Structural controls on the Bonsucesso Zinc-Lead Deposit, Vazante Group, Brazil

Edson Ricardo Maia Ferraz1,*, George Luiz Luvizotto1, Juliana Okubo2, Denis Antonio Batiston2

Abstract
The Bonsucesso zinc-lead (Zn-Pb) sulfide deposit is hosted in carbonate rocks from the Vazante Group (transition of the Mesoproterozoic to the Neoproterozoic time), northwest of Minas Gerais State, Brazil. Regional deformation is associated with the thin-skinned tectonics that led to the formation of the foreland zone of the Brasília Orogen during the Neoproterozoic. These orogenic processes are the trigger of Zn-Pb mineralization in many base-metal deposits in the Vazante Group. Here, we describe the ore textures and the structures of the deposit to define its structural controls in deposit scale and formulate hypotheses about its forming process in the context of other Vazante Zn-Pb deposits. Mineralization distribution is controlled by a high-angle fault zone striking NNW and dipping 60° to WSW. Fault-related fractures functioned as pathways for Zn-Pb-rich fluids to be redistributed and crystallize where chemical conditions were adequate. Mineralization was likely formed in an extensional setting in breccia zones controlled by flexurally induced normal faults related to development of the foreland basin of Brasília Orogen. Later, the entire Vazante sequence underwent an inversion process and extensional structures were reactivated or obliterated. Finally, an understanding of local controls may be of good use to target exploration for new orebodies in the district scale.

KEYWORDS: zinc; structural geology; MVT; Brasília Belt; Morro do Calcário Formation.

INTRODUCTION
Geological structures play a fundamental role in almost all types of mineral deposits. Thus, a better understanding of the structural architecture of the mineralization is a powerful guide to grade continuity and may reduce misinterpretations (Cowan 2014). The relevance of fault systems as host structures for hydrothermal mineralization has long been reported in many deposit types, such as sediment hosted Pb-Zn-Ag, lode Au, and iron oxide Cu-Au deposits (Newhouse 1942, McKinstry 1948, Sibson 1996, Cox 2005). Furthermore, the formation of fault-fracture networks and fluids redistribution in extensional and transtensional regimes plays a crucial role in the formation of many hydrothermal mineral deposits (Sibson 1996, 2000). On the contrary, base-metal deposits related to contractional faults have also been reported, and infilling of mineralization fracture–meshes coeval with compressive settings has been recognized (Ghazban et al. 1994, Liaghat et al. 2000, Hou and Zhang 2015, Zhang et al. 2017).

The Bonsucesso zinc-lead (Zn-Pb) sulfide deposit hosted in carbonate rocks of Morro do Calcário Formation, Vazante Group was recently discovered in the Paracatu region, northwestern Minas Gerais. Although the Vazante Group age is still a matter of debate, there is a general agreement that the upper section of this sedimentary sequence was deposited at about 1000 Ma in the transition of the Mesoproterozoic to the Neoproterozoic (Dardenne 2000, Misi et al. 2014). Together with the known deposits of Vazante (total estimated resources of 60 Mt at 20% Zn), Morro Agudo (total estimated resources of 20 Mt at 5.0% Zn and 1.75% Pb), Ambrósia Sul (2.15 Mt at 5.0% Zn and 0.16% Pb), and Fagundes (2.8 Mt at 4.0% and 0.3% Pb), this discovery is a part of the best-endowed district for Zn of Brazil (Fig. 1A).

At the Bonsucesso deposit, major faults are related to the Brasiliano orogeny (ca 900 Ma–600 Ma, Pimentel 2016), the last tectonic event that led to development of the Brasilia fold-thrust belt and affected the Vazante Group (Almeida et al. 1981, Dardenne 2000, Valeriano et al. 2004, 2008).

The aim of this paper is to characterize the structural controls, ore textures, and geometry of the Bonsucesso Zn-Pb sulfide deposit and to understand its formation. Our study is based on the integration of drill core data, structural analysis of oriented-drill cores, 3D geological modeling, and petrography. Here, we describe the structures, ore, and gangue minerals, discuss its relationships in the deposit and regional scale, and try to formulate hypotheses about its forming processes. Our work might offer contributions to the understanding of local controls of mineralization, and it may be of good use to target exploration for new orebodies in the district scale.
Figure 1. Location of the Bonsucesso Zn-Pb sulfide deposit. (A) Simplified geological map of Vazante Group (former passive margin of São Francisco paleoplate) at eastern portion of the Brasília Belt. Red star represents the Bonsucesso deposit and yellow stars represent the other Zn-Pb deposits in the area. Zoomed-in box shows the projection of Zn-Pb mineralization zone over soil and recent sediments. (B) Schematic lithostratigraphic column of the Vazante Group (after Dardenne 2001) and the stratigraphic position of its Zn-Pb deposits. At right, geochronological data: White circles are U-Pb detrital zircon ages from Rodrigues et al. (2012); Black diamonds are Re-Os ages from Azmy et al. (2008) and Geboy et al. (2013). (C) Schematic geological cross section at the southern sector of Vazante Group (modified from Misi et al. 2014). Lagamar thrust fault juxtaposed older sediments of Vazante Group and younger sediments of Bambuí Group.

REGIONAL GEOLOGY AND STRUCTURAL FRAMEWORK: A REVIEW

The Bonsucesso deposit is located in the Paracatu region, northwest of Minas Gerais State, Central Brazil. Zn-Pb sulfide mineralization is hosted in rocks of the Vazante Group, (Tonian period, ca 1000 Ma, Carvalho et al. 2019, Dardenne 2000, Misi et al. 2014) on the southeast sector of Brasília Belt.

