ASEG-PESA 2015
Geophysics and Geology together for Discovery
24th International Geophysical Conference and Exhibition
15–18 February 2015 Perth, Western Australia

Geophysical Response of the Atlántida Cu-Au Porphyry Deposit, Chile – An Undercover Discovery in an Old District

Matthew Hope
First Quantum Minerals
Santiago, Chile
matthew.hope@fqml.com

Steven Andersson
First Quantum Minerals
Santiago, Chile
steve.andersson@fqml.com

SUMMARY

The discovery of the Atlántida Cu-Au-Mo porphyry deposit is a recent example of exploration success under cover in a traditional mining jurisdiction. Early and appropriate acquisition of geophysics was a key tool in the discovery and in guiding resource definition drilling through the lifecycle of the project. Close review of the geophysical response of the deposit with respect to its lithological distribution and petrophysical properties has allowed it to be fully characterised despite no mineralisation being exposed at surface. Data acquired over the project includes induced polarisation, ground and airborne magnetics, gravimetry and petrophysics.

The distribution of the key lithologies is demonstrated to be readily defined via a combined application of susceptibility and density properties, which agree well with geophysical data acquired at surface. This is in contrast to the electrical properties which instead map the extent of mineralisation associated with the hydrothermal system via chargeability, and the location of copper bearing sulphides via resistivity

In combination these characteristics can be used to infer depth to exploration targets and potential for high grade mineralisation in a geological context. Future exploration will be increasingly reliant on the understanding of the surface manifestations of buried deposits in remotely acquired data. This review summarises the application and results of these principles at the Atlántida project.

Key words: Atlántida, porphyry, petrophysics, discovery

INTRODUCTION

The steady decline in exploration discovery rates and the increasing exploration maturity of traditional mining jurisdictions (Schodde, 2013) is increasingly leading to exploration for mineralisation at depth. Often for deposits with little or no direct indications of mineralisation at surface. Indirect detection techniques including geophysics that allow the explorer to probe beneath cover have a key role to play in many future discoveries. Increased understanding of the geophysical response of blind mineralised systems at all scale and in geological context will be critical in focus for exploration, and to ensure the limited dollars are invested in the best opportunities. The Atlántida porphyry Cu-Au-Mo deposit presents the opportunity for such a study with geophysical data playing a key role in the discovery in a mature, covered terrane. The project has also been covered by range of geophysical techniques including magnetics, induced polarisation and ground gravity. These data coupled with availability of diamond core to allow petrophysical measurements will be discussed in this review.

LOCATION & REGIONAL GEOLOGY

The Atlántida project is located 60km north east of the traditional mining centre of Copiapo, in the Atacama Desert of Northern Chile, at an altitude of 1700m above sea level. Other major copper-gold projects in the vicinity include Carmen and Inca de Oro, 15 and 25km to the North West respectively. These deposits are thought to represent a belt of Upper Cretaceous porphyry style mineralisation. Evidence of small scale historical workings for gold and base metals are common throughout the region.

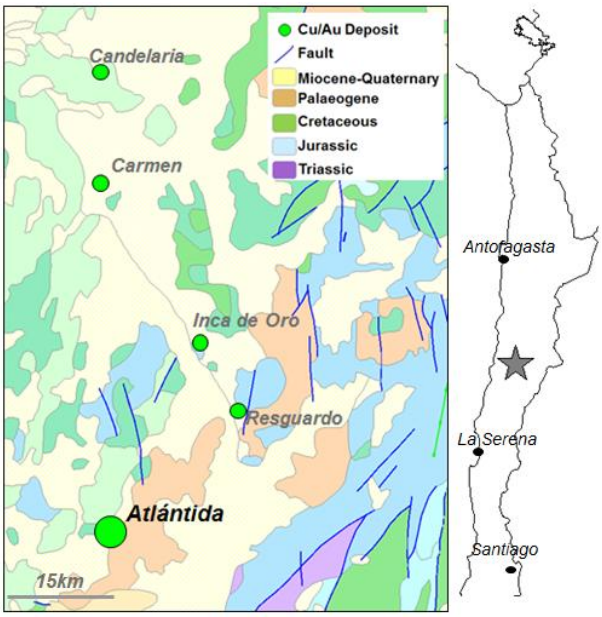

Figure 1. Simplified regional geological map summarised from 1:1 million scale Sernageomin mapping with significant copper deposits

The district geology is described by Matthew et al (2006) and summarised here as dominated by Jurassic to Palaeocene volcanic and volcanosedimentary packages broadly younging to the east. These packages are overlain by a characteristic Miocene to Quaternary gravel cover, infilling valleys between exposed hills giving rise highly variable degree of exposure of underlying sequences (Figure 1). Mapped faults in the region dominantly trend North-South whilst arc oblique structures can be inferred from remote sensing and geophysical data sets.

