The Strategic Role for MT in the Search for New Copper Resources

Phoenix Geophysics Limited
Toronto, CANADA
www.phoenix-geophysics.com

Report prepared under contract to Phoenix Geophysics Ltd. by:

Ken Witherly CPG#11536
Condor Consulting, Inc.
Lakewood, CO, USA
September 2018
www.condorconsult.com

[Some intellectual property in this report is assigned to Phoenix Geophysics Ltd.]

For formal written permission to distribute or copy this document by any means, in whole or part, you must contact:

lfox@phoenix-geophysics.com
INTRODUCTION

Porphyry copper-gold-molybdenum (Por Cu-Au-Mo) and IOCG (Iron Oxide Copper Gold) deposits are the primary source for copper resources in the industrialized world. For porphyry deposits, the primary location for these deposits has long been known and is commonly termed the ‘Ring of Fire’ (Figure 1). IOCGs are more dispersed geographically, most likely due to their greater span of ages than porphyry deposits. IOCG deposits are arguably more complex and diverse geographically and geologically.

A type-section for the Por Cu Cu-Au-Mo model is shown in Figure 2 and a suite of models that characterize the IOCG ‘family’ in Figure 3. While these illustrations are valuable in helping to understand the overall nature of these systems, they lack information required to assess the style of response that can be expected from geophysical surveys. A reasonable effort is shown in Figure 4 for the porphyry style target. This however, captures only what can be defined as the background or average responses for the magnetic and IP-resistivity parameters, very dependent on the erosional level. The overall geophysical character can be considered to be the expected response for a ‘disseminated’ mineral system.

For IOCG’s, the population of deposits is much smaller than porphyries and as a result of this, fewer have been characterized petrophysically, mainly from deposits in Australia. The variability of responses can be appreciated in Figure 3 when the mineral components are examined, specifically pyrite, chalcopyrite, magnetite and hematite.

While average petrophysical responses are useful to help gauge the expected general geophysical character of deposits, Condor Consulting Inc (Condor) has investigated a number of porphyry deposits which show very anomalous geophysical character due to what is best described as a massive sulfide component in an otherwise disseminated sulfide environment. In most cases as well, these features appear to be emplaced at a depth beyond the reach of most geophysical techniques but well suited to mapping with the Magnetotelluric (MT) method. For IOCG deposits, the evidence for anomalous conductivity points to both deposit and district scale responses, the later being part of what is suggested to be part of mineral system response.

This work will be reviewed and the exploration implications discussed. While it is premature to suggest a new geological model is being defined, from an exploration targeting perspective, these features are defined for the present study as ‘GAFs’ for Geophysically Anomalous Features. At the present time, the generally accepted geological models for porphyry systems lack what could be considered an explanation as to why such heterogeneous geological features with an associated anomalous geophysical response occur. A working hypothesis is that while the emplacement of the porphyry system is generally a continuous and regular process, there can be irregularities or ‘speed bumps’ which favor the formation of GAFs. It is hoped that with a well-defined population of GAF examples, a suitable formational mechanism will be defined. Finally, GAFs are deemed economically important as they are typically associated with higher grade zones of mineralization, which can offset their generally greater depth from surface, thus making them potential underground mining targets.
Figure 1: Global distribution of porphyry copper-au and IOCG deposits-Sillitoe 2012.

Figure 2: Type section through porphyry deposit-Sillitoe 2012.
Figure 3: Range of IOCG deposit styles-Barton and Johnson 2004.

Figure 4: Stylized geophysical response of porphyry deposit-Hübert et al. 2016.
THE MT Technique

Magnetotellurics (MT) is an electromagnetic geophysical method for inferring the earth’s subsurface electrical conductivity from measurements of natural geomagnetic and geoelectric field variations at the Earth’s surface. Investigation depth ranges from <100 m below ground by recording higher frequencies down to 10,000 m or deeper with long-period soundings.

Once MT data is acquired, it is commonly modeled with 2D and sometimes 3D inversion codes. 1D modeling was once common and it sometimes still used for QA/QC purposes but seldom for interpretation.

