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Research Article

Lithogeochemical Characterization and Alteration Model to Determine its Implication in the Controls of the Mineralization of the VMS Cerro Lindo Deposit

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ABSTRACT

The objective of this study is to characterize, using lithogeochemistry, the magmatic series and the enclosing rock that took place in the formation of the Cerro Lindo VMS; At the same time, alteration lithogeochemistry was performed to determine the relationship between mineralogy, lithogeochemistry and intensity of alteration, obtaining as a result, vectors towards the center of the system. The primary purpose is to bring this 2D information from the lithogeochemical diagrams to a 3D approach, and thus establish correlations with other mineral occurrence controls (structural, geophysical, geochemical, and lithological). From the analysis and interpretations it was determined that Cerro Lindo belongs to a calc-alkaline magmatic series with high K content, the box rock definitely corresponds to felsic volcanic with degree of differentiation from andesite to rhyodacite according to the degree of proximity to economic zones; that is to say, the deposit is located in the oldest bimodal felsic level of the Casma basin, and it is these first stages of rupture that are usually better enriched in economic mineralization contents, mainly of base elements, followed by the presence of Ag*-Au, It is precisely this location that makes it much more powerful than the other VMS in the area. The SerK+ChlFe (Py) alteration halo has greater potency and dominance in deep, lower-angle faults, which have brought economic Zn-Cu mineralization (NW-SE and NE-SW), faults related to high- grade bodies and to high chargeability areas; while the shallow NW-SE faults, with greater angles, which bring low-grade mineralization and related to low chargeability edge bodies, would correspond to the Ser-Chl alteration and towards the most distal zones of the system, the SerNa-Chl alteration appears. Chl Mg.

Keywords: lithogeochemistry, alteration model, VMS deposit, major elements, rare earths.

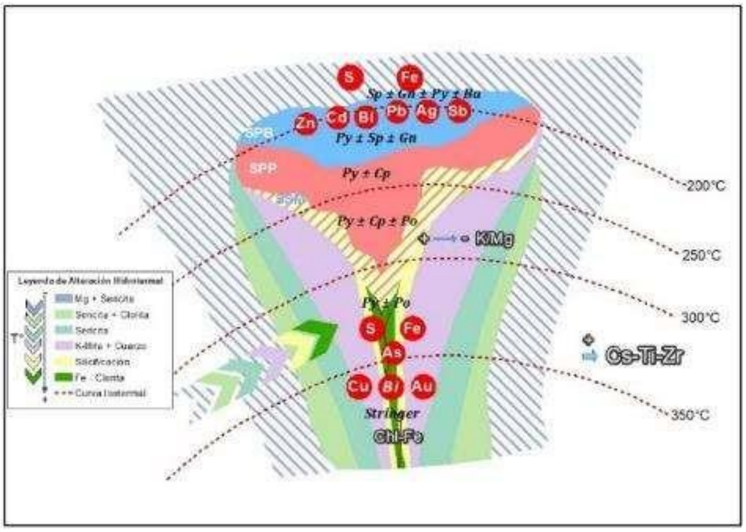
INTRODUCTION

The study area is located in the western part of Peru, in the province of Chincha, department of Ica, 175 km SE of Lima. Cerro Lindo is a volcanogenic massive sulfide deposit VMS of Zn-Cu (Ag-Pb), 52 Mt of Reserves (P+P) with 1.44%Zn, 0.61%Cu, 0.20%Pb, 0.68 oz/t Ag (2020), and is composed of several subvertical bodies.

The deposit is located in the Cretaceous back-arc basin in felsic rocks grading from andesitic, dacitic to rhyodacitic composition; being the proximal rocks the ones that have the greatest relationship with mineralization (rhyodacites).

Cerro Lindo has a peculiar inverted cone geometry with geothermal gradients ranging from 200° to 350°C which are related to the zoning of mineralization and alteration; the high-temperature zone (Po-Py) and low-temperature zone (Sp-Gn-Py-Ba) (Figure 1).

Figure 1. *Schematic model of hydrothermal alteration in Cerro Lindo (Cerro Lindo Exploration Report, 2018).*



METHODOLOGY

A selective sampling of altered volcanic rocks in DDH drill holes was carried out, which were selected taking into account the variability of the box rock and its interception with the different orebodies.

The samples were then classified by their degree of proximity to the ore body: proximal if they are less than 20 m (floor rock), intermediate of 20 to 30 m and distal when they exceed 30 m of distance from the orebody (roof rock).

