Porphyry Copper Targeting Under Gravel Cover in Northern Chile

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ABSTRACT
An integrated, mineral system approach was used for the interpretation of geophysical, geochemical and spectral data at a project-scale case study. This approach demonstrates how map layers relevant for vectoring to and within porphyry copper mineral systems can be created in areas of extensive gravel cover using independently derived data sets. An immediate implication is that robust porphyry copper targets can be developed rapidly and at a reasonable cost without necessarily relying on more costly and time consuming methodologies like pattern drilling or detailed ground geophysics. In addition, the integration of these layers contributes to an overall narrative regarding prospectivity. The map layers comprise bedrock geology, distribution and intensity of alteration mineralogy and assemblages, ilelite crystallinity, porphyry alteration footprints from trace element patterns, green mineral vectors, and a ‘black map’ layer within which economic potential is empirically considered as nil. These layers are designed to provide the greatest possible amount of geological context and understanding of porphyry related processes in an area mostly covered by gravel. The map layers together are a direct decision making tool for commitment to further exploration expenditure or not. Our case study builds a compelling scenario of multiple, magmatic-hydrothermal related alteration systems in an area of extensive post-mineral cover, the data components of which comprised a modest expenditure outlay. We aim to leave the reader with the question “is there sufficient evidence to justify further exploration and expenditure commitment, and if so, what next?”

INTRODUCTION
Undercover exploration has been an often repeated phrase in the previous 10 years of mineral exploration. One of the places that new technologies and methods have periodically been applied is northern Chile, host to some of the biggest copper deposits in the world, but with areas of extensive gravel cover. Exploration efforts in northern Chile are influenced by a dogmatic perception that most of the outcropping deposits have either been found, or are located in tightly held tenure positions. In addition, recent exploration expenditure appears to have focused mostly on the brownfields environment, where the inherent clustering characteristics of porphyry copper formation makes this a conceptually lower risk investment. A by-product and opportunity of the above paradigms is the greenfields exploration potential in the large metallogenic belts of northern Chile, under post-mineral cover. A shift to focusing on what lies under the gravel plains is both a natural and necessary step towards future discoveries.

Here we present how regional geophysical data can be used in combination with project-scale geochemical and spectral data to vector to porphyry copper systems underneath gravel plains. Specifically, in areas of partial outcrop where there is historic drilling in post-mineral cover that can be sampled. The data are used in an integrated fashion to provide the greatest amount of geological context of a project area, as well as making an assessment of the size potential and quality of an undercover mineral system. This assessment is a critical part of the decision whether to pursue further data acquisition for target definition, or to discontinue with a project. Under normal circumstances, this can be a rapid assessment at a modest cost that provides mostly empirical results.

During this exercise we have not attempted to visualize copper distribution as a stand-alone map layer. With evidence of advanced argillic alteration and in-situ leaching having occurred, the current distribution and pattern of copper is likely to reflect post-mineralization processes that act to conceal a hypogene copper source. We present a framework that uses mineralogical and immobile trace element pathfinders to understand alteration systems as a whole, and also guide vectoring and targeting to hypogene copper mineralization.

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LOCATION AND SETTING
The case study is within a (confidential) project area currently being actively explored by Quantum Pacific Exploration Chile Ltd. (QPXC), located in the Paleocene belt of northern Chile (Figure 1). Unfortunately, as tenure position is a complex issue in Chile, precise location information cannot be included here. The Paleocene belt is characterized by extensive Miocene gravel and local volcanic cover over mainly intermediate volcanic host rocks to Paleocene age porphyry copper deposits, with an average of 80% cover along the belt (Figure 1).

The project area is approximately 23 by 19 km in dimension, with around 80% cover that comprises Miocene and recent gravel and alluvial deposits (Figure 2). Logging of RC drill chip spoils from extensive historic pampa drilling reveals that the gravels are up to 60 m thick, with an average thickness of around 30 m. Topographic relief is mild, with low hills at a scale of tens to several hundreds of metres above the gravel plains. Outcrops comprise Cretaceous to Lower Paleocene andesite
lavas and tuffs as well as Upper Paleocene intermediate to felsic intrusions (Figure 2). Some of the outcrop areas are altered to advanced argillic mineral assemblages; elsewhere there are locally developed quartz-sericite and epidote-chlorite alteration assemblages.

