Multiscale Integrated Interpretation Leading to Exploration Success Under Cover: A Case Study from Northern Chile

Hope, M. [1], Farrar, A. [1], Ireland, T. [1], Jones, S. [2]

1. First Quantum Minerals Exploration (Chile), Apoquindo 4445, Las Condes, Santiago, Chile
2. University of St Andrews, Irvine Building, North Street, St Andrews, Fife, KY16 9AL, United Kingdom

ABSTRACT

The search for giant ore deposits is moving into ever more challenging environments, with lack of exposure and more cryptic mineralisation signatures likely becoming characteristics associated with the next wave of major discoveries. This exploration reality demands a modification of traditional exploration approaches and increasing integration of diverse data to maximize the opportunity of discovery success. Research continues to uncover new understanding of these cryptic signatures, however this is unlikely to deliver us the silver bullet. Fortunately for the exploration geoscientist, the abundance of quality datasets at multiple scales, in addition to high quality and user friendly 3D visualisation tools, means we are better placed than ever to respond to these challenges by optimizing what we already have via fully integrated interpretation.

The Greater Victoria District (GVD) is a largely covered project area located in the world-class porphyry-Cu mineral province of the Domeyko Corridor, Northern Chile, and provides an ideal case study of integrated interpretation at multiple scales in a mineral system framework, leading to discovery of a large, mineralised, magmatic hydrothermal system. Chile is blessed with quality regional datasets and the GVD has been subject to near continuous mineral exploration for over 20 years. This work has left a wealth of geoscientific information for future explorers to utilise and is representative of many projects in highly prospective districts. All the historical data from regional satellite gravity and Landsat data down various scales to available historical drillhole assays and fluid inclusion work have been interpreted collectively and combined within 3D visualisation software wherever possible.

This review was interpreted in tandem with traditional field mapping of sparse outcrop and available drill spoils left at surface. This allowed planning of targeted data acquisition to answer key geological questions flagged by the process and ensure the relevant characteristics of the mineral system could be inferred. The resulting information, when integrated in 3D, allowed recognition of a large, previously untested anomalous zone, interpreted to reflect a hydrothermal alteration system with potential for a giant ore deposit. Recent exploration drilling of this covered target known as Pampa Vaquillas confirms a previously unknown, mineralised hydrothermal system, located in one of the world’s premier mineral belts. A highly integrative and mineral systems driven approach to the geoscience datasets has led to this exciting exploration result.

INTRODUCTION

The application of mineral systems to exploration strategies calls for a focus on critical processes in the formation of ore systems at various scales and is outlined in detail by McCuaig et al. (2010). The critical processes of source, pathway, throttle, trap and preservation need be considered at appropriate scales, from regional to target and within the context of the mineral system sought. The focus of this exploration methodology encourages identification of interpreted proxies for critical processes in our available geoscience datasets. The integration of these interpretations allows for a holistic and flexible targeting approach, especially when combined with the more traditional deposit model and direct detection driven exploration processes.

The Pampa Vaquillas prospect is located within the highly prospective Domeyko Corridor of northern Chile, approximately 130 km south of the giant La Escondida deposit (Garza et al., 2001), and 100 km north of Codelco’s El Salvador mine (Gustafson et al., 2003). The prospect is located within a large tenement group, explored by First Quantum Minerals (FQM) under a series of joint ventures and commercial option arrangements, known internally as the Greater Victoria District (GVD). This district is considered highly prospective for Eocene-Oligocene porphyry copper deposits and has been subjected to near-continuous mineral exploration by various explorers, targeting various commodities, including Cu, Au and Ag for over 20 years (Figure 1).

Securing exploration access over this large ground-holding exhibiting significant post mineral Miocene gravel and ignimbrite cover, poses as an exciting exploration opportunity. At the project scale, its lack of outcrop exposure, along with an extensive exploration history and attendant geoscience datasets, lends itself well to a highly integrated mineral systems approach. Exploration activities conducted by FQM at the GVD have led to discovery of the Pampa Vaquillas prospect, and characterization of an associated large hydrothermal alteration cell. The prospect is entirely covered by gravel and ignimbrite deposits of 50–200 m thickness and remains in the early exploration stages. This paper attempts to highlight the focus on integration of data in a mineral systems context at various
scales. The Pampa Vaquillas experience is used to illustrate the methodology and identify learning and both positive and negative aspects throughout the process. Where possible the application of 3D visualization and new or evolving exploration technologies will be discussed, however the focus of this paper will remain on optimization of relatively common and accepted datasets within an integrated framework.

