THE VAZANTE-PARACATU ZINC DISTRICT: GEOLOGY AND METALLOGENY

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ABSTRACT

The Vazante Group hosts the major zinc-(lead) deposits of Brazil. 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). 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°C), sulfur-deficient, metalliferous fluid. Local controls on physicochemical conditions and sulfur supply would have resulted in the different ore types observed in the district. Mineral chemistry, fluid inclusion, and isotopic data indicate that progressive fluid mixing processes involving sulfur-deficient metalliferous fluid and sulfur-rich, strongly radiogenic 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 from reduced shale units above the sulfide-rich orebodies. 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.

Palavras-chave: carbonate hosted Zn-(Pb) deposit, non-sulfide zinc deposit, Vazante, Morro Agudo, willemite

INTRODUTION

The Vazante Group (Dardenne et al., 1998) is the host to the major zinc-(lead) district in Brazil, This unit covers a 250 km long, N-S-striking region along the western margin of the São Francisco Craton in the northern Minas Gerais State. The main deposits in the district, such as the Vazante and the Morro Agudo deposits, have been exploited since the 1960's. Currently, the Vazante non-sulfide zinc deposit has estimated reserve of 20 million tones with 20% Zn and the Morro Agudo deposit, the main sulfide-rich deposit in the district, has estimated reserves of 7.6 million tones, with 5% Zn (T.F. Oliveira, 2005; personal communication). Since the last decade, studies in this area prompted changes in the genetic models, with important consequences for the mineral exploration. In special, the non-sulfide zinc mineralization styles, represented in the district by the Vazante deposit, have become very attractive exploration targets worldwide. This paper summarizes the main geological attributes for this important metallogenetic district.

SULFIDE-RICH ZINC-LEAD DEPOSITS

The Morro Agudo Zn-(Pb) deposit is hosted by breccia, dolarenitic breccia, and dolarenite. The ore is mainly composed of disseminated fine-grained brown-colored sphalerite, galena, and pyrite. These sulfides cemented unconsolidated allochemical grains. Honey-colored coarse-grained sphalerite, white dolomite, and barite also occur as open-space infillings. Colloform sphalerite, galena, and pyrite are also recognized in the 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; Misi et al., 1999).

Fagundes is a stratabound deposit hosted by dolostones. The main ore is represented by rhythmically banded, colloform, and zoned pyrite, sphalerite and galena. Later veins and breccia ore types reflect epigenetic mobilization, related to brittle-ductile structures. The Ambrósia mineralization is mainly fault-controlled and hosted by brecciated dolostone, which is tectonically imbricated with black shales and slates. Pyrite, marcasite, sphalerite and minor galena occur in

brecciated comb-veins and veinlets, which overprint stylolites and tectonic fractures.

NON-SULFIDE ZINC DEPOSITS

The Vazante deposit is one of the major known non-sulfide zinc deposit (Hitzman et al., 2003) and includes both supergene (hemimorphite, hydrozincite, smithsonite, pyromorphite) and hypogene (willemite) ore types. The supergene ore is associated with karst-related collapse breccias developed in pelitic-dolomitic units of the Vazante Group and controlled by NE-oriented brittle faults and fractures.

The Vazante hypogene non-sulfide zinc ore occurs tectonically imbricated with brecciated dolomites, slates and small metabasite bodies, within the Vazante Shear Zone. This type of ore displays variable amounts of sphalerite and galena. The richest zinc ore is composed mainly of coarse-grained colloform or fibrous-radiating willemite, baroque dolomite, quartz, and franklinite within a matrix of fine-grained willemite (±hematite). The absence of remnant sphalerite in this ore type suggests willemite precipitation directly from hydrothermal fluids. Sphalerite and galena at Vazante occur either in structurally-controlled, sulfide-rich orebodies with a well-developed mylonitic fabric or as late-vein infillings. The willemite crystallization in the sulfide-bearing orebodies occurs along the mylonitic foliation, through the reaction $2ZnS + SiO_2 + O_2 = ZnSiO_4 + S_2$, indicating that high fO_2/fS_2 conditions had an important role in the stability of this assemblage (Monteiro et al., 1999).