As is common with all EM techniques MT is being diffusive in nature (compared with wave style energization such as seismic signals), the recoverable signal tends to blur out the response: consequently, some sharpening techniques in the modeling are often used to compensate for this. Nevertheless, the recovered models of the subsurface are non-unique and are generally best assessed with additional complementary data such as magnetic or gravity data. Active source EM or galvanic data can be helpful as well.

THE EXAMPLES

Condor conducts applications research on various deposit styles and geophysical techniques. This is done to both allow Condor to better understand a diverse range of deposit signatures as well as the characteristics of different acquisition systems and data processing techniques. Where data can be accessed, Condor can undertake its own data processing but, in some instances, work by other groups can be used if properly documented. In the present assessment, it has been a mixture of Condor work and work by others. Examples of Por Cu-AU-Mo are presented first followed by some IOCG examples. These are all drawn on work others have carried out.

Porphyry Copper-Au Examples

<table>
<thead>
<tr>
<th>Deposit Name</th>
<th>Location</th>
<th>Survey/Data Types</th>
<th>Processing work carried out by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casino</td>
<td>Yukon</td>
<td>Titan IP/MT</td>
<td>Condor</td>
</tr>
<tr>
<td>Morrison</td>
<td>BC</td>
<td>ZTEM/MT</td>
<td>Condor/University of Edmonton</td>
</tr>
<tr>
<td>Resolution</td>
<td>Arizona</td>
<td>MT/ZTEM</td>
<td>Quantec/Condor</td>
</tr>
<tr>
<td>Bingham</td>
<td>Utah</td>
<td>MT</td>
<td>Fugro</td>
</tr>
<tr>
<td>Collahuasi</td>
<td>Chile</td>
<td>TEM</td>
<td>Glencore</td>
</tr>
<tr>
<td>Santa Cecilia</td>
<td>Chile</td>
<td>CSAMT/Orion (IP-MT)</td>
<td>Quantec</td>
</tr>
</tbody>
</table>

Casino-Yukon

The Casino porphyry deposit is situated in western Yukon, 380 km NW of Whitehorse. Casino was discovered in 1969 as a result of drilling a geochemical anomaly. Since then numerous companies have undertaken extensive exploration work. Western Copper and Gold Corporation (WCG) currently owns
Casino and is moving the project through permitting. A reserve of 965 million tonnes mill ore + 157 million tonnes heap leach (proven + probable), containing 4.5 billion lbs copper and 8.9 million oz gold has been published for the deposit.

Since discovery, a variety of geophysical techniques have been applied to the deposit including aeromagnetics, radiometrics, ground mag, IP and MT. Early IP work did not penetrate the thick weathered zone (the area was unglaciated). In 2009, a Titan IP and MT survey was carried by Quantec out over the deposit area. Condor entered into an agreement with WCG in early 2017 to process the available geophysical data, including the Titan results. The location of the survey lines with respect to the deposit is shown in Figure 5.

The IP and MT data were modeled by Condor with 2D and 3D inversion codes. These results are discussed in Witherly et al. 2018. When the IP and MT results were assessed, the IP chargeability results showed several highs which appeared to be related to steeply dipping structures. The MT however, shows shallow erratic conductivity but then defines a clear discrete high that lies at a depth of ~650 m along the southern margin of the deposit. This is illustrated in Figure 6 as the green body labeled “MT isosurface”. The MT feature had not been previously recognized in the processing carried out by Quantec in 2009.
It is believed that the extensive supergene blanket present over the deposit possibly made the acquisition and processing of the data survey data difficult. Condor did not locate any discussion of these issues in the Quantec assessment but the 2D sections provided to the client by Quantec were deemed noisy and difficult to interpret. Also, Quantec did not provide a 3D model of the results which Condor felt was important for a proper assessment.

No drilling tested the MT feature and no additional geophysics has been carried out which could validate this response. Condor suggested to WCG that ground TEM could be a suitable technique to employ to validate the target prior to potential drilling. Geological opinion as the source of this feature has been sought out and the possibility of this feature being a zone of massive sulfides has been deemed reasonable by a number of geologists familiar with porphyry copper deposits.

