayan group. The basaltic tuff is in turn overlain by barren sedimentary and basic volcanic rocks.

Post-mineral dykes are common in CO and comprise rhyolite, biotite granodiorite, hornblende–biotite andesite and dacite dykes. The CO is overlain to the east by barren conglomerate, mudstone, and siltstone. Along its southern margin, the CO block is juxtaposed against the SWO deposit area by an east-west-striking fault that is now occupied by a rhyolite dyke (the Rhyolite Fault).

Mineralization in the CO deposit is characterized by an upward-flaring, high-sulfidation zone that overprints and overlies porphyry-style chalcopyrite-gold mineralization. A secondary-enriched supergene chalcocite blanket tens of meters in thickness overlies the high-sulphidation covellite-pyrite zone. Chalcopyrite-gold mineralization is dominant on the south and western margins of the CO deposit within either basalt or quartz-monzodiorite adjacent to intrusive contacts with basalt. The high-sulfidation part of the CO deposit lacks significant gold and contains a mineral assemblage of pyrite, covellite, chalcocite/digenite, enargite, tennantite, cubanite, chalcopyrite, and molybdenite. Higher-grade mineralization is associated with disseminated and coarse-grained fracture-filling sulphides in zones of intense contorted quartz stockwork veins and anastomosing zones of hydrothermal breccias. Hydrothermal breccia consists of quartz vein and quartz-monzodiorite fragments within an intensely sericitized matrix. The sulphide-filled fractures cut both the quartz veins and enclosing wall rock.

A supergene enrichment zone overlies the high sulfidation assemblage and underlies a 20-60 m-thick, hematitic limonite, goethite-rich leached cap. The supergene zone consists of pyrite, hematite, and chalcocite/digenite, with lesser amounts of colusite, enargite, tenorite, covellite, bornite, chalcopyrite, cuprite, molybdenite and minor exotic copper oxide mineralization.

Chrysocolla, malachite and neotocite occur over a 400 m x 300 m area as a thin 2-4 m thick layer at the base of the gravels.

Biotite-chlorite and intermediate argillic alteration coincide with chalcopyrite-gold mineralization within basalt. Advanced argillic and sericite alteration coincides with the high-sulphidation within quartz-monzodiorite and basaltic tuff/breccia.

The biotite-chlorite zone consists of an assemblage of biotite, chlorite, epidote, sericite, albite, carbonate and anhydrite. Hematite and minor magnetite occur in veins and as disseminations. Biotite has been overprinted by chlorite and sericite, and magnetite has been altered to hematite.

Intermediate argillic alteration forms a narrow zone separating the advanced argillic and sericite alteration from the biotite chlorite alteration. Intermediate argillic alteration is characterized by a creamy yellow to pale green-coloured assemblage of kaolinite, chlorite, pyrophyllite and illite.

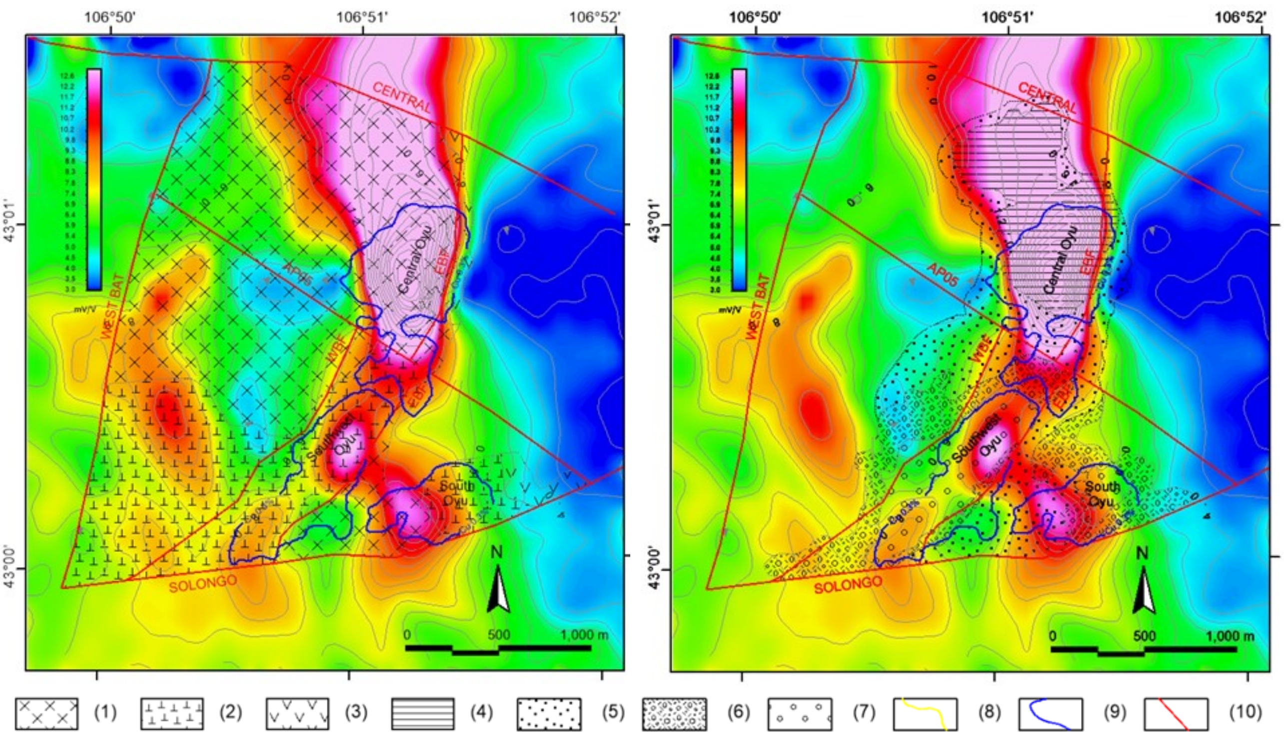
Advanced argillic and sericite alteration are associated with high-sulfidation, hosted primarily within basaltic fragmental rocks and quartz-monzodiorite. The advanced argillic assemblage consists of topaz, quartz, zunyite, diaspore, alunite, illite, andalusite, late kaolinite and dickite.