**CONTINENTAL SCALE**

Major trans-continental cross-arc lineaments are, at times, a point of debate across the industry as to their geological meaning and significance for ore formation. Despite this, these features often display a strong spatial relationship with major ore deposits of various styles (Bourne and Twisdale, 2007). They may be observed in available datasets as an alignment of geological features and can often be composite in nature, composed of a number of lines of evidence. These structures have long been recognized in northern Chile, as a set of dominantly north-west trending lineaments, and the GVD straddles one such structure known as the Culampaja Lineament (Figure 1). Importantly the Escondida and El Salvador deposits are also located at the approximate juncture of the north-south oriented Domeyko Fault Corridor and major lineaments (Richards et al., 2001). The near fractal distribution of these lineaments and associated deposits can be readily observed at the regional scale (Raines, 2008). This draws attention to the GVD, which sits within a gap where no major porphyry copper system has yet been discovered, despite known fertility of the corridor.

**REGIONAL SCALE**

Favourable loci for emplacement of mid crustal stocks can be determined at the regional-scale, leading to identification of associated porphyry systems (Sillitoe, 2010) and a focus for exploration areas. Defining these areas is an interpretive process, made all the more challenging by the relatively low abundance of outcrop in northern Chile. Key criteria which are thought to be indicative of favourable emplacement sites include major cross-arc structures, direct evidence for intrusive units of prospective ages and deep-tapping, reactivated normal structures. In all cases, interpretations should consider these processes dynamically with consideration to the geological setting at the relevant mineralisation age. These criteria in many cases must be interpreted via application of proxies, which can be mapped from other datasets. Chile, like many high quality exploration districts, is fortunately blessed with a large amount of geoscience data, including geological maps, geophysics and geochemistry. Many of these data are either freely available or may be accessed or collected for a modest cost and time commitment.
The regional analysis conducted by FQM covered a vast region of northern Chile from south of El Salvador to north of Quebrada Blanca. The focus of this work was identifying large-scale structural plumbing and evidence of good source rocks. Key datasets for this regional interpretation included: geological map sheets, of various scales, made available by Sernageomin, in-house geochronology compilations, and mapped structures. This surface-based information was then combined with interpretations of available geophysical data. This reduced the bias toward outcropping areas and led to defining new covered terranes as target areas. Datasets included digital elevation models, airborne magnetics and gravity (Figure 2). Gravity data was obtained from the EGM2008 gravity model (Pavlis et al., 2008). Isostatic correction of gravity data allows a view of fundamental deep structure and geological domains, which may not be evident when viewing surface geological maps.

The contention of the mineral systems approach is that the absence of a given critical process significantly reduces prospectivity (McCuaig et al., 2010). This is a powerful concept in regional exploration, but must be tempered by our imperfect ability to map or understand all the critical processes required at the time of formation. The generative team at FQM created a prospectivity map to better understand the mineral system and its components. This approach, as described by Czarnota et al. (2010), attempts to reduce user bias and generate a prospectivity map across the region of interest.

The resulting prospectivity map derived from Fathom Geophysics Georithm software (Core, 2015) is shown for an area extending from south of El Salvador to Escondida in Figure 3. It resulted from various model iterations. Mineral deposits and occurrences were not used as a direct input to this map, to address the natural tendency for results to be biased toward outcrop. The map highlights three favourable domains: two are associated with the known large systems and the third is roughly centred on the GVD. The influence of the Domeyko fault zone is apparent, as are cross-arc features which may act to localize stock emplacement. Known systems are captured within some of the highest ranking zones, including El Salvador and Escondida.

Application and implementation of such a prospectivity map is highly iterative in nature. Field reviews both positive and negative are fed back into the interpretative inputs as knowledge is gained or new data encountered to refine results. Ranking and prioritization within the defined areas of interest may be achieved via review of direct evidences. Such as mineral deposits, occurrences and alteration mapping achieved via processing of remotely sensed data.