Macroscopically, it was noted that rocks proximal to the body were more felsic than distal rocks and that constituent minerals presented greater alteration intensity (J. Bueno & M. Mendoza, 2019).

These samples were analyzed in laboratories by the ICP-MS type of analysis by the MA200 methods (multi-acid digestion that determines 45 trace elements) and by LF200 (fusion in lithium metaborate), for characterization of total rock plus 32 trace elements). In the diagrams of this work, the results by the LF200 total melting method have been preferred.

First, in a general way, a lithogeochemical characterization of the box rock was carried out and then a lithogeochemical characterization of alteration was carried out, to complement our analysis and interpretation.

For the three-dimensional alteration model, the interpretations of the lithogeochemical diagrams of the Box Plot Alteration (Large et al., 2001) and Hashimoto's alteration index (AI, Ishikawa et al., 1976) were taken as a reference, for this analysis 500 samples of diamond drill holes in box rock areas (roof rock-floor rock) were included.

Based on the results obtained, alteration assemblies were established which were plotted in the diamond drill holes and cross-sections were made in order to generate an alteration model, based on the interpretations.

As OB1 and OB2 are the bodies with more lithogeochemical information, which allows establishing a better analysis and therefore a better supported 3D model, and considering that OB1 and OB2 present a differentiated mineralization behavior from each other, because they are of different events (justified with paragenetic sequences) and have structural controls associated with different fault systems (Figure 2).

The alteration model in OB1 and OB2 is fed by 27 diamond drill holes that were sampled in a timely manner only in the volcanic box rock and systematically according to the depths of the diamond hole. From this, the alteration model was developed, taking the mineralized bodies as a reference, which allowed us to determine the alteration guide vector for the search for new mineralized bodies; by establishing correlations with the structural, geophysical and geochemical controls of the mineralization studied in Cerro Lindo, to complement this interpretation, the geochemistry of Zn-Cu was plotted, in order to have delimited the areas with the highest grade for these elements and finally the isovaleric map (Al/CCPI) of the entire deposit was elaborated to be able to correlate it with the metallic coefficients of the base elements.

***Diagram 1**. Process of the methodology applied.*

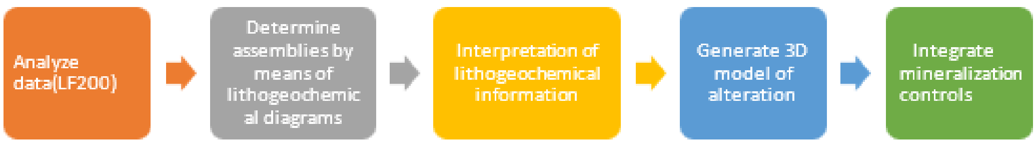
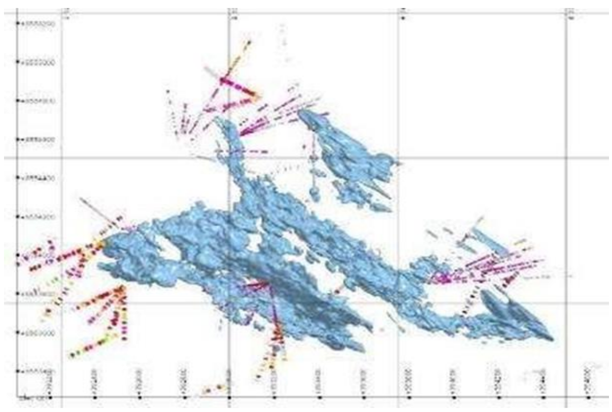


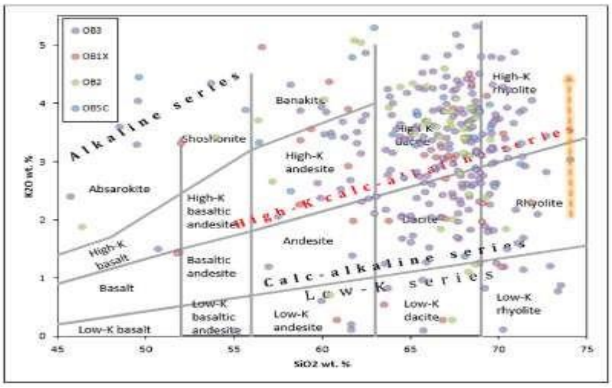
Figure 2 *Spatial distribution in the plan of diamond drill holes with alteration assemblies*



LITHOGEOCHEMICAL CHARACTERIZATION OF THE BOX ROCK

For the lithogeochemical classification of the box rock that presents strong alteration, it is convenient to use these diagrams: SiO_2 vs K_2O (Graph 1), Nb/Y vs Zr/TiO_2 (Graph 2) and TiO_2 vs Al_2O_3, (Graph 3), from which we deduce that the host rock presents differentiation that grades from andesitic to rhyolitic rocks, corresponding to the most distal rocks to the most proximal rocks of the deposit. they also present a strong degree of alteration and place Cerro Lindo within a bimodal felsic deposit corresponding to a calc-alkaline series enriched in potassium.

