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Lead isotope constraints on the genesis of Pb–Zn deposits in the Neoproterozoic Vazante Group, Minas Gerais, Brazil

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Abstract

The Neoproterozoic Vazante Group at the western border of the São Francisco Craton, Brazil, hosts the largest Zn–Pb district in South America. Several authors have classified this mineral district as Mississippi Valley-type (MVT), based on the intimate association with carbonates and the epigenetic character of most ore bodies. In this paper, we present 47 new lead isotope data from four deposits located along the 300 km N–S Vazante–Paracatu–Unai linear trend. Pb isotope ratios indicate sources with relatively high U/Pb and Th/Pb ratios. Considering the $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios as indicative parameters for the source, we suggest an upper crustal source for the metals. The small variation on the Pb isotope ratios compared to those observed in the classical MVT deposits, and other geological, fluid inclusion and sulphur isotopic data indicates a metallogenic event of long duration. It was characterized by focused circulation of hydrothermal fluids carrying metals from the basement rocks and from the sedimentary pile. The data obtained are more compatible with an evolution model similar to that of IRISH-type deposits. The existence of three Pb isotopic populations could be the result of regional differences in composition of the source rocks and in the fluid–rock interaction since the mineralization is a long-term process.

Keywords: Pb isotopes; Pb–Zn deposits; Vazante Group; Neoproterozoic metallogeny; Brazil

1. Introduction

The Neoproterozoic Vazante Group outcrops along a 300 km N–S trending belt at the western border of the São Francisco Craton, Brazil. This mega stratigraphic unit represents a passive margin dominant carbonate sedimentation that correlates to the platform carbonate sedimentation of the Bambuí Group to the east, as demonstrated by Misi et al. (1997, 2004), Misi (2001) and Azmy et al. (2001), based on chemostratigraphic studies (Fig. 1).

The Vazante Group hosts the largest Zn–Pb district in South America. Morro Agudo and Vazante mines, and several other minor deposits like Ambrósia and Fagundes are hosted in dolomitic rocks of the Vazante Group. The entire production of zinc and lead in Brazil comes from former two mines, which have been exploited continuously for 15 years. Ore reserves at Vazante and Morro Agudo are 18 Mt (23% Zn) and 5 Mt (6.3% Zn, 2.9% Pb), respectively. Vazante is presently producing 0.9 Mt/year (run of mine) having 13.5% Zn and Morro Agudo 0.95 Mt having 5% Zn and 2% Pb.

The lead–zinc deposits of the Vazante Group have been compared to Mississippi Valley-type (MVT) (Amaral, 1968; Rigobello et al., 1988; Iyer et al., 1992), sedimentary-exhalative (SEDEX) (Misi et al., 1996; Freitas-Silva and Dardenne, 1997) and IRISH-type (Hitzman, 1997a; Cunha et al., 2000; Misi et al., 2000; Dardenne, 2000; Monteiro, 2002). The Zn mine of Vazante was classified as "Vazante-type" (Monteiro et al., 1999), because of the willemitic nature of the ore. Hitzman (2003) refers to the Vazante deposit as the major example of a new deposit

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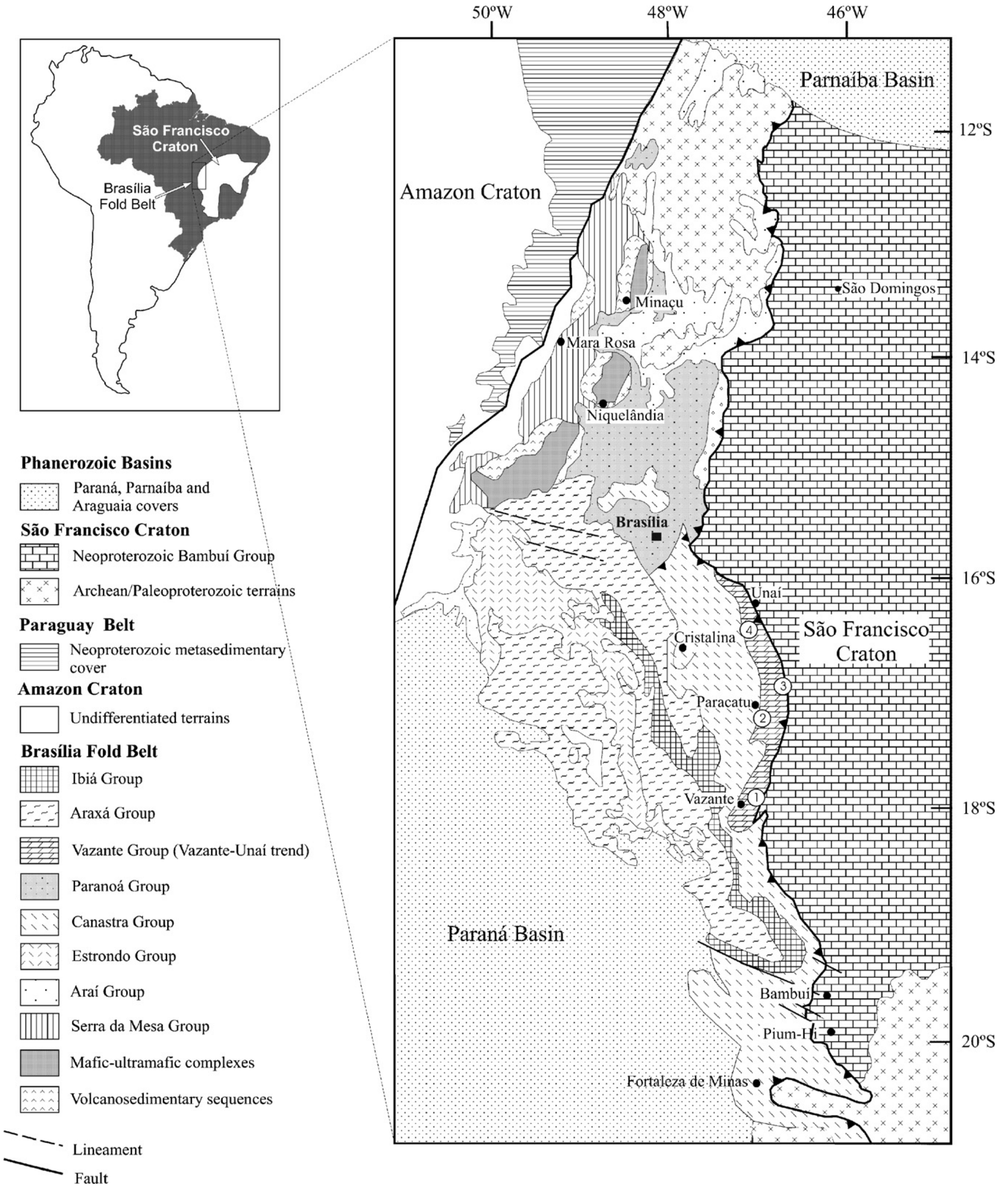


Fig. 1. Simplified geological map of the Brasilia Fold Belt showing the Palaeo-Meso-Neoproterozoic units, according to Marini et al. (1984), Dardenne (2000), Pimentel et al. (2001) and Valeriano et al. (2004). The deposits studied are indicated by numbers: (1) Vazante, (2) Morro Agudo, (3) Fagundes, (4) Ambrósia.

class, named as "carbonate-hosted willemite deposit" or "non-sulfide zinc deposits".

This paper discusses new lead isotope analyses of sulphide samples from the Morro Agudo, Vazante, Fagundes and Ambrósia deposits. Pb isotope investigation is mainly used to constrain the possible source rocks of the metals in these deposits. With geological and petrographic data, S isotope analyses and fluid inclusion studies, we suggest a possible metallogenic evolution model for this important zinc–lead district.

2. Geological and geotectonic setting

2.1. The Brasilia Fold Belt

The lead–zinc ores are contained within the Vazante-Unaí trend at the external zone of the Brasília Fold Belt (BFB). This trend extends over 300 km in N–S direction, parallel to the western margin of the São Francisco Craton (CSF) (Fig. 1). The Brasilia Fold Belt (Almeida, 1993), extending for more than 1000 Km in the same direction, represents an unstable tectonic unit with a long history of deformation and metamorphism, especially during the Pan African/Brasiliano orogeny (~600 Ma) (Marini et al., 1981; Pimentel et al., 2001).

The main units of the BFB are: (a) Palaeo- to Neoproterozoic meta-sedimentary sequences, including Neoproterozoic carbonate and siliciclastic sequences of the Vazante and Bambuí Groups; (b) Palaeo- to Mesoproterozoic igneous intrusions (including anorogenic granites) and volcano-sedimentary sequences; (c) Neoproterozoic syn- to post-orogenic granites and mafic+ultramafic intrusions (Dardenne, 2000).