DISCOVERY

Discovery of significant Cu-Au porphyry mineralisation at Atlántida was made by the Inmet Chile exploration team during 2011. The project potential became clear after review of work by previous explorers which had focussed attention on adjacent outcropping skarn mineralisation with limited success. Despite this focus previous explorers had collected induced polarisation surveys over the project which identified a large chargeability anomaly located entirely under post-mineral gravel cover.

Historical drilling revealed that the chargeability anomaly starting from 150m-200m below surface had been essentially untested. Nearby drill holes having terminating in low grade mineralisation within argillic altered tonalite porphyry. In response to this an aggressive program of geophysics and drilling was initiated by Inmet from 2010-2012 with initial drilling based largely on the footprint of the induced polarisation and magnetic data. This drilling confirmed the existence of a significant, entirely covered Cu-Au-Mo porphyry deposit, with distinctly zoned mineralisation by style (Table 1). The project remains open at depth and with potential extensions to the south.

Type	*M Tonnes*	*Cu %*	*Au g/t*
Porphyry Cu-Au	257.5	0.25	0.21
Porphyry Au	130.5	0.06	0.53
Skarn	39.1	0.3	0.62
TOTALS	**427.1**	**0.2**	**0.34**

Table 1, Preliminary resource estimation from 38 drill holes (Andersson, 2012)

DEPOSIT GEOLOGY

The deposit mineralisation footprint as defined to date is approximately 1.5 x 1km elongated to the NNW and entirely obscured at surface by relatively shallow gravel cover of 25-80m (Figure 2). Two main intrusive phases can be recognised and host the bulk of the mineralisation by volume. The earliest intrusive phase has a tonalitic composition and is thought to be pre-mineral. This is in turn intruded by a granodiorite, feldspar rich porphyry phase, the contact zones between these phases is variably brecciated, with the brecciation most intense and extensive within the tonalite. The intrusive phases are hosted by a package of intermediate volcanic and limestone units. Where the limestone is found in contact with the intrusive phases, contact alteration is present in the form of epidote-chlorite-calcite-magnetite/specularite skarns. These skarn are important as they carry volumetrically significant, higher grade and shallower mineralisation. A plan of the distribution of major units is given in figure 3.

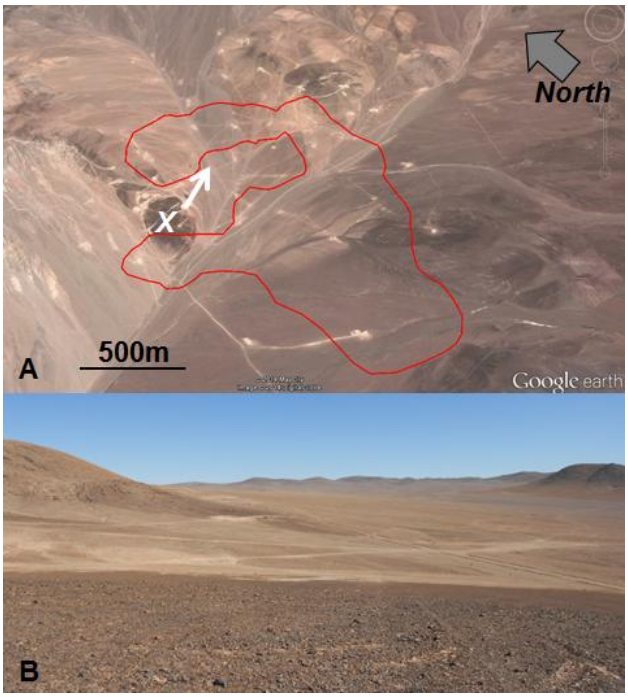

Figure 2. A: Remote sensing image with copper ore shell projected to surface. White "X" marks location of photo B. B: Photo taken looking NW over the buried porphyry complex from low lying skarn outcrop.