Alteration within the supergene zone is characterized by illite, muscovite, kaolinite, alunite and pyrophyllite. Montmorillonite, smectite, kaosmectite, illite and kaolinite are the dominant clay minerals in the leached cap.

GEOPHYSICAL SURVEY METHODS

Induced Polarization

In 2001, Ivanhoe Mines contracted Delta Geoscience of B.C. Canada and they carried out time domain gradient IP survey lines orienting east-west and on 100 m spaced lines using multiple AB current electrodes. The spacing of the AB electrodes was ranging from 1000 m to 12600 m and the spacing of MN electrodes was 100 m. This survey identified a continuous zone



(1) Quartz-monzodiorite; (2) Augite Basalt; (3) Ignimbrite; (4) Advanced Argillic alteration zone; (5) Phyllic alteration zone; (6) Prophyllitic alteration zone; (7) Potassic alteration zone; (8) Gold grade isoline – 0.3 ppm; (9) Copper grade isoline – 0.3%; (10) Faults

Fig. 4. The Induced Polarization survey results (AB = 11000, MN=100): Chargeability overlapping with lithology (left), and Chargeability overlapping with alteration zones (right);

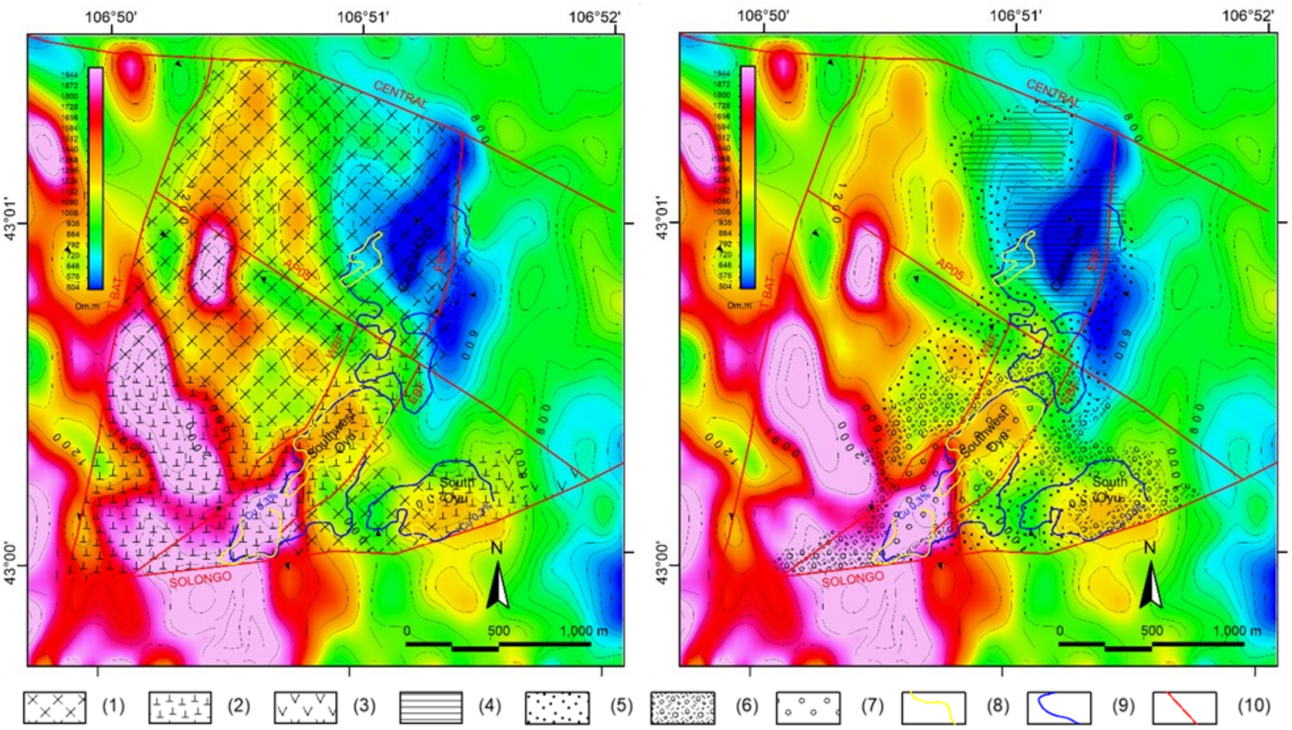


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Fig. 5. Induced Polarization survey results (AB = 11000, MN=100): Resistivity overlapping with lithology (left), and resistivity overlapping with alteration zones (right);

of sulphide mineralization extending north–northeast from the southwest end of the SWO through to the northernmost extent of the deposits, for a total strike length of approximately 5 km.

In 2009, the Zeus™ induced polarization (IP) and resistivity survey were carried out traversing the Oyu Tolgoi trend. Line spacing of 100 m was applied and lines were oriented east-west. Zeus™ induced polarization (IP) uses same Gradient array except that powerful Zeus Transmitter (100 KW) used and AB spacing was larger ranging from 5000 m to 20000 m.

The Induced polarization survey is the most effective geophysical method of locating a disseminated copper-sulphide porphyry mineralization zone, the metallic sulphide minerals are highly conductive and introduce high polarization effect.

Ground Magnetic Survey

Ground magnetic surveys with 100 m x 20 m and 50 m x 10 m grids were completed over the Oyu Tolgoi area in 2002 and 2003. In 2012, 2013, more detailed ground magnetic survey was completed by 25 m line spacing with continuous reading every 3 seconds to acquire a high-resolution magnetic image of the area. Survey lines was performed along the east to west oriented acquisition lines. Proton Magnetometers (GEM GSM-19T v7) were used for measurement of the total magnetic field. The Ground Magnetic Data then were diurnally corrected, gridded, reduced to magnetic pole, and processed for further interpretation and modelling.

