NON-SULFIDE AND SULFDE-RICH ZINC DEPOSITS OF THE VAZANTE-PARACATU BELT, MG, BRAZIL: EVOLUTION OF THE HYDROTHERMAL SYSTEM

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INTRODUCTION

The Vazante-Paracatu belt, northern Minas Gerais state, represents the most important zinc district in Brazil. The Neoproterozoic Vazante Group (Dardenne et al., 1988) is host to all zinc deposits in the belt. At the northern part of this belt, carbonate-hosted zinc deposits (Morro Agudo, Fagundes, Ambrósia, Poções) composed mainly of sulfides are hosted by dolostones of the upper Morro do Calcário Formation, which is overlain by black carbonaceous slate and phyllite of the the Lapa Formation. At south, the Vazante deposit, which represents the major known non-sulfide zinc deposit (Hitzman et al., 2003), is hosted by metapelitic-carbonatic units of the stratigraphically lower Serra do Poço Verde Formation.

Although exploitation for non-sulfide zinc deposits, especially the supergene ores (smithsonite, hemimorphite, and hydrozincite), started hundreds of years ago, these deposits are becoming attractive exploration targets for the mining industry when compared with sulfide deposits, mainly because they characteristically lack Pb, S, and other deleterious elements, offer low-energy recovery of zinc, and possess higher "in situ" economic value (Borg, 2002). According to Sangster (2003), the non-sulfide zinc deposits also require a subtle change in exploration procedure in relation to sulfide bodies, because they do not lend themselves to geophysical exploration. Many non-sulfide zinc deposits remain to be discovered at the surface by means of a simple recognition of a wide variety of both supergene and hypogene non-sulfide zinc minerals. However, new models that consider specific geological controls and metallogenetic parameters are of fundamental importance to exploration of these deposit types.

The non-sulfide zinc deposits traditionally were regarded as of supergene origin, however, it is becoming increasingly clear that many willemite-bearing deposits are of primary hypogene origin (Monteiro, 1997; 2002; Monteiro et al., 1999; Brugger et al., 2003; Groves et al., 2003; Hitzman et al., 2003). Examples of hypogene non-sulfide deposits, according to Hitzman et al. (2003), include Beltana and Aroona (Australia), Berg Aukus and Abenab (Namibia), Star Zinc and Kabwe (Zambia) and the Vazante deposit (Minas Gerais, Brazil).

Also the Vazante ore types have been regarded as derived from supergenic alteration of primary Mississippi Valley-type sulfide ores (Amaral, 1968), since the 1960's. The occurrence, at surface, of willemite involving remains of sulfides strongly replaced by chalcocite, covellite, cerussite, and malachite with typical crustiform textures, was considered as evidence of the willemite secondary origin (Amaral, 1968). Petrographic studies indicate, however, that sphalerite replacement by willemite was largely structure controlled and preceded the supergene mineral formation (Monteiro, 1997). Structural studies indicate that the bulk willemite mineralization was related to the development of the Vazante Shear Zone (Pinho et al., 1990; Monteiro, 1997). Relatively high temperatures for the willemitic assemblage were estimated by stable isotopes (~ 260 ^{o}C; Monteiro, 1997; Monteiro et al., 1999) and fluid inclusion studies (~180 ^{o}C; Dardenne and Freitas–Silva, 1999). All these studies support an epigenetic-hydrothermal origin for this ore type from mineralizing fluids at high fO_2/fS_2 (Monteiro et al., 1999; Hitzman et al., 2003).

In the Vazante-Paracatu district, a puzzle of complex relationships among non-sulfide and different styles of sulfide mineralization (syndiagenetic and epigenetic) is recognized. These different styles of hypogene mineralization are related to regional scale thermal regime and fluid flow, but are also strongly controlled by local stress, sulfur sources, and physicochemical conditions. The present paper aims to present the evolution of the regional hydrothermal system and the role of specific controls on non-sulfide and sulfide-rich styles of mineralization.