There are two small porphyry copper occurrences in the area, both of which have been drilled historically and discontinued due to the lack of economic potential in terms of both size and ore grades. There are numerous drill collars and pads in the project area that occur both in outcrop and in gravel covered areas (Figure 2). A large proportion of these are RC drill holes where bagged chips have been left behind on the pad, easily sampled.

**STRATEGY**

**Field Collection and Sample Analyses**

A targeted field collection campaign of lithogeochemical and spectral data from key outcrop locations and all possible RC drill pad locations was undertaken. Bedrock samples were taken from the RC drill chips. Where drill holes had reached significant bedrock depths, several samples were taken over their vertical extent. The gravel-bedrock interface in RC chips was generally easily recognized due to prominent lithological and textural changes.

All samples were described in the field, then with follow up detailed descriptions using a binocular microscope in the office. All samples were analysed at ALS Global using a 4 acid (“near total”) digest and ICP-AES with an ICP-MS finish for ultra-trace detection limits of 48 elements (method ME-MS61). Additionally, all samples underwent a spectral analysis using a Spectral Evolution benchtop model PSR-3500 to obtain short wave infrared (SWIR) information. Most, but not all drill collars indicated in Figure 2 yielded bedrock sample material.

**Bedrock Lithology Interpretation**

A geochemical classification of lithogeochemical data was undertaken in ioGas (Figure 3). This produced a best estimate of rock composition based on element groupings, which could be compared to field and detailed office descriptions, and a final lithology assigned for each sample. A structural framework was interpreted using 200 m line-spaced magnetic data, this formed the ‘skeleton’ within which interpreted lithologies could be integrated (Figure 4). The geochemical and structural interpretations were combined to produce an integrated interpretation of the bedrock lithology in the area (Figures 4 and 5).

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1 Four acid digestion will dissolve the vast majority of silicate minerals prior to mass spectrometry analysis of the liquor, the exception being partial digestion of resistate phases such as zircon and rutile, hence the term “near total”.

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**Figure 1:** Location of the Paleocene metallogenic belt in northern Chile with respect to potential host rocks, exposed Paleocene intrusions, and Paleocene and younger cover material.

The zones of ‘concealed intrusions’ consider areas where there is strong evidence in the magnetic data for extension of outcropping or intersected intrusions under thicker volcanic cover. Occasionally the intrusions are intersected in deeper drill holes below several hundred metres of gravel and volcanic cover. All of the intrusions outlined in Figure 4 have attendant U-Pb zircon ages collected by QPC. They are all Paleocene, and range in age from 67 to 58 Ma. Similarly, the assigned Cretaceous to Lower Paleocene age of the host volcanic sequence is supported by U-Pb zircon geochronology.
Figure 2: Surface geology map of the project area highlighting the large proportion of gravel and alluvium cover versus outcrop. The large number of historic drill holes in the area is not unique to this area—many gravel covered areas have been the focus of previous shallow and phosphate drilling programs. The lithology legend is based on existing and new field descriptions. Note that many of the drill hole locations could be sampled directly in the field, the gravel-bedrock interface is usually easily recognized, and bedrock could be directly sampled.

Figure 3: Summary diagram of geochemical classification of intrusive rocks. The diagram is impacted only slightly by the effects of weathering and alteration as P, Ti, Al, and Sc tend to be immobile under a wide variety of conditions. The elements Ti and Sc are used as denominators in the above ratios as they represent immobile proxies for ferromagnesian (mafic) minerals in any given rock. The elements P and Al are used as numerators; they are (generally) immobile elements which are broadly representative of felsic components in the form of apatite (P) and feldspars (Al). Essentially, increasing values on either axis represents increasingly felsic compositions and vice-versa. Additional separations in terms of compositional (genetic) groupings is possible using immobile elements. For a general classification this method is robust and repeatable, although please note that the process includes iterative review and grouping of similar compositions using a variety of additional immobile elements, such as Cr, V, Co, and Ni (as mafic proxies), as well as Y, Zr, Th, and Nb, combined with validation and cross-checking against field observation and hand sample descriptions. A similar approach was applied to non-intrusive rock type classification.
Targeting 1: Deep or Under Cover

