An Empirical Geophysical Model for Porphyry Copper Deposits in the Laramide Copper Province

Brendan Howe
Teck Resources Limited
brendan.howe@teck.com

Sarah G. R. Devriese
Teck Resources Limited
sarah.devriese@teck.com

SUMMARY

The Laramide copper province is located in southwestern North America, covering parts of Arizona, New Mexico, and Texas in the U.S, in addition to Sonora, Chihuahua, Sinaloa and Baja California in Mexico. Porphyry copper mineralization is associated with Laramide age (~80-45 Ma) magmatism and has been estimated to represent ~300 million tonnes of copper metal, making it a globally significant accumulation of the red metal. The geological and geochemical manifestation of these mineralizing systems have been well documented. Specifically, exploration models based on alteration zonation and trace element geochemistry have been developed and successfully deployed in the province since the late 1960's. As a result of post Laramide extension and deposition, much of the province is covered by post-mineral rocks or sediments, and it can be argued that the greatest residual potential for future discoveries is located within the covered regions. Consequently, geophysical datasets are playing a more prominent role in integrated targeting of porphyry systems. In this extended abstract, we present a series of observations and interpretations of geophysical data from various deposits in the province with the goal of developing an empirical model to guide selection of geophysical method, interpret subsequent results and ultimately contribute to future exploration success.

Key words: Porphyry, Laramide, Geophysical Model, Magnetics, Electrical

INTRODUCTION

The Laramide porphyry province, located in southwestern USA and extending into northern Mexico, represents one of the world's preeminent regions for porphyry copper mining and exploration (Figure 1). Bulk copper production commenced in the early 20th century and total endowment, including historical production, reserves, and resources is estimated at ~300 Mt (Singer et. al., 2008). The Laramide porphyry deposits were emplaced during a period (80 – 45 Ma) of flat slab subduction and associated strong compression and calc-alkalic plutonism. Hypogene copper mineralization is dominated by chalcopyrite (+/- bornite), and commonly associated with K-silicate to sericitic alteration. Subsequently during mid-Tertiary extensional tectonism, episodes of weather-related oxidation, leaching, and enrichment occurred, producing supergene and oxide ore (Leveille and Stegen, 2012). Despite the long mining and exploration history, it is estimated that 54% of the province is covered by post-Laramide rocks or unconsolidated cover, indicating significant potential for future discoveries.

Porphyry copper systems have been the subject of extensive research since the 1970's (e.g., Lowell and Guilbert, 1970; Figure 1(B)), leading to the development of robust deposit scale models describing both the lateral and vertical zonation of alteration, mineralization and pathfinder geochemistry that have become a critical tool in global exploration (Sillitoe, 1993; Seedorf 2005; Holliday and Cooke, 2007, Sillitoe 2010, Halley *et al*., 2015). In contrast, there has been relatively little research into development of complimentary models that describe the geophysical behaviour of a porphyry system. Geophysical research has largely focused on individual deposit studies (e.g., Ware, 1979; Sha *et. al*., 2013; Steinberger *et. al*., 2013; Hope and Anderson, 2016). However, little has been published describing geophysical exploration models based on either petrophysical measurements or geophysical field data. Sillitoe (2000) present a geophysical model although it is largely conceptual with no discussion of geophysical data or physical property measurements to support. Garwin (2019) present a geophysical model primarily based on observations of the Batu Hijau deposit in Indonesia. Mitchinson *et al*., (2013) describe petrophysical relationships with lithology, alteration, and mineralization for 6 alkalic porphyry deposits in the British Columbian cordillera, with the objective of developing physical property-based criteria for ranking porphyry targets. Hubert et al., (2016) combine the petrophysical data from Mitchinson *et al*., (2016) with geologic models from Lowell and Guilbert (1970) and Sillitoe (2010) to develop a conceptual geophysical model, however supergene and oxidation effects are not accounted for.

