THE 2.86 Ga HADES AND HADES NORDESTE COPPER DEPOSITS, SW CARAJÁS: IMPLICATIONS FOR THE MESOARCHEAN DEFORMATION-MINERALIZATION PROCESSES

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ABSTRACT

The Hades and Hades Nordeste deposits are situated in the southwestern sector of the Carajás Domain, along a WNW-ESE regional shear system correlated to the Canaã Shear Zone. The deposits are hosted by metagranodiorite, amphibolite and actinolite-tremolite schists that are intersected by basalts, andesitic basalts and rhyolites. In both deposits, an early alkaline (orthoclase-albite) alteration was followed by a venular calcic assemblage (epidote I-actinolite±apatite±titanite±calcite) with alkaline halos, commonly related to subordinate mineralization (chalcopyrite I-pyrite I-magnetite-galena I-pentlandite). An extensive chlorite-quartz-rich alteration was associated with quartz recrystallization linked to foliation (S_{n+1}) development. The latter was related to the main ore stage represented by chalcopyrite II-bearing breccias of ca. 2.86 Ga age (Re-Os in molybdenite). The reported mineralization age is coeval to a regional deformation event related to the collision between Rio Maria and Carajás domains. This is the oldest copper mineralizing event ever registered in the Amazonian Craton. A younger hydrothermal system, likely Paleoproterozoic (1.8 Ga) in age, is registered by strong potassic, propylitic and sericitic alteration that crosscut host rocks and overprints previous alteration stages. This system is not accompanied by expressive sulfide mineralization and has similarities with the magmatic-hydrothermal event described at the Iriri-Xingu Domain, correlated to the Uatumã SLIP.

PALAVRAS-CHAVE: Mesoarchean; Hydrothermal alteration; Carajás Province.

INTRODUCTION

In the last decades, the discovery of important world-class mineral deposits in the Carajás Province attracted research that contributed to the ore formation understanding and its relationship with magmatic, metamorphic, and deformation events and crustal evolution of the province. The Hades and Hades Nordeste deposits, which belong to Vale S.A. company, are located in the westernmost sector of the Carajás Domain, an area that lacks detailed and

integrated geological and metallogenetic information, hampering the understanding of its geological and hydrothermal evolution. The geological units of the region, which is close to the Iriri-Xingu Domain (Central Amazonian Province), are represented by a Mesoarchean granite-gneiss association and by a metavolcanosedimentary and banded iron formation succession of the São Félix Group (Macambira and Vale 1997; Avelar et al. 1999). The mafic and ultramafic lithotypes of the Cateté Intrusive Suite and the Paleoproterozoic volcanic rocks of the Sobreiro and Santa Rosa formations crosscut the previous units (Macambira and Ferreira Filho 2002; Juliani and Fernandes 2010).

This study provides geological and geochronological data for the Hades and Hades Nordeste deposits in order to characterize the hydrothermal alteration patterns and mineralization styles. This work brings new information regarding the association between Mesoarchaean deformation and copper mineralization in the extreme southwest sector of the Carajás Domain.

MATERIAL AND METHODS

The geological characterization of the deposits was based on detailed macroscopic and petrographic core descriptions of four drill holes belonging to Vale S.A. company (PKC HADES DH00001/DH00012; PKC HADES NE DH00001/DH00002) and of samples collected on a regional geological survey. Representative samples were chosen for optical microscopic analysis (n = 75), performed at the Institute of Geosciences, University of Campinas (IG-UNICAMP). Two samples were selected for in situ U-Pb titanite dating in the host foliated metagranodiorite. The isotopic analyses were carried out on a Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) at the Isotopic Geology Laboratory of the IG-UNICAMP. Molybdenite grains from ore samples were separated for Re-Os dating at the Canadian Centre for Isotopic Microanalysis, University of Alberta (Canada) by N-TIMS (Negative Thermal Ionization Mass Spectrometry) using a ThermoScientific Triton instrument.

RESULTS

The Hades and Hades Nordeste deposits (~6 km apart) are located at the extreme western sector of a WNW-ESE regional shear system nearly 20 km long (possibly correlated to the Canaã Shear Zone) and are hosted by metagranodiorite, and alternating amphibolite and actinolite-tremolite schist. Undeformed basalts, andesitic basalts and rhyolites intersect this sequence.