Figure 3: Prospectivity analysis output based on mineral system critical elements at the regional scale. Note that both El Salvador and Escondida are located within anomalous zones and that the Greater Victoria District marks a third area of interest.

**PROJECT SCALE**

At the project scale of the Greater Victoria District (approximately 50 km x 50 km), the exploration for porphyry copper turns towards more tangible porphyry evidence under the gravel plains (Figure 4). The related criteria include: identification of favourable exposure levels; evidence of large-scale hydrothermal processes; long-lived multi-cyclic magmatism; and mineralisation. As with many mature exploration projects historical data compilation was required and was conducted during the first phase of exploration. In this case, these data required significant time investment to homogenize formatting due to the large number of various explorationists who had been previously active in the district. This laborious data stage proved essential to allow all data to be effectively integrated into a 3D viewing platform. In many cases, previous exploration datasets were incomplete and/or previous groups were exploring for other deposit styles, with manifestations different to that of a porphyry Cu. Despite this, all available data was interrogated for evidence (or absence) of large porphyry systems.
The data integration process quickly revealed that historical targets and mineralisation centres had been adequately tested. Targeting then turned to identifying undercover opportunities which may be covered by the vast gravel plains that dominate the northern portion of the GVD. Here it was found that known surficial porphyry and epithermal systems and their extensions were being effectively mapped undercover via regional- and line-based induced polarization (IP) surveys. However, the majority of these targets were not of a dimension to suggest a large hydrothermal centre (Figure 5). The exception to this is a very large chargeability anomaly, entirely beneath cover, having dimensions of ~7 km x 1.5 km. This feature initially appeared to have been well tested by drilling when reviewing the drillhole collars. Despite the apparently well-tested nature of the target, it became the focus area for more work due to its large scale. This work included a complete 3D inversion of the combined historical IP surveys using the UBC 3DIP code. Integration of the new results with drilling in 3D visualization packages revealed that historical drilling had failed to reach appropriate depths to intersect the target area, and that the anomaly had the potential to be a very large hydrothermal system. In addition, the anomaly is adjacent to existing epithermal Au-Ag mines and was essentially untested. This result was a significant advancement for the project (Figure 6) and became known as the Pampa Vaquillas prospect.

Much work was still required to convert the Pampa Vaquillas anomaly into a porphyry target. The next phase of field work was initiated with several key objectives: understanding the district-scale structural context; performing geochronology; and reviewing drill spoils left at surface to allow mapping of alteration assemblages beneath cover. Regional-scale structural field mapping was conducted in the deeply incised valleys which cut near perpendicular to the local stratigraphy. Rare marker horizons were then used to demonstrate the overall structural regime is dominantly normal/extensional, with only modest movement associated with compressional reactivation of these structures (Figure 7). No evidence for large-scale strike-slip movement along the strands of the Domeyko fault was observed, in contrast to conclusions proposed further north near the Chuquicamata deposit (Ossandón, 2001). Evidence for strike-slip movement was observed during pit mapping of the historic Mina Vaquillas silver-gold deposit and this locally anomalous structural feature was to prove important later in the program.

Detailed field mapping also led to development of an in-house project-scale stratigraphic column which greatly assisted geophysical interpretations and later interpretation of the drilling results. Systematic review of drill spoils at surface around the target led to identification of quartz-sericite pyrite alteration in shallow RC drilling chips at several locations north of the Pampa Vaquillas zone. These observations elevated the prospectivity of the zone from a simple geophysical anomaly to an apparent footprint of a very large, phyllic hydrothermal alteration cell consistent with the signature of a large porphyry deposit. The observation of abundant pyrite and absence of evidence for leaching or supergene processes were strongly suggestive of hypogene mineralisation and helped to define the primary exploration target. This hypogene-only target style, along with the interpretation of a probable dyke-like porphyry target, has important economic implications on maximum viable exploration depth for a porphyry system.