CARBONATE-HOSTED SULFIDE-RICH DEPOSITS

The Morro Agudo Zn-(Pb) deposit is the main sulfide-rich deposit in the district, with estimated reserves of 7.6 million tones with 5% Zn (T.F. Oliveira, 2005; personal communication). The deposit is hosted by breccia, dolarenitic breccia and dolarenite. The ore is mainly composed of disseminated fine-grained brown-colored sphalerite and galena, with subordinated pyrite and galena. These sulfides cemented unconsolidated allochemical grains and progressively replaced diagenetically-modified coated grains. Commonly, the sulfides show convolute or compaction structures. This mineralization style has been considered mainly as syndiagenetic (Dardenne, 1979; Hitzman, 1997). Colloform sphalerite, galena, and pyrite and coarse-grained, zoned honeycolored sphalerite represent a late mineralization stage at the Morro Agudo deposit, which could be considered as late-diagenetic or epigenetic, very similar to the main mineralization stage of the Fagundes deposit. The mineralized bodies are bounded by a normal fault with a strike of N350°, which has been considered as a syn-sedimentary feeder zone and a preferential conduit for the metalliferous fluids (Dardenne, 1979; 2000; Misi et al., 1999).

Fagundes is a stratabound deposit hosted by dolostones and is characterized by strong silicification, dolomitization and a Fe-rich carbonate alteration halo. The main ore is represented by rhythmically banded, colloform, and zoned pyrite, sphalerite and galena, related to wall rock dissolution and sulfide infilling, which probably occurs late during the burial diagenesis. Later veins and breccia ore types reflect epigenetic mobilization, related to brittle-ductile structures.

Ambrósia mineralization is mainly fault-controlled and related to brecciated dolostone, which is tectonically imbricated with black shales and slates. Typical features shown are host rock recrystallization, minor silicification, baroque dolomite and ankerite formation. Pyrite, marcasite, sphalerite and minor galena occur in brecciated comb-veins and veinlets, which overprint stylolites and tectonic fractures, suggesting an epigenetic origin for the ore.

THE VAZANTE NON-SULFIDE ZINC DEPOSIT

The Vazante deposit has estimated reserve of 20 million tones with 20% Zn (T.F. Oliveira, 2005; personal communication) and includes both supergene (hemimorphite, hidrozincite, smithsonite, piromorphite) and hypogene (willemite) ore types. The supergene ore is associated with karst-related collapse breccias developed in pelitic-dolomitic units of the Vazante Group (Dardenne et al., 1998) and controlled by NE-oriented brittle faults and fractures. Supergene processes were also responsible by extensive oxidation of the hypogene non-sulfide ore to depths of more than 50 m, resulting in zones enriched in chalcocite, covellite, acantite, cuprite, cerussite, malachite, auricalcite, brochantite, linnarite, greenockite, anglesite, argentite, chlorargyrite, and native silver and copper.

The Vazante hypogene zinc ore contains willemite, dolomite, siderite, quartz, hematite, Cd-rich sphalerite, galena, Zn–rich chlorite, barite, franklinite, zincite, smithsonite, magnetite, and apatite. This type of ore occurs tectonically imbricated with brecciated dolomites, slates and small basite bodies, within the Vazante Shear Zone. Mineralization processes were accompanied by strong fracture-controlled hydrothermal alteration, involving dolomitization, silicification, sideritization, hematitization, and chloritization, related to a complex zone of net veined and hydraulic breccias.

In the Vazante deposit, within the Vazante Shear Zone, the non-sulfide zinc ore displays variable amounts of sphalerite and galena. The richest zinc ore is composed mainly of colloform or fibrous-radiating willemite, baroque dolomite, quartz, franklinite, and zincite. Brittle–ductile deformation of willemite produces granoblastic textures and mineral stretching; it is accompanied by hematite and chlorite formation. Brittle structures contain cataclastic breccias with willemite fragments surrounded by cloudy saddle dolomite. The absence of remnant sphalerite in this ore type suggests willemite precipitation directly from hydrothermal fluids.