Deformation and metamorphism are progressively more intense towards the west of the BFB. Based on the deformation pattern and on the degree of metamorphism, Dardenne (1978) and Fuck (1994) identified three different zones: (a) the internal zone, to the west, with intensely deformed rocks and metamorphosed up to amphibolite+granulite facies; (b) the external zone, in the central area, with moderately deformed and metamorphosed rocks that includes the Vazante Group; (c) the cratonic zone, to the east, where the Bambuí Group outcrops, showing undeformed or slightly deformed rocks and a metamorphic grade up to lower greenschist facies.

Marini et al. (1981, 1984) recognized an E–W lineament in the central part of the BFB that divides the orogenic belt in two segments, with different geotectonic evolution. In the northern segment, the degree of metamorphism is low, reaching only the greenschist facies. These weakly metamorphosed sediments are well preserved. In the southern segment, where the Vazante Group outcrops, the deformation and the metamorphism are more intense.

2.2. The Vazante Group

Meta-sediments of the Vazante Group extend ca. 300 km in N–S direction in the external zone of the Brasilia Fold Belt (Fig. 1). This group is divided into seven formations, briefly described as follows from base to top (Fig. 2). The basal unit is the Santo Antônio do Bonito Formation, formed by quartzite, conglomerate, diamictite and slate. According to Dardenne et al. (1998), the diamictites are debris flows deposited in relatively deep water glacio-marine environment. This formation grades upward to rhythmites (pelites and siltstone) of the Rocinha Formation that hosts large phosphate deposits (e.g. Rocinha and Lagamar mines). The Lagamar Formation is dominantly made up psammo-pelitic rocks (basal conglomerate, quartzite and slate) and dark-gray limestone with columnar stromatolites. The Serra do Garrote Formation consists of a thick succession of open marine, dark-gray to greenish-gray slate, locally rhythmic, carbonaceous and pyrite-rich. Overlying Serra do Poço Verde Formation has dominantly dolomites and is divided into four members. The Morro do Calcário Formation is formed by carbonate sequences, composed of stromatolitic dolomites, dolarenites and dolorudites. The known Pb–Zn mineralizations are hosted by the two dolomitic carbonate formations (Serra do Poço Verde and Morro do Calcário). They are overlain by rhythmic carbonaceous phyllite, sericite-chlorite phyllite and carbonate bearing metasiltstone of the Serra da Lapa Formation.

There is no consensus concerning the age and geotectonic environment of the formation of the Vazante Group and this is probably due to the intense deformation of the rocks during the Brasiliano orogenic cycle. Some authors (e.g. Campos Neto, 1984; Almeida, 1993; Fuck, 1994) place the Vazante sediments in a typical passive margin depositional setting. The great thickness of the sedimentary package (at least 2500 m) could support this hypothesis (Dardenne, 1981; Marini et al., 1981). Nevertheless, Dardenne et al. (1998) and Dardenne (2000) suggest that the sediments of the Vazante Group were deposited in foreland basins, during the initial phases of the Brasiliano orogeny.

The presence of Conophyton (*Conophyton* cf. *cylindricus* Masloy; Moeri, 1972) in the Lagamar Formation suggests an age between 1650 Ma and 950 Ma for sedimentation. Cloud and Dardenne (1973) report an age interval from 1350 Ma to 950 Ma based on the occurrence of *Conophyton metula* Kirichenko in the same stratigraphic unit.

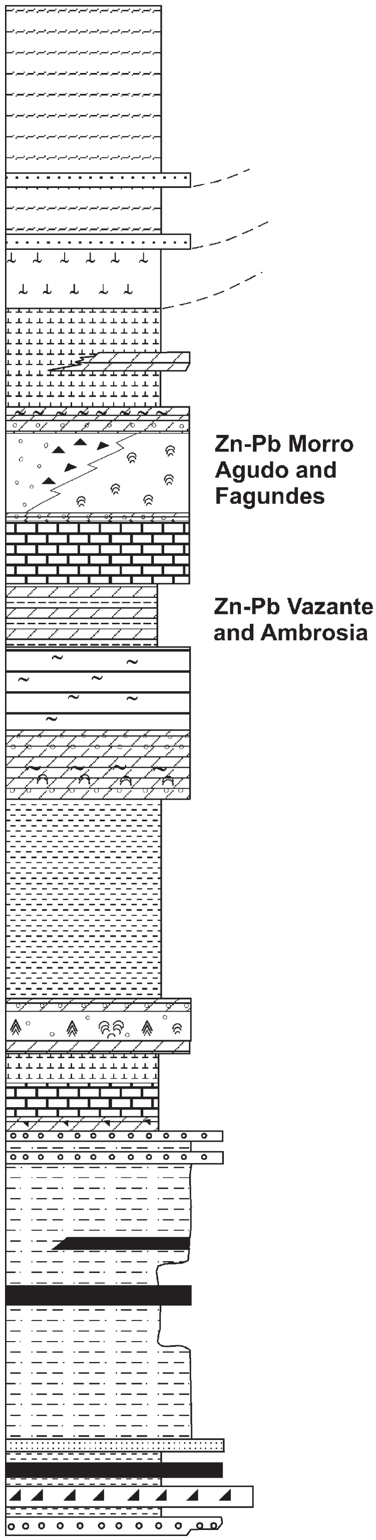
Rb–Sr whole rock isochrons from pelitic meta-sediments of the Vazante Group indicate ages of 600±50 Ma (Amaral and Kawashita, 1967) and 680±10 Ma (Parenti Couto et al., 1981), close to those obtained for pelites intercalated with carbonates of the Bambuí Group by the same authors (640±15 Ma). However, the high $^{87}Sr/^{86}Sr$ ratio obtained from associated carbonate (0.7109 and 0.7255) and the metamorphic overprint suggests that these are not depositional ages, but may reflect partial to complete re-equilibration during metamorphism.

Pb–Pb model ages obtained from galenas of the Vazante and Morro Agudo mines range between 780 and 600 Ma (Amaral, 1968; Cassedanne and Lasserre, 1969; Cassedanne et al., 1972; Iyer, 1984; Iyer et al., 1992; Misi et al., 1997). Based on model III of Cumming and Richards (1975), Iyer et al. (1992) obtained ages of 650±50 Ma and 1850±150 Ma interpreted as the galena formation age and the source rocks of the metal, respectively.

Chemostratigraphic studies of the carbonate units by Misi et al. (1997), Misi (2001) and Azmy et al. (2001) support a Neoproterozoic age for the Vazante Group. $^{87}Sr/^{86}Sr$ ratio of well preserved carbonate cements and carbonate fluorapatite (0.70641 to 0.70771) also indicate this age and a possible correlation with the platform carbonates of the Bambuí Group, to the east.

3. General characteristics of the deposits

The Morro Agudo and the Vazante mines as well as other zinc–lead deposits (Fagundes, Ambrósia) occur along the Vazante-Unaí trend (Fig. 1). Mineralization was controlled by a fault system and confined to some stratigraphic units of the



Description	Member	Formation	Group
Gray phyllite	Serra da Anta	Paracatu	CANASTRA
Carbonaceous phyllite with quartzite layers	Morro do Ouro		
Gray carbonatic phyllite	Serra do Landim		
Gray carbonate-rich slate lenses of dolomite; black carbonaceous slate	Serra da Lapa Velosinho	Lapa	VAZANTE
Stromatolitic bioherm, facies of breccia and dolarenite	Upper Pamplona	Morro do Calcário	
Pink dolomite with stromatolitic mats, barite nodules and mud cracks	Middle Pamplona	Serra do Poço Verde	
Gray and green slates, with intercalations of pink dolomite	Lower Pamplona		
Dark gray dolomite with stromatolitic mats and bird´s eyes	Upper Morro do Pinheiro		
Gray to pink dolomite, breccia and dolarenite	Lower Morro do Pinheiro		
Gray slate		Serra do Garrote	
Stromatolitic bioherm Dark gray limestone Dolomitic Breccia	Sumidouro	Lagamar	
Conglomerate	Arrependido		
Rhythmite with phosphorite		Rocinha	
Dark gray pyritic and phosphatic slate			
Rhythmites			
Intercalations of quartzite, phosphorite, diamictite and slate		Santo Antônio do Bonito	

Fig. 2. Lithostratigraphy of the Vazante Group with the stratigraphic position of the deposits studied. From Dardenne (2001).