In this study, we aim to build a geophysical model for Laramide porphyry deposits by focusing on geophysical manifestations (magnetic and electrical methods) combined with geological observations from several major deposits

(Figure 1(A)). We argue that the porphyry systems in the Laramide require a specific model due to distinctive characteristics: a) copper mineralization associated with sericitic alteration (Manske and Paul, 2002), b) presence of post-mineral modification, oxide and supergene enrichment, and c) prevalent post-mineral cover material.

(A) (B)

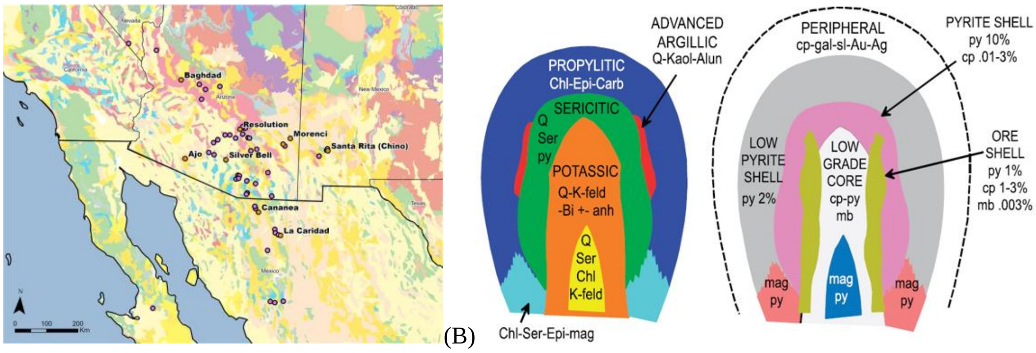

Figure 1. (A) Approximate location of the Laramide porphyry province (geology after Garrity and Soller, 2009) and selected deposits referred to in this study. Yellow-light yellow indicates the extent of post Laramide cover material. (B) Example porphyry copper deposit model (modified from Lowell and Guilbert, 1970).

Deposit	*Age (Ma)*	*Contained Cu (Mt)*
Ajo	63	6.27
Baghdad	72	14.49
Cananea	59	32.15
La Caridad	53.7	15.94
Morenci	56	47.72
Resolution	63.5	23.87
Safford	56	4.02
Santa Cruz	68	8.53
Santa Rita (Chino)	55.5	10.34

Table 1. List of deposits referred to in this study (age and contained copper sourced from Leveille and Stegen, 2012).

Magnetics

Brand (1966) provide an excellent overview of magnetic susceptibility variation within the major rock types of the Laramide porphyry province (Table 1). The syn-genetic Laramide-age intrusive lithologies are extremely low, suggesting magnetite poor protolith rather than altered or oxidized magnetite. In contrast, the magnetic susceptibility of the country rock (e.g., Precambrian granites, Pinal Schist) display values commonly 2 orders of magnitude larger. Based on these data, it can be inferred that syn-genetic Laramide intrusions will manifest as relative negative anomalies in typical magnetic surveying. Furthermore, Laramide mineralization characterized by sericitic alteration and post-mineral oxidation can be assumed to additionally decrease susceptibility (Clark *et al.*, 2004, Howe and Kroll, 2010) superimposing additional negative anomalism.

Open file magnetic datasets (Sweeney and Hill, 2001) and Thoman (2014) have been reviewed to test the implications of the petrophysical data (Figure 2). Each deposit, with the exception of Safford and Santa Rita (Chino), displays a discernible negative sub-circular magnetic anomaly of ~100-200 nT with diameters ranging from 2-5km. When compared against geological maps, the negative anomaly closely reflects the mapped extents of the causative Laramide intrusive associated with copper mineralization (Figure 2). The position of mineralization with respect to the causative intrusion (negative magnetic anomaly) alternates from the margin (e.g., Ajo, Cananea) to the center (e.g., La Caridad, Morenci). The Safford deposit displays a moderate magnetic response which can be attributed to the presence of overlying magnetic tertiary volcanics (Robinson and Cook, 1966). The Laramide porphyry at Santa Rita (Chino) was intruded into Paleozoic carbonates (Reynolds and Beane, 1985), generating magnetite-bearing skarn mineralization that results in the strong positive magnetic anomaly. The Resolution deposit is located at a depth of >1km (Manske and Paul, 2002), and it is unlikely the observed response is related entirely to Laramide intrusive. Therefore, the magnetic response is generally expected to be negative except where the deposits underlie significant cover or lie at depth where other responses will dominate.