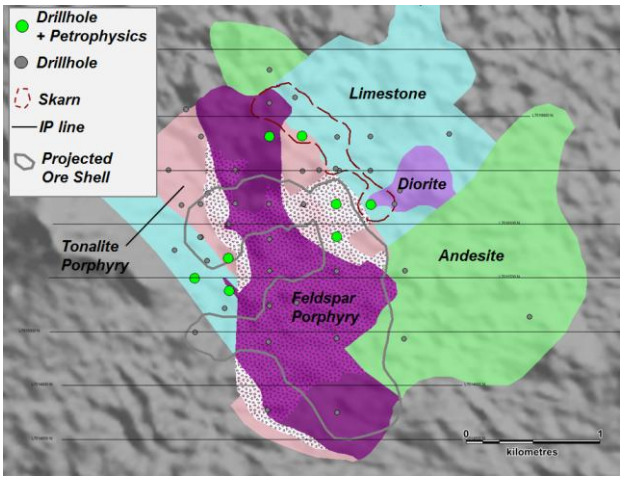

Figure 3. Deposit scale basement geology map with drilling coverage and location of petrophysically sampled holes

Alteration assemblages and distribution follow the classical zonation as proposed by Sillitoe (2010) and others. High level argillic alteration makes way to a phyllic alteration as defined by presence of sericite that appears to be retrograde over a potassic core of biotite dominant style. Potassic alteration is best developed in the feldspar porphyry, and seen only at depths greater than 500m. Lateral development of propylitic alteration, whilst poorly tested appears relatively spatially restricted and possible fault bounded as defined by presence of chlorite.

The bulk of the porphyry style mineralisation commences from 300m below surface and is associated with locally intense

stockwork veining. Mineralisation occurs mostly in association with disseminated and vein hosted pyrite with chalcopyrite being the dominant copper ore mineral. Overall sulphide abundance in the feldspar porphyry is 7-12%. This is significantly lower in the tonalite porphyry with the exception of the brecciated zones, which have abundant fine pyrite in the matrix. High grade Cu-Au mineralisation is associated with the skarn altered limestone units. These units have highly variable sulphide content from 1-60% pyrite in association with chalcopyrite blebs. Importantly, skarn style mineralisation has been encountered significantly shallower than the porphyry mineralisation, from depths of ~150m.

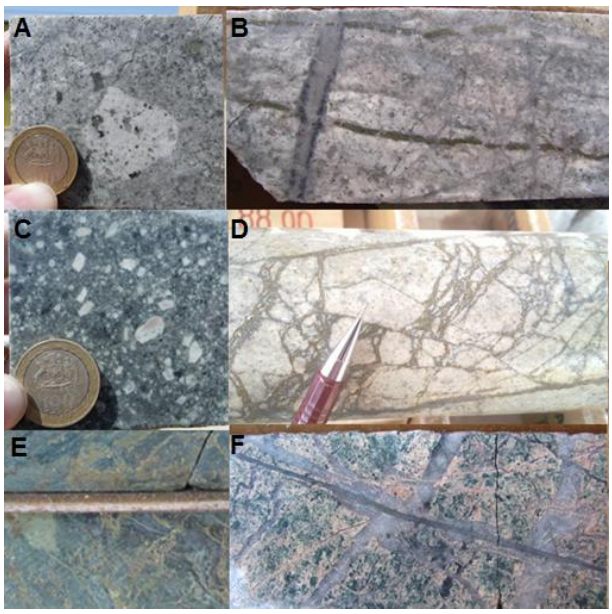

Figure 4. Representative samples from the Atlántida deposit. A: Tonalite porphyry. B:Retrograde phyllic alteration of feldspar porphyry with quartz-molybdenum veins. C: Granodiortic feldspar porphyry. D: Monomictic jigsaw fit tonalite breccias with abundant pyrite as fracture fill E: Sulphide rich skarn. F: A and B vines in potassic altered feldspar porphyry (Andersson, 2012)