Vazante Group. Morro Agudo and Fagundes deposits are hosted by dolarenites and microbial laminites of the Morro do Calcário Formation, with black carbonaceous slate of the Lapa Formation on top. Vazante and Ambrósia deposits are hosted by pink dolostone interbedded with slates of the Serra do Poço Verde Formation (Fig. 2). Baroque dolomite, pervasive silicification and Fe-rich minerals (e.g. ankerite) are some of the indications of important hydrothermal alteration processes associated with the mineralization in all the studied deposits.

3.1. Morro Agudo deposit

The sulphide mineralization at Morro Agudo mine is composed of sphalerite, galena and minor pyrite. They are accompanied by calcite, microquartz (length slow), megaquartz and barite. Massive and disseminated mineralization is distributed along a fault zone striking N10–20W and dipping 75° to S. The main fault is a normal fault and mineralization was restricted to hanging wall. It is subdivided into four main types (Romagna and Costa, 1988) (Fig. 3):

M orebody: composed of coarse-grained galena and sphalerite forming irregular bodies in dolarenites at the top of the Morro do Calcário Formation.

N orebody: composed of fine-grained, stratiform mineralization in dolarenitic beds. The alternating lamina of chert, galena, sphalerite and pyrite and the presence of millimetric beds of ultra-fine sphalerite suggest a syngenetic to syndiagenetic mineralization for this ore body, as demonstrated by Cunha (1999) and Misi et al. (2005). Nodular sulphide mineralization is associated with microcrystalline, fibrous and length-slow quartz, suggesting that a previous evaporític facies controlled the mineralization (Folk and Pittman, 1971). The N orebody is confined to the argilo-dolomitic sequence (SAD) on the top of the Morro do Calcário Formation.

JKL orebody: consists of massive fine-to coarse-grained sulfides (mainly sphalerite), cementing peloidal dolarenitic beds. Peloidal and oncolitic grains are neomorphosed and dolomitized and partially preserved from late silicification.

GHI orebody: consists of coarse-grained sphalerite and galena cementing brecciated structures. Breccias contain angular clasts and blocks of dolostones, including clasts of the N orebody. The clasts characteristics suggest that at least part of the breccia bodies were formed by dissolution and collapsing of the upper strata.

3.2. Vazante deposit

The Vazante mine is mainly composed of willemite with minor sulphides (sphalerite and galena) and oxidized ore (hemimorphite, hydrozincite, smithsonite, franklinite and pyromorphite). Willemite mineralizations occur mainly in centimeter to meter wide veins, and are associated with silica and hematite in hydrothemally altered dolostones (silicification and sideritization). Monteiro et al. (1999) demonstrated the stratigraphic control of the primary mineralization that is confined to the upper part of the

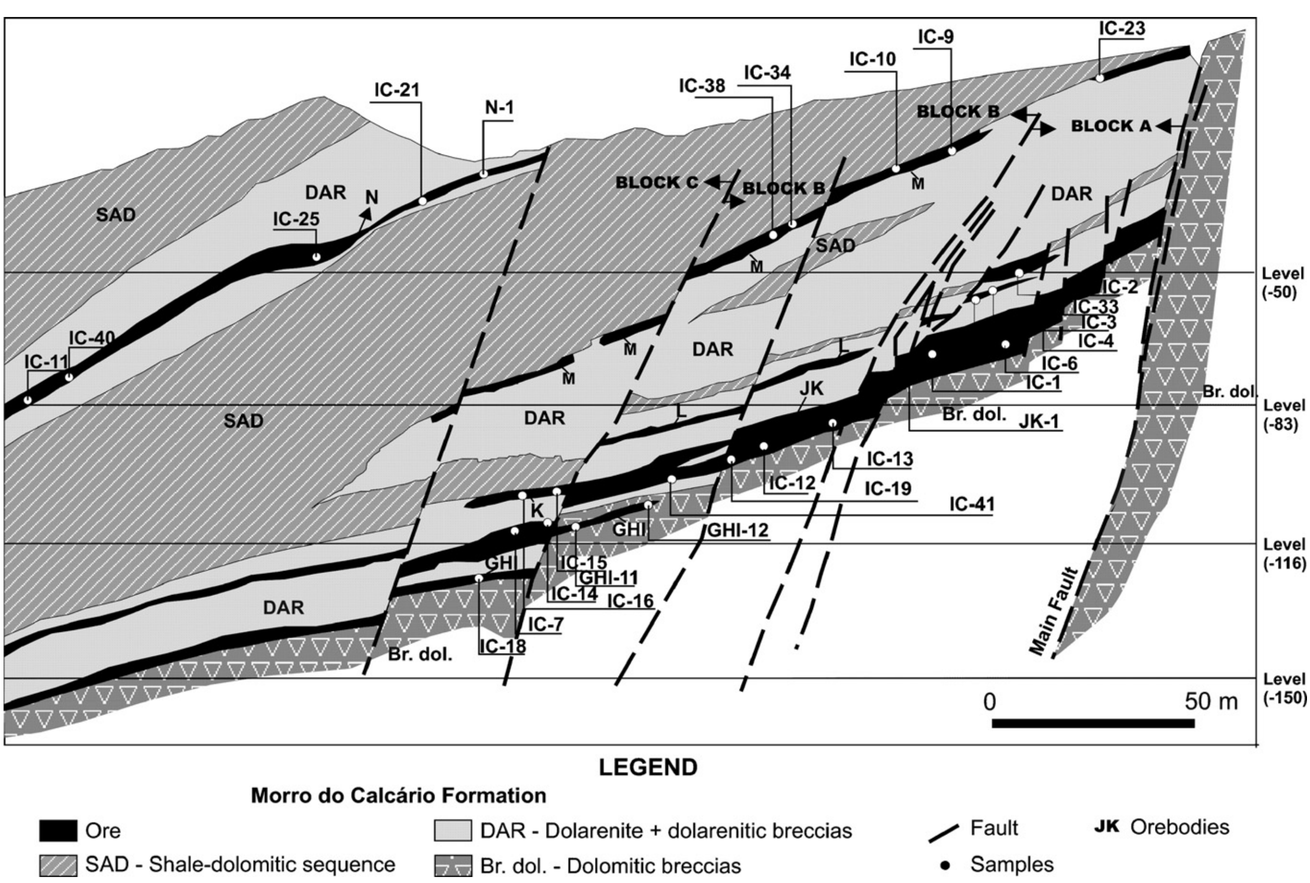


Fig. 3. E–W cross-section across the Morro Agudo deposit showing the location of the main orebodies. According to Votorantim Metais Zinco.