Targeted geochronological samples were also analyzed by Sernageomin from surface drill spoils. Analysis was performed on sericite via K-Ar methods (Sillitoe et al., 1996). Results confirmed the age of the hydrothermal sericitisation event to be 39.8 Ma +/- 1.4 Ma. This date places the hydrothermal alteration, and thus the likely causative porphyry centre, within the same time window as the adjacent large deposits of the Domeyko fault system, and serves to significantly upgrade the target and its economic potential. This age when combined with the presence of an adjacent Cretaceous porphyry copper system at Picaron, confirms this segment of the Domeyko fault zone to have been associated with porphyry emplacement, at least episodically for a long period of time. This supports the interpretation of a favourable structural regime at the project scale and scope for long lived and/or repeated magmatic centres.
Figure 6: 3D imagery looking down and northeast highlighting the scale of the chargeability anomaly greater than 20 ms based on 3D inversion of historical data. Historical drilling is shown with sulphur % (S_pc) to confirm the target has yet to be intersected; note effective mapping of the Picaron system by the 3D modelling. Molybdenum results from soils are also shown as a grid draped over topography; these results were later interpreted to be associated with shedding from adjacent mudstone units. The ability to visualize all historic data and combine in 3D was key in recognizing scale potential of the system. MT section line 2 is presented in Figure 9.

Figure 7: Structural interpretations taken from rare exposure of Jurassic marker horizons in valleys were used to assess the structural regime at the project scale. Mapped structures show a dominantly extensional history with late and localized reverse movement.
Despite the increasingly favourable indications for a genuine porphyry target at Pampa Vaquillas, the absence of nearby intrusive units within a prospective time window, which could be indicative of a viable source stock, remained a concern from a mineral systems point of view. Additionally, the lack of knowledge about the thickness of gravel cover was a major concern, given the economic sensitivities to depth of most porphyry systems. Geophysical solutions were proposed to assist with answering these questions and providing a complement to existing geoscientific datasets. This led to commissioning the collection of regional gravity and magnetotelluric (MT) data over the Pampa Vaquillas area.

Gravity data was acquired on a 500 m spaced grid across all covered regions and flanking outcrops of the project area. The gravity technique was selected because of the strong density contrast between basement units and the overlying gravel sequences. This contrast results in shallow cover zones being mapped as relative gravity highs, and conversely gravity lows may be indicative of deeper gravel cover. Whilst this relative approach is in itself useful, there remains much ambiguity and a more quantitative approach was required to assist drilling and reducing uncertainty in determining gravel depth. Constrained inversion was used to achieve this objective, and was completed using the VPmg code available from Mira Geoscience within the GoCAD platform (Fullagar et al., 2008).

This data inversion approach is solution-based and allows the user to effectively interrogate available datasets for solutions to posed problems. The available gravity data and district knowledge forms a priori information used to constrain the inversion and reduce uncertainty in the final model, as outlined by Pears and Chalke (2016). These results conform to known basement depth pierce points obtained from historic drilling, whilst also permitting interpretation of lithology from density variations and thus a stratigraphy to be proposed. The final cover and basement models were found to honour both the gravity data and the known geology.

Results of the survey and estimated depth to prospective basement are displayed in Figure 8 together with the distribution of historic drill holes which were used as constraints. Here the depth-to-basement surface is shown as a 2D map for simplicity of visualization, however the 3D output can be readily integrated into project drill planning. The modelled basement depth over the Pampa Vaquillas target was interpreted to be relatively shallow and generally less than 100 m, indicating favourable exploration conditions for economic porphyry-style mineralisation. A rapid deepening of cover gravels was noted to the immediate north of the target area, with cover in excess of 200 m. Based on this model much of the northern gravel cover zones potential for large scale economic mineralisation was downgraded.

The magnetotelluric method, which utilizes the Earth’s natural electromagnetic fields, (Cagniard, 1953) was applied along selected lines over the Pampa Vaquillas area. The power of this technique lies in its capacity to image the deep electrical structure of the earth to great depths. The configuration applied here targeted the upper 6 km – 8 km of the crust in order to map the deeper plumbing, which may be related to a large scale porphyry system. Evidence for the emplacement of a large parental stock and associated hydrothermal and metasomatic alteration processes may also be recognized via their impact on the apparent electrical resistivity of the host rock sequence.

![Image](image.png)

**Figure 8:** Left: Regional gravity data imaging both variable depth of low density cover and changes in basement lithologies. Right: Modelled depth to basement derived from gravity data constrained by drilling, rock exposure and magnetic data.