Age - Rock Type	*Locality*	*Susceptibility ($\times 10^{-6}$ SI) Range*
Laramide Schultz Granite	Miami, Castle Dome	1.6 - 40
Laramide Quartz Monzonite Porphyry	San Manuel, Esperanza	3.2 - 8
Laramide Monzonite Porphyry	Ray, Ajo, Morenci, Bagdad	2.4 – 19.9
Tertiary Schieffelelin Granodiorite	Tombstone	143
Diabase	Ray, San Manuel, Magma	79.6 – 358.1
Precambrian Granite	Ray	159.2
Precambrian Gabbro	Prescott	8 - 557
Pinal Schist	Magma, Ray, Bisbee, Miami	4 – 119.4
Precambrian Schist	Humboldt	119.4 – 397.9
Tertiary Basalt	Tombstone, Superior, Jerome	119.4 – 397.9
Tertiary Dacite	Tombstone, Ray, Magma	8 – 63.7
Skarn Zones	Nevada	318.8

Table 2. Magnetic susceptibility measurements from major rock types in the Laramide province (After Brant, 1966).

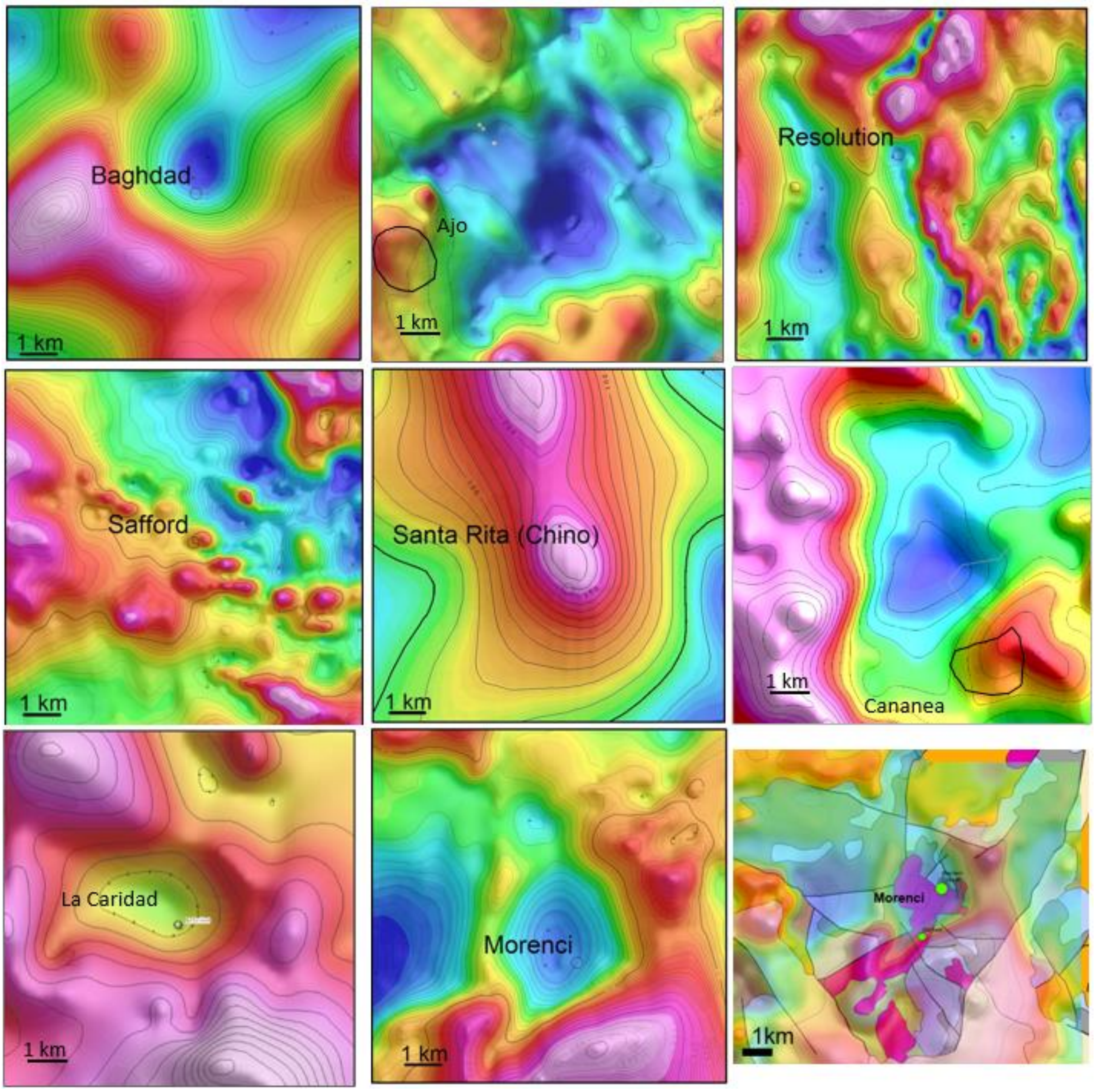

Figure 3: Reduced to pole magnetic responses for the deposits referred to in this study. Figure 1(A) shows the location of each deposit. Morenci has been presented twice to include superimposed semi-transparent geology. Note the Laramide monzonite intrusions in the district (purple) and their close relationship to relative magnetic lows.

Induced Polarization

Induced Polarization (IP) data, specifically complex resistivity or chargeability has been successfully applied in the Laramide province since the 1960's (Brant, 1966). In the Laramide and elsewhere, it is common to target strong high anomalies (Mitchninson *et. al.,* 2013; Howe and Kroll 2016), with a relative low center (i.e., donut shaped features) (Brant, 1966; Garwin, 2019) and interpreting these high anomalies to represent zones of Cu-sulphide (chalcopyrite ± bornite) or pyrite-rich