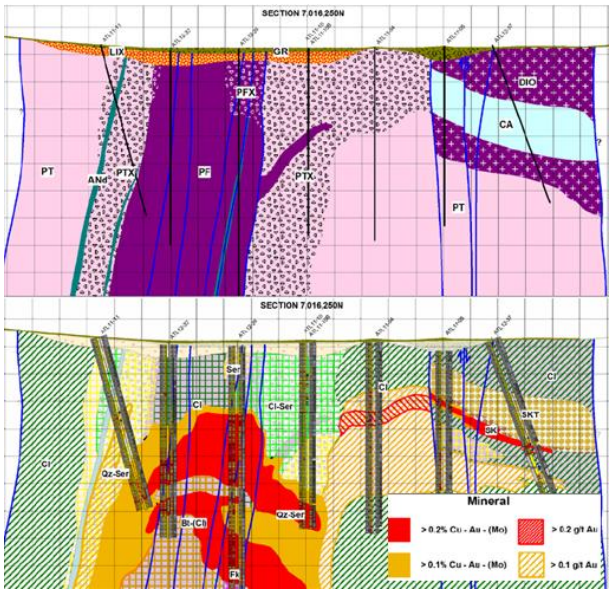

Figure 5, Type section through deposit. Top: Lithology. Bottom: Alteration and mineralisation

GEOPHYSICAL SURVEYS & RESULTS

The Atlántida project has benefitted from a series of geophysical programs. Early induced polarisaiton lines in 2008 first alerted exploreres to the potential of the prospect, this initatied further large programs of ground magnetics and induced polarisation by Inmet Chile. After the purchase of Inmet Mining by First Quantum Minerals further studies have been conducted including; regional airborne magnetic radiometric surveys, ground based gravity programs and petrophysical acqusition. A brief summary of these programs is given in table 2.

Year	*Survey*	*Deposit Response*
2008	PDIP(details unknown)	Identification of large anomaly unexplained by existing exploration or outcrop
2012	Ground Magnetcs (100m spacing)	Magnetic Low defining porphyry phases flanked by local, intense highs associated with skarns and intermediate volcanics.
2012	PDIP (100m dipoles)	Elevated chargeability defines footprint and depth of system. Low resistiivty closely assocaited with higher grade porphyry positions.
2013	Airborne Magnetics (200m spacing)	Mapping of lihological domains and potential alteration centres under cover. Interpretation of fault system orientations and targeting.
2014	Ground Gravity (200-400m)	Strongly eleveated response associated with skarn positions with a subtely elevated response associated with the intrusive phases.

Table 2, Summary of geophysical programs completed. PDIP=pole dipole induced polarisation

Electrical Methods

A program of 43 line kilometres of induced polarisation spaced at 400-500m and using 100-150mm transmitter and receiver dipoles was a key to understanding the covered system. The envelope of sulphide mineralisation was defined with respect to its lateral footprint and depth to top via chargeability. A response >14 mV/V has been found to represent the system margins as currently understood, whilst the copper ore shell is closer mapped by a region of >25 mV/V. These anomalies are present within 150m of surface and continue to bottom of inverted sections with an inferred depth of penetration of 300-400m.

Resistivity data also added considerably to drill targeting. Two anomalously low resistivity zones are noted. A near surface zone which is related to saline water in gravels and a second zone noted at the base of the sections. This zone has been found to be closely associated with the copper ore shell footprint both on a deposit and drill hole scale. A coherent anomaly extends to the south at depth and remains untested. This region is outside of the attendant chargeability anomaly but may suggest superior penetration of resistivity data. The host sequences are mapped as low chargeability and moderate to high resistivity giving rise to strong contrast.