The origin of this fold-and-thrust belt dates back to the São Francisco paleoplate late Mesoproterozoic to early

The understanding of the Brasília Belt evolution (Almeida 1967, Pimentel and Fuck 1992, Dardenne 2000, Valeriano et al. 2008, Sial et al. 2009) has increased over the years and new geochronological and isotopic data have helped to better constrain major tectonic compartments (for recent reviews see Pimentel et al. 2011, Cordani et al. 2013a, 2013b, Araujo et al. 2014, Brito Neves and Fuck 2014, Brito Neves et al. 2014, Pimentel 2016, Carvalho et al. 2019). From west to east, the Brasília Belt can be subdivided as shown in Fig. 1A: Goiás magmatic arc, syn-orogenic basins and metamorphic core, passive margin (the supracrustal sequences of the fold-and-thrust belt primarily deposited over the São Francisco craton margin), and foreland basin (cratonic cover) (Pimentel et al. 2011, Pimentel 2016).

The Vazante Group (Dardenne et al. 1998, Dardenne 2000) extends N-S through nearly 250 km in length, with an average width of 30 km (Fig. 1A). To the west, it is bounded by the Canastra Group (similar age), and to the east, by the Bambuí Group. Metamorphic conditions reached peak at low greenschist facies (Monteiro et al. 2006) with development of pervasive axial plane cleavage in general parallel to bedding and formation of crenulation cleavage related to isoclinal folding and later open folds, respectively (Carvalho et al. 2016).

This unit constitutes a thick metasedimentary sequence originally deposited in shallow waters of the São Francisco paleoplate passive margin. It is divided into seven formations (Fig. 1B), from base to top: Santo Antônio do Bonito, Rocinha, Lagamar, Serra do Garrote, Serra do Poço Verde, Morro do Calcário, and Serra da Lapa (Dardenne et al. 1998, Dardenne 2000). The basal Santo Antônio do Bonito and Rocinha formations are composed of metapelitic units with phosphate concentrations (Dardenne 2000).

According to Dardenne et al. (1998) and Dardenne (2000), the Lagamar Formation represents a metapasmatic-litic unit with basal metaconglomerates, dolomitized breccia, dark gray limestone, and stromatolitic bioherm with columnar stromatolites of the Conophyton and Jacutophyton types. The Serra do Garrote Formation represents a sequence of pyrite (Py)-bearing carbonaceous gray slate and quartzite layers. The Serra do Poço Verde Formation is made up of gray to pink algal-laminated dolomite, gray to green slates, sericite phyllite, dark gray dolomite with bird’s-eyes, marls, and Py-bearing carbonaceous shale. The Morro do Calcário Formation is composed of stromatolitic bioherm facies, intraformational breccia, dolarenite, and subordinate carbonateous shale. These two formations correspond to the dominantly dolomitic sequences that host the Zn-Pb deposits and can represent a continuously deposited dolomitic sequence. The dolomitic sequence is overlain by the Lapa Formation, with black rhythm carbonateous slate and phyllite (Serra do Velosinho Member) and sericite–chlorite phyllite, carbonate-bearing metasiltstone, dolomite, and quartzite lenses (Serra da Lapa member).

The area has been studied since the 1950s, but the Vazante Group age is still an unresolved problem, mainly due to the absence of absolute markers (e.g., volcanic ash layer) and the wide span in time provided by the fossil record (Conophyton stromatolite, 1.35 Ga–0.95 Ga).

An Rb-Sr whole rock isochron for shales from Vazante Group yielded an age of 600 ± 50 Ma (Amaral and Kawashita 1967), which could represent the last closing of the isotopic systems during the Brasiliano metamorphic event. Re-Os ages in organic-rich slates of the Vazante Group (Azmy et al. 2008, Geby et al. 2013), and U-Pb ages of detrital zircons in quartzites distributed along the whole sequence (Rodrigues et al. 2012) provided a late Mesoproterozoic age for the top and an early Neoproterozoic age for the basal units. Furthermore, these late Mesoproterozoic ages agree with seismic, well, and outcrop data that correlate the Vazante Group with the Macaúbas Group located on the east side of São Francisco craton. Both units comprise first-order sedimentary sequences developed over the São Francisco craton margins when supercontinent Rodinia broke up (Martins-Neto 2009, Alamim and Martins-Neto 2012). Based on the geochronological data and field relations, Misi et al. (2014) argued that the upper and older section (Lagamar to Serra da Lapa formations) was thrust (Lagamar fault zone) over the younger lower section (Santo Antonio do Bonito and Rocinha formations). Misi et al. (2014) also suggested a correlation between part of the Vazante Group lower section and the Serra da Saudade Formation of the Bambuí Group (Fig. 1C).

Currently, the biggest base-metal deposits of Vazante Belt are Morro Agudo (Zn-Pb sulphide deposit with 20 Mt at 5.0% Zn and 1.75% Pb) and Vazante (world’s largest hypogene non-sulphide Zn deposit with 60 Mt at 20% Zn, including willemite-ore and supergenic-ore). Vazante Group deposits are hosted in carbonate rocks close to the margin of an uplifted foreland basin and their Zn-Pb ore-minerals contain saline fluid inclusions, both features suggest genetic similarities to Mississippi Valley-type deposits (Appold and Monteiro 2009). These deposits, hosted in carbonate-dominated sequences, formed from basinal brines expelled as a result of tectonic activity (Leach et al. 2010). However, the hypogene Zn silicate of Vazante deposit differs significantly from this model regarding the ore-type and homogenization temperature (Monteiro et al. 1999, Appold and Monteiro 2009).

**Structural framework**

The sedimentary rocks of the Vazante Group, originally deposited along the margin of the São Francisco-Congo paleoplate, were affected by thin-skinned tectonics as São Francisco-Congo paleoplate subducted underneath the Brasilia orogen. Seismic lines from Romeiro-Silva and Zálan (2007) clearly exhibit a deformation of shallow
allochthonous thrust sheets of the Vazante, Canastra, and Bambui groups.

At the seismic section’s western edge, the sheets are shortened and lie over the décollement zone, which marks the unconformity that separates them from the Paraná/ Macaúbas megasequence.

Based mainly on reflection seismic, the advancing knowledge of the São Francisco craton and its surrounding fold-and-thrust belts has allowed for better stratigraphic correlations between Proterozoic sedimentary megasequences and to devise robust structural frameworks (Alkmim and Martins-Neto 2012, Romo-Silva and Zalán 2007).