Figure 4: Point geochemical/petrographic classification of bedrock from outcrop and drill core overlain on 200 m line-spaced reduced-to-pole magnetic data. Note that observational information was used to separate intrusive from extrusive rock types, after which chemical subdivisions were applied based on immobile mafic versus felsic proxies using whole-rock geochemical data. Magnetic formlines and interpreted faults from magnetic data are plotted.

Alteration Interpretation

GER Alteration

Bulk changes in rock chemistry were tracked using general element ratio diagrams (GER), where changes in K and Na relative to Al content are considered to reflect potential location in a hydrothermal system (Stanley et al., 1994; Whitbread, 2002; Figure 6). A qualitative ‘intensity’ was assigned to points based on their proximity to a particular mineral’s stoichiometric node on the diagram. This classification (weak, moderate, or strong) is related to the amount of major element removal or addition in a sample, and reflects both pH and temperature conditions of a hydrothermal fluid. Exceptions and ‘gray areas’ exist in this approach, particularly where advanced argillic alteration has occurred. This alteration style is characterized by strong depletion of both K and Na, and on this basis it is difficult to discriminate geochemically from a strongly silicified rock or heavily weathered material. These variables can be dealt with by using hand sample observation for context, as well as qualifying the alteration classifications with spectral analysis.

SWIR Mineralogy

Short wave infrared analysis is a robust technique in the ‘white rock’ environment (phylllic and advanced argillic), where minerals tend to have a high reflectance and abundant –OH bonds (Herrmann et al., 2001; Ducart et al., 2006; Huaff, 2008; Harraden et al., 2013). Here, analysis using SWIR methods can yield relevant data for vectoring, as well as supporting evidence for interpretation of alteration from observational or geochemical means. In this case, SWIR-derived mineralogy was used to support the results from GER analysis, and in many cases, assign a sub-facies. For example, differentiating between pyrophyllite and dickite facies in the advanced argillic environment (Figure 7).

Alteration Summary

Geochemical and SWIR data for each point sample were iteratively evaluated and combined in iOGas, then compared to field and office sample descriptions (Figures 6 and 7). This resulted in a best estimate of dominant alteration mineralogy and intensity for each sample site (Figure 8). Empirical distinctions between propylitic, phylllic, potassic and advanced argillic alteration assemblages were made using this approach, and in some cases based on more detailed mineralogy information. The output point data interpretations were then integrated with surface mapping and remote sensing data to construct polygons of potentially porphyry related alteration assemblages (Figure 9). There are several instances where polygons have not been placed around porphyry related alteration points. These points were disregarded as system evidence as they constitute semi-isolated or single point features rather than broad regions of hydrothermal alteration. For example, isolated veins in relatively unaltered rock, or hydrothermal/tectonic breccias with restricted alteration. The polygons attempt to map pervasive alteration zones where single point classifications have much less significance than groups of similarly classified data. This approach is considered to be a robust and effective way of defining the kilometre-scale zonation in hydrothermal systems around porphyry copper deposits.
Figure 5: Point geochemical classification of bedrock from outcrop and drill core overlain on the bedrock geology interpretation they were used to create. The intrusions comprise mixed compositions of several phases that is not well represented at this scale. All intrusions are of Paleocene age. Note the greater amount of drill hole collars shown in Figure 2 than bedrock samples shown here. This reflects drill holes that did not reach bedrock or where drill chips could not be sampled.