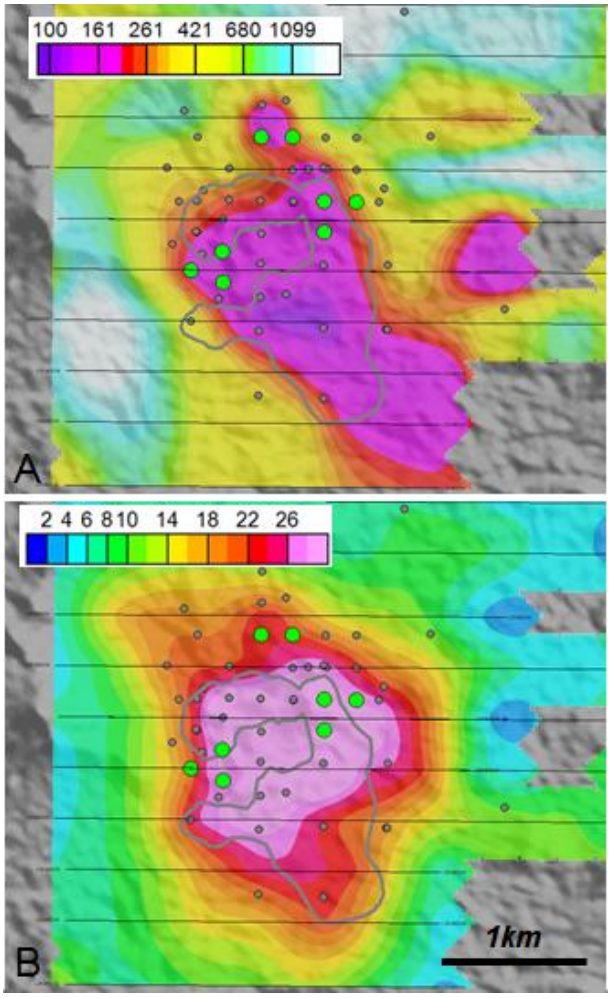

Figure 6. Plan maps interpolated from pole-dipole induced polarisation survey at 1400mRL level, approximately 300m below surface level. Legend from figure 3. A: Resistivity map. B: Chargeability map

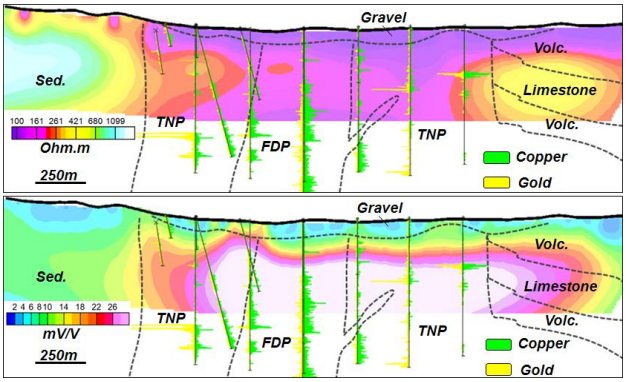

Figure 7. Inverted sections with downhole copper and gold grades and summary geology. Top: Resistivity. Bottom: Chargeability. Image duplicated at end of extended abstract for clarity.

Potential Fields

Whilst electrical techniques have been highly effective for direct targeting under gravel cover, potential field techniques have also been applied successfully to improving geological context of the prospect for regional interpretation and targeting. Ground magnetic data was collected across the tenement area using continuous sampling on 100m spaced lines. The deposit response is a central magnetic low fringed by a number of discrete high intensity localised magnetic anomalies. Spatially the low feature correlates well with the position of the porphyritic intrusive rocks, whilst the magnetic highs are closely linked to skarn alteration within limestone units with an intensity of up to 720nT. Host rocks to the deposit show a variable response but are typically elevated to the east where intermediate volcanics dominate and more subdued to the immediate west where sedimentary units are more common. Abrupt changes in magnetic intensity and texture correlate well with fault boundaries and changes in cover depth.

Recent acquisition of ground gravimetric data was completed as a trial using 200m-400m station spacing's centred over the deposit. The resulting complete bouguer anomaly required significant processing to effectively remove the high intensity regional. The resulting residual anomaly shows subtle anomalism with a range of ~3mGal across the survey area. Despite the subtlety of these anomalies a strong correlation exists between strong local highs of +1-2mGal and the position of skarn alteration. The porphyry intrusives themselves appear linked to a subtle but continuous positive gravity anomaly, this is clearly differentiated from the host sequence which relates to neutral or negative gravity features. Increasing gravel cover to the south results in a progressively more subdued response.

Combining these potential field data allows ready discrimination of the preferential host units from surrounding host rock and further differentiation of skarn alteration from magnetic volcanic packages. This utility is crucial in interpreting the basement lithologies and significantly enhances application of regional potential field datasets, which are much more costs effective the electrical methods for large areas.

