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Petrophysical Signature of the Salobo IOCG Deposit: Insights into Lithology, Hydrothermal Alteration, and Mineralization

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Abstract Summary

Integrating petrophysical and mineralogical data is important for understanding how hydrothermal alteration affects the physical properties of rocks. In this study, petrophysical measurements were combined with mineral mapping from techniques such as TIMA, QEMSCAN, and LIBS to characterize the Salobo IOCG deposit. The results show that different alteration zones have distinct physical signatures. The calcic-sodic zone has low density and magnetic susceptibility with moderate resistivity. A Ca-Fe-K zone marks a transition to more iron- and potassium-rich systems, showing slightly higher resistivity. Iron-enriched areas range from grunerite to almandine and magnetite assemblages, and show high density, magnetic susceptibility, and chargeability. The K-Fe zone is associated with almandine, biotite, and later chlorite, all influencing its petrophysical properties. Potassic alteration lowers resistivity, due to biotite and sulphides. This work demonstrates how combining mineralogical and physical property data improves understanding of mineral systems. A schematic model was developed to illustrate the link between alteration zones and petrophysical responses, offering a useful approach for exploring similar deposits.

Introduction

Understanding the physical properties of mineral deposits and their alteration zones, both at the surface and underground, is important for guiding mineral exploration. As exploration shifts to deeper levels, geophysical data will become more essential, and interpreting this data accurately will require support from geological, mineralogical, and petrophysical studies. Knowing how physical properties change with different rock types, alteration styles, and mineral content helps refine exploration strategies and increases the chances of success. Petrophysical data offers more than just insights into geophysical signatures. It can help interpret a range of geological features, including rock type, weathering, deformation, porosity, and stratigraphy. By combining petrophysical data with geological and mineralogical information, it's possible to better understand how these factors influence physical properties. These relationships can improve core logging, mapping, and the general understanding of mineral systems.

In mining, petrophysical datasets often focus on magnetic susceptibility and density, as they are low-cost and easy to collect. However, studies combining these with mineralogical and geochemical data remain limited. Although some research exists on using mineral and chemical data together, integrated analysis across multiple physical properties is still developing. Salobo, in the Carajás Mineral Province, is one of the largest IOCG deposits globally and one of the few from the Archean era. It is part of a broader group of IOCG deposits that show diverse physical and geophysical characteristics, influenced by differences in mineral content, textures, and structural features. The deposit is associated with the Cinzento shear zone, a major regional structure that marks the boundary between two rock units and acted as a pathway for hydrothermal alteration and deformation. This created a corridor that hosts several IOCG deposits and widespread alteration zones.

Salobo's ore mainly contains bornite, chalcocite, magnetite, and smaller amounts of chalcopyrite and gold, along with other metals like cobalt, nickel, silver, and rare earth elements. This study presents an analysis of Salobo's petrophysical characteristics, such as density, magnetism, resistivity, conductivity, and chargeability, together with its mineral makeup. By linking physical property data to specific mineral assemblages and alteration processes, the study contributes to refining IOCG exploration models and supports better identification of potential targets in similar geological environments.

Method and/or Theory

This study focusing on a multidisciplinary approach that included established tools, and advanced analytics were adopted to investigate the petrophysical signature and mineralogical framework of Salobo. The methodology included petrophysics (multi-tool logging and core measurements), petrography, high-resolution Scanning Electron Microscopy (SEM), such as QEMSCAN and TIMA, as well as laser-induced breakdown spectroscopy (LIBS) data. Drill cores from six representative drill holes were provided by Vale S.A. for these measurements. Additional information for depths in the drill cores can be found in the supplementary material. The drill holes provided (DH00002, 2-1, 2-2, 3, 3-1, and 3-2) were analysed and sampled. A total of 56 samples were collected, encompassing host granites from the Igarapé Gelado Suite, hydrothermal alteration sequences, and the mineralized zone.

The main methodology is based on SEM-based automated mineralogical techniques, integrated with Energy Dispersive X-ray Spectroscopy (EDS), enabled precise mineral identification, elemental analysis, and quantitative evaluation of mineral content, grain size, and associations. Two SEM-based analyses were performed: QEMSCAN (Quantitative Evaluation of Minerals by Scanning Electron Microscopy) and TIMA (TESCAN Integrated Mineral Analyzer). QEMSCAN analysis was conducted at the Institute of Geosciences, University of Brasília (IG-UnB), using a Quanta 650F field emission scanning electron microscope with a tungsten source, operating at 25 kV and 10 nA, and equipped with two Bruker XFlash 6–30 SDD energy-dispersive spectrometers. A total of 20 thin sections were scanned at 15-μm resolution. TIMA analysis was performed at AXT PTY LTD in Australia. This system integrates SEM with EDS, utilizing up to four EDAX Element silicon drift detectors to enhance sensitivity and accommodate high count rates. Fourteen thin sections were analyzed. Both provided detailed quantitative and qualitative mineral data, including concentrations, element distributions, and mineral texture properties. Image analysis generated mineral distribution maps with 47 identified minerals, accompanied by a table of percentages. The same color scale and regrouping method were applied in both analyses.