**Morrison-British Columbia**

The Morrison deposit is situated on the northern edge of the Skeena Arch, a prominent NE-trending transverse zone of uplift during the Mesozoic, in a region underlain by volcanic, clastic, and epiclastic rocks of the Takla, Hazleton, Bowser Lake, Skeena, and Sustut groups (Ogryzlo et al. 1995). NNW-trending horst/graben and tilted faulted blocks disrupt rock units, resulting in older units being juxtaposed and locally truncated against younger units. Intrusive rocks in the area include the Early Jurassic, diorite to granodiorite Topley Intrusion and the Eocene quartz, hornblende, biotite, and plagioclase Babine Igneous Suite.
The Morrison deposit is a strongly zoned classic porphyry copper-gold deposit associated with an Eocene "Babine-type" biotite-hornblende plagioclase phric intrusion. Zoning is symmetrical, with shells of copper sulfides and pyrite distributed concentrically within and around a zone of intense hydrothermal biotite alteration. The symmetry of the deposit has been disrupted by dextral transcurrent shear of unknown vertical displacement and some 330 m of horizontal translation, so that the surface trace of the mineralized zone is that of an elongate "S" (Ogryzlo et al. 1995).

The most recent geology over the deposit is provided by Liu et al. 2006 (Figure 7). Early geophysical work is outlined in Fountain (1968). Subsequent ZTEM surveys are discussed in Witherly and Sattel (2013) and Lee et al. 2017. Figure 8 shows the results of modeling the MT and ZTEM results over the deposit (Lee et al. 2017).

![Figure 7: District and deposit scale geology of Morrison-Liu et al. 2016.](image)

![Figure 8: Modeling of ZTEM and MT data (outlined in Figure 8a) over Morrison deposit-Lee et al. 2017.](image)
Due to the bandwidth and general better signal to noise of the MT at lower frequencies, the MT results can see deeper than the ZTEM, but the ZTEM can map the shallow conductivity better than the sparser MT results. A picture emerges which shows a strongly conductive zone ~1.5 km below the ground surface. The drilling-defined Morrison deposit is far shallower than this feature and is likely dominated by disseminated mineralization with a moderate-to-intermediate conductivity (values of 150 ohm-m to 450 ohm-m based on Walcott 2001).

In Ogryzlo et al. 1995, a suggestion is made that the bottom of the Morrison intrusive system has been faulted up to surface and corresponds to the Hearne Hill zone (Figure 9). This could account for the Hearne Hill zone being conductive (Figure 10), as it is correlative with the Morrison system at depth which the MT results show to be conductive (Figure 8).

![Figure 9: Model of fault off-set of Morrison intrusive, creating the Hearne Hill zone to the south east of Morrison-Ogryzlo et al. 1995.](image)
Bingham-Utah

The Bingham Canyon Mine (also known as the Kennecott Copper Mine) is located in the Oquirrh Mountains, the easternmost fault block in the Great Basin, just west of Salt Lake City, Utah. The Bingham Stock comprises six main rock types (from oldest to youngest): equigranular monzonite, porphyritic quartz monzonite, hybrid porphyry, quartz monzonite porphyry, latite porphyry, and quartz latite porphyry (Figure 11). All phases have been altered and mineralized. Various mineralized phases of quartz veins are present. Later mafic dykes cut the porphyry and may be weakly mineralized. The adjacent Last Chance Stock (mostly barren) is of a similar lithology to the Bingham Stock and is connected to the Bingham Stock via the broad Phoenix dyke. A third, slightly smaller intrusive is present to the south of the Bingham Stock (from Porter et al. 2012).

Rio Tinto (RT) carried out extensive MT surveying over the area and mapped a deep conductive zone that is in-line with the mine Quartz Monzonite porphyry at depth. This feature is illustrated in Figures 12 and 13. Drilling to a depth of ~2 km was required to intersect the feature. RT was not forthcoming as to the likely source of the conductive response (<50 ohm-m) but mentioned sulfides, clays and conductive ground water as contributing sources. Sulfides, likely in concentrations of 15-25% is deemed the most likely source of the response.
Figure 11: Geology of the Bingham Mine-Porter et al. 2012a.