Figure 6: A geochemical interpretation of alteration can be done using this classification scheme. This approach tracks changes in bulk composition (K and Na relative to Al) in reference to an idealized fresh composition for each rock type. KF=K-feldspar, Bio=biotite, AB=albite, Mu=muscovite, Cd=cordierite, Ill=illite, Sye=syenite, Gran=granite, Monz=monzonite, Grano=granodiorite, Ton=tonalite, Dior=diorite, And=andesite, Bslt=basalt.
Targeting 1: Deep or Under Cover

Figure 7: Comparison of SWIR results against GER classification can provide more robust classifications through identification of index minerals for different assemblages. For example, pyrophyllite in this environment is unlikely to exist outside of a true advanced argillic assemblage. Dark coloured minerals with low short-wave albedo, such as chlorite and epidote, are likely to occur in high abundance when identified through SWIR methods. They are difficult to detect in low abundances or when present alongside high albedo minerals such as white micas or clays. In general, alteration classification becomes much more robust by iteratively comparing bulk changes in major element chemistry (GER) with specific mineralogy identified by spectral methods. These are generally complimentary techniques which can provide internally consistent empirical support or clarification of doubt regarding field observations.

Figure 8: Point alteration classification using SWIR and geochemical data overlain on bedrock geology interpretation.
Illite Crystallinity

Illite crystallinity calculated from SWIR analyses measures the degree of organization of the crystal structure in white mica. This is a proxy for temperature of formation, where a better organized crystalline structure reflects mica formation at higher temperatures and vice versa. The calculation involves comparison of a water-related absorption feature found at 1900 nm against an absorption feature related to Al-OH bond flexure at 2200 nm (Ducart et al., 2006; Wilson et al., 2009; Harraden et al., 2013). For internally consistent, filtered datasets (e.g. the one used for this study), relative changes in the illite crystallinity can be used to map temperature gradients in hydrothermal systems. Essentially, higher illite crystallinities correlate with the hotter ‘white mineral’ zones that represent phyllic and, in some cases deep, transitional portions of advanced argillic alteration (Figure 10). In a porphyry system, the illite crystallinity gradients are spatially consistent with SWIR-derived mineralogy and bulk chemical changes in K and Na that reflect allochemical alteration reactions around the hydrothermal center (Figure 11).

Trace Element Pathfinders

The use of trace element pathfinders to define the footprint of porphyry copper deposit alteration systems is increasingly recognized as a robust methodology (Jones, 1992; Dilles, 2012; Halley et al, 2015). The technique is based on consistently observed patterns in the distribution and concentration of certain trace elements around porphyry copper deposits, which can be related to specific parts of porphyry alteration systems. The trace element patterns (and related changes in mineralogy) around a porphyry copper deposit reflect changes in temperature, Eh and pH of an evolving magmatic hydrothermal system (Sillitoe, 2010; Halley et al, 2015).

A subset of the trace elements that reflect the entire vertical distance of a porphyry hydrothermal system was used in this case study. The elements comprise Bi, Se, Sn, W and Mo, which can be used to map from distal to proximal parts of a system respectively (Figures 12 and 13). A nearest neighbor grid was created from the point data for each element, then classified according the element specific threshold defined in Halley et al. (2015, Figure 13). The grid areas containing cells greater than the threshold were polygonised for comparison against other elements (Figure 12). Several element threshold polygons appear to be offset of centre from the data point they enclose—this is a function of the gridding process. The element thresholds used are the same as those presented in Halley et al. (2015, Figure 13).

This technique is essentially a weights of evidence exercise, where single or only two overlapping element threshold anomalies are not considered significant compared to multiple overlapping threshold anomalies. Areas of multiple overlapping threshold anomalies are more likely to host a porphyry system.