Results

Distinguishing the hydrothermal alteration zones within the complex Salobo system can be challenging. Previous studies on the parageneses and mineral associations identified six distinct zones. During sampling, while some of these zones were confirmed, new ones were identified and sampled in a deep portion known as Deep Salobo, below the current open pit of the deposit. In total, seven zones were identified and classified: host rocks, calcic-sodic, iron enrichment, potassic, mineralization (ore), later albitization, and post-ore. Petrophysical data were integrated with mineral content for each zone and subzone, and analysed according to paragenetic sequences, highlighting overprinting relationships.

Considering the six main zones identified in this study, as well as in the research by Melo et al. (2016) and Diniz et al. (2022), the qualitative petrophysical data exhibit significant variations when analysed using boxplots. These populations, evident in the broad range between minimum and maximum values and the interquartile range, underscore the need for further in-depth analysis and discussion. Among the average of hydrothermal alteration zones: 1) density is highest in the ore body (average value ~3.61 g/cm³) and lowest in the post-ore zone (average value ~2.87 g/cm³); 2) magnetic susceptibility reaches its highest value in the potassic zone (average value ~1347.49 x10^{-3} SI) and its lowest in the post-ore zone (average value ~0.34 x10^{-3} SI), which can be considered an outlier; 3) resistivity is highest in the calcic-sodic zone (average value ~2936.70 Ω.m) and lowest in the iron enrichment zone (average value ~1956.56 Ω.m); 4) chargeability is highest in the ore body (average value ~93.51 mV/V) and lowest in the post-ore zone (average value ~9.36 mV/V). Given the substantial petrophysical variations across the six main alteration zones, along with the mineral compositions identified through mineral mapping, new subzones are proposed.

The analysis of density, magnetic susceptibility, resistivity, and chargeability shows distinct signatures for each alteration zone. Host rocks present low density (2.70 - 3.10 g/cm³), very low magnetic susceptibility (~0.001 SI), high resistivity (4,000 - 5,000 Ωm), and low chargeability (<50 mV/V) (Figure 1). These rocks show significant contrast when compared to altered rocks.

Calcic-sodic alteration, an early zone, presents low density (~2.89 g/cm³), low magnetic susceptibility (0.081 - 0.091 SI), and moderate resistivity (~2,781 Ωm). Albite and actinolite dominate this zone, with minor magnetite. The low density and magnetic susceptibility reflect a mafic to intermediate protolith. This zone marks the distal zone and regional alteration halo (Figure 1). The iron enrichment zone, a key transition zone, exhibits high density (>3.30 g/cm³), high magnetic susceptibility (~0.414 - 7.516 SI in magnetite-rich samples), and increased chargeability (62.2 - 89.7 mV/V). Resistivity decreases with higher magnetite and sulphides (~95.1 - 942 Ω.m). Grunerite, almandine, and magnetite dominate this zone, transitioning from distal Na-Ca assemblages. These minerals strongly correlate with density, magnetic susceptibility, and conductivity, highlighting magnetite and ore mineralization (Figure 1).

Potassic alteration, a proximal mineralization zone, presents a moderate density increase (2.85 - 3.05 g/cm³), higher magnetic susceptibility (0.02 - 0.06 SI), and decreased resistivity (1,658 Ωm). Biotite dominates, replacing earlier minerals, and associates with bornite, chalcopyrite, and other sulphides, which makes it difficult to directly identify a petrophysical footprint for biotite. Biotite-associated sulphides decrease resistivity and increase chargeability. Ore minerals, including bornite, chalcopyrite, chalcocite, and pyrite, significantly increase magnetic susceptibility, density, and conductivity. (Figure 1). Later albitization alteration, a transitional zone, presents moderate density (~3.0 g/cm³) and chargeability (~80 mV/V), with complex effects on magnetic susceptibility and resistivity. Chlorite dominates, with Ab and magnetite remnants marking the transition from mineralized systems to later-zone overprinting, indicating extended hydrothermal fluid activity. Post-ore alteration features low density from K-feldspar, Ab, and plagioclase assemblages (Figure 1). These minerals are gangue or accessories, so their impact on the physical properties would not be significant. Intense K-feldspar alteration defines this zone, with weaker epidote, sericite, and chlorite occurrence.