Figure 1. *SiO2 vs K2O determines felsic series - calc-alkaline; enriched in K (Taken from Ewart, Anthony, 1982)*



Graph 2: *Zr/Ti vs SiO2 for Cerro Lindo volcanic rock classification; alkaline calco tendency, predominance of Rhyodacit//dacite (Taken from Winchester, J. A., and P. A. Floyd, 1977*

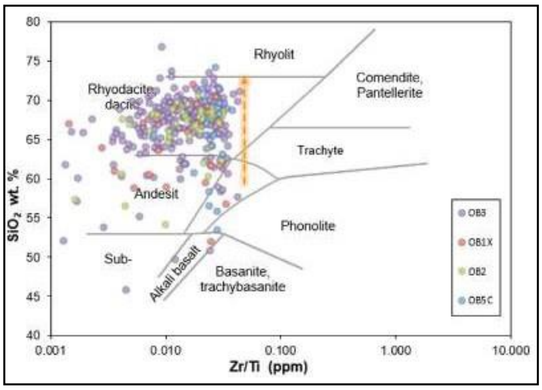
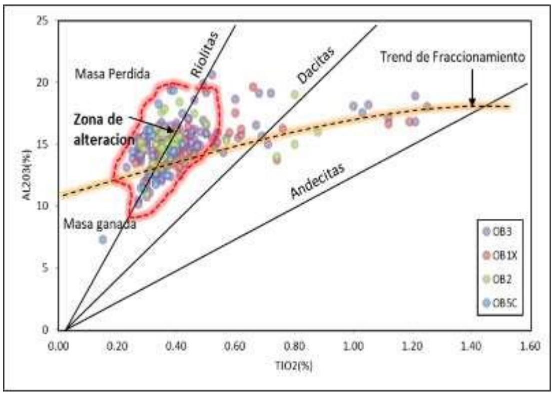


Figure 3. *TiO2 vs Al2O3 highlights the predominance of felsic lithologies that incurred in strong hydrothermal alteration (Taken from Barrett and McLean, 1997).*



Therefore, the permeable conduits are in contact with very favorable rock because they are felsic bimodal (base metals (Zn-Cu-Pb) –(Ag* and punctually Au), it is this characteristic that gives great economic potential to the Cerro Lindo VMS with respect to the other neighboring VMS of the Casma basin, the porosity of this type of volcanic and being part of the first rupture events of the Casma basin (Figure 3).

Cerro Lindo, as we can see according to box rock, is a deposit with a higher content of Zn-Pb-Cu and with respect to precious metals a higher content of Ag and point Au (Figure 4).

Figure 3: *Stratigraphic relationship of the different lithological associations (Taken from Piercey 2011).*

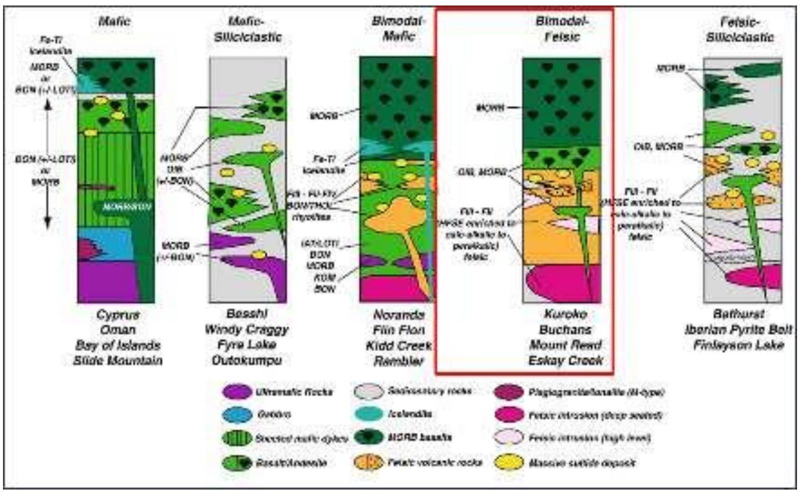
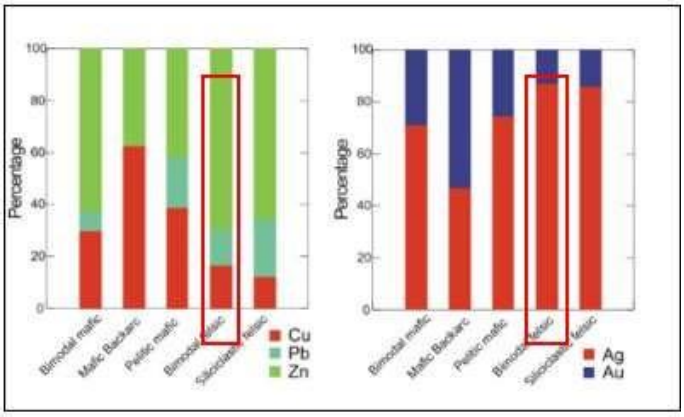