proximal phyllic or sericitic alteration. Based on Thoman (2014) and Nelson and Johnson (1994), we suggest a more complex control on chargeability linked to geological processes observed in the Laramide. Specifically, post-mineral oxidation and supergene processes must be accounted for to develop an improved model. Physical property logging from the Santa Cruz deposit illustrates IP and resistivity characteristics of copper oxide and supergene copper ore. Atacamite (copper oxide mineral) is associated with increased resistivity and no appreciable IP response. Supergene copper, characterized by chalcocite, exhibits both decreased resistivity and elevated IP. We observe this same relationship in the field data from the Morenci deposit (Figure 3). Leached and oxide zones display low IP responses (<10 mrad), whereas the supergene zones are associated with the top of the strong (>30 mrad) response at depth. The remainder of the 30 mrad anomaly is interpreted to represent hypogene sulphide mineralization. Understanding the interplay between oxide, supergene, and hypogene mineralization is critical to understanding and applying a geophysical model in the Laramide. Studying various deposit responses can also aid in understanding the IP responses in under-explored areas which may not have oxide, supergene, and hypogene mineralization. One caveat to be aware of when exploring for Laramide-style copper porphyry deposits under cover is the potential impact of EM coupling on the IP data in the presence of conductive post-mineral cover, which may result in increased IP response at depth which is not related to geology (Wynn and Zonge, 1975).