RELATIONSHIPS OF SULFIDE AND NON-SULFIDE MINERAL PHASES

Sphalerite and galena at Vazante occur either in structurally-controlled, sulfide-rich ore bodies with a well-developed mylonitic fabric or as late-vein infillings. The brittle-ductile structure development is of major importance in mechanical mobilization of sulfides and their replacement by mineral phases of the willemitic assemblage. The initial willemite crystallization in the sulfide-bearing ore bodies occurs along the mylonitic foliation, resulting in two distinct associations: willemite + sphalerite + franklinite ± zincite (without quartz) and willemite + quartz + dolomite + franklinite (without sphalerite). These assemblages suggest that willemite formed from the sphalerite and quartz through the reaction $2ZnS + SiO_2 + O_2 = ZnSiO_4 + S_2$. This indicates that high fO_2/fS_2 conditions had an important role in the stability of willemite-bearing assemblage. In the sulfide-bearing ore, brittle structures also affected willemite crystals, resulting in cataclastic textures, which are filled, in turn, by galena and sphalerite. Late sphalerite veins cut all willemite generations, suggesting variations of the fO_2/fS_2 ratio during hydrothermal fluid evolution. The relationship between willemite formation and the development of mylonitic foliation in sulfide ore bodies suggests that the non-sulfide mineralization and deformation are synchronous episodes inter-related to the development of the shear zone.

FLUID INCLUSIONS

Fluid inclusion studies on sphalerite, quartz and dolomite from the Vazante deposit permit the delineation of two aqueous fluid types: (1) high-temperature (> 250°C) and moderate salinity (~ 15 wt. % NaCl equiv.) fluid, which could represent a metalliferous brine; (2) moderate to low temperature (~ 150 - 90°C) and low salinity (< 5 wt. % NaCl equiv.) fluid, which might correspond to evolved meteoric-derived fluids. These fluid types were also identified in the other deposits in the district. However, a third fluid type with moderate-temperature (140 -

190ºC) and high salinity (> 23 wt. % NaCl equiv.), similar to saline brines, is identified only in the sulfide-rich deposits, mainly in late sphalerite.

SULFUR ISOTOPES

Sulfides at Vazante display chemical homogeneity and a narrow range of $\delta^{34}S$ values (11.8‰ to 14.4‰), which are similar to those reported for the sulfate seawater contemporary with the carbonate deposition. This suggests that the sulfur in the Vazante sulfide ore bodies was derived from thermochemical sulfate reduction at relatively high temperature and without significant fractionation. Other deposits in the district exhibit a distinct isotopic signature ($\delta^{34}S$ = -8.7 to +40.0‰; Misi et al., 1999). These deposits display chemical variations and complex isotopic distributions related to individual deposit paragenetic evolution. The highest $\delta^{34}S$ values are primarily from early sulfide phases, whereas isotopically light sulfur, possibly derived from bacteriogenic sulfate reduction, occurs in paragenetically late sulfides.

STRONTIUM ISOTOPES

In all studied deposits in the Paracatu-Vazante belt, the strontium isotopic compositions in hydrothermal carbonates and sphalerite show a clear relationship with the paragenetic evolution of each deposit. In Vazante deposit, least-mylonitized sphalerite are less radiogenic ($^{87}Sr/^{86}Sr$ = 0.715380) than sphalerite strongly mobilized/mylonitized ($^{87}Sr/^{86}Sr$ = 0.729736). Seemingly siderite, related to the willemitic ore, is more radiogenic than sphalerite ($^{87}Sr/^{86}Sr$ = 0.721904 to 0.722250). This could imply that the fluids associated with deformation and willemite formation were ^{87}Sr-enriched in relation to that involved in the genesis of Vazante sulfide ore. Late epigenetic sulfides from sulfide-rich deposits display the highest $^{87}Sr/^{86}Sr$ ratios (0.742125 to 0.53835), suggesting the contribution of strongly radiogenic brines, possibly derived from shale units, in the late stages of mineralization.

CARBON AND OXYGEN ISOTOPES

The $\delta^{18}O$ (21.6 to +31.8‰) and $\delta^{13}C$ (-5.9 to 1.7‰) values of the gangue carbonate intergrown with sulfides at Vazante are quite different from those of the willemitic ore ($\delta^{18}O$ = 17.4 to 20.4‰; $\delta^{13}C$ = 0.3‰ to 0.9‰) and carbonate intergrown with sulfides at the sulfide-rich deposits ($\delta^{18}O$ = 12.4 to 20.3‰; $\delta^{13}C$ = -2.3 to 0.3‰). The $\delta^{18}O$ and $\delta^{13}C$ trends of carbonate minerals paragenetically related to Vazante sulfides suggests that fluid-rock interaction may be important for the sphalerite precipitation from a sulfur-deficient, metalliferous fluid. Fluid mixing processes involving a metalliferous fluid and oxidized meteoric water channeled within the shear zone could control precipitation of the Vazante non-sulfide ore (Fig. 1), whereas progressive mixing with saline brines is suggested for the sulfide-rich deposits.