Figure 12: MT conductivity map over Bingham deposit-Hinks 2013.
Resolution-Arizona

The Resolution deposit is a deep, high grade porphyry copper system located in the Superior District, Arizona owned by RT and BHP and operated by RT. The deposit lies perched above a major intrusive body and is hosted in a complex sequence of diabase, limestone and quartzite rocks, with some intrusive diking as well. The system is capped by approximately 500 m of unmineralized sedimentary rocks. A section through the deposit is shown in Figure 14.

Figure 13: Section showing MT conductivity and geology through the Bingham deposit-Hinks 2013.

Figure 14: Geological section through the Resolution deposit-Ballantyne et al. 2003.
MT was carried out over the deposit in 2006 and is shown in Figure 15. A part of the overlying sedimentary cover is conductive but there is a distinctive conductive ‘plume’ that correlates closely with the cupola of high grade copper over top of the intrusive core of the system. Ballantyne et al. 2003 state that:

“A halo of unusually strong pyrite mineralization overlies and flanks the >1% Cu shell. Pyrite abundance increases upward to a maximum of about 10 weight percent 100 to 200m above the upper boundary of the >1% Cu zone, then decreases further above the copper zone. Pyrite is most abundant in the quartz-muscovite-illite alteration zone above the >1% Cu zone but also extends laterally into adjacent propylitized rocks.

In 2013, Freeport-McMoRan contracted a ZTEM survey over the Superior area of Arizona; this survey covered the Resolution deposit. Condor processed these data in 2016 and were able to map a conductive zone above the Cu shell. A section through the ZTEM model with the geology is shown in Figure 16. Based on the earlier MT and geological comments about sulfide distributions, it appears likely that the MT and ZTEM surveys are mapping the same zone of elevated conductivity. There is limited geophysical data published on the deposit but borehole petrophysical logging has been carried out and conductivities the order of 40 ohm-m are reported in what is assumed to be the sulfide-rich zone above the copper shell (D. Hinks per. comm. 2016).
Collahuasi-Chile

District Geology: Four main porphyry bodies have been defined in the Collahuasi area: the Rosario Porphyry (34.4 ±0.3 Ma), the Collahuasi porphyry (59 Ma), the Ujina porphyry and the Inés porphyry. The weakly mineralized Inés porphyry is interpreted to have intruded the Ujina porphyry (Figure 17).

Mineralization: Supergene mineralization occurred over the Rosario and Ujina porphyries, represented by high-grade chalcocite and Quaternary gravels cemented by chrysocolla and copper wad.

Hypogene mineralization occurs in all three porphyries, but the grades decrease outwards from the contacts of the Rosario porphyry with the Collahuasi and Inés porphyries. Hypogene mineralization includes chalcopyrite and lesser bornite. In the Ujina porphyry, the highest Cu grades form an annulus around the sulphide-poor potassic core, and coincide with the cylindrical contact between the Ujina porphyry and the volcanic host rocks.

Geophysics was used during the discovery phase and this included aeromagnetics, IP, TEM and remote sensing. Collahuasi was one of the first enriched porphyry deposits which showed a strong EM response from the chalcocite blanket developed over the deposit. However, the presence of what are believed to be massive sulfide veins deeper in the system were not known until the early 2000s. In 2005, ground TEM surveys were carried out which are presented in Figures 18 and 19. This work has never been presented as a geoscience publication, so details on the geophysics and geology are not available. The images provided however, show a strong, deep circular shaped feature that extends to the SW over 3 km from the main Rosario pit. This feature is of the size and conductivity that MT would be quite able to map this style of mineralization.
Figure 17: Geology in vicinity of the Rosario and Ujina deposits—Witherly and Hoschke 2017.

Figure 18: Plan view of Rosario pit and deep conductive annulus—Xstrata Copper 2006.
Santa Cecilia-Chile

Deposit Geology: The regional and district geology are shown in Figure 20. [from McGregor, 2011] In the area of the Santa Cecilia Project, tuffs and breccias of dacite to andesite composition occur together with interbedded lacustrine sedimentary rocks. Drilling has encountered quartz diorite porphyry and microdiorite of unknown extent. Andesitic dykes and sills and small felsic intrusive plugs are present. Three stratigraphic formations have been recognized at Santa Cecilia. The two younger units are separated by a mild unconformity and dip 10° to 15° to the southwest. The older Triassic unit has been folded and is separated from the younger rocks by a distinct unconformity. All of the units are affected by faulting and the lithologies by alteration. Brief summaries of the formations are as follows:

Correlated with the Quebrada Carrizo Formation of Oligocene-Lower Miocene age:

- Rio Nevado Formation or Unit: Grey to pink andesite-dacite crystal tuffs and tuff breccias with grey pink andesite-porphry flows. Lenticular intercalations of grey green conglomerate, sandstone and grey shale
- Aguas Blancas Formation or Unit: At the base and top of this sequence there are pink ignimbrite tuffs, named the Lower and Upper Mantos. Between the two Mantos there are grey conglomerates with subordinate andesitic breccia. Correlated with the La Ternera Formation of Upper Triassic age.
- Caspiche Formation: Green coloured volcanic breccias and agglomerates with interbedded sandstone and red conglomerate.

East of the project the mineralized Caspiche porphyry has been reported to measure 300 by 400 m in plan and does not vary appreciably from those dimensions through 1,200 m of explored depth. Published maps indicate that the longer dimension trends approximately north-northwest. It is surrounded by volcano-
sedimentary host rocks and is overlain by 500 to 750 m of volcanic breccia of uncertain origin. The porphyry system has been described as an "intermediate sulphidation" event consisting of two main intrusive phases namely Early Diorite Porphyry and Early Inter-Mineral Diorite Porphyry. The early intrusive features a multi-directional vein stockwork extending downwards from approximately 4,200 m elevation. Weaker veining occurs in the second phase which cuts the earlier phase and extends beyond the limits of the early intrusive. Various styles of alteration are recognized with both vertical and proximal zoning in relation to the porphyry intrusions.

A number of geophysical surveys have been carried out over the property (McGregor 2011), including MT surveying. Figure 22 shows sections through the 3D MT model and in Figure 23, drilling into the conductive zone associated with Cu-Au mineralization is apparent. The source of the conductive zone is believed to be heavy sulfides in veins that forms part of the intrusive system.
Figure 21: Stacked slices through MT model-Bournas and Thomson 2017.

Figure 22: 3D MT section with 10 ohm-m isosurface and drilling-Bournas and Thomson 2017.
IOCG Examples

<table>
<thead>
<tr>
<th>Deposit Name</th>
<th>Location</th>
<th>Survey/Data Types</th>
<th>Processing work carried out by</th>
</tr>
</thead>
<tbody>
<tr>
<td>Candelaria</td>
<td>Chile</td>
<td>TEM</td>
<td>Lundin</td>
</tr>
<tr>
<td>Santo Domingo</td>
<td>Chile</td>
<td>VTEM/ZTEM</td>
<td>Condor</td>
</tr>
<tr>
<td>Olympic Dam</td>
<td>South Australia</td>
<td>MT</td>
<td>University of Adelaide</td>
</tr>
</tbody>
</table>

Traditionally, IOCG deposits are considered targets for magnetic and gravity surveys and possibly IP-DC resistivity due the dominance of oxide mineralization. Most of the South Australian examples are lacking in a direct conductivity response; i.e. Prominent Hill and Carrapatena. Earnest Henry (Queensland) was found with EM but the source of the conductivity appears to be supergene weathering which produced chalcocite and native copper. Olympic Dam deposit (South Australia) shows some conductive units but the situation is made complex by conductive rocks overlying the deposit. However, MT shows large scale conductivity structure around the Olympic Dam deposit which is believed to represent aspects of the mineral system associated with the deposit.

Two examples from Chile show a directly conductive response associated with the ore mineralization. This suggests there may be a regional aspect to whether or not IOCGs can be expected to have a conductivity response.

Limited information is available from the IOCG district in the Carajás (Brazil). The Alemão deposit shows diagnostic magnetic, radiometric and EM responses (Barreira per. comm. 2003). The EM response is attributed to chalcopyrite veins. The Salobo deposit has no conductivity response in the upper 250 m (Barreira per. comm. 2003).

**Candelaria-Chile**

Geology: (Figure 23). The Candelaria sulphide deposit is located at the boundary between the Coastal Cordillera and the Copiapó Precordillera. The Coastal Cordillera of Chañaral and Copiapó is composed of Permian to Lower Cretaceous intrusions within a basement of metasedimentary rocks of Devonian to Carboniferous age. Volcanic, volcanioclastic, and marine carbonate rocks represent intra- and back-arc sequences that were deposited during Early to Mid-Cretaceous.