Gravity Survey

Geophysical programmes were further expanded to include a gravity survey over the Oyu Tolgoi area in 2002. The survey was controlled by GPS with readings taken on every 50 m within the Oyut prospect areas and every 100 m over buffer zones of prospect areas.

The gravity survey was performed along north-south oriented acquisition lines 200m spacing,

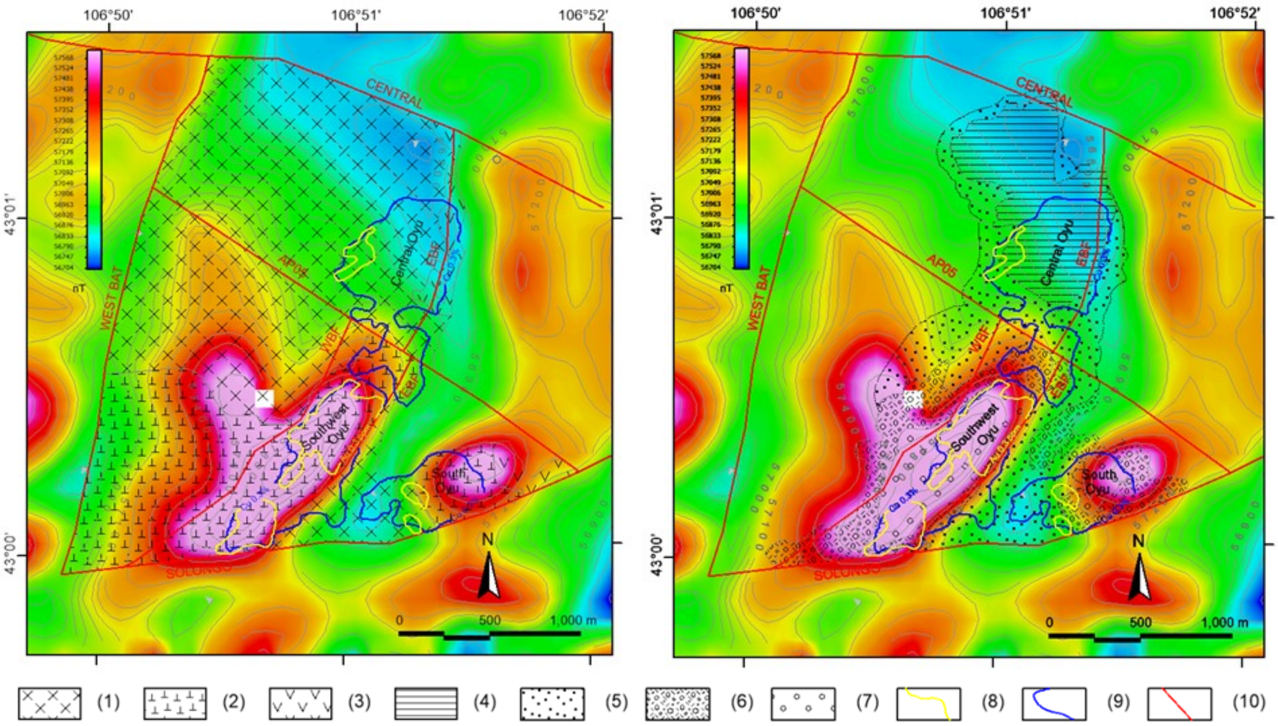

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Fig. 6. Reduced to Magnetic Pole Map: The RTP overlapping with lithology (left), RTP overlapping with alteration zones (right);

using a Lacoste Romberg gravimeter and for coordinates Real Time Kinematic survey was run with Trimble GPS System. The processed Bouguer anomaly Gravity Data was reduced to Residual Gravity using trend removing function of Oasis Montaj and Geosoft for interpretation and modelling.

Geophysical Inversion of Ground Magnetic and Gravity Data

The VOXI Earth Modelling extension of the Oasis Montaj software was used to yield unconstrained geophysical inversions of Gravity and Total Magnetic Intensity data in order to produce 3-dimensional voxel representations of density and magnetic susceptibility data (Gruzdev, 2016). The voxel models are constructed over the areas of interest CO, SWO and SO orebodies.

RESULTS

Induced Polarization

A summary high intensity, north-south trending chargeability anomaly zone is exposed at the northern part of the map (Fig. 4). This anomaly can be divided into 2 sections based on their intensity. The first section is located north of 43°01’ latitude with intensity of 12-16 mV/V, and is characterized by intense advanced argillic alteration, and low content of copper sulphide. The second section is characterized by very high chargeability response, and is located south of 43°01’ latitude with intensity up to 30 mV/V. This section coincides with the CO deposit, which is characterized by advanced argillic altered quartz-monzodiorite with high content of copper sulphides. The Induced Polarization results are presented in the Fig. 4 as chargeability in mV/V while the resistivity results are presented in the Fig. 5 in ohm-m.
Chargeability anomalies associated with SWO and SO deposits show similar characteristics. Intensity of anomalies are up to 12-13 mV/V, and they do not fully cover all areas of high mineralization.