Despite its economic relevance, the northern Vazante Group was addressed only by a few studies concerning its structural geology, and most of these studies were carried out in the southern sector of this unit (Campos Neto 1984, Pinho et al. 1989, Pinho 1990, Freitas-Silva 1991, Pereira 1994, Rostírolla 2002, Marca 2014). The east movement of thrust sheets is inferred by sinuous and mostly convex fault traces on the map. Mineral and stretching lineations indicate the same direction of movement. An interesting aspect is the Rio Escuro reentrant. This syntectal curve divides the belt into two sectors (north and south). The arcuate structure may be a result of the differential advance of the thrust front over a basement high. Rio Escuro reentrant forms a topographic low covered by recent sediments. Coincidently or not, the reentrant marks profound stratigraphic changes (the lack of Serra do Poço Verde formation to the north of it) and peculiar conditions of ore-forming fluids (occurrence of Zn-silicate ore only to the south of it). Zn-Pb deposits (e.g., Morro Agudo and Vazante mines) are at the maximum advance of the thrust front, where the sedimentary pile is thicker.

One major compressive and progressive deformation event is well recognized in the Vazante Group and was responsible for the formation of the slaty cleavage (S0/ S1) and isoclinal folding. Strike-slip faults related to the progression of this event are also documented, besides late folds that affected the previous planar structures. Finally, an extensional phase postdating the compressive structures is also reported (Campos Neto 1984, Pinho 1990, Freitas-Silva 1991, Pereira 1994, Rostírolla 2002, Marcia 2014, Carvalho et al. 2016). Folds and thrusts developed during the thin-skinned tectonics in the Vazante Group have east vergence direction. Thrust faults are low-angle and dip west at 30°–35°. There are high-angle reverse faults that probably formed because of folding, ancient normal fault reactivations, and fault rotation.

**METHODS**

A thick soil layer (approximately 30 m) occurs on top of the Bonsucesso deposit, and no rocks crop out in the studied area. Since detailed field mapping is not possible, the work was carried out using drill hole data and the 3D geological modeling software Leapfrog Geo®.

An electron microprobe JEOL, model JXA-8230, equipped with 5 WDS detectors, EDS detector type SSD, secondary electron detectors, and backscattered electrons (BSE), was used to acquire the compositional maps for carbon (C), Cd, silica (Si), Fe, Mn, and Zn (accelerating voltage of 15 kV and probe current of 100 nA). EPMA maps results were processed using the XMapTools software (Lanari et al. 2014, 2019).

Structural measurements were collected from oriented drill cores according to the following procedures. Inclined drill holes were oriented using the core stub technique, i.e., a steel spear with a sharp point was lowered inside the rods to mark the position of the gravity vector (i.e., to determine the bottom of the hole) on the core stub after the extraction of a full core barrel (Zimmer 1963, Marjoribanks 2010). However, most of the drill holes were oriented using the core barrel method, which orients the drill hole at the moment when the lowest piece of the core is gripped by the lifter before breaking it free (Marjoribanks 2010). The electronic device used was the Reflex ACT III. After the extraction of the core barrel, bottom (or top) of hole marks were made. Thus, broken drill core pieces were laid out over a channel to be reassembled as much as possible. After the reassembling, bottom lines were traced along the run with arrows pointing down-hole.

Three techniques were applied to measure structures: i. the rocket launcher, which consisted of a wood set that replicates drill rig orientation at the coreshed and allows geologists to position oriented core samples as they were in situ and so collect structures; ii. the measurement of internal core angles (alpha, beta, and gamma) later transformed by the Leapfrog Geo® software or spreadsheet into the real strike and dip or trend and plunge values already corrected by the desurveying methods; iii. the vSET™ method, another technique also based on geometrical relationships and more suitable to the measurement of linear structures.

**GEOLOGY OF THE BONSUCESSO DEPOSIT**

**Lithology and stratigraphy**

Two lithostratigraphic units from the Vazante Group occur at Bonsucesso deposit: Serra do Garrote Formation and Morro do Calcário Formation. The hydrothermal dolomitic breccia containing the Bonsucesso orebodies is hosted in metapelite and carbonate rocks of the Morro do Calcário Formation (Fig. 2). Rocks of Serra do Garrote Formation were emplaced within the Morro do Calcário unit by a reverse fault. The following lithological description is restricted to hanging wall and footwall rocks of the Bonsucesso fault-controlled deposit.

**Soil**

The Bonsucesso deposit lies under a 30-m-thick deposit composed of allochthonous soil and recent sediment.
stromatolitic dolostone, dolorudite with lamellar breccia, dolarenite, intraformational breccia, oolitic dolostone, and laminated dolostone (Fig. 2D) are the main lithotypes. Void-filling white dolomite occurs as veins near the damage zone and fault core. Dark chert veins are also related to hydrothermally altered zones. Below the soil cover, weak acidic water flow has promoted strong dissolution of dolostone along bedding planes, joints, fractures, and fault zones to form an intricate system of caves at shallower levels.

Within the dolomite unit, there is a distinctive package of carbonate metamudstone (also referred as metamarl) whose thickness varies from 80 m in the south sector and gradually decreases to 40 m in the north sector. These rocks are interbedded thin carbonaceous mica-rich layers and micritic dolomite with minor terrigenous contribution (clasts of quartz and feldspar) that occur in the hanging wall and footwall blocks (Figs. 2A and 2E). Within this carbonate metamudstone layer, a 1–2 m-thick bed of a mixture of siliciclastic and carbonate material occurs (Fig. 2C). The carbonate layers are composed of fine angular clasts in matrix and gravels of dolomitic mudstone and dolostone, whereas the terrigenous component contains well-rounded coarse quartz grains, angular fine quartz clasts, rare fine feldspar clasts, lithic clasts, and carbonaceous mica-rich matrix (Fig. 2C). Phosphate occurs as a fine agglomerate of cryptocrystalline apatite in matrix. This rock forms very restricted beds frequently separated by erosion surfaces at the bottom and it is generally overlaid by finer-grained sequence enriched in organic matter. Given these very particular features, this layer is an excellent structural and stratigraphic marker and was used to balance cross sections and the 3D model.