Figure 4: *Relative metal content in VMS deposits (Taken from Franklin 2005).*



CHARACTERIZATION OF HYDROTHERMAL ALTERATION

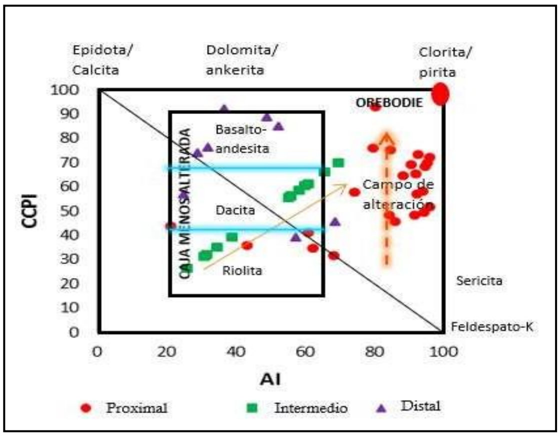
The main alteration in Cerro Lindo is the sericitation throughout the deposit and extends laterally hundreds of meters beyond the massive sulfides, this alteration is generally found in the floor box (Trujillo, 2012).

The CCPI vs AI index (Ishikawa et al., 1976) presents a vector towards mineralization, in the center of the system potassium sericite plus chlorite with high Fe content (chlorite-pyrite) is observed; and in the most distal parts magnesium chlorite, calcite and epidote (Bueno & Mendoza, 2019) (Graph 4).

The emplacement of the massive sulphides from the deposit reflects a strong structural control in their formation and preservation, as the ore bodies are aligned in fault-bounded structural blocks that acted as conduits of heading mineralization (NW-SE). (Hinostroza, 2009).

Alteration assemblies were established by means of lithogeochemical diagrams (Bueno & Mendoza, 2019). These assemblies were plotted in the diamond holes and a 3D alteration model was generated for ore bodies 1 and 2 (OB1 and OB2), in order to determine the alteration trends and establish a correlation with other mineralization guides (structural, geophysical, geochemical) in the spatial context. With this set of information, it was sought to support the creation of an alteration model that, complemented with other exploration tools, serves to generate new targets in the Cerro Lindo Mining Unit.

Figure 4 *Alteration table with the Hashimoto-Hashimoto Alteration Index (AI) (Ishikawa et al., 1976) vs. the Chlorite-Carbonate-Pyrite Index (CICC, Large et al., 2001) for volcanic rocks according to their proximity to the mineralized body.*



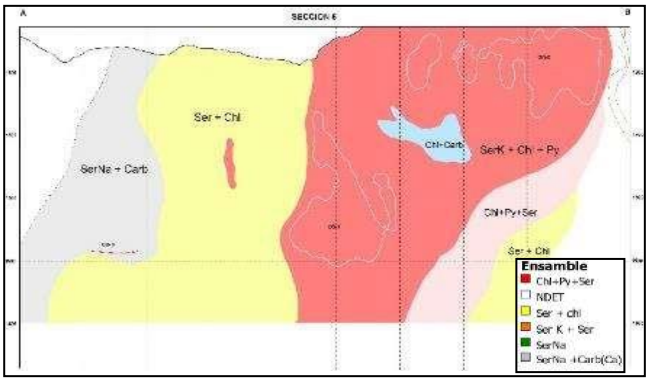
3D MODEL OF ALTERATION

It was considered to make the OB1 and OB2 models due to the different characteristics they have; OB1 belongs to a first event of mineralization (primary event), it is of low grade of Cu and Zn, with lithology mainly of SSM (mineralization in bands on volcanic rock, and controlled by shallow faults NW-SW, which transported Cpy1 type mineralization, it is also located towards the Rim zone of the deposit; while OB2 is a body of massive high-grade sulfides of Cu and Zn, related to subsequent events of the mineralization, with SPB (primary sulphide of Baritine) and SPP (primary sulphide of pyrite), is controlled by deep faults NW-SE and belongs to the main structural corridor that will allow us to better define the alteration vectors (Canales, 2015).