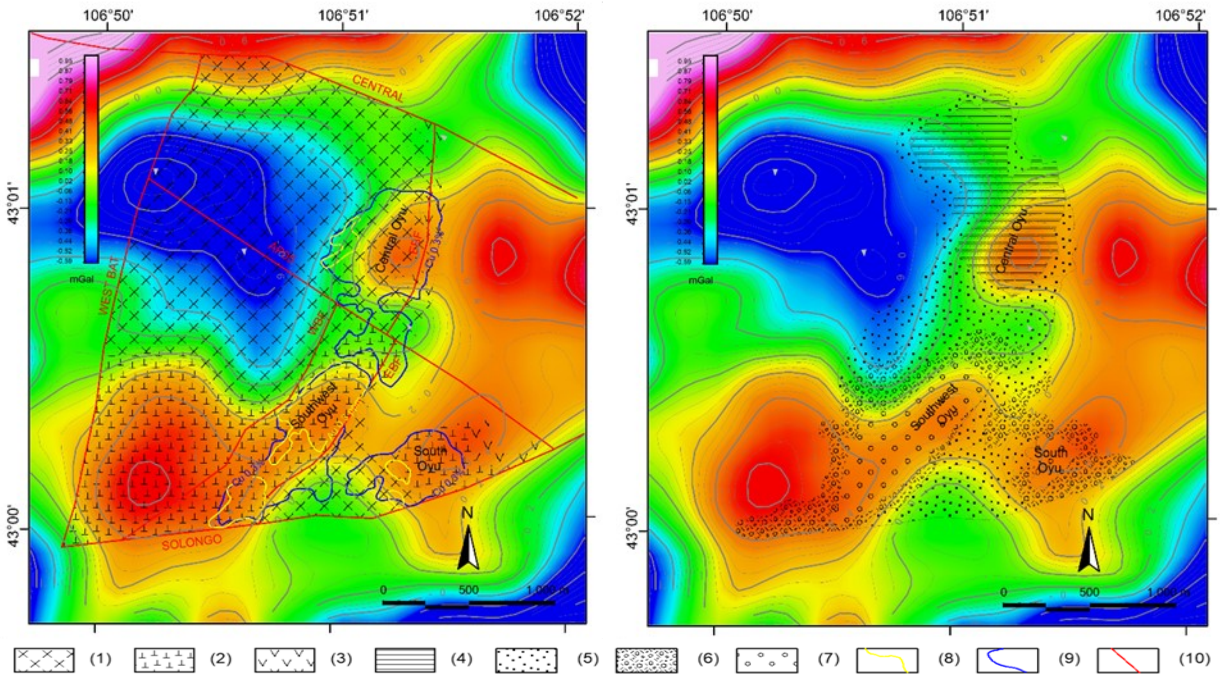

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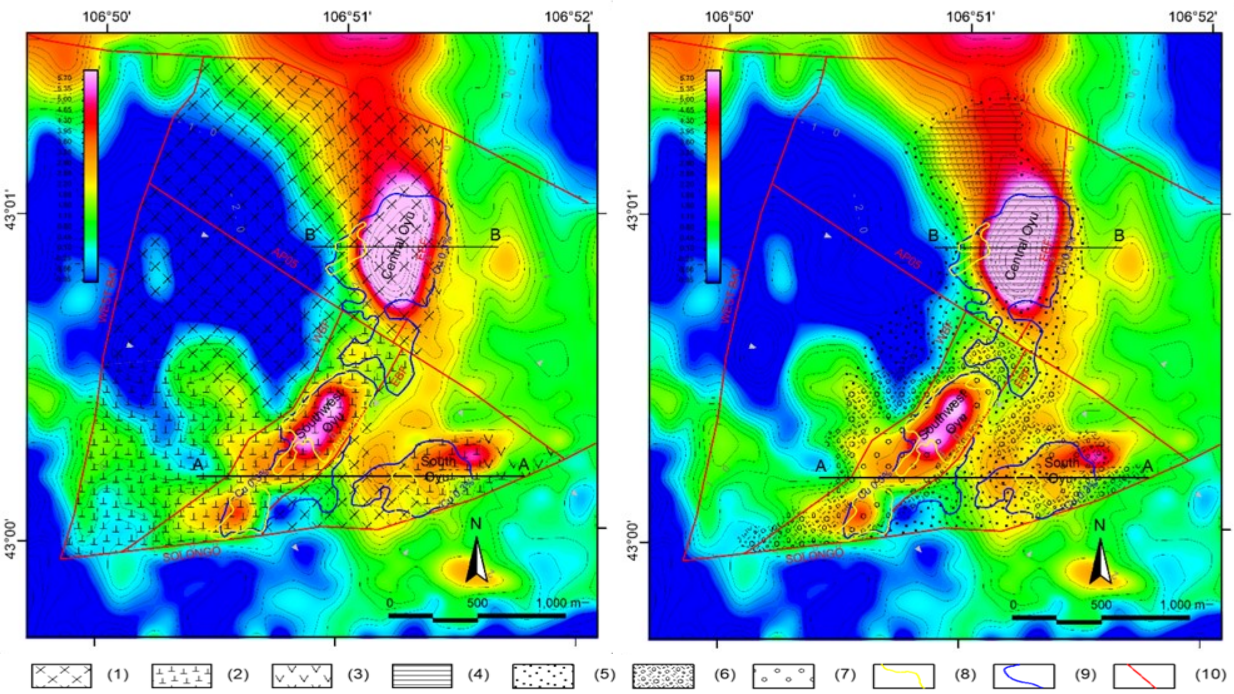
Fig. 7. Residual Gravity anomalies map (regional response removed by 1st trend surface removal method): Residual Gravity overlapping with lithology (left), Residual Gravity overlapping with alteration zones (right);



(1) Quartz-monzodiorite; (2) Augite Basalt; (3) Ignimbrite; (4) Advanced Argillic Alteration zone; (5) Phyllic Alteration zone; (6) Prophyllitic Alteration zone; (7) Potassic Alteration zone; (8) Gold Grade isoline – 0.3 ppm; (9) Copper grade isoline – 0.3%; (10) Faults

Fig. 8. Summary geophysical response map: map overlapping with lithology (left), map overlapping with alteration zones (right);

Resistivity data demonstrates a pattern of intensity decrease towards northeast in the area. Mineralized areas predominantly sit in the zones with approximately 1000-1200 ohm.m values and low resistivity areas (400-600 ohm.m). The relatively low resistivity zone is related to advanced argillic altered quartz monzodoirite and deformation zone with clay infill.

In addition, results of the induced polarization survey in the Oyu Tolgoi ore trend show that the resistivity in the areas with some degree of disseminated sulphide mineralization is 1200-1500 ohm.m or less, and in the non-mineralized areas the resistivity is 3000-4000 ohm.m. Results of the regional survey are not considered here.