Hydrothermal dolomitic breccia: Bonsucesso Zn-Pb mineralization

The Zn and Pb orebodies of the Bonsucesso deposit are hosted in a hydrothermal dolomitic breccia. There are two mineralized zones. The upper zone occurs in the hanging wall along the fault plane, below the carbonate mudstone layer and above the Serra do Garrote carbonaceous phyllite. Its basal contact with the latter has less to no shearing. In the footwall, the mineralized zone also extends along the fault plane, above the carbonate metamudstone package and below the Serra do Garrote phyllite, and its contact with the latter exhibits abundant shearing structures (Fig. 3).

The host rock is a hydrothermally brecciated dolostone with intense veining by white coarse dolomite and sulfides. The length of the deposit along the strike is approximately 4,000 m, but brownfield exploration programs have demonstrated a potential for extension. Breccia zone thickness varies through the strike, and mineralized zones within it may vary as well. The faulting process is a major permeability control, and deformation is heterogeneous. In general, the mineralized zone is hosted in a 50-m-brecciated dolomite, whose extension is controlled by faults.
Figure 3. The contact relationship between Zn-Pb mineralization zones and host rocks in the fault blocks. Circles A and B represent the approximate positions of the drill cores along the same drill hole. (A) Contact between the mineralized zone and the SG rocks in the hanging wall block is a transition contact. (B) Contact between SG rocks and the mineralized zone is marked strong shearing in the footwall block. Occurrence of intense veining by quartz and minor calcite also shows that this is the slip surface (thick black trace). At left, cases containing the drill cores. At right, the schematic representation highlights the main features of the rocks. At bottom, the geological cross section of the Bonsucesso Zn-Pb sulfide deposit (see Fig. 7 for its location).
Two prevailing mineralization types have been described: breccia with angular dolostone-clasts surrounded by sphalerite (Sp), galena (Gn), and gangue minerals (Py, white dolomite, and quartz), and veins of Sp and Gn. The mineralogy of the Bonsucesso is relatively simple. Mineralization is comprised of Sp, Gn, and gangue minerals such as Py, white dolomite, and quartz, with scattered punctuations of pyrobitumen. Sp color ranges from gray to dark gray and pale yellow to amber. The former represents the major Zn sulfide component of the deposit, and the latter is often related to late and coarser Sp mineralization (Fig. 4).

MINERALIZATION AND STRUCTURES AT THE BONSUCESSO DEPOSIT

Ore mineralogy

Colloform Py is frequently observed as a sulfide phase, with texture indicating replacement by Sp and Gn. Mineralization by veining is marked by the injection of Sp and Gn at high angles, often in extensional veins. A well-formed Py and the replacement of sulfide phases by carbonate minerals and quartz are also common (Fig. 4).

WDS compositional maps (Fig. 5) show an iron (Fe) zonation in carbonate minerals with an increase toward the center of Sp. Sphalerite; Gn: galena; Py: pyrite.

Figure 4. (A) Hydrothermal dolomitic breccia almost entirely cemented by gray and yellow colloform Sp and cut by late Sp-bearing veinlets. Sulfide and gangue-minerals, mainly dolomite, under transmitted (B) and reflected (C) light, showing the filling of inter-fragment open spaces in dolomitic breccia. (D) Sp replaced colloform Py. The same Sp is later replaced by carbonate mineral (rhombohedral crystal is indicated by green arrows). (E) Another example of Sp replacing early phase of colloform Py. Both thin sections contain a late phase of euhedral Py.
Figure 5. Paragenetic map and compositional maps of an extensional mineralized vein (see location of map on Fig. 6).

Monteiro (2002) documented the existence of oil inclusions in sulfide phases related to mineralization in the Vazante Belt. At the Bonsucesso deposit, the occurrence of pyrobitumen among hydrothermal mineral phases is very common. The relationship of pyrobitumen with Sp is clearer at the microscopic scale where Sp-bearing veins show oil residues in direct contact with Zn sulfide. At the mesoscale, it is also possible to see specks and needle-like pyrobitumen among gangue minerals (Fig. 6).

Paragenetic sequence

Table 1 summarizes the paragenetic sequence of sulfides at the Bonsucesso deposit. As this study was not able to detail the occurrence of phases of quartz, dolomite, and other gangue minerals, we assume a widespread distribution of these minerals in all major fluid injection events.
Folds

Faults at the Bonsucesso deposit include NNW-striking and WSW dipping reverse fault and ESE–WNW and ENE–ENE high-angle transcurrent faults (Fig. 7). The reverse fault juxtaposed metasedimentary rocks of the Serra do Garrote Formation against dolomite rocks of the Morro do Calçário Formation (Fig. 7). The sense of motion provided by slickenlines indicates that the fault is reverse (Fig. 8). The NNW reverse fault comprises a smoothly curved surface that delineates the occurrence of Zn-Pb mineralization. Fault-morphology was defined by the limits of fault-core, damage zone, and hydrothermal brecciation zone. Slickenlines were measured at fault planes only in phyllite and indicate the top-to-east reverse motion (Fig. 9). Coupled with slickenline vectors, the duplication of carbonate mudstone layers was also a guide to determine the kinematics as reverse.

Using the likely displaced mineralized zones (Bonsucesso and Ambrósia Norte deposits) intersected on both sides of these transcurrent faults, offset was estimated to be around 200 m with a dextral shear sense at the Santa Rita Creek fault (south end of Bonsucesso deposit). At the current northern end of Bonsucesso deposit, the NNW reverse fault is truncated by strike-slip fault and offset to west. More district-scale field work addressing these faults is fundamental to determine more precisely the kinematics of the strike-slip component and also a normal dip-slip component cannot be ruled out.

Folds

Anticlinal folds were observed in phyllites of the Serra do Garrote Formation and comprise a group of centimeter to meter folds characterized by folding of bedding with fold axis plunging around 10° to either SE or NW. Localized isoclinal folds related to shear zones are also observed (Fig. 10).

At Bonsucesso deposit, the axial cleavage parallel to regional isoclinal folds (Monteiro et al. 2006) was not recognized.