Based on the alteration assemblies determined by the interpretation of the CICC/AI diagram, this information was taken to the diamond drill holes and e

interpreted sections that established the following domains related to the same mineralization event: (Figure 5)

Figure 5 *Cross-section N° 6, alteration domains according to CCPI vs AI graph assembly.*



The closest assembly to the mineralized zone is determined by SerK+ChlFe [0.8-1] (hot zone). Towards the most distal area, thin halos of Ser-Na [0.4-0.6] are observed, and in a very isolated manner at the edges of ChlMg [1-1.6] (cold zone) (Figure 4)

- **SerK+ChlFe (Py) [0.8-1] (hot zone),** is the alteration halo closest to the mineralized zone that covers at its greatest power 500 m wide by 600m deep, it is the most extensive and pervasive halo that encompasses both the roof rock and the floor rock. This area is marked by the loss of Na_2O and CaO, but enrichment in K. Pyritization occurs as disseminations, patches and veins enriching in Fe the chlorite of alteration of this area.

o The SerK+ChlFe (Py) zone is mainly related to the weakness zone (fault). This alteration becomes more powerful towards the bodies of high-grade massive sulfides (OB2), the second mineralization event (Figure 6).

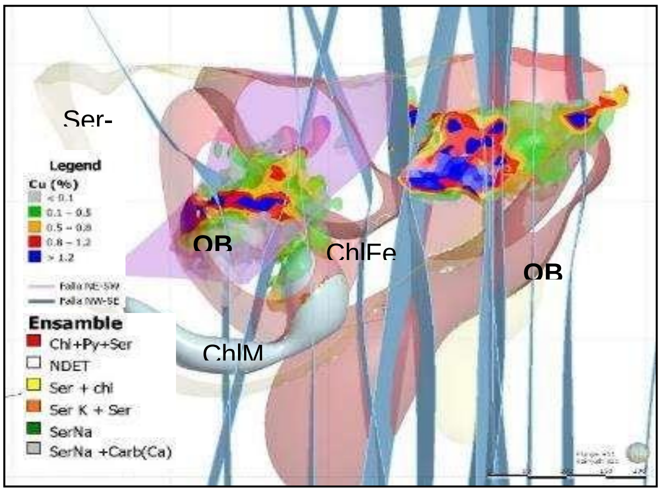
- **Ser+Chl [0.8-0.4]** zone of intermediate temperature, are thin halos that occur occasionally and are located in the areas where contact between

Rhyodacites and rhyolites. In this area, the presence of mineralization, disseminated pyrite and patches with the punctual presence of chalcopyrite (SSM) begins to be marked. The loss of Fe in chlorite and K in sericite is evidenced. It extends with a greater proportion towards low-grade bodies (first mineralization events) (Figure 6).

- **Being - Na [0.4-0.6]- cold zone,** are halos of little dimension, this alteration is non-pervasive, related to less differentiated andesite-dacite rocks. Marked decrease in K and increase in Na in micas (Figure 6).

- **ChlMg [1-1.6] (cold zone),** this alteration is punctual, related to intrusive zones and andesitic dams, which corresponds to the earliest events of alteration, Mg enrichment mainly in chlorite and calcite in veins (Figure 6).

Figure 6. *3D alteration model in the Cerro Lindo Deposit with Cu geochemistry (OB1- OB2).*



In the same way with the AI/CICC ratios, the isovaleric map of the entire deposit was elaborated, taking into account the alteration assemblages: SerK-ChlFe, Ser-Chl and SerNa-ChlMg according to the proximity of the mineral zone.