Ground Magnetic Survey

Magnetic characteristics of the porphyry copper systems are usually subject to the geological settings of the deposits and magnetic anomalies can be expected from disseminated sulphides in some cases. Magnetic high anomalies could be due to the additional magnetite that was introduced at the time of mineralization. Magnetic low anomalies on the other hand, may represent in some cases, destruction of pre-existing magnetite by later alteration event (Mailot and Summer, 1966; Fig. 6).

The high magnetic anomalies with intensity of 57400-58000 nT have a good spatial correlation with Potassic altered augite basalt and 0.3 ppm gold grade isoline. The SWO deposit is outlined clearly by the Magnetic high anomalies. The SO deposit is partly correlated with the magnetic highs. Magnetic lows are located in the northern part of area and have a good spatial correlation with clay alteration zone and, the CO deposit. Theoretically, we can assume that the decrease in magnetism is due to the conversion of magnetite to hematite, which is observed in the Hugo deposit at Oyu Tolgoi. We have not discussed the Hugo deposit here, and the advanced argillic alteration zone in CO is strongly developed.

Magnetic fields of structural blocks that confined by main fault structures show relatively uniform behaviors. Faults are characterised by abrupt changes of magnetic fields (especially WBF, EBF faults) and linear magnetic lows. Structural interpretation was mainly based on magnetic survey results such as RTP (Reduced To Pole) map, first vertical derivatives map, tilt derivatives map of RTP and other geophysical surveys.

Gravity Survey

Gravity anomalies associated with disseminated sulphides of porphyry copper deposits are complex. Density of host rock can be reduced by fracturing and alteration, but at the zones where significant mineralization occurs, the density

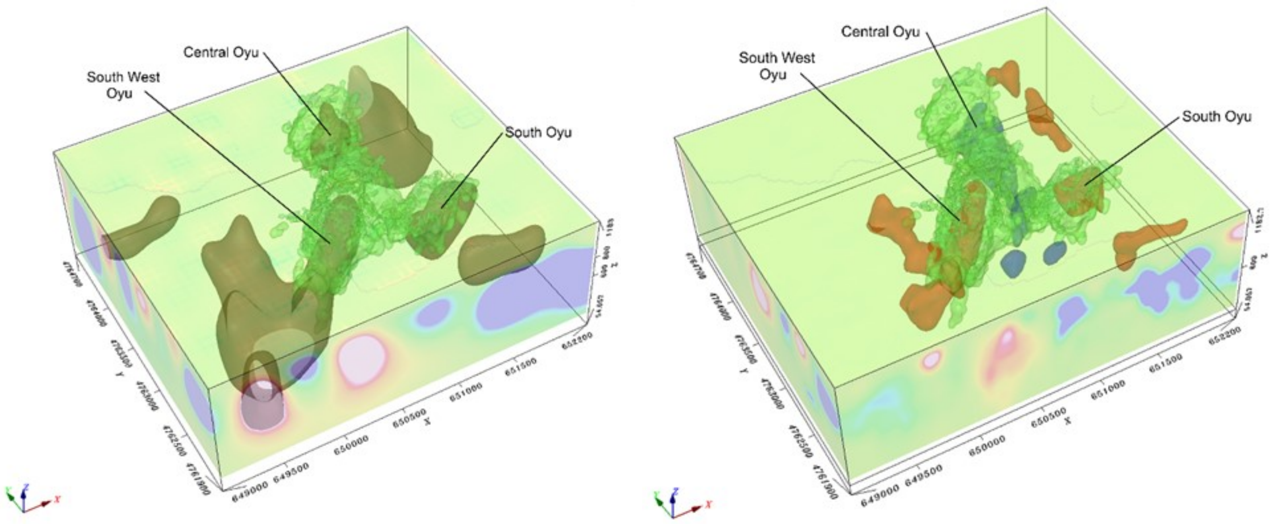


Fig. 9. The inversion results of gravity (Left) and magnetic (Right): a dark brown iso-surface inside gravity inversion is 0.05 g/cm^3 bulk density iso-surface; a brown iso-surface in magnetic inversion is 0.05 SI magnetic susceptibility iso-surface; a blue iso-surface inside magnetic inversion is - 0.06 SI magnetic susceptibility iso-surface; a green iso-surface is 0.3% copper iso-surface from core sample assay results;

can be slightly increased by sulphide enrichments. Moreover, leached and oxidized zones above sulphide mineralization cores are abnormally low density, and subsequently it may reduce the resultant gravity field at surface (Fig. 7).
The gravity responses from the SWO, SO, CO deposits are generally similar, generate 0.2-0.4 mGal positive gravity anomalies. The unmineralized or weakly mineralized augite basalts have high gravity responses with more than 0.4 mGal. Fresh augite basalts might have had high density fields, and it then might be reduced by later fracturing and alteration events during ore-forming process. Likewise, the unmineralized or weakly mineralized quartz-monzodiorite has negative gravity and generates less than -0.4 mGal gravity field. It shows that mineralized quartz-monzodiorite is denser than unmineralized quartz-monzodiorite and generates approximately 0.4 mGal positive gravity field.

Integrated Interpretation

An optimal combination of geophysical methods is used for detection of copper porphyry mineralization. Data interpretation methodology developed by Vahromeev and Davidenko (1987) was used to demonstrate the ability to fully detect the mineralized area in the exploration of the Oyu Tolgoi deposit. The methodology is explained below.
In order to compare and summarize survey results numerically, scales of survey results should be compatible. Ground magnetic field values have range from 56500-59000 nT, while chargeability values have scale from 0-35 mV/V.
To re-scale (normalize the data) the data, the mean values are subtracted from every reading and divided by standard deviation. As a result, the normalized data are comparable to each other and they all have with zero mean values and standard deviation values are equal to 1. This way, different scale survey readings can be combined and summarized. The re-scaled responses from geophysical survey results then can be used for creating the summary response map.
When summarize the rescaled values need to account that both positive and negative magnetic anomalies are interesting, absolute values of rescaled magnetic responses must be taken in calculation and inverse values of resistivity should be taken, given the fact that sulphide orebodies are indicated by low resistivity. Therefore, higher values on the resulting map indicate higher possibility of finding mineralization.
As you can see in the summary of geophysical response map shown in the Fig. 8, the isolines with values higher than 2.0 have a very strong spatial correlation with alteration and copper-gold mineralization zones. This indicates that the combination of geophysical surveys used in the exploration of the deposit is sufficient to detect the mineralization.