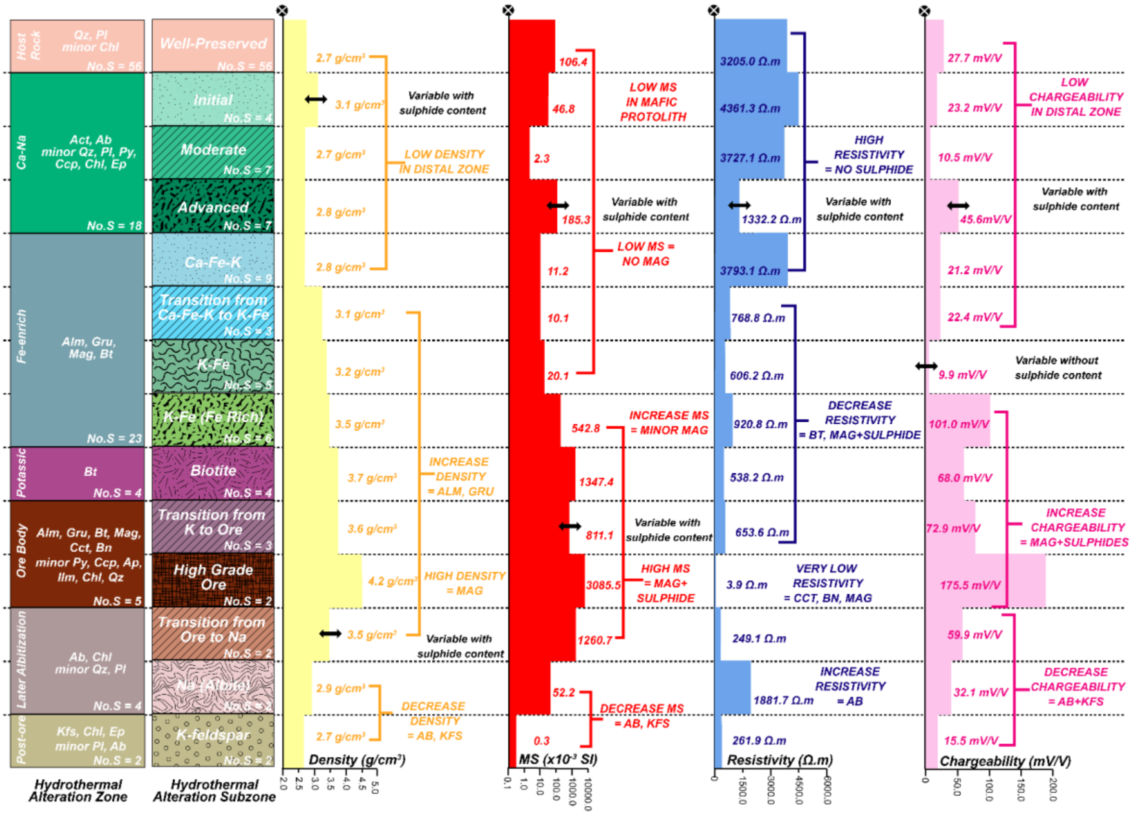

Figure 1: Petrophysical illustrative log of hydrothermal zone and subzone of Salobo deposit samples, main minerals, and physical properties average. *Abbreviations: Ab -Albite, Act – Actinolite, Alm – Almandine, Ap – Apatite, Bn Bornite, Bt - Biotite, Cct - Chalcocite, Ccp - Chalcopyrite, Chl – Chlorite, Ep – Epidote, Gru -Grunerite, Ilm - Ilmenite, Kfs - K-Feldspar, Mag - Magnetite, No.S - Number of Samples, Pl – Plagioclase, Py – Pyrite and Qz -Quartz.*.

Conclusions

The Salobo deposit's petrophysical patterns highlight the connection between hydrothermal alteration and mineralization, though overlapping events make alteration zones hard to separate. A combined analysis of physical rock properties is needed to improve zoning and target definition. Calcic-sodic alteration helps in identifying alteration halos, while iron-rich and potassic zones are more directly linked to copper and gold mineralization. Using multiple geophysical methods—magnetics, gravity, resistivity, and chargeability—improves exploration. Magnetic data is useful but may reflect barren zones; gravity helps map denser mineralized areas; resistivity and chargeability are more reliable for locating ore zones, especially when used together. Exploration should focus on areas with high magnetism, density, and chargeability, and low resistivity, though these signals may not overlap. Understanding how these signals relate to specific minerals (e.g., magnetite with magnetics, sulphides with chargeability, almandine with density) helps reduce misinterpretation and improve targeting. The study provides a framework for applying integrated methods to other IOCG deposits, improving exploration efficiency and reducing risk.

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