Results across all lines confirm the presence of a sub-horizontal low resistivity (<100 ohm.m) zone between 3–5 km from surface with an apparent lopolithic geometry. This feature appears to terminate against the inferred position of a major strand of the Domeyko fault system inferred from surface data. This behaviour is considered consistent with that of a batholithic unit utilizing a major fault to allow emplacement into a basin sequence (Figure 9). Whilst it remains unclear what may be the cause for low resistivity associated with this body, the interpretation is it may represent a source stock, which is attractive and consistent with the geometrical relationships proposed by Sillitoe (2010).

Immediately east of the inferred controlling fault and on all lines, a sub-vertical low resistivity body is observed and appears to be located above the interpreted deep-source zone. The geometry of this feature is suggestive of a sub-vertical dyke-like body emplaced into the upper parts of the host sequence. These vertically-oriented, low resistivity features are spatially coincident with chargeability anomalies derived from IP surveys. This spatial relationship suggests they have a genetic relationship to the widespread sericite-pyrite alteration observed in RC samples and may represent metal- and sulphide-rich porphyry intrusive bodies. It should be noted that due to inherent limitations in the configuration of the MT survey, shallow features should be interpreted with relatively low confidence.
The presence of a large-scale porphyry-style hydrothermal alteration system was determined at the prospect scale. The dyke-like bodies are centred on confirmed sericite-pyrite alteration, but could not be readily explained by known local lithologies due to modest post-mineralisation cover. The combining of these data gives rise to the suggestion of an elongated and roughly symmetrical system. Various synthesis maps based on all available data were created in an effort to distil the critical elements of the target. The synthesis maps attempted to convert abstract information derived from geophysics and regional mapping into a targeting concept which honours our understanding of porphyry targets and what is known of the project geology. An illustrative example is given in Figure 10.

Interpretation and Testing

The synthesis maps which focus on highlighting the key mappable criteria derived from the available data led to recognition of two main centres, originally referred to as Vaquillas Norte and Pampa Chaco. These are divided by an inferred northwest trending structural corridor, observable in geophysical datasets and consistent in orientation and location with the inferred Culampaja Lineament (Figure 1). A drilling approach of both diamond and reverse circulation holes was selected to reduce costs, whilst ensuring target depths could be reached in key holes. Once the footprint of the system was determined, the distribution of phase 1 drill holes was designed to ensure complete characterization of any potential system. This approach requires a roughly even distribution of holes, rather than a focus on a particular area or anomaly type. This approach proved to be significant in interpreting vectors to the centre of the system for later drill holes.

Detailed sections were interpreted for all drill holes to clearly outline the conceptual target in a porphyry exploration space; an example is shown in Figure 11. These sections were required to assess whether all available datasets were honoured in a 3D environment and were internally consistent across sections. They served as an important tool to ensure the system was adequately tested, and the objective of each drill hole was clearly understood by the exploration team. Again this conversion from an abstract geophysical target to a more tangible geological concept was useful in allowing the drilling to be conducted dynamically, and based on results as encountered, to assess the respective degree of agreement with the target model.
Results and Reinterpretation

Initial drilling results from the southern target “Pampa Chaco” (Figure 10) were disappointing: intersections of an epidote-pyrite altered intermediate volcanic body were made under shallow cover, which were intruded by fresh magnetite-bearing micro-diorites. These results focused exploration to the northern portion of the prospect. Here an unexpected sequence of high-energy phreatomagmatic and hydrothermal breccias was encountered, terminating in a late diatreme in the extreme north of the prospect, which produced a pronounced topographic low beneath the gravels with >170 m of cover. These intermediate volcanic rocks had been subjected to strong sericite-pyrite alteration throughout. Locally, zones of relict potassic alteration overprinted by chlorite-sericite were observed. Within these zones, porphyry style quartz-molybdenum pyrite veins were intersected at depth before passing through to a skarnified, locally magnetite-rich sedimentary package (Figure 12). These skarnified horizons are interpreted to belong to the Profeta Formation limestones which outcrop in valleys south of the prospect and were observed in drill chips east of the Mina Vaquillas deposit.