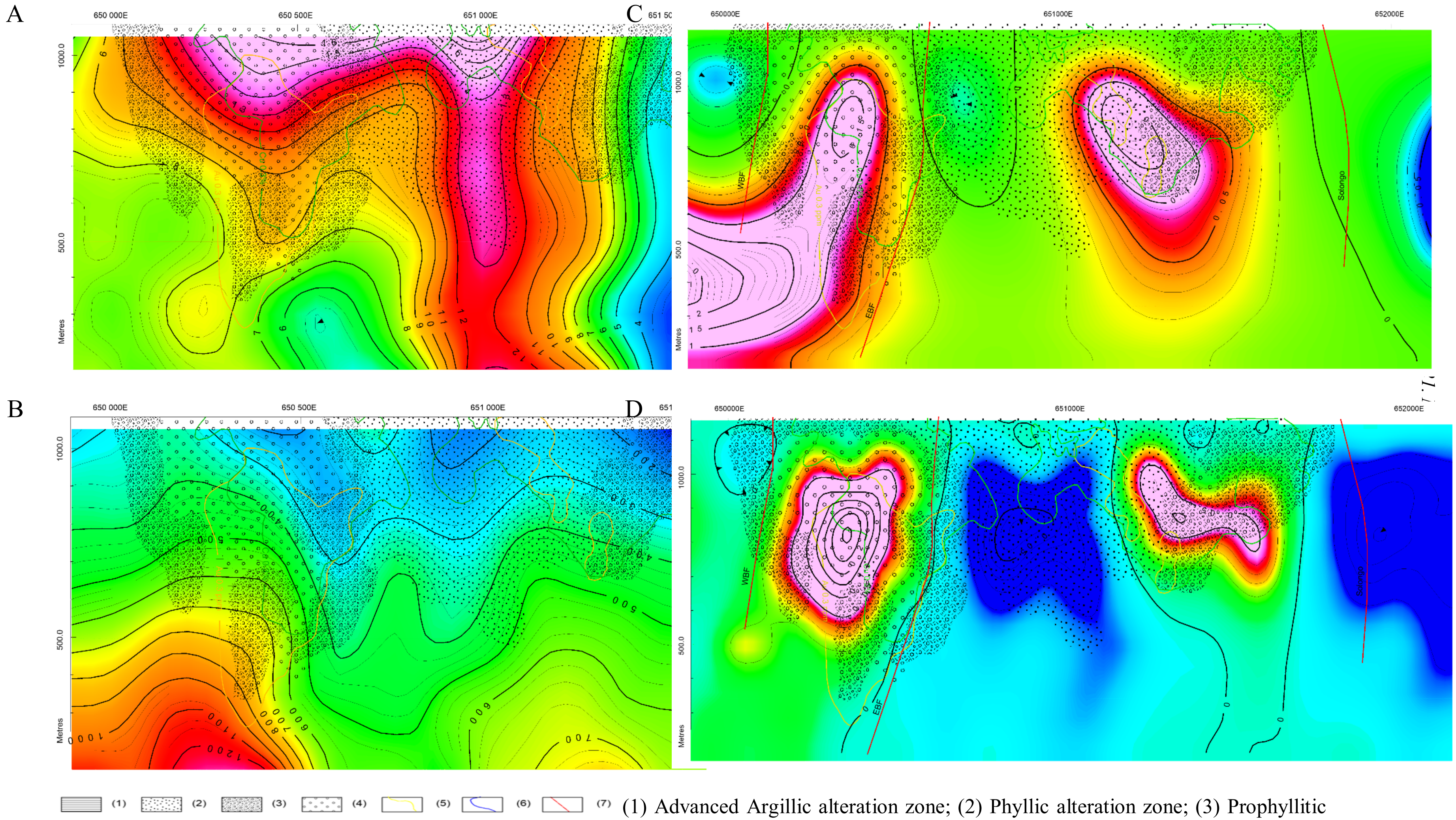
Geophysical Inversion of Ground Magnetic and Gravity Data

Dimension of the modelled area is 3.2 x 2.8 km and totalling ~8.96 km^2 area. The cell size of the block model is 25 × 25 × 12.5 m in X, Y and Z directions respectively, and the number of cells is 128 × 112 × 29. Maximum depth of the model is approximately 1.1 km from the surface.
These inversion results will assist in defining the density and magnetic susceptibility changes due to porphyry-copper mineralization (Orekhov, 2011). Inversion results of gravity and magnetic are shown in Fig. 9.
Results of inversion products were effectively located with porphyry copper sulphide mineralization data, and density and magnetics susceptibility distribution have good spatial correlations (Gonzalez, et al., 2018) with copper mineralization.
In the next section, the results of the study are considered in terms of sections AA and BB shown in Fig. 8, and the results of this inverse calculation are considered in sections.