Green Mineral Vectoring

Trace element concentrations and ratios in chlorite and epidote within propylitic altered rocks have been used in recent years to define vectors to magmatic hydrothermal centres (Jago et al., 2014; Wilkinson et al., 2015). Here, we use the natural logarithmic ratio of Ti/Sr to define proximity vectors to hydrothermal centres using laser ablation (LA-ICPMS) data from chlorite (Figure 14). This follows the logic outlined in Wilkinson et al. (2015) with respect to the exponential heat decay profile away from a cooling intrusion and the relationship of Ti and Sr concentrations in chlorite away from porphyry hydrothermal centres. The method was calibrated at Batu Hijau, where the Ti and Sr ratios reflect zonations around a large porphyry copper deposit. These data are used in conjunction with the alteration mineralogy, illite crystallinity and trace element footprint data to help define vectors within hydrothermal systems.
Figure 10: Illite crystallinity point data overlain on interpreted bedrock geology. There is a strong correlation between the highest crystallinities (hottest alteration) and the two known prospects. In addition, there is a wider zone of elevated values over a north-northeast trending, fault bound suite of intrusions in the western part of the project area.

Figure 11: Illustration of the link between mineral assemblages, temperature and illite crystallinity for vectoring in hydrothermal systems. The colour stretch of the cells is not a direct correlation with the illite crystallinity values in Figure 10. Modified from Leach and Corbett (1995).
Figure 12: Zoned trace element thresholds that define ‘footprints’ of porphyry related alteration. Refer to Figure 13 for details of trace element distribution in porphyry copper alteration systems.

**Black Map Interpretation**

A black map is used here to define areas of rock that are interpreted to have little or no chance of hosting a porphyry copper mineral deposit. The areas are defined largely using the alteration and trace element footprints, where there is evidence that no porphyry related alteration exists (Figure 15). This is a useful exercise for search space and tenement reduction; when compared against the minimum expected footprint for an economic porphyry deposit in the district it leads to definition of areas that have sufficient space to contain a porphyry centre.

**OBSERVATIONS**

**Structure**

The magnetic data yields a strong north-south to north-northeast structural grain that overlaps with discrete northeast and northwest trending structures. There appears to be mutual cross-cutting relationships between the interpreted north-northeast and northeast structures (Figure 4). There is a strong relationship between the location of interpreted intrusions and an apparent north-northeast trending fault corridor in the central west of the area. The complex of intrusions is bound by interpreted faults on its eastern and northern borders, as well as dissected internally by other faults (Figure 4). The known porphyry prospect in the northwest of the area overlaps with an interpreted fault, the relationship of the eastern porphyry prospect to structure is less clear. Little is known about the geometry and orientation of the volcanic bedrock. Gentle to moderate dips of bedding occur in outcrop, no evidence exists to suggest tight folding or significant stratigraphic offset in the project area. Locally developed northeast trending structures demarcated by hydrothermal and tectonic breccia up to several metres wide occur on the main outcrop of volcanic rocks in the west of the map area. Kinematics of the structures are unable to be determined. The structures are locally affected by quartz-sericite and advanced argillic alteration that does not persist for more than 5 – 10 m into the surrounding wall rock.

**Lithology**

Patterns in the magnetic data closely match groups of point data lithology classification, where zones of strongly magnetic, demagnetized and strongly stippled magnetic character correlate with sample groups classified as intrusions of variable compositions (Figures 4 and 5). The magnetic data and occasional point data from deeper drill holes suggest significant extents of concealed intrusions (Figures 4 and 5). However, some zones of interpreted concealed intrusion could be related to alteration or thermal aureoles in the andesitic host rock. Different compositions evident in the point classification have been grouped using the magnetic data as a guide. There appears to be significant complexity and compositional variation within any one intrusive body.

There is a very strong magnetic aureole around the known porphyry prospect in the east. This likely reflects magnetite addition to the wall rock andesite, as the point data classification and outcrop pattern do not indicate intrusive rock extending beyond the current surface outcrop.

The porphyry copper prospect in the west of the project area is associated with breccias in the point classification data, with lesser intrusive rocks (Figures 4 and 5). A concealed intrusion at depth has been interpreted immediately to the north of the prospect, but there is insufficient data to define an intrusion at the bedrock-cover interface.
At this scale no attempt has been made to differentiate the volcanic host rock into lavas, tuffs and sedimentary units. Compositionally, the different units in the package are quite similar with intermediate compositions.