The Candelaria, Santos, and Alcaparrosa mines are located in the district of Punta del Cobre. The polymetallic sulphide deposits are hosted in volcanic rocks of the Punta del Cobre Formation. Polymetallic sulphide deposits in the Punta del Cobre district are located to the east of the main branches of the Atacama fault zone, a subduction-linked, strike-slip fault system stretching over 1,000 kilometres along the Chilean coast and active at least since the Jurassic. The dominant structural elements of the Punta del Cobre area are the north east trending Tierra Amarilla Anticlinorium, a southeast-verging fold-and-thrust system and a series of north-northwest-to northwest-trending high-angle faults.

The copper-gold sulphide mineralization found at the Candelaria Copper Mining Complex is generally referred to as iron oxide copper gold (IOCG) mineralization. The sulphide mineralization occurs in breccias, stockwork veinlets, disseminations in andesite, and as an internal tuff unit. There are also some localized
controls to mineralization in the form of faults, breccias, veins, and foliation. Candelaria has become an exploration model for Andean-type IOCG deposits that display close relationships to the plutonic complexes and broadly coeval fault systems. Depending on lithology and the structural setting, the polymetallic sulphide mineralization can occur as veins, hydrothermal breccias, replacement mantos, and calcic skarns. The Candelaria IOCG system lies within the thermal aureole of the Lower Cretaceous magmatic arc plutonic suite in the Candelaria-Punta del Cobre district. (SRK 2015).

The primary geophysical discovery paper (Matthews and Jenkins 1997) shows that IP and magnetics assisted in the discovery. However, following the purchase of the deposit by Lundin Mining in 2014, Lundin carried out deep TEM surveys to help map out a significant manto zone at depths greater than 800 m below the surface. It is believed that the manto zone was known prior to Lundin’s work but Lundin has shown EM as an effective means to map out this zone at great depth. Figures 25 and 26 show a summary of some of these results. There are rumors that Freeport (previous owner) undertook some MT work but this has never been made public.
Figure 24: 3D view of deep TEM survey results and manto ore zone at 800 m depth below the Candelaria pit-O’Brian 2017.

Figure 25: 3D view of geology and geophysical results below bottom of Candelaria pit-O’Brian 2017.
Santo Domingo-Chile

Geology: The main IOCG ore bodies at SD are Santo Domingo Sur (SDS), Iris (IR), and Iris Norte (IN)—Figure 26. Daroch (2011) indicates that these three ore bodies are “physically continuous” along a roughly north-south structural trend and all three share similar host and ore mineralogy. Based on the drilled extents of the ore bodies, SDS and IR are contiguous (referred to as SDS-IR) and there is an approximately 1 km separation between IR and IN. The Estrellita (ES) orebody is located approximately 3 km northwest of SDS along an east-west structural trend referred to as the Santo Domingo Fault (SDF) which is host to at least three IOCG veins, breccias, and minor mantos (Daroch, 2011) in addition to ES.

According to Daroch (2011), the mineralization at SDS-IR and IN occurs primarily as semi- to massive specularite and magnetite mantos (greater than 50% iron minerals) which are up to 20 m thick with clots and stringers of chalcopyrite. A distinct zonation exists in SDS-IR, where an outer rim of specular-hematite grades into a magnetite-rich core (designated by “IM” in the plan view map at the top of Figure 4 with the zonation shown in the bottom section). The copper minerals are associated with the specular-hematite rim while pyrite is the dominant sulphide in the magnetite core. Mineralization in the ES orebody is in specular hematite-rich bodies and stockworks with copper oxides near surface and with minor copper-iron-sulphides located at depth.

The numerous faults on the property exhibit significant control on the distribution of mineralization. Daroch (2011) suggests the fault displacement may be the result of reactivation along earlier structures which may have provided a path for mineralizing fluids at SDS. The east side of SDS-IR and IN is coincident with an extensive, north-south trending normal fault dipping approximately 60–70° to the west. At the south of SDS, the ore body is truncated by a northwest trending fault with dip 60° to 70° to the southwest which is the contact between the mineralized volcanics on the north and limestone to the south. At ES, the SDF dips 70° to 80° to the north and controls the mineralised occurrences surrounding the ES deposit. [Moul and Witherly 2017].