These initial results confirmed the presence of a mineralized system of porphyry style beneath the gravels. They also largely explained the presence of the chargeability anomaly being related to abundant secondary pyrite and both sericite-chlorite and propylitic alteration styles. Despite this early success, no causative porphyry intrusive had been intersected, and only trace chalcopyrite was observed in drill core. At this point, phase 1 was terminated to allow the team to consider the results and analyse existing data in the context of these results. All drill samples were subjected to complete geochemical analysis, via 4 acid digestion and fire assay on 2 m composites. Pulps for each sample were also spectrally analysed by ALS Laboratories for an independent determination of the main alteration phases.
Analysis of these results allowed production of both lithogeochemical and alteration maps (Figures 13 and 14). The results of these analyses strongly supported initial interpretations of clear vectors towards a single porphyritic centre rather than multiple centres (Figure 15).

**Figure 13:** Geochemical analysis shows a clearly zoned system centred on drill hole -002 and terminated in the south by the inferred structure and in the north by a diatreme.

**Figure 14:** Zoned prograde alteration assemblages interpreted from geochemical analysis and ASD over the Pampa Vaquillas prospect. Mgt - Magnetite.

Assays confirmed the suspected low copper grades sampled throughout drilling which was concerning to our copper exploration program. Despite this, some highly positive indications were determined from the gold results, with definition of a highly anomalous zone centred on relict potassic alteration and increased vein density. This zone included a single hole (VAQ-002) which intersected a significant, yet sub-economic Au resource, which essentially forms the base of the gravel sequence. These positive results, coupled with the excellent pedigree of the project location, intensified the desire to understand the apparent absence of copper in the system and to discover the early mineral porphyry. To address the question of copper fertility, fluid inclusion samples were collected (Nash, 1976) and analysed by the CODES group at the University of Tasmania. Results confirm the fluids associated with the hydrothermal system were indeed capable of generating a copper-bearing system, with abundant S, NaCl, Cu and Fe (Figure 16). With the knowledge we were yet to find the causative porphyry body and that the system should be copper fertile, a reassessment of the data and our assumptions was required.

**Figure 15:** Initial simplified post-drilling interpretation of vectors within the system. These were generated from a combination of lithogeochemistry, alteration logging and ASD mineralogy.

**Figure 16:** Fluid inclusion studies conducted to assess copper fertility of the system confirmed the fluids have abundant S, NaCl, Cu and Fe required for formation of porphyry Cu systems (modified from Danyushevsky, 2016).
A modest size magnetic anomaly adjacent to the western fault boundary had been noted during phase 1. A single drill hole was planned to test this zone as magnetic anomalies were known to sometimes relate to magnetite-bearing fresh diorites. Final results however showed a compelling spatial relationship between this magnetic feature and the best in-hole mineralisation. The feature was found to be central to all porphyry vectors derived from logging and geochemical, spectral data. A detailed review and modelling of the in-hole magnetic susceptibility measurements confirmed that the source of the anomaly had not been intersected by drilling. This discovery initiated a more thorough review of the magnetic data to understand how the target was missed, and to assess the residual size and depth potential of this anomaly.

During the earliest stages of exploration at the GVD, the various ground magnetic surveys had been merged to form a single coherent dataset over the project. This data had proven extremely useful in the interpretation at the project scale, in the identification of structure and magnetic domains reflecting underlying lithological changes. The disadvantage of this approach was to reduce the resolution of the some of the highest quality surveys. Phase 1 drilling had relied on interpretation and modelling based on this merged magnetic output, leading to the sub-optimal placement of the drill hole designed to test the magnetic feature. On detailed review of data at the target scale, it was realized that a very high resolution magnetic survey had been completed in the area (Figure 17).

Interpretation and 3D inversion modelling were then conducted using these rediscovered magnetic data. These data when combined with drill results, not only confirmed the coincidence of the untested magnetic body with best in-hole results, they also permitted a new look at the structural controls and kinematics of the prospect area. 3D modelling via inversion of the magnetic data was conducted using Geosoft’s magnetic vector inversion (MVI) tools that enabled the previously diffuse source body to be resolved as two discrete sources. These results gave a shallow zone of high susceptibility and an additional deeper, sub-vertical source zone. This deeper source is seen to be located adjacent to the district scale western boundary fault and localized by northwest and northeast camp scale features. The body, strongly supported by all existing datasets and previous drilling became a viable target for phase 2 drilling (Figure 18).