DISCUSSION

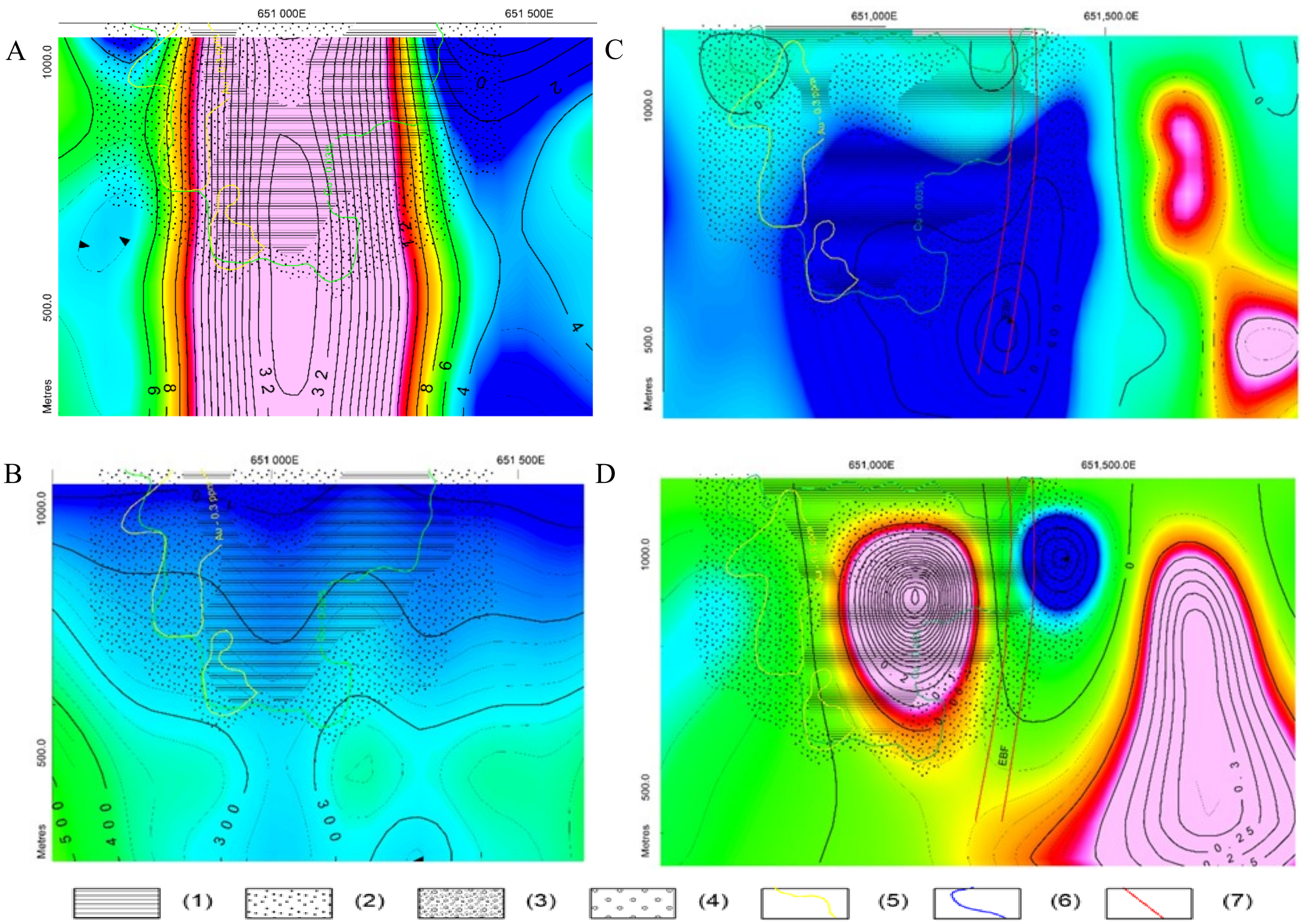
Interpretation and Modelling

The density and magnetic susceptibility sections are extracted from VOXI inversion of gravity and magnetic survey data, and the sections of chargeability and resistivity are the results of Zeus™ Gradient follow up induced polarization



(1) Advanced Argillic alteration zone; (2) Phyllic alteration zone; (3) Prophyllitic alteration zone; (4) Potassic alteration zone; (5) Gold grade isoline – 0.3 ppm; (6) Copper grade isoline – 0.3%; (7) Faults

Fig. 10. Sections of SWO and SO along A - A lines: The chargeability (A), the resistivity (B), the magnetic susceptibility (C), and the density (D);



(1) Advanced Argillic alteration zone; (2) Phyllic alteration zone; (3) Prophyllitic alteration zone; (4) Potassic alteration zone; (5) Gold grade isoline – 0.3 ppm; (6) Copper grade isoline – 0.3%; (7) Faults

Fig. 11. Sections of CO along B - B lines: The chargeability (top left), the resistivity (bottom left), the magnetic susceptibility (top right), and the density (bottom right);

survey. Geophysical sections along lines A – A and B – B are shown in Figs. 10 and 11. Location of section lines (A - A, B - B) is shown in the Fig. 8.

Chargeability of SWO and SO varies from 8 to 16 mV/V and chargeability highs show only top of the mineralization zone. Chargeability of CO is very high, varies from 8 to 32 mV/V, and is interpreted as due to intensive advanced argillic alteration and sulphide mineralization.

Resistivity of all mineralized and altered zones are relatively low, and it is less than 300-400 ohm.m. The shape of resistivity lows is similar to mineralization parts and outlines better than chargeability.

The chargeability and resistivity data were collected by expanding gradient array and sections are plotted using the "Real Section" method which was developed by Perparim Alikaj (Frankcombe, 2011).

Since our used IP inversion software in this study can only compute data collected by Dipole -Dipole and Pole Dipole devices, we used the "Real Section" plotting method, and in next studies, we will use inverted IP sections.

Real section method is a pseudo-section plotting, it assumes that plot depth for pseudo-section is between 0.125 and 0.2 of current electrode separation A-B. According to Frankcombe (2011), the Zeus IP method has a poor sensitivity in depth and dipping of bodies.