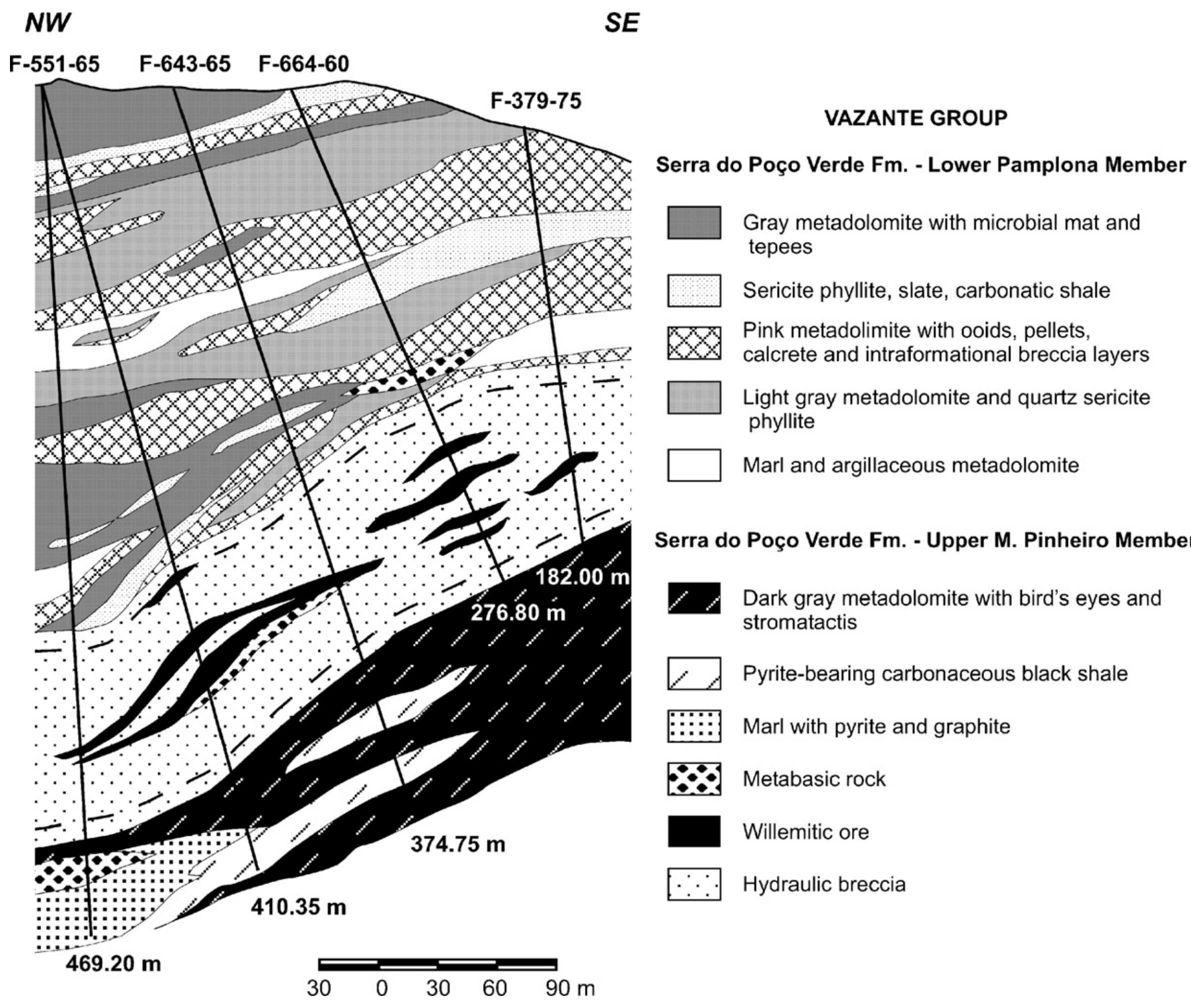


Fig. 4. NW–SE cross-section across the Vazante deposit. Lines labelled "F-number" indicate drill holes made by Votorantim Metais Zinco. From Monteiro (2002).

Morro do Pinheiro Member of the Serra do Poço Verde Formation. A fault zone striking N50E and dipping 60NW, known as the "Vazante Fault", controlled the ore formation (Fig. 4). Dardenne (2000) suggested that the fault system was originally related to a syn-sedimentary growth fault, reactivated several times during the Brasiliano orogeny. According to Hitzman (1997b, 2003), several kinematics indicators suggest that the final movement of the Vazante Fault was reverse, despite the general trend of the normal fault. Reversal of movement from extensional to compressive led to the appearance of reversed faults that disrupted veins and hydrothermally altered dolomite layers (Hitzman, 1997b, 2003). Metabasites tectonically imbricated with rocks of Pamplona and Morro do Pinheiro members along the Vazante fault zone were interpreted as of Cretaceous age (Rigobello et al., 1988). Nevertheless, the metamorphic mineral assemblage (chlorite, clinozoizite, epidote, talc, sericite, quartz, rutile, leucoxene, apatite), and milonitic fabrics are not recorded in Brazilian Cretaceous rocks (Monteiro et al., 1999).

Based on scanning electron microscopic (SEM) images of euhedral contacts of willemite and intergrown sphalerite, Hitzman (2003) proposed co-precipitation of willemite and co-existing sulfides in Vazante. Oxygen and carbon isotopic composition of the gangue minerals led Monteiro et al. (1999) and Monteiro (2002) to suggest that the oxy-redox conditions for sulfide and willemite mineralization were similar.

3.3. Fagundes deposit

Fagundes deposit is hosted by stromatolitic dolostone (Fig. 5), in the uppermost part of the Morro do Calcário Formation (Monteiro, 2002). Apparently, it is in the same stratigraphic position as the N orebody of the Morro Agudo mine (Fig. 2). Mineralization is mainly stratabound and veins, and comprises sphalerite, galena and pyrite. Intense hydrothermal silicification predates mineralization (Monteiro, 2002). Veins of chalcedony grades to pervasive silicification of the host dolostone forming nodules with length-slow quartz, suggesting replacement of sulfates in evaporative environment (Folk and Pittman, 1971). Baroque dolomite and pyrite replace silica and earlier dolomite. According to Monteiro (2002), primary sulfides are partially remobilized, forming zoned and deformed sphalerite. There are also late sulphide mineralizations, forming clear-yellow sphalerite

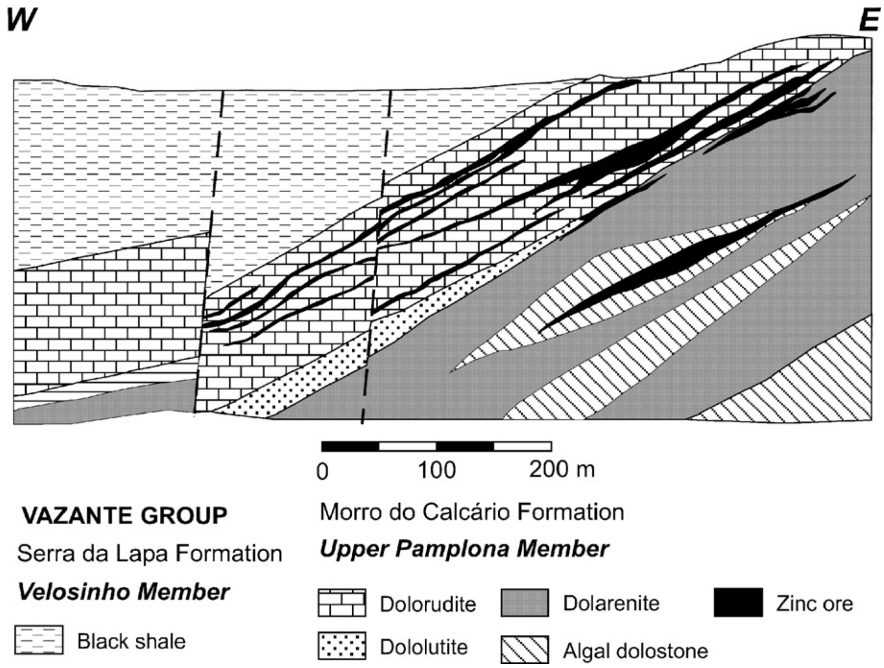


Fig. 5. Schematic cross-section of the Fagundes deposit, according to Temerid Mineração S.A. From Monteiro (2002).

and cross-cutting veins. Locally, late sphalerite may crystallize around primary mineralization.

3.4. Ambrósia deposit

Sulfide mineralization at Ambrósia deposit is mainly composed of pyrite, marcasite, sphalerite and minor galena. It occurs in brecciated comb-veins and veins with coarse-grained white dolomite. Mineralization is hosted by brecciated stromatolitic dolostone from the Lower Pamplona Member of the Serra do Poço Verde Formation, in the same stratigraphic level of the Vazante mine (Fig. 2) (Flávio T. Oliveira, personal comm.). Fibrous pyrite and marcasite occur also in concentric bodies (Monteiro, 2002), suggesting replacement of sulphate nodules. Sphalerite is also present in these nodules, replacing pyrite. A high-angle fault zone aligned N30W dipping 60° to 80°SW (Fig. 6) is observed.

4. Analytical procedures

Galena samples for analysis were selected after a detailed petrographic study. They were separated by hand picking under a binocular microscope. The majority of the samples are from drill cores and the remaining samples are from underground galleries or from trenches.

The lead isotope analyses were carried out on galena crystals at the Center of Geochronological Research of the University of São Paulo, Brazil. The galena was dissolved in 7 N HNO_3 in a teflon beaker and evaporated to almost dryness. About 2 μl (ca. 200–400 ng of Pb) of the solution was loaded onto rhenium filaments with silica gel and phosphoric acid, and the Pb isotopic compositions were measured on a Micromass VG 354 thermal ionization mass spectrometer equipped with five collectors. All ratios were normalized to the values of NBS 981 by applying a mass discrimination factor of 0.12% per atomic mass unit. Estimated precision for the Pb ratios is about 0.1%.

5. Results

Lead isotope analyses were made of 47 galena samples representative of the main types of mineralization in the deposits of Morro Agudo ($n=34$), Vazante ($n=4$), Fagundes ($n=6$) and Ambrósia ($n=3$). The analytical data are presented in Table 1. Considering all studied ore bodies, some variation is observed on the Pb isotopic ratios ($^{206}Pb/^{204}Pb=17.59$ to 18.00, $^{207}Pb/^{204}Pb=15.61$ to 15.94, $^{208}Pb/^{204}Pb=37.00$ to 37.86). Three different populations of data can be observed when the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios are plotted using Zartman and Doe (1981) and Stacey and Kramers (1975) models (Figs. 7 and 8). They are discussed in the following sections.