**Alteration**

The combined SWIR-GER point data alteration classification highlights the two known porphyry copper prospects as moderate to strongly sericite altered features in multiple samples at each site (Figure 8). The eastern prospect transitions rapidly outwards into propylitic and background alteration, and lacks an advanced argillic signature. The western prospect has a more extensive footprint in the point data that comprises sericite and moderate intensity dickite facies advanced argillic that transitions into propylitic to the south and east. This occurs over 1 to 2 km and is an encouraging, albeit small, pattern and scale of alteration system.

The most prominent area of alteration in the point data occurs over a north-northeast trending suite of intrusions in the central west (Figure 8). Here, there is evidence of moderate to strong sericite and advanced argillic alteration extending over an area of at least 5 x 7 km. The altered area contains two distinct ‘hot’ zones, defined by strong sericite (Figure 5). Of these two zones, the one in the north is also associated with strong advanced argillic-pyrophyllite alteration (Figure 8). Even with these two local hot zones, this larger area of alteration is characterized by a variable alteration mineralogy across its width. There is no clear evidence in the point data of a multiple-kilometre area, coherent sericite trend that is significantly larger than the two known prospects in the area.

The interpreted alteration polygons (Figure 9) support zoned, porphyry style alteration systems around the two known prospects. However, the larger zone of alteration over the north-northeast trending intrusions remains the most prominent. Here, a zonation pattern that depicts two centres within a larger area of alteration is clearer, with the northern most centre having a phyllic zone rimmed by a pyrophyllite-bearing advanced argillic zone. Interestingly, the alteration in this location correlates closely with the interpreted fault network (Figure 9).

With the exception of a single moderate intensity sericite point, the central part of the project area is characterized by background to propylitic alteration (Figure 8). The intrusions in the central part of the project area do not appear to be associated with any significant hydrothermal alteration. A large zone of background alteration has been interpreted in the northwest of

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**Figure 13:** Vertical and lateral trace element distribution in a porphyry copper alteration system. We used a selection of representative elements in Figure 15 to define the vertical and lateral components of alteration footprints in the project area. Figure from Halley et al. (2015).
the project area (Figure 9), however the point data do not indicate significant alteration intensity (Figure 8).

The illite crystallinity data highlights the mineralogy of the two known porphyry copper prospects as ‘hot’, along with overall elevated and local ‘hot’ points within the larger area of alteration in the central west (Figure 10). With the exception of two isolated points, the centre of the project area is characterized by low illite crystallinities. These two points by themselves are not considered significant in the context of a porphyry related alteration system.

The highest illite crystallinities in the north-northeast trending suite of intrusions correlate with points classified as moderate to strong sericite and pyrophyllite (Figures 8 and 10). The most coherent and hottest illite crystallinity trend correlates with zoned phyllic to advanced argillic and pyrophyllite alteration. This area defines the most coherent alteration centre within a larger area of alteration along the north-northeast intrusions (Figures 9 and 10).

The trace element pathfinder patterns (Figure 12) yield significant information about the size and nature of the alteration systems. From a ‘weights of evidence’ viewpoint, the prospect in the far east does not have a compelling overlapping trace element anomaly pattern. Only three of five thresholds calculated are present, and only with small dimensions and poor spatial overlaps. This is in contrast to the prospect in the far west that has four of the five thresholds at a multi-kilometre scale and near 100% overlap (Figure 12). This difference in pattern suggests that a stronger, potentially higher quality alteration system exists in the far west prospect. Of significance is that both of these prospects have been drill tested with numerous holes, neither yielding economic mineralization.

The largest trace element pathfinder patterns occur over the north-northeast trending suite of intrusions, where a prominent Mo anomaly of up to 3 x 7 km in dimension mirrors the trend of the intrusions (Figure 12). Within the Mo anomaly, there are several locations where multiple anomaly thresholds overlap. The maximum overlap is four of the five pathfinders in the central part of the Mo anomaly, but with a limited dimension of around 1 x 1 km (Figure 12). Three trace element thresholds overlap in the northern part of the Mo anomaly, this location correlates with a zone of previously outlined strong and ‘hot’ sericite-pyrophyllite alteration mineralogy (Figure 9, Figure 10).