At the zones where significant mineralization occurs, the density is slightly increased by sulphide mineral enrichments, and it is clearly

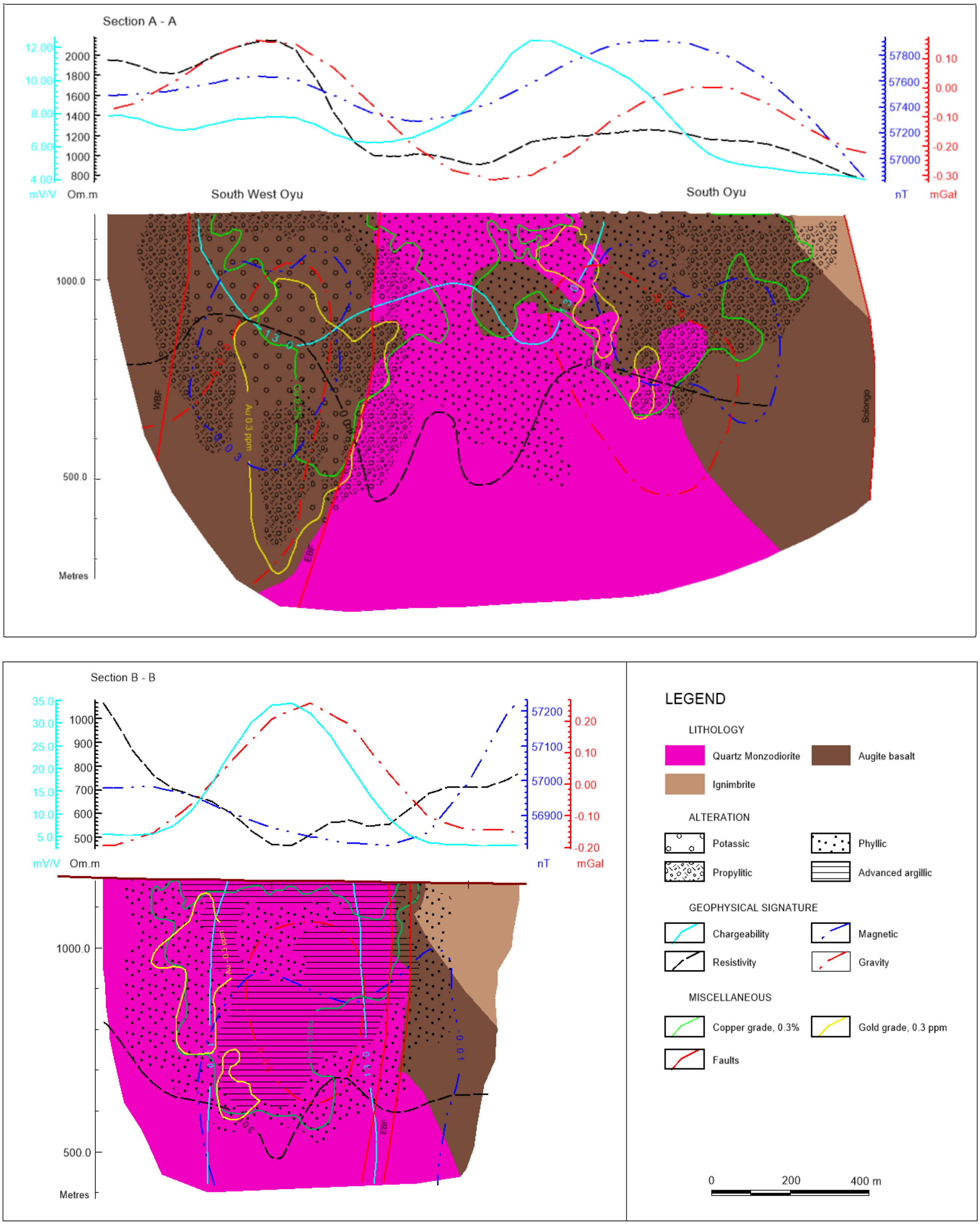


Fig. 12. Typical geological-geophysical models for deposits of CO, SO and SWO

illustrated in the Oyut deposits. The excess mass related with SWO and SO deposits reaches 0.15 g/cm^3, and increased over 1.0 g/cm^3 at the CO deposit - much higher than the other 2 deposits. All the density highs are located approximately in the center of copper mineralization zones.

Mineralization zone associated with high positive magnetic susceptibility changes are mostly related with potassic altered augite basalt and gold enriched zones. This is well observed in the SWO deposit. However, advanced argillic alteration causes depletion of magnetic materials and produces negative magnetic susceptibility changes in the CO deposit.

In anomalous fields of induced polarization, hydrothermally altered rocks are especially well displayed, while their magnetic susceptibility practically absent as in the example of Armenia porphyry copper deposit (Manukyan and Minasyan, 2015).

Based on geological and geophysical information, we have produced typical geological - geophysical numerical model for each deposits of the CO, SO and SWO (Fig. 12). Lithology, alteration and mineral grade information were used in sections above. These information were extracted from 3D model of current resource and ore control geology model of the Oyu Tolgoi mine. The information was simplified to emphasize relationships of geological and geophysical patterns.

IP field data collected by gradient array with AB=11000 m and MN=50 m was used in the study. Only Reduced to Magnetic Pole correction were applied to magnetic data. In the graph, the local gravity curve is after removing 1st trend surface from the complete Bouguer Map.

CONCLUSION

Typical responses from Oyut deposits are approximately:

- up to 0.1 mGal Gravity positive anomaly above background
- 100-200 nT low or high Magnetic anomaly below or above background (~ 57000 nT) depending on the geological setting
- Up to 12-30 mV/V chargeability anomaly
- Low resistivity 100 to 400 ohm.m

Geological-geophysical sections constructed at the CO, SO and SWO deposits are in agreement with the premise that the combination of Induced Polarization, Gravity and Ground Magnetic Survey is effective in exploration.

Hence, Data interpretation methodology developed by Vahromeev and Davidenko (1987) used an integrated geophysical anomaly map to show that more than 2 values of the summary index correspond well to the mineralization zone. Thus, the combination of Induced Polarization, Gravity and Ground Magnetic Survey is suitable for the exploration of porphyry copper-gold system, as shown by the example of Oyut deposit.

There are many issues to be discussed during this study, but they will be discussed in more detail in future research.

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