5.1. Morro Agudo deposit

Data for 34 galena samples from the Morro Agudo deposit (Table 1) show $^{206}Pb/^{204}Pb$ isotope ratios ranging from 17.59 to 18.00, $^{207}Pb/^{204}Pb$ from 15.61 to 15.94 and $^{208}Pb/^{204}Pb$ from 37.00 to 37.86. The average values of 17.75 ± 0.08, 15.72 ±0.07 and 37.25 ± 0.20 indicate homogeneity when these ratios are compared to those obtained from MVT deposits (Doe, 1970; Leach and Sangster, 1993) and even to the isotopic ratios obtained from galena deposits found in the São Francisco craton (Iyer et al., 1992; Misi et al., 2000). Two separate populations of Pb isotopic composition can be

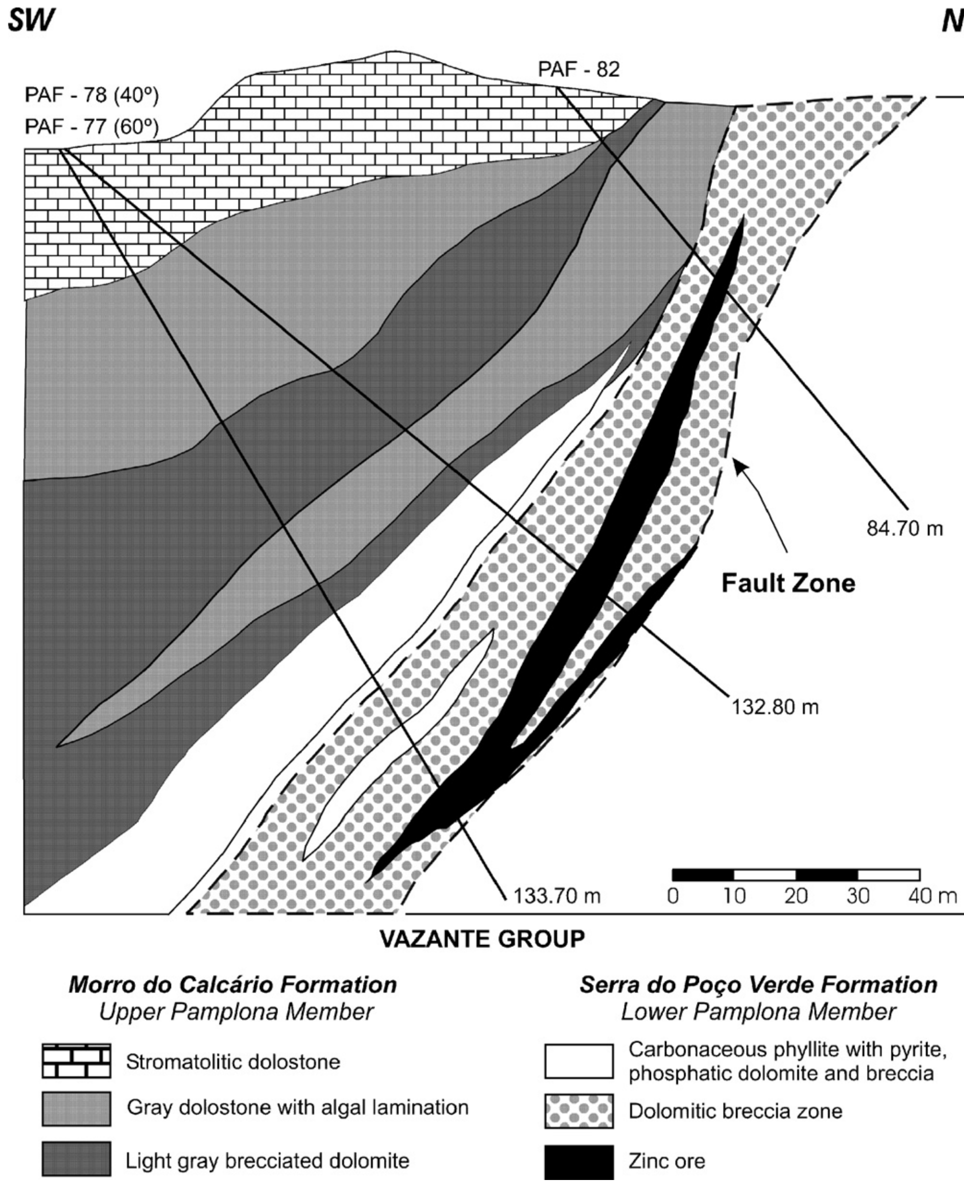


Fig. 6. SW–NE cross-section across the Ambrósia deposit. Lines labelled "PAF-number" indicate drill holes made by Votorantim Metais Zinco. From Monteiro (2002).

observed. These differences are probably related to the type of mineralization and the source of the fluids (Fig. 8a,b).

Population I corresponds to the stratiform mineralization (N orebody) that shows petrographical evidences of a syndiagenetic formation (Cunha, 1999; Misi et al., 1999). The lead isotope compositions obtained from these samples are less radiogenic than from other orebodies. $^{206}Pb/^{204}Pb$ ratios range from 17.59 to 17.85 (average 17.67 ± 0.08, $n=10$). The $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ isotopic ratios show relative homogeneity, averaging 15.67 ± 0.05 and 37.13 ± 0.13, respectively.

Population II represents orebodies GHI, JKL and M in which mineralization is epigenetic (open-space filling, veins or cementing breccias). This population shows an apparent linear trend in a $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$, and there is no remarkable distinction between the isotopic characteristics of the different orebodies. The $^{206}Pb/^{204}Pb$ compositions range from 17.68 to 18.00 (average of 17.77 ± 0.07), $^{207}Pb/^{204}Pb$ from 15.61 to 15.94 (average 15.72 ± 0.07) and $^{208}Pb/^{204}Pb$ from 37.00 to 37.86 (average 37.30 ± 0.2).

5.2. Vazante deposit

The $^{206}Pb/^{204}Pb$ ratios range between 17.70 and 17.76 (average 17.73 ± 0.02). The $^{207}Pb/^{204}Pb$ ratio varies between 15.65 and 15.71 (average 15.67 ± 0.02). The $^{208}Pb/^{204}Pb$ data are slightly more scattered and range from 37.07 to 37.30, averaging 37.18 ± 0.09. When plotted in a $^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ diagram, the Vazante data fall in the same field of Population II defined by the sulfides of the Morro Agudo deposits (Fig. 8a,b).

Table 1
Pb isotope data from Vazante, Morro Agudo, Fagundes and Ambrósia deposits