CORRELATION OF LITHOGEOCHEMISTRY WITH OTHER MINERALIZATION CONTROLS

1.1 *Lithogeochemistry-Geochemistry Vs Structural Geology*

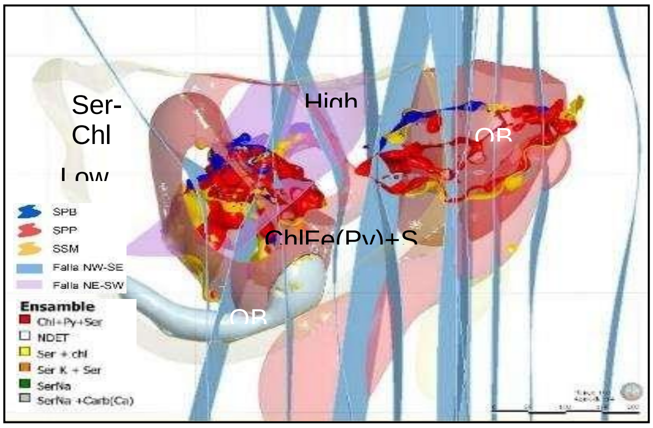
The Cerro Lindo site is hosted in a felsic volcanic sequence with exposed outcrops in a NW-SE direction strip. This volcanic level presents large halos of alteration with different mineralogies and intensity of alteration, which have been affected by thermal variations and by the large systems of NW-SE faults and subsequent N-S faults.

The OB1 whose control has been marked by shallow NW-SW faults of greater angle and with greater spacing between them, are edge faults with little drag of economic mineralization, related to the Ser –Chl alteration and the NE-SW faults which have been the conduits of the high-grade point zones in OB1, these areas have a strong halo of SerK+ChlFe (Py) alteration (Figure 7)

In OB2 a large system of deep NW-SE faults is observed, which bring economic mineralization and approach the SerK+ChlFe (Py) zone (Figure 7).

As there is deep structural control with fault systems (NW-SE) whose stresses have been continuous and the dip of a smaller angle, they are the most favorable to form economic zones and will present the relationship with the guide alteration towards the center of the body.

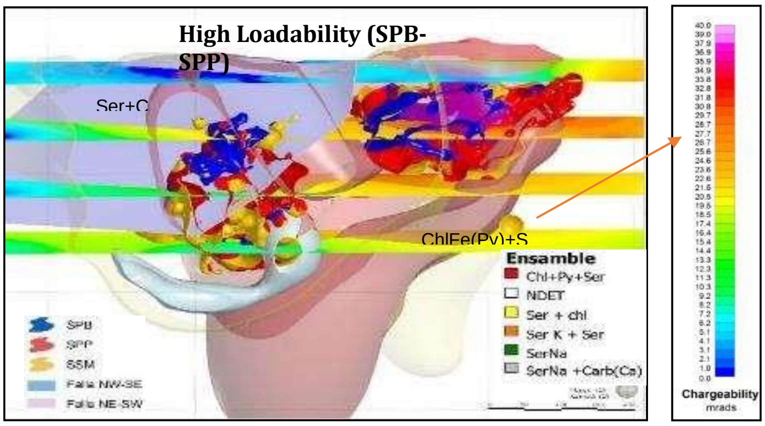
Figure 7 *Alteration Model Vs Structural Vs Lithology*



1.2 *Lithogeochemistry-Geochemistry Vs Geophysics*

According to the PI geophysics work carried out in 2017, anomalies of low resistivity (40ohm-m) and high loadability capacity (40mrad) were detected. This could indicate a continuation of mineralization of the mining unit (Figure 8).

Figure 8 :*Geophysics (chargeability) vs alteration vs lithology.*



OB1 has low chargeability due to lithology type (SSM), with a content of 20 to 50 % of sulfides. This area is related to the low-grade zone (lower part of the body) where the Ser+Chl halo extends and ChlMg appears in a punctual manner (Figure 8).

OB2 has high chargeability due to the massive emplacement of >50% sulfide (SPP-SPB) and is related to the alteration zone that is the guide to the center of the orebodies (Figure 8).

RESULTS

The alteration model for OB1 and OB2 suggests that the SerK+ChlFe (Py) alteration forms the proximal halo bordering the mineralization. This halo varies in power depending on depth and temperature. At higher temperatures, the alteration becomes more extensive and is related to (Cpy-Po zone) while; at the top of the VMS system the power decreases (Sp-Gn-Ba zone), and the power of the Ser+Chl alteration increases.