Figure 17: Left – Regional reduced to pole magnetic imagery used for phase 1 drill planning. Right - Simplified reprocessing and reinterpretation of ground magnetic data post drilling allowed realization of a close link between magnetic anomalous and the best results from phase 1.
FQM size criteria allowed two drill holes to test the magnetic source bodies on both sides of the western fault during phase 2 drilling to test the hypothesis that the magnetic bodies reflected either the signature of the porphyry intrusive, or were directly associated with an adjacent magnetite-rich alteration zone. Drilling was directed towards the west to better test the apparent easterly dip of the deep magnetic source body. It was acknowledged at the outset of drilling that due to the depth of the deeper magnetic source, some encouragement in the form of positive results would be required earlier in the hole to warrant drilling to the planned depth of 500 m.

The first hole of the program again encountered some 70 m of gravel cover before passing immediately into a magnetite veinlet-bearing dioritic porphyry. This sequence then changes to a chlorite-sericite altered dioritic porphyry with far less veins and instead garnet-bearing skarn horizons. At 150 m depth, the sequence returns to a porphyritic diorite unit with secondary biotite overprinted by chlorite-sericite. Towards the base of the hole, a series of quartz-pyrite-molybdenum veins similar to those encountered in phase 1 were intersected. Gold grades in this hole were elevated and strongly correlated with the magnetite and quartz veinlets (Figure 19). Due to similar mineralogy and a highly gradational boundary with the overlying porphyritic volcanics, samples of the suspected intrusive where sent for petrological review and confirmed the presence of at least two porphyry intrusive phases within the strongly altered porphyritic sequence (Cornejo, 2017).

The two phases of alteration are characterized by abundant actinolite, chlorite, pyrite and locally magnetite and albite, with only trace chalcopyrite. This assemblage is considered indicative of a “calc-potassic” assemblage. This in turn has significant implications on both the structural setting of the prospect and copper prospectivity of the system.

The final drill hole of the program was collared immediately west of the inferred western boundary fault and delivered a surprise result once again. Under less than 2 m of gravel a sequence of fresh mudstone and shales with diagenetic pyrite was intersected, this sequence continued to the end of hole at 147 m. This unit is not seen locally in exposures in valleys and its low density nature compared to adjacent units had not been considered when modelling depth to basement. This led to the basement depth model being inaccurate in these areas and overestimating the depth of cover. This result confirmed the presence and importance of the western boundary fault, and that is had been active post emplacement of the hydrothermal system. The kinematics of this activity are not yet understood, however the degree of movement, suggested by the juxtaposing of highly altered sequences against fresh sediments, had not been predicted by regional mapping. This strengthens the argument for localized structural emplacement controls operating at the deposit scale. While these may be difficult to identify in covered terranes, they may be recognized from interpretation of remotely-sensed and geophysical datasets.

A working interpretation of these results proposes that a series of near north-south faults locally controlled the exposure levels of the hydrothermal system. The level of the system appears to deepen to the west, starting at the breccia-hosted Mina Vaquillas intermediate sulfidation epithermal Au-Ag deposit, which likely formed on the shoulder of a lithocap environment relatively close to the paleosurface (Cass, 2007). This is adjacent to a zone of intense phreatomagmatic brecciation and sericite-chlorite alteration to the immediate west. This is suggestive of a slightly deeper environment, more proximal to porphyry copper formation. Further west, the porphyritic signature becomes stronger with skarnoid mineralisation and presence of higher temperature alteration increasing towards the western limit of the near north-south corridor, coincident with the chargeability anomaly. Finally, the western boundary fault has sharply cut off the system, most likely via either strike-slip or reverse movement. This interpretation is shown schematically by Figure 20.
Figure 19: Phase 2 drilling led to an explanation for the magnetic anomalies observed in surface data and discovery of the porphyry body which likely gave rise to the associated skarnification and alteration. Py - Pyrite, Cpy - Chalcopyrite, Qtz - Quartz, Mgt - Magnetite.

The size of the encountered porphyry body and surrounding magnetite-rich hornfels and skarn alteration appears modest and well-resolved via a combination of drilling and magnetic data (500 m x 300 m). This remains somewhat enigmatic given the large-scale alteration footprint marked by pyritization of the volcanic units and mapped out by chargeability data (7 km x 1.2 km). There are several working hypotheses for the genesis of the pyrite which honour existing data, the most accepted being massive devolatilization during the diatreme/phreatomagmatic breccia event prior to copper precipitation. Structural removal or dismemberment of the system by later fault movement facilitated this. An alternative is that an unknown porphyritic body remains to be discovered at depths greater than the 550 m defined by existing drilling.