Sample	Description	Orebody	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Morro Agudo					
MA-N-7	Fine stratiform	N	17.63	15.66	37.09
MA-N-8	Fine stratiform	N	17.65	15.64	37.06
MA-IC-11	Fine stratiform	N	17.65	15.64	37.07
MA-IC-24	Fine stratiform	N	17.69	15.68	37.14
MA-IC-25	Fine stratiform	N	17.59	15.64	37.07
MA-IC-39	Fine stratiform	N	17.62	15.61	37.00
MA-IC-40	Fine stratiform	N	17.66	15.64	37.05
MA-IC-46	Fine stratiform	N	17.63	15.65	37.07
MA-N-4a	Fine stratiform	N	17.79	15.79	37.37
MA-N-4c	Fine stratiform	N	17.85	15.77	37.40
MA-IC-9	Coarse, forming pods	M	17.75	15.68	37.20
MA-IC-10	Coarse, forming pods	M	17.79	15.74	37.37
MA-IC-34	Coarse, forming pods	M	17.77	15.70	37.27
MA-IC-37	Coarse, in veins	M	17.82	15.79	37.55
MA-IC-47	Coarse, in veins	M	17.82	15.77	37.52
MA-IC-48	Coarse, in veins	M	17.84	15.79	37.56
MA-IC-4	Coarse, in dolarenitic matrix	JKL	17.68	15.61	37.00
MA-IC-12	Coarse, forming pods	JKL	17.76	15.72	37.33
MA-IC-14	Coarse, in dolarenitic matrix	JKL	17.72	15.65	37.08
MA-IC-16	Coarse, in dolarenitic matrix	JKL	17.76	15.70	37.28
MA-IC-19A	Fine, in dolarenitic matrix	JKL	17.71	15.63	37.07
MA-IC-19B	Coarse, in dolarenitic matrix	JKL	17.74	15.63	37.19
MA-IC-33	Fine, in dolarenitic matrix	JKL	17.70	15.65	37.12
MA-IC-33B	Coarse, in dolarenitic matrix	JKL	17.73	15.66	37.14
MA-IC-41	Coarse, forming pods	JKL	17.77	15.76	37.47
JK 1a	Coarse, in dolarenitic matrix	JKL	18.00	15.94	37.86
JK 2a	Coarse, in dolarenitic matrix	JKL	17.87	15.77	37.40
MA-IC-44	Coarse, filling breccia	GHI	17.73	15.66	37.14
MA-IC-45	Coarse, in veins	GHI	17.79	15.75	37.40
MA-IC-50	Coarse, in veins	GHI	17.81	15.76	37.47
MA-IC-51	Coarse, filling breccia	GHI	17.75	15.68	37.20
MA-IC-53	Coarse, filling breccia	GHI	17.68	15.66	37.13
MA-IC-52	Coarse, filling breccia	GHI	17.74	15.66	37.14
GHI 1b	Coarse, filling breccia	GHI	17.85	15.79	37.43
Vazante					
VZ-IC-F797	Coarse, in pods with sph.	–	17.72	15.67	37.18
VZ-IC-F1106	Coarse, in pods with sph.	–	17.73	15.67	37.17
VZ-IC-F1136	Coarse, in pods with sph.	–	17.76	15.71	37.30
VZ 01	Coarse, in pods with sph.	–	17.70	15.65	37.07
Fagundes					
FG-64-14A	Coarse, in veins	–	17.82	15.70	37.37
FG-76-15	Coarse, in veins	–	17.83	15.68	37.34
FG-76-42	Fine stratiform	–	17.76	15.66	37.25
FG-79-2	Coarse, in veins	–	17.83	15.71	37.45
FG-IC-F64	Coarse, in veins	–	17.81	15.67	37.27
FG-IC-F76	Coarse, in pods	–	17.77	15.65	37.23
Ambrósia					
AM-IC-F104	Coarse, in veins	–	17.74	15.69	37.48
AM-IC-F98	Coarse, in veins	–	17.74	15.63	37.26
AM-73-15	Coarse, in veins	–	17.85	15.67	37.33

5.3. Fagundes and Ambrósia

Isotopic data obtained from nine galena samples of the Fagundes and Ambrósia deposits define the Population III field (Fig. 8a,b). Data are more radiogenic than those of Morro Agudo and Vazante. The ranges of $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ are, respectively, 17.74 to 17.85, 15.63 to 15.71 and 37.23 to 37.48 (averaging 17.79±0.04, 15.67±0.02 and 37.33±0.08, respectively).

6. Fluid inclusions and sulphur isotopic studies

In previous studies, Cunha (1999), Monteiro (2002) and Misi et al. (2005) have determined composition and homogenization

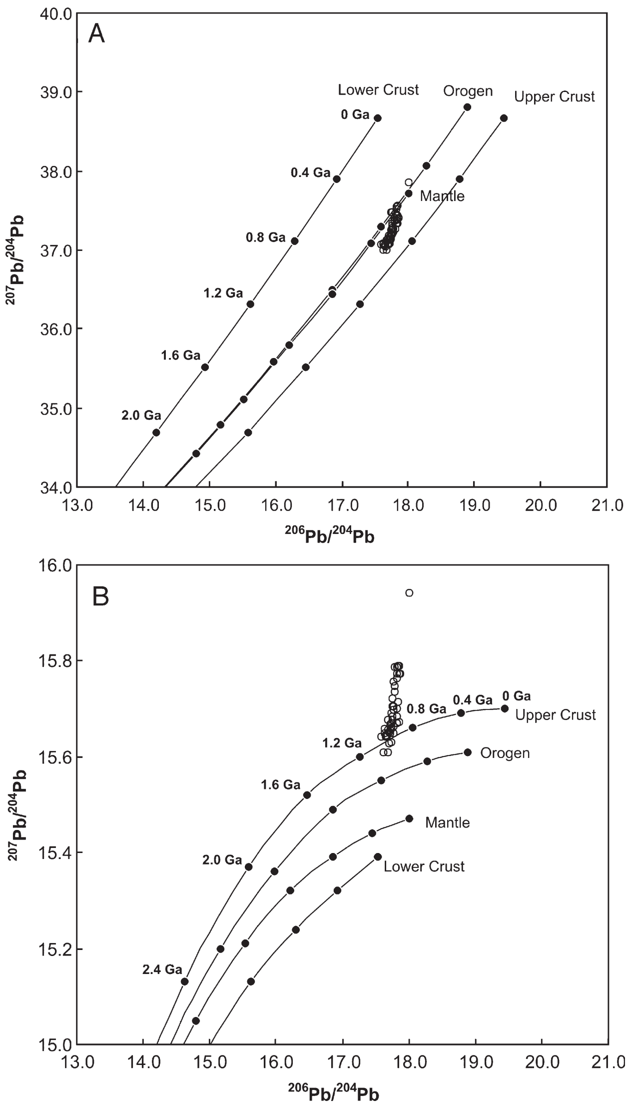


Fig. 7. (a) Plot of $^{208}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ of galena samples from the Vazante, Morro Agudo, Fagundes and Ambrósia deposits. (b) Plot of $^{207}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ from the same deposits. Evolution curves according to the plumbotectonic model of Zartman and Doe (1981). UC—upper crust, OR—orogen, MN—mantle, LC—lower crust. Every increment represents 400 Ma.

temperatures of primary and pseudo-secondary fluid inclusions in sphalerite from Morro Agudo, Vazante, Fagundes and Ambrósia. The same authors have also studied sulphur isotopic composition of sulfides and sulfates from Morro Agudo and Vazante.

6.1. Fluid inclusions

In Morro Agudo, composition of fluid inclusions in sphalerite crystals indicates moderate saline solutions, around 14% wt eq. NaCl (range, 4% to 22% wt eq. NaCl). The wide range of salinity values within the ore bodies is apparently related to a zonality distribution in relation to the "main fault" zone controlling the mineralization. Total homogenization temperatures (T_H) indicate also a zoning pattern closely related to the "main fault" zone. They are relatively higher close to the fault zone, varying from 122 to 283 °C with mode at 170 °C in the JKL ore body. Away from the fault, to the west, palaeo-temperatures are gradually lower, ranging from 80 to 168 °C with mode at 155 °C. The GHI ore bodies, in the same position, give similar values (88 to 209 °C, mode 150 °C). The stratiform 'N' orebody, in the upper part of the section, exhibits the lowest temperature interval, varying between 120 and 144 °C with mode at 138 °C (Fig. 3).

In Vazante, homogenization temperatures (T_H) of fluid inclusions in sphalerite range between 201 and 232 °C (mode at 210 °C) and salinities between 15.3 and 23% wt eq. NaCl; in Fagundes, T_H and salinities varies between 127 and 265 °C (mode at 190°) and between 14.6% and 20.2% wt eq. NaCl, respectively; in Ambrósia, T_H in fluid inclusions show 167 to 281.6 °C (mode 260 °C) and salinity ranging from 14.6% to 20.2% wt eq. NaCl (Monteiro, 2002).

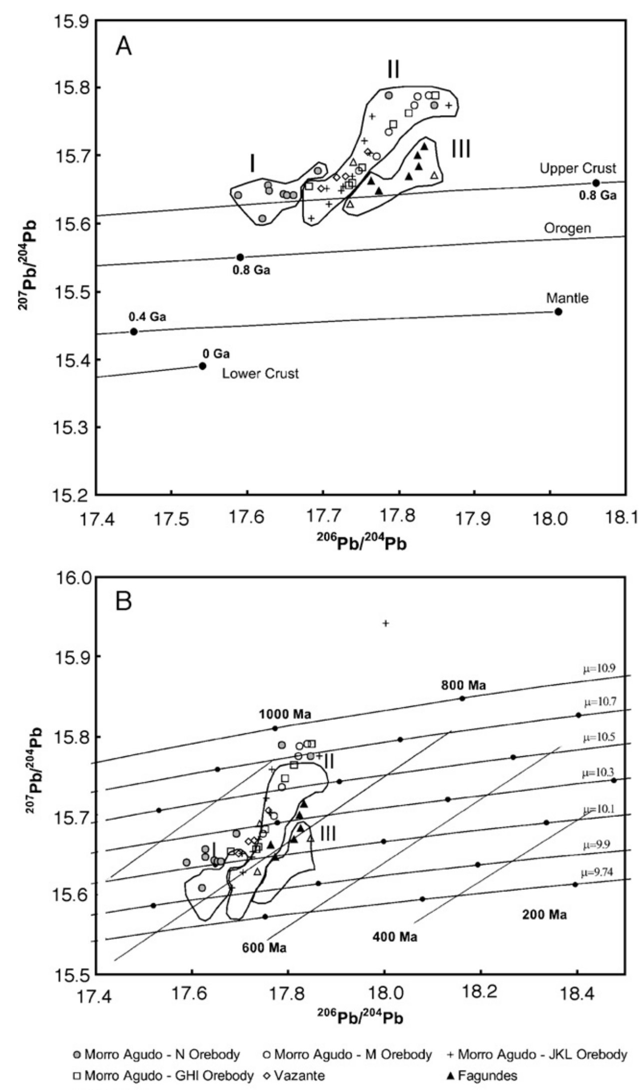


Fig. 8. Lead isotope composition of galena samples from the studied deposits showing three different populations of data: (I) N orebodies at the Morro Agudo deposit; (II) orebodies M, JKL and GHI (Morro Agudo) + Vazante deposits; (III) deposits of Fagundes and Ambrósia. a) Evolution curves of the plumbotectonic model (Zartman and Doe, 1981). (b) Evolution growth curve of Stacey and Kramers (1975).