Table 1. Paragenetic sequence of Bonsucesso deposit sulfides.

<table>
<thead>
<tr>
<th></th>
<th>Pre-ore</th>
<th>Main mineralization</th>
<th>Late mineralization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colloform pyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euhedral pyrite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sphalerite</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Galena</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Structures

Faults

Faults at the Bonsucesso deposit include NNW-striking and WSW dipping reverse fault and ESE–WNW and ENE–ENE high-angle transcurrent faults (Fig. 7).

The reverse fault juxtaposed metasedimentary rocks of the Serra do Garrote Formation against dolomite rocks of the Morro do Calçário Formation (Fig. 7). The sense of motion provided by slickenlines indicates that the fault is reverse (Fig. 8). The NNW reverse fault comprises a smoothly curved surface that delineates the occurrence of Zn-Pb mineralization. Fault-morphology was defined by the limits of fault-core, damage zone, and hydrothermal brecciation zone. Slickenlines were measured at fault planes only in phyllite and indicate the top-to-east reverse motion (Fig. 9). Coupled with slickenline vectors, the duplication of carbonate mudstone layers was also a guide to determine the kinematics as reverse.

Using the likely displaced mineralized zones (Bonsucesso and Ambrósia Norte deposits) intersected on both sides of these transcurrent faults, offset was estimated to be around 200 m with a dextral shear sense at the Santa Rita Creek fault (south end of Bonsucesso deposit). At the current northern end of Bonsucesso deposit, the NNW reverse fault is truncated by strike-slip fault and offset to west. More district-scale field work addressing these faults is fundamental to determine more precisely the kinematics of the strike-slip component and also a normal dip-slip component cannot be ruled out.

Folds

Anticlinal folds were observed in phyllites of the Serra do Garrote Formation and comprise a group of centimeter to meter folds characterized by folding of bedding with fold axis plunging around 10° to either SE or NW. Localized isoclinal folds related to shear zones are also observed (Fig. 10).

At Bonsucesso deposit, the axial cleavage parallel to regional isoclinal folds (Monteiro et al. 2006) was not recognized.

Mineralized veins

Mineralization in veins occurs mainly in high-angle veins within the hydrothermal breccia zone. Although they do not correspond to the most volumetric component of mineralization (i.e., Zn-Pb sulfides filling breccia-matrix), these high-angle veins are mostly extensional veins grown by open-space filling process without shear (Fig. 11). There are also Sp-bearing veins with lower dips.

A possible metallogenic model: Discussion

Timing of mineralization

The zinc and lead mineralization of the Bonsucesso deposit is hosted in a hydrothermal breccia. The origin of this breccia is directly linked to the faulting process because the presence of this fault-related breccia defines the mineralized zone.

The present setting of rocks is the result of a reverse fault that emplaced phyllites of the Serra do Garrote Formation between dolomite rocks of the Morro do Calçário Formation and generated a stratigraphic duplication attested by the repetition of carbonate mudstone in both fault blocks.

Another important aspect to understand the evolution of the deposit is the common absence of shearing between the base of hanging wall mineralized breccia and top of Serra do Garrote phyllite. Additionally, many drill core intervals show a gradual transition from the dolomite unit to the lower siliciclastic unit (Serra do Garrote Formation). In contrast, the contact between the base of the Serra do Garrote phyllite and the top of the footwall-mineralized breccia exhibits strong shearing structures, with evidence of top-to-east sense of motion.

Furthermore, the Serra do Garrote Formation rocks do not bear any ore mineralization, and the hydrothermal minerals occurring within this unit are only vein filling quartz and calcite around the reverse fault, but there is no replacement by ore minerals or any sign of interaction with the Zn-Pb mineralizing fluids (e.g., a hydrothermal halo).

Regarding the structural evolution of the Bonsucesso deposit, three different scenarios (Table 2) are suggested for the formation of the Zn-Pb mineralization: mineralization was formed during local extensional regime, and before or during basin inversion completion, Bonsucesso mineralization was generated during a local and regional compressive state regime during basin inversion. Its high angle fault is the result of reactivation of inherited normal faults. Phyllite between fault blocks is the result of progressive advance of the thrust front, and controlling structures and mineralization were formed during local and regional compression regime. Bonsucesso high-angle fault was primarily of low angle and then rotated to the current position.

Our preferred scenario is the mineralization formed during local extensional regime before or during basin inversion (Fig. 12).
Figure 7. The 370-m-elevation geological map showing the mineralized reverse fault truncated by strike-slip faults. At upper right, lower-hemisphere equal-area stereographic projections of the structures in the Bonsucesso area. From top to bottom: "Phyllite-SG" stereonet shows the attitude of Serra do Garrote (SG) Formation rocks emplaced between the two fault blocks; the other two stereonets show measurements of bedding on hanging wall and footwall blocks. In the lower part, a perspective view of geological cross sections along the entire Bonsucesso Zn-Pb sulfide deposit. The second cross section from south to north contains a drill hole positioned farther to west. This drill hole has confirmed the continuation of the stratigraphic pile and the lower dip of the rocks at this location, which is distant from the reverse fault zone.
Figure 8. 3-D model of the Bonsucesso Zn-Pb sulfide deposit. The dolomite rocks were taken out to ease the visualization of the geometry of the ore zone. Drill holes have crossed the carbonate metamudstone in the hanging wall, the upper breccia zone, the phyllites of the Serra do Garrote Formation emplaced by fault, the mineralization in the footwall, once again the carbonate metamudstone, but in the footwall, and, finally, the Serra do Garrote Formation rocks once again. Note that the upper mineralization zone is smaller, and along the deposit, its geometry is more irregular. At the extreme north of the geological map, the main mineralization is now located in the hanging wall block.

Figure 9. (A) Slickenlines on reverse fault surface. Lineations (white dashed line) mark the direction of movement. The sense of the steps (yellow lines) indicates this side of the fault moved down and the other side moved up (sense of movement indicated by white arrow). At left, lower-hemisphere equal-area stereographic projection of the slickenlines. (B) Reverse fault plane. Drill core showing intense shearing and veining by quartz and minor calcite at the fault zone. At left, lower-hemisphere equal-area stereographic projection of poles to fault planes. (C) Sigmoid dolomite clast indicates movement to the east. The clast is contained within a fault gauge zone. Also, some deformed Py clasts at the right half of the core sample. There is also some early Py inside the dolomite clast.