Foliated metagranodiorite (Fig. 1A) is medium- to coarse-grained (500 μm to 4 mm) light gray or brownish pink, composed of plagioclase (40-50%), quartz (15-25%), K-feldspar (5-15%; orthoclase and microcline), and accessory titanite, zircon, apatite, monazite, and hornblende, with hydrothermal chlorite (up to 10 %), sericite (up to 10%), and epidote (up to 5%). Feldspar and quartz crystals show interlobate boundaries and incipiently to well-defined grain orientation. In intensely deformed samples, incipient and spaced foliation (S_n) is defined by chlorite stretching and orientation, quartz ribbon, and minor feldspar subgrains orientation. These foliated rocks show feldspar porphyroblasts with tails (recrystallized crystals or chlorite alteration veins and fronts), core-and-mantle structure, tapering and bent twin planes. Quartz crystals have undulose extinction with subgrain development.

The amphibolite is dark green, fine- to medium-grained, has netamoblastic to polygonal granoblastic texture and roughly parallel spaced to continuous foliation planes (S_n; Fig. 1B). This rock is mainly composed of hornblende (40-70%, mainly altered to actinolite), plagioclase (25-35%), quartz (up to 10%), with accessory ilmenite (5%), magnetite (5%), sulfides (3%), and titanite (2%). The metamorphic minerals align with the dominant foliation/banding planes (S_n). Banding is defined by leucocratic millimeter-scale with small-sized (250-500 µm) plagioclase, hornblende, and minor quartz crystals, alternating with melanocratic layers with medium-sized hornblende (~450 µm to 2 mm). Amphibole-rich schist is formed by actinolite-tremolite (up to 70%) with accessory plagioclase (20%), chlorite (up to 10%), chromite and sulfides along a continuous and anastomosed foliation plane (S_n).