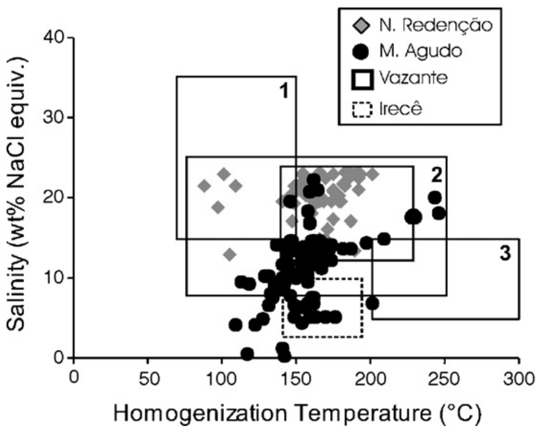


Fig. 9. Homogenization temperatures and salinities from primary and pseudo-secondary fluid inclusions in sphalerite crystals from the studied deposits, and comparison with the databank of classical models of sediment-hosted sulfide deposits (Goodfellow et al., 1993; Hitzman, 1995). Range for the Vazante mine from Monteiro (2002) and for Irecê deposit from Kyle and Misi (1997). (1) Mississippi Valley-type (MVT), (2) Irish-type, (3) SEDEX-type. Modified after Misi et al. (2000).

Comparing with T_H and salinities from typical MVT, SEDEX and IRISH deposits, The obtained data fall in the field of the IRISH-type (Fig. 9) (Misi et al., 2005).

6.2. Sulfur isotopes

Cunha (1999) and Misi et al. (2005) have analysed sulphide and barite samples from Morro Agudo and Vazante deposits. In Morro Agudo, these authors showed that "there is a clear trend in the δ^{34}S values for the sulfides with highly enriched values in the stratigraphically lowermost breccia-type GHI orebody, to less enriched values in the overlying oolitic stratabound JKL and moderate to slightly depleted for the stratiform N orebody". Average values for the N, JKL and GHI orebodies (Fig. 3) are respectively −3.7‰ CDT (n=13), +21.7‰ (n=19) and +29‰ (n=6). Geothermometric calculations using the sulfur isotope data of co-genetic sphalerite-galena pairs show increasing temperature values stratigraphically downward from N (100 °C), JKL (150 °C) to GHL (250 °C) ore bodies types" (Misi et al., 2005). Although the sulfur isotopic composition of sphalerite and galena in Vazante are less enriched (average of

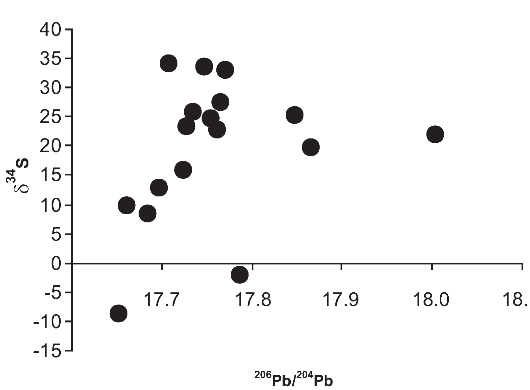


Fig. 10. Plot δ^{34}S vs. ^{206}Pb/^{204}Pb of galena samples from the deposits of Morro Agudo and Vazante. Modified after Misi et al. (2005).

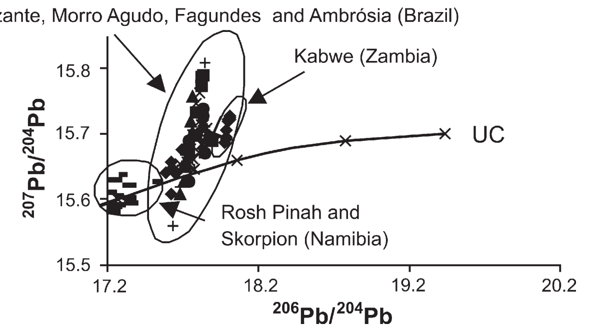


Fig. 11. Plot of ^{207}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb from some Neoproterozoic sedimentary-hosted sulphide deposits of Africa compared to the studied deposits. UC = upper crust evolution curve (Zartman and Doe, 1981). Data from African deposits: Burnard et al. (1993), Kamona et al. (1999), Frimmel et al. (2004).

+15.2‰ CDT (n=5)) compared to those from Morro Agudo, the values obtained in the two deposits indicate derivation of the sulfur from a Proterozoic seawater sulfate source.

The absence of a clear correlation between δ^{34}S and ^{206}Pb/^{204}Pb, as observed by Cunha (1999) and Misi et al. (2005) (Fig. 10) for some sulfide samples from Morro Agudo and Vazante, suggest that lead and sulfur are derived from at least two independent sources.

7. Discussion and conclusions

The Pb isotope data (Table 1) plot on and above the upper crustal uranogenic and thorogenic evolution curves (Fig. 7a,b) of Zartman and Doe (1981) indicating a derivation from an upper crustal source with a relatively high U/Pb and U/Th ratios (Figs. 7a,b and 8a). The data also plot well above the Stacey and Kramers (1975) Pb growth evolution curve (Fig. 8b). Since the isotope ratios do not fit to the Pb evolution models, no Pb model ages can be determined for the galena ores and consequently no age constraint can be obtained. However, these variations on the Pb ratios can yield some information about the source of the fluids.

Samples from the Morro Agudo mine show a relatively scattered distribution in the Pb isotopic diagrams (Figs. 7 and 8), mainly in the uranogenic diagram (Fig. 8a) of the Plumbotectonic model of Zartman and Doe (1981). Galena samples from N orebody present the less radiogenic Pb ratios (Population I, Fig. 8a,b), probably because this galena is older and was formed during the earlier stages of the mineralization process. Its petrographic characteristics and other data, as discussed by Misi et al. (2005), support this hypothesis.

Other orebodies (GHI, JKL and M) from the Morro Agudo deposit are more radiogenic and present less homogeneous Pb compositions (Population II, Fig. 8a,b); sulfides from the Vazante deposit also fall in the field defined by Population II. These data show a trend which is too steep to define an isochron and we interpret them as a result of incomplete mixing of Pb from at least two sources with different μ values. The Population II falls above the average crustal Pb evolution curve of Stacey and Kramers and is between curves of μ_2 ranging from 9.9 to 10.7, clearly indicating the participation of the upper crust as the source of Pb.

However, the observed isotopic variation suggests at least two sources, one with high μ value (>10.7) and the other with lower value, close to (or lower than) the 9.74 value defined in the Stacey and Kramers' model (Fig. 8b). The differences on the Pb isotopic ratios (and the μ values) could be attributed to local differences in the composition of the source rocks which could be an indication of a common process involved in the formation of both deposits. However, data from the Vazante deposit have a smaller range compared to the Morro Agudo orebodies which suggests a more homogenous Pb source (μ values between 10.1 and 10.4) for the Vazante mineralization. A similar, more homogenous, Pb isotopic behavior was also observed on titanites from mafic dikes (Babinski et al., 2005) cutting the dolostones from the Vazante Group, suggesting that the titanites (derived from hydrothermal alteration of ilmenite) and the sulfide mineralization were formed by the same fluids (Babinski et al., 2005).