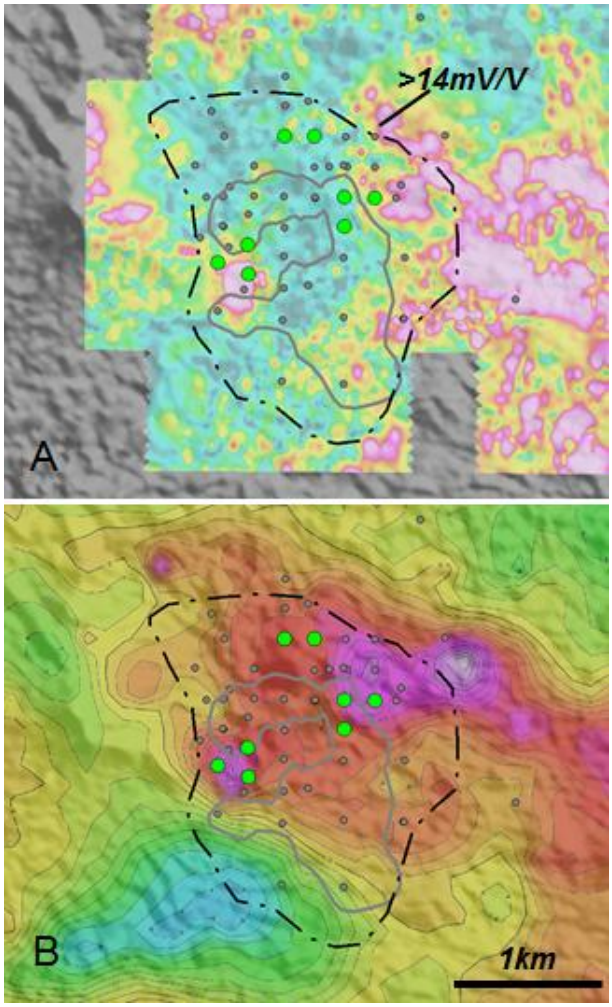

Figure 8. A: Analytical signal filtered ground magnetic data with projection of ore shell and chargeability footprint. B: Residual gravity image (0.1mGal contours)

PETROPHYSICS

Due to the absence of systematic magnetic susceptibility capture and to confirm existing interpretations a petrophysical program has been commenced. The program was designed to select representative samples from across the deposit of the various lithologies, alteration and mineralisation styles. The program is comprised of 68 samples and measurements are completed using in house petrophysical equipment including SM30 magnetic susceptibility meter, high precision scales and a GDD SCIP Electrical Tester for chargeability and resistivity properties. At the time of writing only susceptibility and density readings have been completed.

Lithology	*Susceptibility (SI x10^{-3})*	*Grain Density (g/cc)*
Tonalite Porphyry	0.09	2.70
Feldspar Porphyry	2.31	2.69
Skarn	16.46	3.07
Volcanics	23.00	2.62

Table 3, Summary petrophysical properties shown as mean values of susceptibility and density

Petrophysical results strongly support the interpretations to date, with each major lithological group plotting in discrete zones with relatively little overlap on a susceptibility/density graph (Figure 9). This allows interpretation of buried basement lithologies with a high degree of confidence. Skarns are found to be the highest density unit in the deposit with a mean of 3.07g/cm^3 whilst the porphyritic intrusive units are slightly elevated from the background with 2.69-2.7g/cm^3 against a value of 2.62 g/cm^3. Importantly the tonalite porphyry shows two populations in response to degree of brecciation, whilst the feldspar porphyry has very low density variability.

Magnetic susceptibility data when viewed collectively shows only small variation with the feldspar porphyry, appearing to have a modestly elevated magnetic intensity in comparison to the tonalite porphyry 2.31 and 0.09 SI x 10^{-3} respectively. However when viewed in detail the distribution of the feldspar porphyry is zoned according to alteration type. Deeper samples with preserved potassic alteration record susceptibility values on the range of 10-20 SI x 10^{-3}, in contrast to retrograde phyllic alteration which has resulted in essentially non-magnetic samples.

Comparison of petrophysical properties with both copper and gold grade also has the potential to provide insight to drill hole targeting on the prospect scale. Figure 10 shows copper by way of example. These data suggest that mineralisation does not directly have a significant impact on the susceptibility or density with results tending to cluster according to lithology irrespective of grade. Clearly here the electrical properties of the rock may be more directly applicable, with some strong correlations inferred from sulphide percentages in mineralised samples.