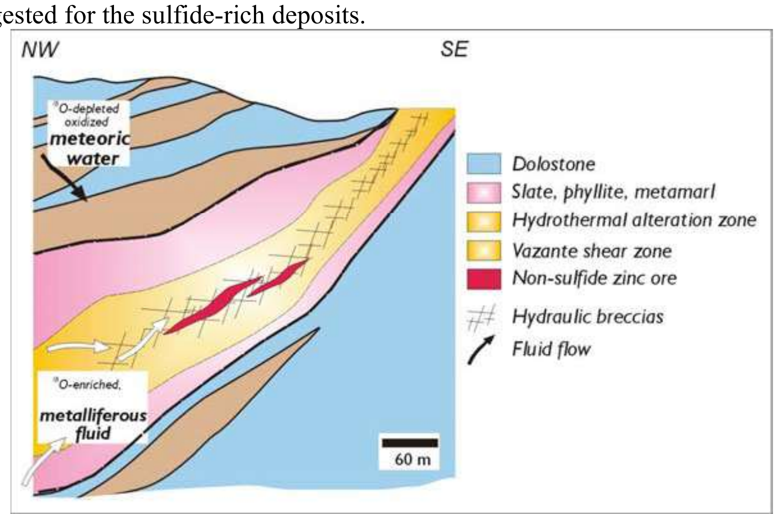

Figure 1 - Schematic model of fluid flux flow in the Vazante deposit.

CONCLUSIONS

Different styles of hypogene zinc mineralization in the Vazante–Paracatu district may be attributed to syndiagenetic (Morro Agudo, Fagundes deposits) and epigenetic-hydrothermal processes (Vazante and Ambrósia deposits), related to the long-term hydrothermal system evolution associated to diagenesis and deformation of the Vazante Group, during the Brasiliano Orogeny. Despite the differences in mineralogy, alteration styles, ore controls and textures, all these zinc deposits might be associated with the regional migration of high-temperature (~250 ºC), sulfur-deficient, metalliferous fluid. Local controls on physicochemical conditions and sulfur supply would have resulted in the different ore types observed in the district. Fluid inclusion and isotopic data indicate that progressive fluid mixing processes involving oxidized, sulfur-deficient, metalliferous fluid and sulfur-rich, saline hydrothermal fluids were important for the genesis of the sulfide-rich deposits in the district. The predominance of the highly saline and radiogenic brines in later epigenetic mineralization episodes, might be related to episodic expulsion of tectonic saline brines (Fig. 2). Such brines could be derived from reduced shale units above the sulfide-rich orebodies, which may also represent an alternative sulfur supply for these deposits.

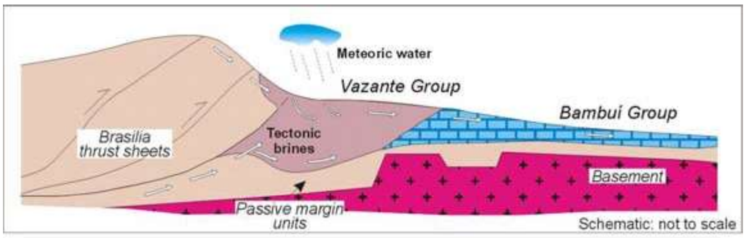

Figure 2 - Schematic model of fluid flow in the Vazante basin, showing the interplay of ascending metalliferous fluid, descending meteoric waters, and tectonically expelled brines.

The Vazante non-sulfide zinc deposit results from the overall mixture between sulfur-deficient metalliferous fluid and meteoric fluids channeled to the Vazante Shear Zone, which enable the high fO_2/S_2 conditions responsible for the stability of the Vazante willemitic assemblage. These high fO_2/S_2 conditions would be also favored by the lack of reduced sequences above the Vazante deposit, which could represent a limitant factor for H_2S supply.

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