Dating of the porphyry phase is currently being carried out via U/Pb methods on zircons. The purpose of this study is to make an age comparison to that of the sericite dates obtained from surface chips. These results should confirm or refute a link between this intrusive body and the main hydrothermal stage. At the time of writing these results have not yet been received, but will be important in understanding residual potential of the system, albeit this potential would most likely be at significant depth.

Figure 20: Schematic and highly simplified diagram of the interpreted evolution of the Pampa Vaquillas porphyry system. WBF – Western Boundary Fault
The acquisition of petrophysical data in undercover exploration is a powerful tool to improve geophysical interpretations and confirm when geophysical anomalies have been adequately tested (Hope and Andersson, 2016). Eighty-four representative hand samples were collected across the Pampa Vaquillas prospect area, and were then analysed using in-house protocols with a GDD SCIP electrical tester for both resistivity and chargeability properties (Figure 21). A modest increase in the resistivity values is noted with depth of drilling. Chargeability values are as anticipated elevated throughout, consistent with the extensive chargeability anomaly measured at surface. These values are highest in the pyrite-rich, phyllic and chlorite-sericite alteration zones. These results confirmed that alteration assemblages are the primary control on the electrical properties of the system. No direct relationship between copper or gold grade and electrical properties is observed.

CONCLUSIONS

The exploration of the Greater Victoria District and discovery of the under-cover Pampa Vaquillas porphyry system has been an exercise in optimal use of available data and application of mineral system targeting. The project involved the combination of many layers of data, at many scales, with a highly integrated exploration team that included internal and external specialists when required. The vast quantities of data available and its compilation into 3D was critical in quickly recognizing and focusing further exploration efforts to areas with potential for development of a large porphyry copper system. Despite the large quantity of indirect targeting data and lack of exposure, extended field campaigns were crucial in constraining and interpreting information in a geological context. Willingness to interpret data holistically, and in the face of new information, perform reinterpretation, with the strong support of management, ultimately led to the discovery of this large hydrothermal system. Current results suggest a copper-deficient system, or possible post-mineral dismemberment and perhaps loss through erosion. This discovery at modest depth in a mature exploration terrane is supportive of the methodology applied to exploration programs in areas characterized by superficial geological cover. Ongoing application of new and improving technologies will doubtless improve success rates across the industry. Despite this, a silver bullet solution from geochemistry or geophysics remains elusive and improbable. Therefore, detailed data integration, with sound application of geological principles and readily available technology, especially in data-rich, high quality terranes is deemed a preferred approach for encountering the next wave of large ore deposits. Such an approach is highly cost effective in times of reducing budgets and remains a search strategy with outstanding potential to improve exploration success rates.

ACKNOWLEDGEMENTS

This compilation would not have been possible without the permission of management from the exploration parties involved. The authors would like to thank First Quantum Minerals and Hoschild’s Mining for their willingness to share the exploration methodology and results of this active exploration project. A special thanks and acknowledgement must also be given to the Chile Exploration team, including but not limited to Steve Andersson, Juan Burlando, Felix Waechter and Yandira Amezquita who have all impacted the direction and outcome of this project at various times. It is the hope of the authors that continued sharing of exploration results and exploration process, may improve discourse and success rates across our industry.

REFERENCES


Danyushhevsky, L., 2016, Fluid inclusion study on behalf of First Quantum Minerals (company report).


Getech UK, 2016, Gravity Data, NW South America (company report).


Mccuag, T., S. Beresford, and J. Hronsky, 2010, Translating the mineral systems approach into an effective exploration targeting system: Ore Geology Reviews, 38, 128-138.


Venegas, C., N. Astudillo, M. Cervetto, P. Cornejo, F Espinoza, C. Mpodozis, and H. Rivera, 2013, Carta Sierra Vaquillas Altas, regiones de Antofagasta y Atacama: Escala 1:100,000, SERNAGEOMIN, Carta geológica de Chile.