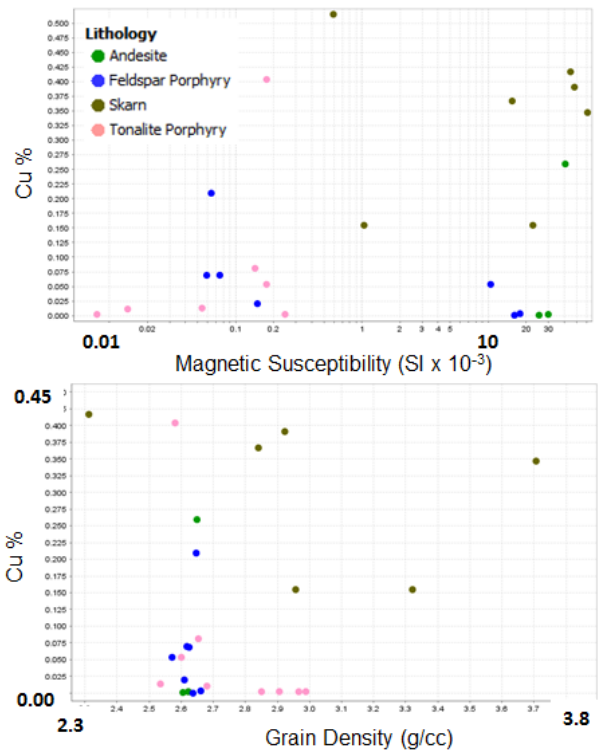

Figure 10. Copper grade against magnetic susceptibility and density coloured by lithology taken from core measurements

CONCLUSIONS

Integrated application of geophysical techniques with geological understanding and petrophysical measurements are a key pillar to successfully exploring, cost effectively testing and characterising blind deposits. As the collection of these data increases across exploration projects recognition of deposits signatures will improve and success rates presumably increase. These concepts are underpinned by a robust understanding of the geological controls on emplacement and mineralisation style.

The Atlántida project demonstrates the application of cost effective geophysical programs to assist in designing drill programs for resource definition, exploration targeting or sterilisation of satellite opportunities under cover. Petrophysical programs should be carried out early in the exploration pipeline to ensure geophysical data is fully leveraged and integrated with potentially significant costs savings.

The project also illustrates how different parts of a mineralised system may respond and be discriminated by differing techniques and the need to view geophysics holistically rather than a series of discrete projects to ensure optimal interpretation. Once appropriate techniques have been defined these can be applied regionally to pre-existing datasets.

REFERENCES

Andersson, S., 2012, Atlantida, A New Cu-Au Porphyry Skarn Discovery in a Known Belt, Atacama Regiona, Chile, Mexico Explo, Mexico City.

Matthews, S., Cornejo, P and Riquelme, R., 2006, Carta Inca De Oro, Region De Atacama: Carta Geología de Chile, Escala 1:100,000, No.102.

Schodde, R., 2013, Long term outlook for the global exploration industry – Gloom or Boom?: Geological Society of South Africa GeoForum 2013 Conference, Johannesburg.

Sillitoe, R., 2012, Porphyry Copper Systems, Economic Geology, Volume 105, pp 3-41.