In the A-A ´ section taken from a diamond drill hole we see that the high-grade zone comprises precisely the ChlFe (Py) + SerK alteration and less than 20 meters from this mineralized zone where the grades begin to decrease is the predominance of Ser + Chl, take into account that very close to the high-grade zone a thin halo of Ser K is formed just to the East where the others are evident orebody sites of the deposit (Figure 9)

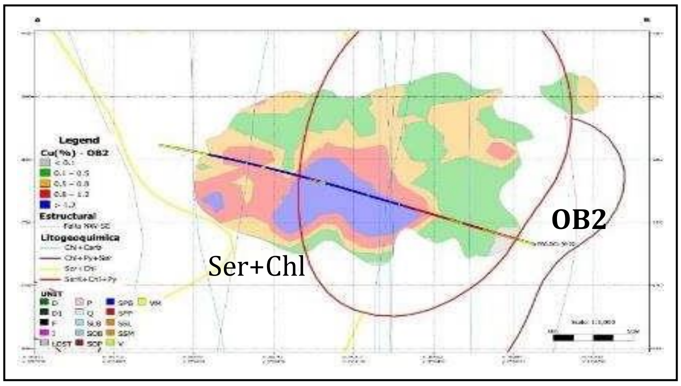


Figure 9 : *Section A-A', Diamond Exploration Drilling, with Characterization ofalteration and geochemistry of Cu in OB1,*

Isovalue alteration maps:

The isovaleric map was prepared based on the AI/CPPI alteration ratios, where it is evident that the zone of massive bodies of the central mineralization corridors (primary pyrite sulfide and primary barite sulfide), would be encompassed by the alteration halo of SerK+ChlFe, while the Edge Bodies that correspond to Semimassive lithologies and mineralized volcanic are located within the Ser+Chl halo.

On the other hand, it is worth mentioning that the volcanic areas of andesites with K content that grade to dacites are associated with intermediate zones that correspond to the Ser +Chl alteration, while the less porous and more distal mafic rocks of

the influence of structural control is evidenced in a less pervasive alteration of Ser Na + Chl (Mg).

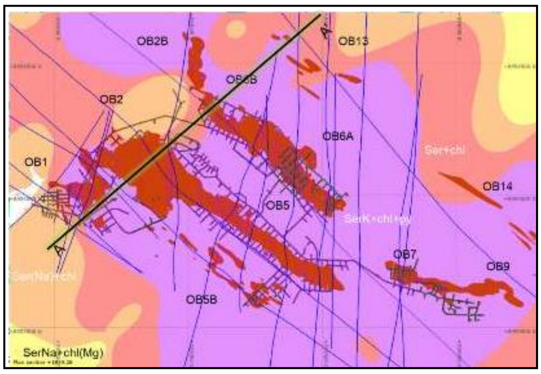


Figure 10.*Plan view of isovaleric map by alteration assembly.*

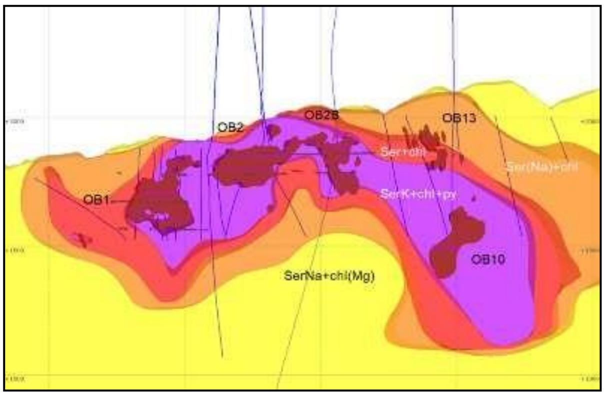


Figure 11 *: Section A-A', of the alteration halos.*

2. CONCLUSIONS AND RECOMMENDATIONS

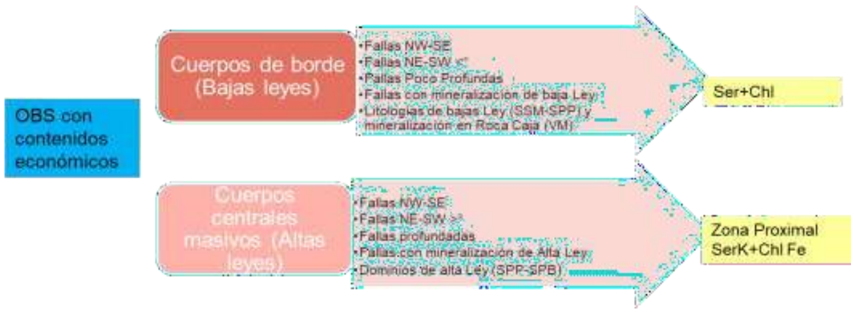
From the lithogeochemistry it was deduced that Cerro Lindo is linked to a chalco-alkaline magmatic series enriched in K, the volcanic series is characterized by horizons of andesites – dacites-Rhyodacites and rhyolites punctual placed as domes, and taking into account the petrographic characteristics and chemical content is that they present quite an affinity for the placement in large lenses of mineralized bodies, due to their high porosity and because the box rock is located near the conveyor faults, they have great potential in size and grades within the VMS.