TIMING OF THE MINERALIZATION EVENTS

Despite the intrinsic difficulties concerning the timing of carbonate-hosted mineralization, different mineralization episodes are recognized in the district:

(1) Syndiagenetic mineralization stages

The main evidence of syndiagenetic styles of mineralization is represented by early sulfide cementation of unconsolidated allochemical grains, progressive replacement of diagenetically modified coated grains and relationships between sulfides and convolute or compactation structures from the Morro Agudo deposit (Dardenne, 1979).

(2) Late diagenetic mineralization stage

Colloform sulfides and coarse-grained zoned sphalerite associated with pyrite, galena, and dolomite represent a minor late mineralization stage at Morro Agudo and the main stage of the Fagundes deposit. This stage, related to wall rock dissolution and sulfide infilling, probably occurred late during the burial history of the sedimentary sequence.

(3) Epigenetic mineralization stage

The emplacement of epigenetic–hydrothermal mineralizations and the occurrence of mobilization of ore phases related to migration of late hydrothermal fluids during the late Brasiliano collisional event are also ubiquitous in the district. The Ambrósia and the Vazante non-sulfide Zn deposit represent syntectonic mineralization episodes. The latter was synchronous and inter-related with development of the Vazante Shear Zone.

WHOLE-ROCK GEOCHEMISTRY

Hydrothermal alteration and mass balance

In Vazante, fracture-controlled alteration produced a complex zone of net-veined breccia filled by dolomite, zincian dolomite, siderite, jasper, hematite, and chlorite. Pervasive alteration is represented mainly by silicification and replacement by dolomite, siderite, jasper, hematite, and chlorite. Mass balance calculations indicate that hydrothermalized rocks display strong relative gains of $Fe_2O_{3(T)}$, Rb, Sb, V, U, SiO_2, and La, besides decrease of $\delta^{18}O$ and $\delta^{13}C$ values towards the mineralized zones.

The Ambrósia hydrothermally altered dolostones display recrystallization and replacement by coarse-grained dolomite. Mass balance calculations indicate relative gains in $Fe_2O_{3(T)}$, Zn, Pb, Cd, S, and La in the altered rocks. In the Fagundes deposit, silicification and replacement of the dolostone by white coarse-grained dolomite has been a common pre-mineralization process of open-space filling. These alteration processes were not accompanied by relative gains in $Fe_2O_{3(T)}$ or Zn. They possibly represent more focused variants of the burial dolomitization mechanisms, representing ground preparation of favorable zones for fluid migration.

All sulfide-rich zinc ores in the district, including the Vazante small sulfide-rich ore bodies, display a similar signature represented by $Fe_2O_{3(T)}$, Zn, Pb, Cd, Ag, S, As, Sb, Au, Hg, Se, Co, Cu, and Ni, suggesting a common metal source.

MINERAL CHEMISTRY

Carbonates

The gangue dolomite from the Morro Agudo deposit has the higher $FeCO_3$ (up to 10 mole %) and $MnCO_3$ (up to 1.8 mole %) in the district (Bez, 1980). The Fagundes dolomite has a remarkable chemical homogeneity, with low $FeCO_3$ (up to 0.7

mole %) and $MnCO_3$ (up to 0.2 mole %) contents. The Ambrósia and Vazante dolomite shows intermediate $FeCO_3$ and $MnCO_3$ contents. The incorporation of $FeCO_3$ and $MnCO_3$ in dolomite would reflect the proximity of hydrothermal fluid discharge areas. This could suggest either a northward flow of Fe- and Mn-rich fluids from the proximal Morro Agudo towards the distal Fagundes area, or interaction with local sources of Fe and Mn during multiple flows.

Zinc incorporation is considerable in Fagundes (up to 3.2 mole % of $ZnCO_3$) and Vazante (up to 4.5 mole % of $ZnCO_3$) dolomite. As zincian dolomite is relatively unstable in the presence of H_2S, the incorporation of considerable amounts of $ZnCO_3$ in dolomite from these deposits could suggest that the metalliferous fluid is sulfur-deficient.