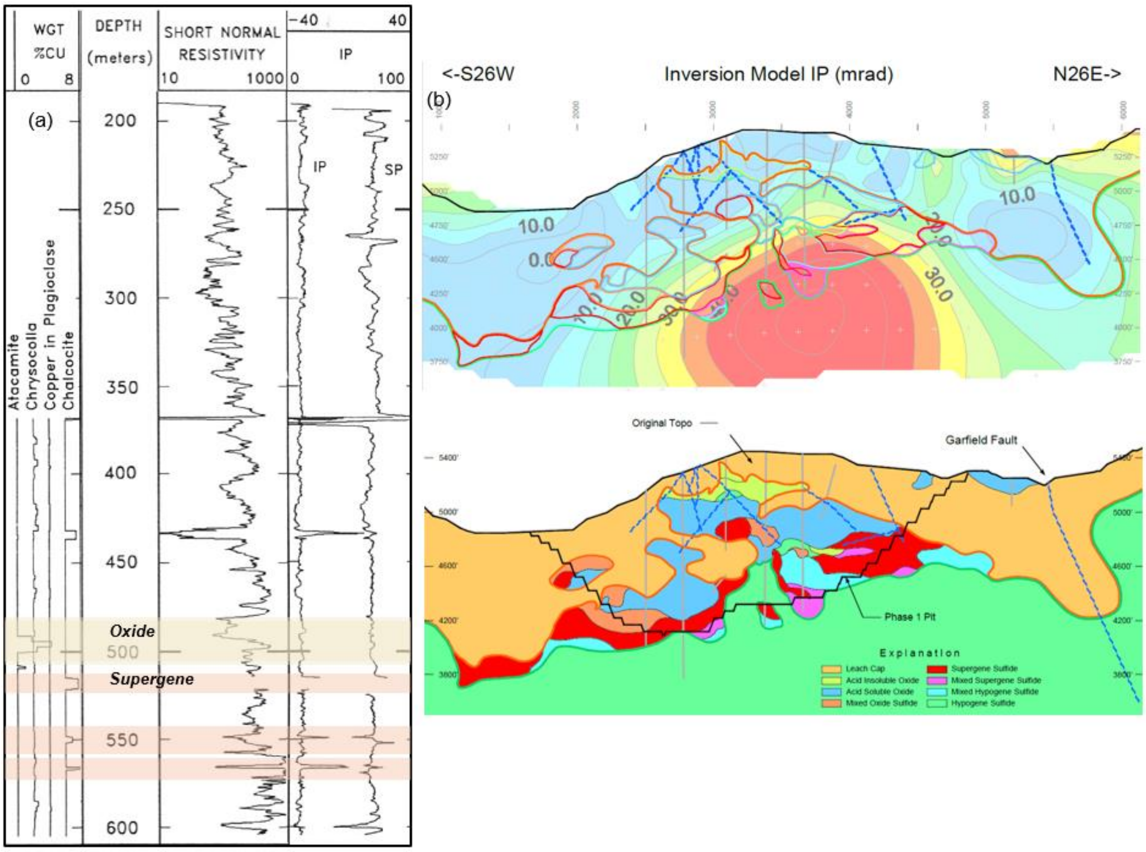

Figure 3: (left) Modified from Nelson and Johnson (1994), wireline logging results demonstrating physical properties of oxide and supergene mineralization from the Santa Cruz deposit. (right) Modified from Thoman (2014), frequency domain IP section from the Morenci deposit and associated mineralization model.