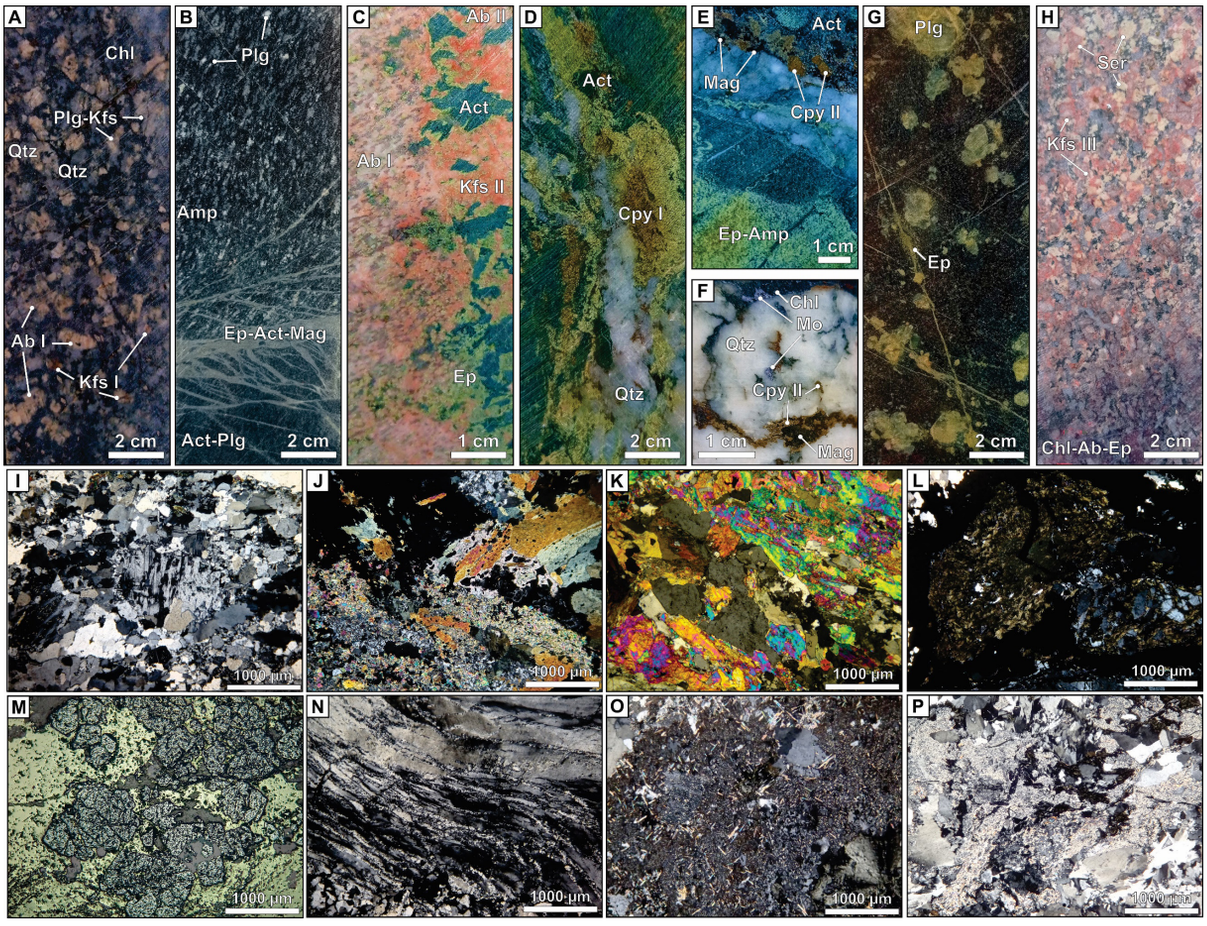

Figure 1. Macroscopic and petrographic features of the main host rocks, hydrothermal alteration and mineralization of the Hades and Hades Nordeste deposits. A: Altered metagranodiorite (Hades Nordeste). B: Foliated amphibolite (Hades Nordeste). C-D: actinolite-epidote veins with alkaline halos (Hades). E: Actinolite-epidote mineralized vein (Hades Nordeste). F: Main mineralization related to chlorite-magnetite breccia (Hades Nordeste). G: Porphyritic basalt (Hades). I: Potassic and sericire alteration (Hades Nordeste). I: Hydrothermal albite I (Hades). J: Actinolite-epidote-magnteite vein (Hades Nordeste). K: Apatite in epidote-actinolite vein (Hades). L-M: Ore breccia (Hades). N: Deformed quartz crystals in ore breccia (Hades Nordeste). O: Late potassic alteration (Hades Nordeste). P: Sericite alteration (Hades Nordeste).

The volcanic rocks, which do not host copper mineralization and the associated hydrothermal alterations, are massive, light green to brownish gray, isotropic, aphanitic, aphyric to porphyritic (Fig. 1G). The basalt and andesite basalt have a fine-grained matrix (up to 100 µm) composed of

pyroxene, plagioclase, and subordinate amphibole. Porphyritic samples have altered subhedral plagioclase phenocrysts (up to 1 cm). Phenocrysts of quartz and plagioclase and calcite or quartz amygdales are millimeter-scale (1 to 3 mm). The porphyritic rhyolite shows a holocrystalline matrix, plagioclase phenocrysts, amygdales filled with pyrite, and epidote-quartz veins.

At the Hades deposit, pervasive sodic (albite I) and potassic (microcline I) hydrothermal alteration prevail. The hydrothermal albite I shows chessboard twinning (Fig. 1I) and occurs in igneous feldspar rims. The potassic alteration is marked by microcline I formed at the mineral interstices. These initial hydrothermal alteration stages are followed by actinolite-epidote I (±apatite±titanite±calcite) veins associated with albite II-microcline II-orthoclase halos (Fig. 1C, K). The epidote-actinolite assemblage occurs in irregular veins that may be related to minor and initial mineralization (chalcopyrite I-pyrite I-galena I-pentlandite±magnetite; Fig. D).