The final setting of the Bonsucesso Zn-Pb sulfide deposit may seem simple (T4, Fig. 12), but to reach this geometry, a more complex evolution is necessary. The amount of Serra do Garrote rocks situated above the cutoff point is greater than the displacement required to only reconnect the marker beds (T3, Fig. 12) if the cross section is restored. Thus, a greater extension (T2, Fig. 12) would be needed to resolve the final geometry. This model is capable of combining an explanation for the final geometry, the formation of a high-angle extensional ore-controlling structure, and its associated high-angle vein system. Segmentation of ore zones would be a post-ore event. Also, the same slip surface of the normal movement may not be the slip surface of the inversion movement. This could explain some features as the preservation of contacts between the mineralized zone and the basal unit (Serra do Garrote Formation) without shearing (Fig. 3) in the hanging wall block.
Another important factor is the mechanical contrast between the dolomite rocks and the rocks of siliciclastic origin. The dolostone unit is more prone to fracturing and its rocks are made up of more chemically reactive minerals (essentially dolomite), whereas the more ductile basal units may have favored the normal dragging and set multiple likely planes of slip.

One final and brief comment on the nature of the mineralizing fluids is important. Besides the secondary porosity and permeability enhanced by the Bonsucesso fault system,
a sulfide mineralization needs the right chemical conditions to form. In simple terms, a source of sulfur, a source of metals, and the reductant environment/agent are required. The complete understanding of this process is beyond the scope of this study, but we have presented here some data related to the mineralogy of the deposit and the presence of oil residues is intimately associated with the ore and gangue minerals. Then, we suggest that the Bonsucesso fault system may have some connection with oil reservoirs prior to the Zn-Pb mineralization. Brines (source of sulfur and metals) moving through different reservoirs encountered the mobile reductant agent (hydrocarbons) in the Bonsucesso fault system and precipitation took place.

Deformation history

Sequence of deformation events at Bonsucesso deposit is summarized in Table 3. Generation of normal faults with influx of hydrothermal mineralizing fluids occurred in early stages of collision (D1). As the Brasília thrust front advanced (D2), S1 cleavage and isoclinal folding were formed together with thrust faults and with subordinate mineralization. The Serra do Garrote phyllite was emplaced between the carbonate rocks from the Morro do Calcário Formation during this phase. Stage D3 is marked by a strong strike-slip component and open-folding. A final extensive regime characterized by normal faults with small displacement or only joints is well recognized regionally.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Elements to support this hypothesis</th>
<th>Elements to argue against this hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineralization formed during local extensional regime before or during basin inversion</td>
<td>High-angle of the controlling fault; High-angle of mineralized veins; Normal faults are efficient conduits for hydrothermal flux (Sibson 2000) and in many cases form barriers for hydrocarbon accumulations (Hardman and Booth 1991); Disposition of mineralized breccias into two segments divided by an allochthonous phyllite. Emplacement of Serra do Garrote Formation rocks between carbonate rocks of Morro do Calcário occurred after main mineralization process, once the latter are deformed by the former.</td>
<td>Which major regional extensional event was responsible for mineralization prior to complete inversion? Layers in both fault blocks show minimal thickness alteration when considering their association with normal faults related to Vazante Group deposition. Therefore, it appears that the extension occurred after the deposition of the Vazante Group. However, a significant event capable of causing such extension before the completion of basin inversion is the synorogenic formation of the foreland basin, which hosts the Bambuí Group sediments (Brito Neves et al. 1996, Almeida et al. 2000, Alkimin 2004, Reis and Alkimin 2015). Reis et al. (2017) have described extensive normal faulting as a result of a forebulge uplift in the east. Nevertheless, the effects of this process on the Vazante Group rocks remain unclear. Additionally, similar to the Vazante Group, the Bambuí sediments were also affected by thin-skinned tectonics, and large thrust faults are identifiable along the foreland sedimentary sequence (Reis and Suss 2016, Reis et al. 2017).</td>
</tr>
<tr>
<td>Mineralization generated during a local and regional compressive state regime during basin inversion</td>
<td>Similar to the previous hypothesis, the fault promoted an increase in rock permeability within the damage zone and facilitated the connection of overpressured fluids from sealed reservoirs. These fluids then migrated to a precipitation site where favorable geochemical conditions were present. The inversion of inherited normal faults is often invoked to explain the formation of certain mineral deposits controlled by high-angle reverse faults, as described in Sibson’s model of fault-valve (Sibson et al. 1988). This is because, under compressional conditions (horizontal sigma 1), the development of high-angle thrust faults is not favorable. For these reactivations to occur, fluid pressure must exceed the lithostatic load. Consequently, significant quantities of overpressured fluids accumulate below until they are suddenly discharged to higher structural levels once this pressure threshold is reached. This cycle may be repeated multiple times, as hydrothermal mineralizing fluids can seal the cracks, leading to pressure buildup once again.</td>
<td>The high-angle fault itself is an issue, similar to the high-angle extensional veins. The mineralizing fault-valve process is well-known in orogenic gold deposits, where controlling high-angle faults often extend deep into the seismogenic crustal limit (Sibson et al. 1988). However, there is currently no evidence to suggest that the Bonsucesso fault or any thrust fault in the Vazante Belt has such deep extensions.</td>
</tr>
<tr>
<td>Controlling structures and mineralization were formed during local and regional compression regime</td>
<td>The mineralized zones are controlled by a reverse fault. The high angle of the controlling fault may be attributed to a rotation caused by the absorption of regional shortening.</td>
<td>Low-angle thrust faults are commonly associated with high dilation zones. Mineralized veins at the Bonsucesso deposit do not exhibit shear. Even when veins and fault planes are back-rotated to a position close to a common low-angle thrust fault, the mean veining attitude does not align with the expected Riedel-shear fractures.</td>
</tr>
</tbody>
</table>
Open folds with SW-NE axis may be contractional fault-related folds, resulting from different depths of detachment and displacement transfer with a strike-slip component (i.e., a mechanism of drag folding). These interacting faults (transcurrent and thrust faults) may also control the emergence of deeper layers and also segment orebodies.