Resistivity

The contrasting resistivity responses from the Safford (Lone Star) and Resolution porphyry copper deposits warrant discussion on the resistivity responses within the Laramide province. Resistivity information in both cases has been derived from Z-Axis Tipper Electromagnetic (ZTEM) datasets. Whilst absolute resistivity values from the ZTEM are difficult to derive (Holtham and Oldenburg, 2010), review of relative amplitudes and geometry still yield valuable information to the development of a geophysical model. Methods, like ZTEM, that are only sensitive to changes in resistivity can be more effective than their DC resistivity counterparts when exploring in areas of post-mineral cover, as shown in the yellow colours in Figure 1(A). The Safford (Lone Star) ZTEM response is presented in Figure 4 (Thoman, 2014). The deposit is characterized by a sub-circular resistivity high, flanked by a more conductive halo. Based on knowledge of the deposit, this has been interpreted to represent the thick oxide zone (resistive) transitioning to non-oxidized hypogene ore at the margins. This interpretation is consistent with observations from Nelson and Johnson (1994). In contrast, the Resolution deposit manifests as a strong conductive anomaly. The Resolution deposit does not contain appreciable oxide or supergene mineralization, and instead high copper grades are associated with overprinting sericitic alteration events. In the immediate hanging wall, which is associated with the strongest part of the conductive anomaly, pyrite up to 14% is reported. The lower part of the conductive anomaly is associated with 3-7% Pyrite and ~3% Chalcopyrite (Manske and Paul, 2002).

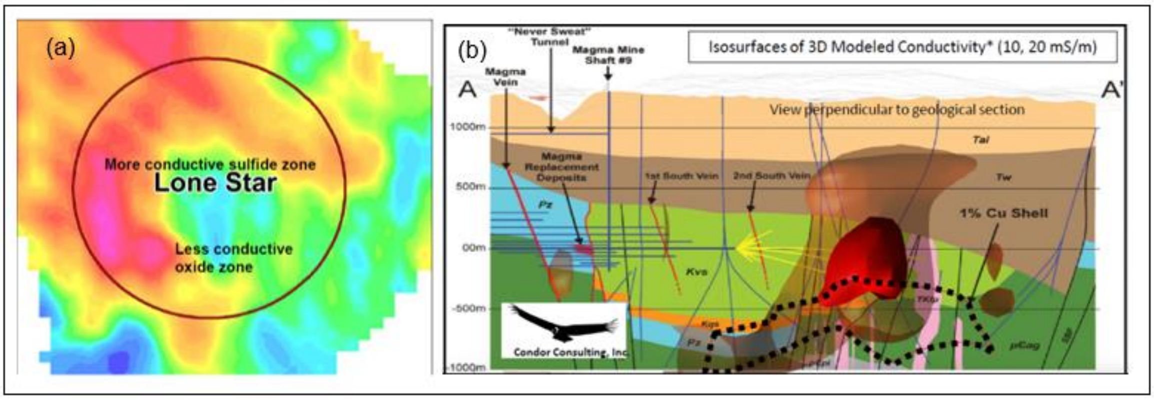

Figure 4: (a) After Thoman (2014), Plan-view ZTEM Total Divergence (28 Hz) data from the Safford (Lone Star) deposit. (b) Modified from Woodhead (2019), 3D ZTEM conductivity inversion result superimposed on Resolution geological cross section.

Geophysical Model

Based on the physical property and field data discussed in this study, a generalised geophysical model is proposed for copper porphyry deposits within the Laramide province (Figure 5). The model incorporates common country rock (Precambrian granites and tertiary volcanics), typical alteration zonation, oxidation, and supergene processes. The recognition of magnetic lows and understanding of oxide and supergene effects on electrical datasets present a deviation compared to previously published models (e.g., Garwin, 2019).

The relative negative magnetic anomaly is most prevalent when the leached cap and oxide zones are preserved. As the system is eroded and the exposure level approaches the K-silicate core, this anomaly will become less prevalent. The stronger response on the margins of the Laramide stock relate to magnetic Precambrian granites +/- Tertiary volcanics. Overall magnetic data responses are dominated by the protolith with smaller contribution from alteration. Chargeability data over the leached and oxide zones will display negligible response over the center of the system with flanking highs coincident with the broader propylitic halo. Progressing deeper in the system, the response of the K-silicate +/- overprinting sericitic event will increase to the level of the propylitic halo. Chargeability data is generally controlled by alteration (and associated sulphides) and oxidation level. The resistivity response demonstrates the largest variation. In the presence of the oxide zone a strong resistor is observed which reverses to a conductor when entering the K-silicate + sericitic zone. Similar to chargeability, the resistivity response is largely a function of oxidation level and alteration.