The Hades Nordeste exhibits an extensive sodic (albite I) followed by sodic-calcic alteration (actinolite I-scapolite) and calcic-iron veins (actinolite II-epidote I-quartz-magnetite I±calcite±scapolite), which are associated with alkaline (albite-orthoclase) halos and mineralized veins (chalcopyrite I-magnetite I-pyrite I-molybdenite I-galena) (Fig. 1E, J)

These alteration stages are crosscut by a chlorite±calcite assemblage related to the main ore stage. The latter at the Hades deposit is represented by the chalcopyrite II-pyrite II-galena II-molybdenite assemblage related to chlorite-quartz±apatite±titanite±calcite±epidote fronts (Fig. 1L-M). At the Hades Nordeste deposit, the mineralization occurs as chalcopyrite II-pyrite II-magnetite II-molybdenite II veins, stockwork and breccias with chlorite-epidote-quartz±calcite, biotite-chlorite-quartz±calcite (Fig. 1F), and stilpnomelane-biotite-chlorite-quartz±calcite assemblages. The ore breccias in both Hades and Hades Nordeste exhibit strong evidence of dynamic recrystallization (i.e., quartz ribbon, subgrain formation, stretching, and folding; Fig. 1N). Chalcopyrite occurs especially along the foliation (S_{n+1}) defined by the preferential chlorite orientation and quartz stretching (Fig. 1N). Molybdenite (Re-Os) model ages of 2869 ± 12 Ma were obtained for crystals in ore breccias of the Hades Nordeste deposit.

Late alteration is represented by potassic (K-feldspar; Fig. 1 H, O), propylitic (chlorite-epidote-albite±titanite) and sericite (Fig. 1H, P) alteration affecting both metagranodiorite and volcanic rocks. In addition, late epithermal veins with open space-filling and comb textures crosscut especially Paleoproterozoic volcanic rocks (rhyolite, basalt, andesite basalt), and are filled by quartz (eventually bladed), calcite, fluorite, K-feldspar and epidote.

DISCUSSION AND CONCLUSIONS

Regional geology and petrographic evidence demonstrate that Hades and Hades Nordeste deposits record a protracted evolution and a complex hydrothermal history, likely related to multistage hydrothermal events. In both deposits, the copper ore is hosted by Mesoarchean deformed and foliated rocks. Hydrothermal minerals form along S_n and S_{n+1} foliation planes, adjacent to metamorphic minerals. Ore styles varies from granular crystals and massive aggregates to breccias filling intracrystalline spaces, and mineral cleavages or fractures. Molybdenite associated with chalcopyrite-bearing breccias interpreted as the main mineralizing event yields Mesoarchean age (ca. 2.86 Ga) and is the oldest copper mineralizing event ever registered in the Amazonian Craton. This mineralization appears to be coeval with a deformation event, associated with stretching, folding and mineral recrystallization and with a well-defined chlorite-calcite foliation (S_{n+1}).

The hydrothermal succession in both deposits is characterized by an early alkaline (orthoclase-albite) alteration followed by a calcium-rich (epidote-actinolite±apatite±titanite± calcite) venular assemblage with alkaline halos, commonly related to minor mineralization (chalcopyrite-pyrite-magnetite-galena-pentlandite). An extensive chlorite-quartz-rich alteration is associated with quartz recrystallization and foliation development (S_{n+1}) related to the main ore stage represented by chalcopyrite (pyrite-galena-molybdenite) breccias. A second hydrothermal system is evidenced by the occurrence of strong potassic, propylitic and sericitic alteration that crosscut host rocks and previous alteration stages. These late alterations are associated with brittle and discontinuous veins and breccias in volcanic and granitic rocks, with open-space filling and comb textures. This alteration system resembles a Paleoproterozoic magmatic-hydrothermal system (ca. 1.8 Ga) correlated to the Uatumã SLIP, well-described at the Iriri-Xingu Domain of the Central Amazon Province.

Foliation (S_{n+1}) and evidence of dynamic recrystallization due to shearing in ore breccias likely indicate a structurally controlled mineralization. The molybdenite ages may represent that the chalcopyrite-bearing breccias are coeval with a regional deformation event at late Mesoarchean (3.0-2.8 Ga; Araújo and Maia, 1991; Holdsworth and Pinheiro, 2000) related to the collision between the Rio Maria and Carajás domains (Silva et al. 2018; Marangoanha et al. 2019; Silva et al. 2021).

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