A variety of geophysics, including one of the first commercial Falcon (airborne gravity gradiometry) surveys were used to help define the Santo Domingo deposit (Moul and Witherly 2017). Ground TEM was trialed and parts of the mineralized system were noted to be conductive. Subsequently, when Capstone Mining had acquired the property, VTEM and ZTEM were both trialed over the deposit and strong EM responses were noted over two of the three zones that form the deposit. An image of the VTEM results is shown in Figure 27. As the deposit has not been developed, it is not clear if deeper conductive zones are present but with conductive zones at a shallow depth, it is expected this character would persist with depth.
Figure 26: District geology of Santo Domingo deposit-Daroch 2011.
Figure 27: VTEM results over Santo Domingo; deposits outlined with white lines-Moul and Witherly 2017.

Olympic Dam-South Australia

Geology: [summarized from Porter 2012] Olympic Dam and all of the other significant known IOCG mineralized systems of the Mesoarchaean to Mesoproterozoic Gawler Craton are hosted within Palaeo- to Mesoproterozoic rocks, and are distributed along the eastern rim of the currently preserved craton to define the Olympic IOCG Province. Olympic Dam lies below the Neoproterozoic Stuart Shelf, where >300 m of flat lying, barren, Neoproterozoic to lower Palaeozoic sedimentary rocks unconformably overlie
both the craton and the ore deposit. Some 75 km to the east, this cover sequence expands over the major NNW trending Torrens Hinge Zone at the edge of the craton, into the thick succession of the north-south aligned Neoproterozoic Adelaide Geosyncline rift basin, that masks the mid- to late-Palaeoproterozoic suture between the Gawler craton and Palaeo- to Mesoproterozoic Curnamona Province to the east.

Mineralization at Olympic Dam is hosted by the 50 km$^2$ Olympic Dam Breccia Complex (ODBC) that is developed within the Mesoproterozoic (1600 to 1585 Ma) Roxby Downs Granite. The Roxby Downs Granite is a pink to red coloured, undeformed, unmetamorphosed, coarse to medium grained, quartz-poor syenogranite with A-type affinities that is petrologically and petrochemically similar to granitoids of the Hiltaba Suite. Other lithologies within the ODBC comprise a variety of granite- to hematite-rich breccias, sedimentary facies, felsic/mafic/ultramafic dykes, volcaniclastic units, basalts and their altered/mineralized equivalents. The ODBC and the surrounding Roxby Downs Granite form a local basement high on a broader regional basement uplift.

The better mineralization and strongest alteration outside of the barren core corresponds to the best-developed hematite-granite breccias. The concentric, moderate to steeply inward dipping breccia zones of the ODBC are cut by a convoluted, but overall roughly horizontal, ~50 m thick layer characterised by chalcocite and bornite, ~100 to 200 m below the unconformity with the overlying Neoproterozoic cover sequence. Both the upper and lower margins of this zone are mappable. Above the upper margin, sulphides are rare and little copper mineralization is found in the same hematitic breccias. The lower margin marks a rapid transition to chalcopyrite, which decreases in copper grade downwards, corresponding to an increase in the pyrite:chalcopyrite ratio. While this zone is largely horizontal, as it approaches the central barren core it steepens markedly, but is still evident at depths of >1 km below the Neoproterozoic unconformity. A deposit scale geology map is shown in Figure 28.

Gravity was a key vectoring tool for the discovery of the Olympic Dam deposit (Esdale et al. 2003) and while DC resistivity and EM techniques were applied, the complexity of the conductivity associated with the deposit geology and host and cover rocks meant the EM approach was of limited value. However, subsequent work of a more regional nature in the Gawler Craton that hosts the Olympic Dam deposit shows a conductivity structure deep within the earth that researchers now believe is the ‘foot print’ of the mineral system that created the Olympic Dam deposit. This is illustrated in Figure 29. While an attribution is given to Heinson et al. 2006, the work is a composite of university, government and private sector carried out over a number of years.
Figure 28: Geology map of Olympic Dam-Reynolds 2000.