Cerro Lindo is located in the oldest felsic bimodal level of the Casma basin, and it is these early stages of the break that is usually best enriched in economic mineralization contents mainly of base elements followed by the presence of Ag*-Au, it is precisely this location that makes it much more powerful than the other VMS in the area.

By taking the lithogeochemical data generally used in interpretation diagrams to a three-dimensional model, it has allowed to have a better correlation with the lithological, geophysical, geochemical and structural control, and it was possible to establish a vector defined as follows (rhyolite-rhyodacite + NW-SE faults (mineralized) + SerK+ChlFe (Py) + high loadability). This vector, which combines all the controls of mineralization, would lead us to approach areas with economic potential in a VMS type deposit more accurately.

From the alteration model, it is concluded that towards massive bodies with high grades in Zn–Cu such as OB2, the assembly domain prevails (Serk+ChlFe (Py)) and towards pyrittuous bodies with scarce chalcopyrite and remnants of box rock, the halo with the greatest predominance is Ser (K)+Chl.

The SerK+ChlFe (Py) alteration halo has greater power and dominance in deep faults that have brought economic Zn-Cu mineralization (NW-SE and NE-SW), faults related to high-grade bodies; while the shallow NW-SE faults, which bring low-grade mineralization, are related to the Ser-Chl alteration.



Geophysics tells us that high chargeability is related to massive bodies. Therefore, OB1 is a body made up mainly of SSM lithology (volcanic with disseminated pyrite), so it has little chargeability; on the other hand, OB2 is a massive body of sulfides (Py-Cpy-Sp), which gives it greater chargeability. We determined that the SerK+ChlFe (Py) alteration is limited to areas of high loadability (potentially economic zones).

The methodology used in this work can be extended to obtain similar exploration models for the other sectors of the district (Chavín del Sur, Pathuasi Millay, etc.).

Based on this alteration trend, we used these criteria in conjunction with the structural and lithological control, and the result obtained in the exploration of OB12 (Exploraciones Cerro Lindo, 2019), led us to conclude that in other parts of the Cerro Lindo mineralized system, similar vectors of alteration towards massive sulfide bodies are observed. (Figures 12 & 13).

Figure 12 : *Section A-A', Diamond exploration drilling, with Characterization of alteration in OB12 and OB3-4.*

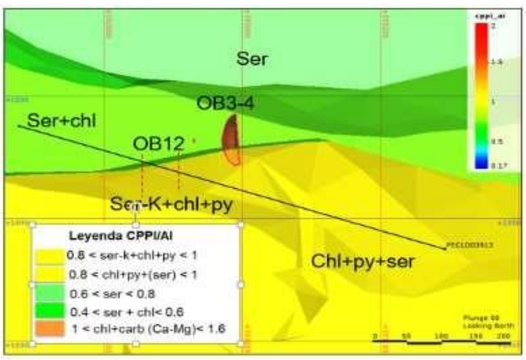
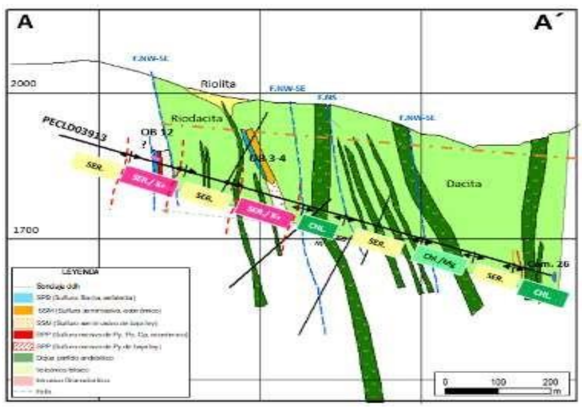


Figure 13 : *Section A-A', Exploration diamond drill hole with alteration halosOB12 and OB3-4.*



It is recommended to increase the data in other reference bodies with the trends already determined to corroborate the vectors and establish alteration signatures.

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