There are multiple, smaller trace element anomalies adjacent to the large Mo zone. These anomalies usually comprise one or two points, with inconsistent overlaps of different elements and in several places comprise only single element anomalies. These zones overlap with propylitic and lesser argillic style alteration outlined in Figures 8 and 9. In the context of the larger area of alteration they are adjacent to, these anomalies appear to constitute ‘noise’.

The large Mo anomaly, along with the multiple smaller pathfinder anomalies surrounding it, does not show a coherent pattern of overlap on a scale that is consistent with a large, high quality alteration system. Examination of the point data details reveals that many of the stand-alone alteration and trace element anomalies in this area occur within metre-scale structures and breccias. These features are associated with extremely localized alteration in field observations. With this consideration, the actual size, quality and intensity of the apparent large area of alteration is diminished.

Figure 14: Map of ln(Ti/Sr) ratio in chlorite that is a proxy for distance from the centre of a porphyry related alteration system. The ratios here are compared to the ranges determined originally from Batu Hijau in Wilkinson et al. (2015). Note that the two known porphyry copper prospects have moderate to strong ln(Ti/Sr) features of 4 to 5 compared to the Batu Hijau index, but never obtain ratios greater than 6, which occurs within the pit at Batu Hijau.
The use of ln(Ti/Sr) data from chlorite in the project area highlights the two known porphyry copper prospects as moderate to strong features with respect to the Batu Hijau proximity index (Figure 14). Elsewhere, the data indicates mostly weak (distal) signatures, with the exception of a moderate strength feature that overlaps with multiple pathfinder elements and interpreted phyllic alteration at the northern end of the large Mo anomaly in the central west (Figures 9 and 14). Other chlorite ln(Ti/Sr) data from within and close to this large Mo anomaly are consistent with distal indicators. No additional hydrothermal centres are recognized within the anomalous Mo area. A second moderate strength feature is located in an intrusion in the central north of the project area. This point overlaps with a zone of interpreted background alteration (Figure 9) and it does not correlate with any anomalous trace element pathfinders (Figure 14).

The black map polygons (Figure 15) are largely based on trace element pathfinder patterns. In most places, they skirt the defined trace element anomalies, the exception being in the west where there is some overlap between three different trace element anomaly areas and the black map (Figure 15). A closer examination of the points that define these trace element anomalies reveals locally developed structures, breccias and restricted alteration that may not be related to a pervasive porphyry system.

Following construction of black map polygons, and considering the defined extents of the alteration systems and sample distribution, the remaining available space to conceal a porphyry alteration system under cover becomes restricted. The remaining under cover search space lies logically to the immediate north of the zoned phyllic to advanced argillic pyrophyllite bearing area at the northern end of the large Mo anomaly in the central west (Figure 15). There is an opportunity to collect bedrock information that could link this area to a stand-alone Mo anomaly approximately 2 km to the north.

**DISCUSSION**

The distribution of available data from outcrop and drill holes through the cover sequence enabled the construction of a robust geological context, where the cover is essentially stripped away and not regarded during map layer interpretation. This integrated approach allowed a coherent structural framework to be constructed, upon which subsequent layers relevant for the understanding of porphyry mineral systems could be added.

There are several strengths to this approach. One is that we consider the data and interpretation in terms of a geological architecture and processes specific to porphyry copper systems within the framework of that architecture. Another strength is that we can use regional (more readily available and cheaper) magnetic data, along with modestly priced geochemical and spectral analytical data. The total analytical cost of the point data was around USD$30,000, the cost of which mainly constitutes lithgeochemistry and LA-ICPMS analysis of chlorite.

The different map layers and observations reveal at least three different porphyry style alteration systems within the project area. Two of these are already known as historic porphyry Cu prospects that yielded limited size potential from drilling. The larger area of alteration in the central west of the project area yielded two distinct centres, but these are not compelling targets by themselves in terms of dimension and apparent intensity and quality.