Figure 29: Composite image of MT and seismic with 3D magnetic modeling-Heinson et al. 2006.
SUMMARY

The geological model used to guide exploration for porphyry copper-gold deposits has not changed significantly since 1970 with the seminal Lowell and Gilbert article (Lowell and Gilbert 1970). This paper, while very significant, is not an exploration targeting discussion; this the authors left for others to develop. Geophysical case studies of porphyry systems have tended to accept the model ‘as is’ and aim to define how a particular situation matches a theoretical model. It is estimated that 95% of the geophysical literature until 10 years ago focused on IP and magnetics as the main techniques used to explore for porphyry copper systems. Starting 10 years ago, a modern AFMAG system (called ZTEM) began commercial surveying and early work showed that this technique could delineate large scale intrusive systems quite effectively of the variety typical of porphyry copper deposits. While not as sophisticated as the MT technique, ZTEM helped regenerate interest in EM for porphyry copper exploration and more MT alone or MT + IP surveys have been commissioned since then. Also, legacy MT data, often ignored in the past, is now being reprocessed to see what geoscience information may have been missed when first collected.

The results presented here show that in a number of cases, porphyry systems have a component termed GAFs which are sulfide distributions which reaches concentrations which are high enough to warrant being called a ‘massive sulfide’, at least in the geophysical sense that this mineralization is likely responsive to EM techniques (or DC resistivity if shallow enough). As not every porphyry possesses a GAF, this attribute might be considered geologically exceptional or an “anomaly”. However, in this review, six widely dispersed deposits show a conductive feature amenable to be mapped with EM. In a number of the cases as well, MT would be the preferred technique due to the depth of potential EM feature or complexity of the response.

Apart from an apparent geophysical success story, these conductive zones are often representative of higher grades of economic mineralization and hence present a means to ‘up-grade’ a deposit’s economic status. The Casino example is a good such illustration. The likelihood of this remote, large tonnage, low grade system being developed as an open pit operation is quite unlikely. If however, the conductive zone located with the MT were of 15-25 Mt and had a copper grade of 2-3%, it could possibly sustain an underground operation.

A better geological understanding of GAFs should hopefully allow a means to predict the likelihood of a GAF being present as part of a Por Cu-Au-Mo system.

The IOCG population examined was half the size of the available porphyry copper studies. However, while not examined in detail, a number of other deposit examples were reviewed and suggested that there may be more variability in the IOCGs style of deposits regards whether a conductive zone associated with higher sulfides is present. In the Iron Belt of Chile two examples were defined, but the Carajás and Gawler Craton examples are less clear that they have a direct conductive component which could be mapped with MT.

The MT results from Olympic Dam area suggests EM mapping can be important at the terrain scale where the problem first is to define if a deposit footprint can be defined prior to even knowing if an actual deposit was formed and preserved.

Ken Witherly/September 21, 2018
REFERENCES


Bournas N. and Thomson, D., 2013, Case history of Santa Cecilia Deposit, Chile ORION 3D DCIP-Mt and CSAMT surveys. Commercial publication.


Heinson, G.S., Direen, N.G. and Gill, R.M., 2006, Magnetotelluric evidence for a deep-crustal mineralizing system beneath the Olympic Dam iron oxide copper-gold deposit, southern Australia; Geology; July 2006; v. 34; no. 7; p. 573–576; doi: 10.1130/G22222.1; 2 figures.


O’Brien, N., 2017, Candelaria: An example of Successful resource development; Renovation Chile Explore Congress, September 2017


Porter, M., 2012 Update on Olympic Dam, Porter GeoConsultancy.


Witherly, K. and Hoschke T., 2017, Compilation of Aeromagnetic and Other Geoscience Data for Porphyry Copper Deposits, CAMIRO Project 205.

Witherly, K., Thomas, S., and Sattel, D., 2018, New riches from old data; a revaluation of legacy data from the Casino Deposit, Yukon; KEGS-PDAC Workshop March 3, 2018, Toronto Canada.

Xstrata Copper, 2006, Analysts Presentation, Collahuasi JV, November 2006