Sulfides

Sphalerite from Vazante, Morro Agudo, and Fagundes has low Fe (< 1%) and high Cd contents (up to 11,000 ppm in Vazante) and low Zn/Cd ratios (64 to 439) (Dresch, 1987; Monteiro, 2002). In Fagundes sphalerite, Ge-concentrations are as high as 7,000 ppm. The Vazante sphalerite displays little compositional variation, whereas oscillatory variations in the content of the minor elements in the Fagundes zoned sphalerite suggest mixing of hydrothermal fluids. Sphalerite composition from these deposits could be better explained by a source from brines leaching sedimentary sequences, which would most likely remove loosely bound metal (Fe, Zn, Cd, Ge, etc.). Additionally, the sphalerite composition also indicates that the metalliferous fluid was sulfur-deficient, because this could favor formation of Cd-rich sphalerite and incorporation of Ge in the sphalerite. This could have had a major importance for the low sulfidizing capacity of the Vazante willemitic ore, but also imply in a key role of an additional sulfur supply for the genesis of the sulfide-rich deposits in the district.

The Ambrósia epigenetic sphalerite has higher Fe-content (up to 2.54 %), lower average Cd-content (257 ppm) and high Zn/Cd ratios (mean of 1510). The higher Fe-content in Ambrósia sphalerite might be related with late hydrothermal fluid pulses from a distinct source. Additionally, the Ambrósia sphalerite Zn/Cd ratios (1510) are similar only to those reported for sphalerite from deposits genetically linked to hydrothermal-metamorphic process.

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

GEOTHERMOMETRY

Stable isotopic geothermometers indicate temperatures of 257 to 330°C for the sulfide bodies (sphalerite-galena), 254 to 294°C for willemitic ore (willemite–quartz, hematite–quartz) and 206 to 260°C for hydrothermal mineral phases (siderite–quartz) of veins and breccias (Monteiro et al., 1999). The crystallization temperatures of chlorite from cataclastic breccias with willemite fragments from Vazante range from 230 to 245°C. Minimum temperatures of the mineralization estimated for sphalerite from Morro Agudo, Vazante, Fagundes, and Ambrosia deposits (up to 260°C) are also consistent with predominance of low- to moderate temperature fluids in the district (Cunha et al., 2000, Monteiro, 2002).

ISOTOPIC GEOCHEMISTRY

Carbon and oxygen isotopes in carbonates

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 suggest that fluid-rock interaction may be important for the sphalerite precipitation from a sulfur-deficient, metalliferous fluid. Stable isotopic signature of carbonates from sulfide-rich deposits and willemitic ore indicate fluid mixing processes.

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 mineralizations display chemical variations and complex isotopic distributions related to the paragenetic evolution of individual deposits. 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 the Vazante deposit, least-mylonitized sphalerite are less radiogenic ($^{87}Sr/^{86}Sr$= 0.7154) than strongly mobilized/mylonitized sphalerite ($^{87}Sr/^{86}Sr$= 0.7297). Seemingly siderite, related to the willemitic ore, is more radiogenic than sphalerite. 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 the Vazante sulfide ore. Late epigenetic sulfides from sulfide-rich deposits, mainly in the Ambrósia deposit, display the highest $^{87}Sr/^{86}Sr$ ratios (0.7421 to 0.7538), suggesting the contribution of strongly radiogenic brines, possibly derived from shale units, in the late stages of mineralization.

CONCLUSION

Different styles of hypogene zinc mineralization in the Vazante–Paracatu district may be attributed to the evolution of the hydrothermal system, associated with diagenesis and deformation of the Vazante Group, during the Brasiliano Orogeny. All these zinc deposits might be associated with the regional migration of high-temperature (~250°C), sulfur-deficient, metalliferous fluids. Fluid inclusion and isotopic data indicate that progressive fluid mixing processes involving this metalliferous fluids and sulfur-rich, strongly radiogenic saline brines were important for the genesis of the sulfide-rich deposits in the district. The latter might be related to episodic expulsion of tectonic saline brines. Such brines could be derived from reduced shale units above the sulfide-rich orebodies, which may also represent an alternative source of sulfur for these deposits. 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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