The model is a simplification and does not explicitly include the effect of post-mineral cover, skarn metasomatism, or tectonic deformation. It is suggested post-mineral cover will attenuate the magnetic field response leading to more subtle negative anomalism and may be a source of false positive anomalism in resistivity datasets. Skarn development, as observed at Santa Rita (Chino), may lead to strong positive magnetic anomalism, obscuring the negative response from the porphyry related mineralization.

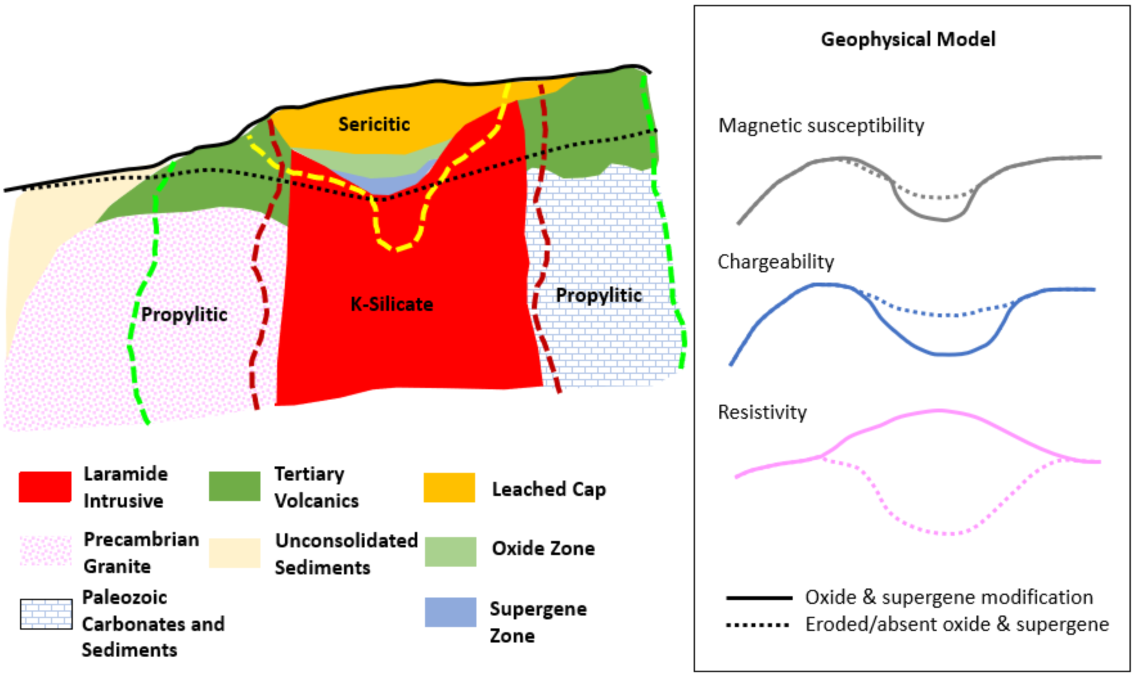

Figure 5: (left) Geological model modified from Sillitoe and McKee (1996) and (right) geophysical model developed from the observations made in this study.

CONCLUSIONS

This model, when viewed in the context of the presence of post-mineral modification through oxidation and supergene processes can be applied as a tool for ongoing exploration in the Laramide province. The study presented here reviewed several key deposits within the Laramide, most indicating a circular, relative negative magnetic anomaly and a varied chargeability and resistivity response depending on the erosion level. This work also highlights the importance of collecting physical property data to better understand the relationships between the Laramide intrusives, different parts of the copper porphyry systems, and any volcanic or sedimentary cover. Only by fully incorporating these pieces with the geophysical expressions can we aim for continued exploration success in the Laramide province, especially under cover with variable resistivity and thicknesses.

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