**Figure 12.** Evolution model for the Bonsucesso Zn-Pb sulfide deposit. To accommodate the final geometry of the deposit (T4), a single thrust fault is not enough to explain the amount of SG rocks emplaced. If the dip of layers is preserved and the marker beds are reconnected (T3), there is some SG rocks left out, thus a greater extension (L2) is needed to reach a point of minimal offset to compensate for the total displacement (T2), considering that the movement is mainly down-dip during extension and up-dip during inversion. Proposed metallogenic model favors a mineralization phase related to an early extension (T1). Geometry of SG rocks in the hanging wall block presented in T1 and T2 are probably due to drag folds associated with normal fault zone.

**Table 3.** Deformational phases of the Bonsucesso deposit.

<table>
<thead>
<tr>
<th></th>
<th>D0</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bedding</strong></td>
<td>Flexurally induced normal faults</td>
<td>Thrust faults, S1 cleavage, Isoclinal folding with low plunge to NW and SE</td>
<td>Open folds SW-NE, Strike-slip faults</td>
<td>Mineralization is deformed</td>
<td>Late normal faults with small offset (Pinho et al. 1990, Rostirolla et al. 2002, Cordeiro et al. 2018)</td>
</tr>
<tr>
<td><strong>Main mineralization</strong></td>
<td>Local extension/foreland</td>
<td>Late mineralization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Passive margin</strong></td>
<td>Compressive regime/Brasilia belt thrust front</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Comparison between the Bonsucesso deposit and the other Vazante Belt deposits**


Mineralization in the Morro Agudo deposit is interpreted to be related with fluids ascending from a main normal fault located in the east limit of the deposit (Dardenne and Freitas-Silva 1999, Misi et al. 1999, 2005, 2014, Cunha et al. 2000, 2007). Likewise, Cunha et al. (2000) and Misi et al. (2005) showed a cooling pattern in homogenization temperature, salinity, and isotopic data toward deeper and distal sectors from the main fault. Nonetheless, there is a set of smaller normal faults with an oblique component which offset the orebodies and host rocks (Cordeiro et al. 2018). These faults are ore modifiers and have the same attitude of the main fault and also the main fault does not feature any clue of hydrothermal alteration expected to a feeder zone. Therefore, the referred structure would be only other later but larger normal fault modifying the whole rock sequence (Cordeiro et al. 2018). So, without contradicting the recognized cooling pattern, Cordeiro et al. (2018) call for any conduit capable of mobilize fluids before faulting into smaller blocks and that a major feeder may have been eroded or simply not intersected by drilling yet. Hence, mineralization at the Morro Agudo deposit took place before basin inversion.

In this sense, even if Morro Agudo had multiple phases of ore fluids injection, they all point to an early bulk mineralization event that happened before overprinting of compressive structures and may be contemporaneous with a hypothesis of pre-thrust mineralization of Bonsucesso. Cordeiro et al. (2018) discussed that there is a strong, although overlooked, strike-slip component in Morro Agudo, possibly related to the collisions between the Amazonian, São Francisco, and Paranaean paleoplates (Brito Neves andFuck 2013).

The Ambrósia, Ambrósia Sul, and Bonsucesso deposits form an aligned cluster of Zn-Pb mineralization (Fig. 13) with minor offset by strike-slip fault and may constitute an earlier permeable normal fault system with high influx of hydrothermal fluids later overprinted by thrusting.

The Ambrósia Sul deposit represents another Zn-Pb sulfide deposit formed during an early extensional event and is located...
in the same trend 5 km southward from the Bonsucesso deposit. According to Botura Neto and Danderfer Filho (2022), mineralization is associated with a syn-orogenic extension during formation of Bambuí Group foreland basin and normal faulting is related to forebulge uplift (Reis et al. 2017). Although the emergence of basal layers in the Ambrosia Sul deposit is not as evident as in the Bonsucesso deposit, Neto (2018) interpreted the high-angle mineralized veins formed during a compressive regime cut by late low-angle thrust faults associated with minor Sp-bearing veins.

The Ambrosia Norte Zn-Pb deposit, also known simply as Ambrosia Zn-Pb deposit, is associated with epigenetic processes (Monteiro et al. 2006) and is also controlled by a high-angle fault. This deposit is located just 1.5 km to the south from Bonsucesso and its mineralization style (Monteiro et al. 2006, 2007) is similar to Bonsucesso. These deposits are separated by a transcurent fault zone and projection of their mineralization onto the surface shows a 200 m relative offset if it is assumed that they are controlled by the same fault.

The mineralization of Vazante non-sulfide Zn deposit is controlled by a 12 km long fault zone trending northeast and dipping 60° to northwest (Monteiro et al. 2007). This major shear zone also shows a complex deformation history (Dardenne 1974, Pinho 1990, Rostirolla et al. 2002) and an important role in the mineralization process as the main conduit, besides many particular features involving willemite formation and hydrothermal alteration processes unequal in the world (Monteiro et al. 1999).

### Bonsucesso deposit × Tectonic settings of MVT Pb-Zn deposits on Earth history

As discussed by Leach et al. (2010), the tectonic setting of ore deposits is the conjuncture where they are formed and eventually destroyed. Also, this moment on an evolving Earth “determines the host-rock type, ore controls, temperature, and pressure of the depositional processes, as well as the survivability of the deposit during tectonic recycling” (Leach et al. 2010).

According to Bradley and Leach (2003), the most suitable environments for MVT mineralization are former passive margin platform carbonates that ended up beneath foreland basin deposits generated during the collisional orogeny. After orogeny has ceased, a hydrologic flux of basinal brines would be favorable, which percolates through the normal faults induced by crustal flexure occurred during the formation of accommodation space of the foreland basin (Leach et al. 2010).