Figure 15: ‘Black map’ polygons over the project area along with trace element footprints for reference. The hatched zones comprise areas considered to have very little to no chance to host a porphyry copper deposit based on available alteration and porphyry related trace element patterns.
The dimensions and boundaries of the large area of alteration correlate closely with the extents of the interpreted north-northeast trending intrusive complex. The Paleocene intrusions that comprise this complex are interpreted to be bound on their eastern boundary by a fault, which separates them from older, Cretaceous host rocks. The presence of ‘exposed’ bedrock intrusions in this corridor, compared to the extent of concealed intrusions interpreted to the east of the fault, is consistent with block movement across the fault, where the north-northeast corridor of intrusions is uplifted relative to the east (Figure 5). Overlap of alteration with the uplifted block is not interpreted to be favourable for the presence of a porphyry copper deposit in this area. The presence of such a widespread Mo anomaly with an apparent lack of strong focus suggests dispersed, magmatic hydrothermal fluids related to the structural-intrusive corridor, rather than a large porphyry copper alteration system. This interpretation is supported by the variability of other trace element anomaly distributions, where W, Sn, Sn and Bi occur sporadically within the Mo anomaly (Figure 12). This pattern does not support a coherent single porphyry related source, but rather a large, unfocused distribution of alteration and anomalous trace element values related to multiple magmatic injection events along a long-lived structural-magmatic corridor of now-exposed intrusions. The exposure level of the north-northeast intrusive corridor is potentially the source chamber for associated porphyries. Hence, too deep for preservation of any Paleocene age porphyry copper system in the intrusions themselves.

There are two zones of potential ‘flux’ in the large anomalous area, defined by overlapping strong sericite, elevated illite crystallinities and coincident Mo, Sn, Se and Bi anomalies (Figures 8, 10 and 12). The northernmost of these zones has potential to increase in size to the north, as it is unconstrained and could be a larger anomaly. The fact that it overlaps with mostly volcanic host rocks at the edge of the intrusion is encouraging, and suggests potential for an appropriate preservation level, further supported by the presence of local advanced argillic alteration. This zone is also supported by a moderate ln(Ti/Sr) feature. Using the black map outlines (Figure 15), there is sufficient space to the north of this zone for a large porphyry copper deposit to occur, which is not yet covered by point data.

OUTCOME AND CONCLUSIONS

The interpreted layers permit to build a comprehensive geological context of multiple potential alteration cells in the project area. Of these, one may have merit in further work (potential area in Figure 15). The decision to be made is should further work be conducted in the area and if so, which exploration technique should be applied?

Conclusions

1. We can define the architecture and mineralogical and geochemical footprints of multiple alteration systems in areas of extensive cover, provided that there are existing drill holes through the cover sequence. The same methodology could be applied in locations of partial outcrop that lack drill holes, to establish vectors away from outcrop and into covered areas. Broad-spaced pattern drilling in areas where historic RC spoils and/or outcrop is unavailable or poorly distributed may represent a good investment in a similar geological setting.

2. The integrated use and interpretation of geophysical, geochemical and spectral data using both established and new methodologies for data combination and treatment was critical to establishing a robust geological context in a project area with extensive cover. Key to the outcomes was integrating multiple lines of evidence iteratively and on a variety of scales, beginning with point data (field observations, geochemistry, and handheld SWIR), proceeding to the extrapolation of outcrop polygons, and finishing with extrapolation under cover using RC holes and airborne magnetic information. A notable outcome of this approach is that analysis at the macro scale can impact interpretation at the micro scale and vice versa. Essentially, any coherent evaluation of a hydrothermal system needs to be consistent at all scales.

3. The two known porphyry copper prospects appear to have limited size potential based on their footprint size and geochemical characteristics. Of the two, the prospect in the northwest appears to be of greater quality based on architecture, as well as patterns in trace element pathfinders, illite crystallinity and alteration mineralogy.

4. The large anomalous area in the central west of the project area has multiple, poorly defined focal points. It does not appear to represent a single large, economic porphyry copper mineral system.

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REFERENCES