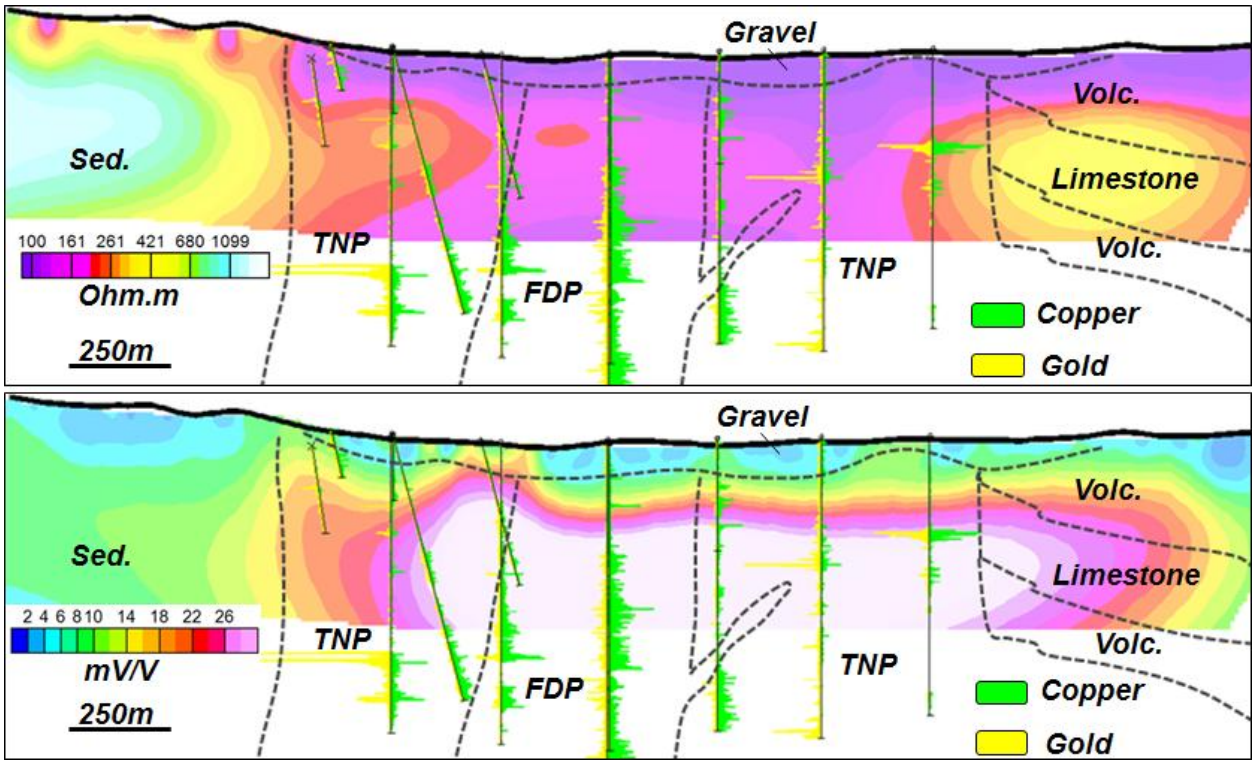

Figure 7. Inverted sections with downhole copper and gold grades and summary geology. Top: Resistivity. Bottom: Chargeability.

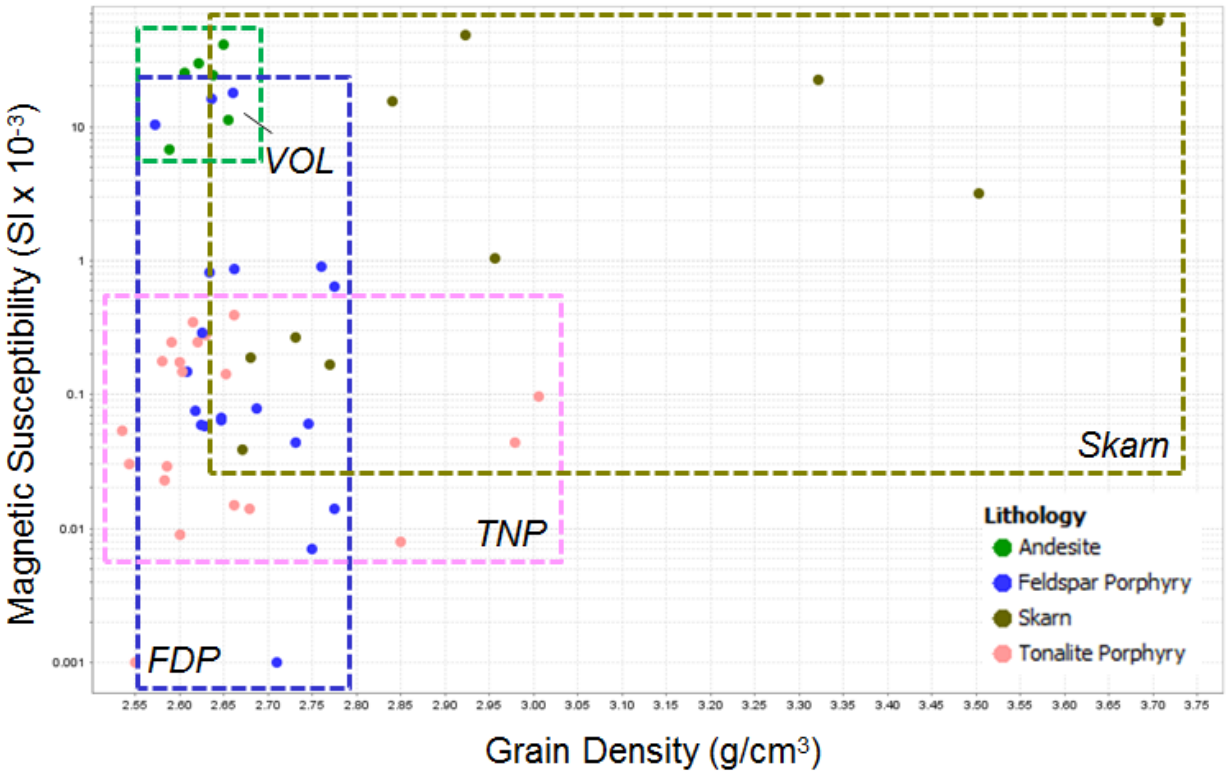

Figure 9. Grain density and susceptibility values from core measurements define clear lithological domains