The way that Bonsucesso’s mineralization fits in this model is that it is hosted in former passive margin platform carbonates beneath a foreland basin; it is controlled by high-angle dilational structure; and the salinity, isotopic, and homogenization temperatures of near-by deposits have an upper crustal/basinal signature (Monteiro et al. 2006, 2007). Although, Vazante Group has undergone a shortening process that lasted longer than the foreland basin deposition process and the latter was also involved in the thin-skinned tectonics as it was added to external domains of Brasilia Belt during the late stages of assembly of West Gondwana (Alkmim et al. 1996, 2001, Brito Neves et al. 1999, Pedrosa-Soares et al. 2001, 2007, Alkmim 2004, Brito Neves 2004, Valeriano et al. 2004, Caxito et al. 2014, Reis and Alkmim 2015). Finally, an extensional phase of mineralization before basin inversion with some late remobilization also agrees with Misi et al. (1999, 2005, 2014), Monteiro et al. (2006, 2007), Cunha et al. (2000, 2007), and Dardenne and Freitas-Silva (1999) proposals for Morro Agudo, Ambrosia, Fagundes, and Vazante deposits.

### Implications for mineral exploration

The Zn-Pb deposits in the Vazante belt are intimately linked to fault zones (Dardenne and Freitas-Silva 1999, Monteiro 2002, Misi et al. 2005, Monteiro et al. 2006, Cordeiro et al. 2018). The flow of metal-rich fluids occurred throughout the Vazante basin, and dilatational structures functioned as avenues for them to be redistributed along the strike and crystallize where chemical conditions were adequate. Contrasting rheological properties of brittle dolomite rocks from Morro do Calçário Formation and more ductile phyllites from the Serra do Garrote Formation could have transformed Vazante Group in a giant fluid trap, where the permeability in carbonate rocks increased by faulting and different reservoirs were allowed to interact.

Historically, mineral exploration programs evolved through the follow-up of outstanding geochemical anomalies in the regolith (e.g., metal rich gossan). In the Paracatu and Vazante regions, it was not different; all major orebodies currently mined were once cropping out. In the entire region, the Bonsucesso deposit is the first orebody discovered lying under a 30-m-thick pile of recent sediments. Although, its discovery is particularly
connected with a gossan 1 km to south slightly with the same strike (Ambrósia Norte) and targeted for decades.

Our model presents a likely set of regional proportions involving flexurally induced normal faults later affected by thrust and strike-slip faults. High-angle reverse structures such as the Bonsucesso fault may suggest a direct link between mineralization and compressive regime, but early extensional features related to the main stage of Zn-Pb sulfide formation are identified and better fit the general model proposed for most of the Vazante Belt deposits of bulk mineralization pre-inversion (Misi et al. 2005, 2014, Monteiro et al. 2006, 2007).

High-angle fault-zones dipping to the west (the general dip of the thrust belt) may be mistaken as originally thrust-faults and disguise other exploration opportunities such as their likely own antithetic pair. Regarding that, normal antithetic faults controlling mineralization are already known in the Ambrósia Sul deposit (Botura Neto and Danderfer Filho 2022) and are poorly explored along the Vazante Belt. In addition to that, current strike-slip faults also might have worked as transfer faults during extension phase and flipped their dip as it is documented in many extension sets around the world (Milani and Davison 1988, Chorowicz 1989). Therefore, these possibilities should be taken into account when exploring in regions of interacting faults.

CONCLUSION

The Bonsucesso Zn-Pb sulfide deposit is hosted in a hydrothermal dolomitic breccia controlled by a high-angle reverse fault striking N20W and dipping 60° to SW. Mineralization is hosted mainly in the breccia-matrix, but it also occurs in high-angle extensional veins. We suggest various mineralizing scenarios, but our preferred model is that bulk mineralization was likely formed mainly in the breccia-matrix, but it also occurs in high-angle extensional veins. We suggest various mineralizing scenarios, but our preferred model is that bulk mineralization was likely formed in an extensional regime setting in breccia zones controlled by flexurally induced normal faults, and mineralized zones were segmented by the injection of the more ductile basal unit (Serra do Garrote Formation). Contrasting rheological properties of brittle dolomite rocks from the Morro do Calcário Formation and ductile phyllites from the Serra do Garrote Formation acted as a fluid trap as permeability in carbonate rocks increased by faulting and different reservoirs were allowed to interact. Our model presents a possible set of regional proportions involving flexurally induced normal faults later affected by basin inversion. Thrust structures such as the Bonsucesso fault may suggest a direct link between mineralization and compressive regime, but early extensional features related to main stage of Zn-Pb sulfide formation are identified which agrees with the model proposed for most of the Vazante belt deposits of bulk mineralization pre-inversion. The mineralization process at Bonsucesso fits the model proposed by Bradley and Leach (2003) for well-known MVT provinces as follows: it is hosted in former passive margin platform carbonates beneath a foreland basin; it is controlled by high-angle dilatational structure; and the salinity, isotopic, and homogenization temperatures of near-by deposits have an upper crustal/basinal signature. The search for mineralization extensions controlled by faults should take into account an early normal faulting setting deformed by basin inversion.

ACKNOWLEDGMENTS

The authors thank Lucio Molinari, Paulo Ravacci, Juliano Ferreira e Helber Thomazella from Nexa Resources for permission to carry out the research and all the financial and logistics support. They also especially thank the geologists Saulo Oliveira and Rafael Caixeta for their contributions to the 3D modeling. They are thankful to Professors Fernando Alkmim and Humberto Reis for their thoughtful discussions during regional field work and on drill core analysis. They are also grateful to the geologist Regiane Fumes for helping with the XMapTools software. This research was partially funded by CAPES and forms part of Edson R. M. Ferraz’ s MSc in Geosciences and Environment Graduate Program of São Paulo State University (UNESP).

ARTICLE INFORMATION


E.R.M.F.: Lead writer of the article; G.L.L.: Supervision and Mentor; J.O.: Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing; D.A.B.: Formal analysis, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Competing interests: All authors declare that there are no competing interests.

REFERENCES