Variations on the $^{207}Pb/^{204}Pb$ ratios observed on Population II could also be attributed to some influence of Archean rocks from the basement or from the sedimentary pile via detritus derived from old rocks. Although no Pb isotope data are available for the hosting rocks, which would allow us to verify this hypothesis, Sm–Nd model ages determined on the metasedimentary rocks of the Vazante Group yielded old model ages (Pimentel et al., 2001). Samples from the Serra do Poço Verde and Serra do Garrote formations showed T_{DM} ages between 1.8 and 2.3 Ga, while sediments of the upper Lapa Formation have T_{DM} values between 1.7 and 1.9 Ga. These Sm–Nd T_{DM} model ages indicate that the sedimentary rocks of the Vazante Group hosting the mineralization were formed by a mixture of detritus of Archean and/or Palaeoproterozoic crustal sources with a small contribution of a younger source (Pimentel et al., 2001). This younger source could be rocks from the Neoproterozoic Goiás Magmatic Arc (930–640 Ma), which is located to the west of the Brasília Fold Belt (Pimentel et al., 2001).

As demonstrated by geological and petrographic investigations (Cunha, 1999; Misi et al., 2005), at least part of the N orebody at Morro Agudo deposit is associated with evaporitic facies, suggesting a marine origin for the sulfur. The $\delta^{34}S$ values of sulfates (layered, nodule and pods) are in the range expected for the Neoproterozoic seawater taking in account the evolution curves by Claypool et al. (1980) and Strauss (1997). However, the absence of a clear correlation between $\delta^{34}S$ and $^{206}Pb/^{204}Pb$ observed for some sulfide samples from Morro Agudo and Vazante (Fig. 10) led Cunha (1999) and Misi et al. (2005) to suggest that lead and sulfur are derived from at least two independent sources.

High temperatures obtained for the ore deposition from fluid inclusion and sulfur isotope fractionation of coexisting sulfide pairs suggest that sulfides may have formed by thermochemical reduction of sulfates (Misi et al., 2005). Nevertheless, in the Morro Agudo deposit, the process of ore formation appears to be more complex. The $\delta^{34}S$ values of the sulfides at Morro Agudo vary according to the morphology of the orebody and its proximity to the main fault. The zoned distribution of $\delta^{34}S$ values along the vertical and horizontal directions to the west of the main fault zone suggests the participation of at least two sulfur sources, with distinct $\delta^{34}S$ values. In addition to the seawater sulfate (likely major source), the other could be the circulating metal-bearing mineralizing fluids. According to Misi et al. (2005), "the high positive $\delta^{34}S$ value near the fault zone and the zoned distribution of the isotopic ratios may be explained by the mixing of ^{34}S-enriched marine sulfate with less enriched sulfur of circulating hydrothermal fluids".

In general, the association with carbonate rocks and the epigenetic character of the majority of the deposits led some authors to classify the Pb–Zn deposits of Morro Agudo as Mississippi Valley-type (MVT). Nevertheless, other attributes like fluid inclusions, temperatures + composition and isotope signatures of ore mineral and host rocks must be taken in account when considering the metallogenic evolution. The attribution of a pre-defined classification like MVT or IRISH is not always recommended, principally due to the complexity of processes and products involving a metallogenic system to form a metal concentration. Nevertheless, some parameters, especially the geotectonic regime during mineralization, the kind of fluid circulation forming the deposits, the isotopic signatures and a few others, are characteristics of specific groups of deposits. In this sense, there is a relative small variation of the Pb isotope data compared to those of classical MVT deposits (Doe, 1970). In the MVT model, hydrothermal fluids were able to circulate for long distances through a variety of rocks, giving place to a high degree of heterogeneity in the lead isotope composition of sulfides (Leach and Sangster, 1993).

Although remarking some controversies, Russel (1986) and Banks et al. (2002), based on geological and fluid inclusions evidences, propose for the Irish mineral province that the focused circulation of saline seawater via faults during periods of extension, leached metals from the basement rocks immediately below the sedimentary host rocks or from the sedimentary pile itself. The small variation of the lead isotope ratios for individual deposits in the province, remarked by Hitzman and Beaty (1996), as well as the radiogenic character of the lead isotope ratios obtained by O'Keefe (1986) and Rohl (1996) (referred and complemented by Kinnaird et al., 2002), could probably be explained by using the model of Russel (1986), adopted by Banks et al. (2002).

The data obtained in this study are more compatible with a model involving focused circulation of hydrothermal fluids, with the metal sources coming from local basement rocks. In addition to the fault-controlled mineralization, the fluid inclusion data of primary and pseudo-secondary inclusions in sphalerite crystals from Morro Agudo indicate a zoned distribution of homogenization temperatures (T_H) and salinities in relation to the fault zone, as discussed above. The range of values (T_H above 200 °C and as high as 300 °C, salinities between 3% and 20% wt eq. NaCl) are in agreement with similar figures obtained for the IRISH deposits, as reported by Hitzman and Beaty (1996). Concerning the sulfur isotopic data discussed above, there is also a zoned distribution in relation to the fault zone that supports this model.

Comparing the results with those from some Neoproterozoic sulfide (Rosh Pinah and Kabwe) and non-sulfide (Skorpion) Zn–Pb deposits of African continent, we observe that all the data fall on and above the upper crustal curve of the plumbotectonic model (Zartman and Doe, 1981). In addition, the Pb isotopic data from the African deposits fall close to or in the same field of the studied deposits in Brazil (Fig. 11). Therefore, it is possible that a similar metallogenic process and a common metallogenic event were involved in the formation of these deposits.

In conclusion, the lead isotope data combined with geological and petrographic information, suggest that the zinc–lead deposits of Morro Agudo, Vazante, Fagundes and Ambrósia derived from a common metallogenic event. This event was characterized by a long-term duration of focused circulation of hydrothermal fluids that leached metals mainly from the basement rocks.

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References

Almeida, F.F.M., 1993. Limites do Cráton do São Francisco em Minas Gerais-Síntese dos conhecimentos. II Simpósio do Cráton do São Francisco. Anais, Salvador, Brazil, pp. 256–259.

Amaral, G., 1968. Geologia e depósitos de minério na região de Vazante, Estado de Minas Gerais. Ph.D. thesis, University of São Paulo, Brazil.

Amaral, G., Kawashita, K., 1967. Determinação da idade do Grupo Bambuí pelo método Rb/Sr. XXI Congresso Brasileiro de Geologia, Sociedade Brasileira de Geologia (SBG), Anais, Brazil, pp. 214–217.

Azmy, K., Veizer, J., Misi, A., Oliveira, T.F., Sanches, A.L., Dardenne, M.A., 2001. Dolomitization and isotope stratigraphy of the Vazante Formation, São Francisco Basin, Brazil. Precambrian Research 112, 303–329.

Babinski, M., Monteiro, L.V.S., Fetter, A.H., Bettencourt, J.S., Oliveira, T.F., 2005. Isotope geochemistry of the mafic dikes from the Vazante Nonsulfide Zinc Deposit, Brazil. Journal of South American Earth Sciences 18, 293–304.

Banks, D.A., Boyce, A.J., Samson, I.M., 2002. Constraints on the origin of fluids forming Irish Zn–Pb–Ba deposits: evidences from the composition of fluid inclusions. Economic Geology 97, 471–480.

Campos Neto, M.C., 1984. Litoestratigrafia e evolução palaeogeográfica dos Grupos Canastra e Paranoá (Região Vazante-Lagamar, Minas Gerais). Revista Brasileira de Geociências 14, 81–91.

Cassedanne, J., Lasserre, M., 1969. Análise isotópica pelo método do chumbo em algumas galenas brasileiras: descrição do método utilizado. Mineração e Metalurgia 293, 215–224.

Cassedanne, J.PP., Duthou, J.C., Lasserre, M., 1972. Análise isotópica pelo método de chumbo de uma terceira série de galenas brasileiras. Mineração e Metalurgia 355, 12–19.

Claypool, G.H., Holser, W.T., Kaplan, I.R., Sakai, H., Zak, I., 1980. The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation. Chemical Geology 28, 199–260.

Cloud, P.P.E., Dardenne, M.A., 1973. Proterozoic age of the Bambuí Groupe in Brazil. Geological Society of America Bulletin 84, 1673–1676.

Cumming, G.L., Richards, J.R., 1975. Ore lead isotope ratios in a continuously changing earth. Earth and Planetary Science Letters 28, 155–171.

Cunha, I.A., 1999. Estudos de inclusões fluidas e de isótopos de enxofre dos corpos de minério de Morro Agudo, Minas Gerais. MSc thesis, Federal University of Bahia, Brazil.

Cunha, I.A., Coelho, C.E.S., Misi, A., 2000. Fluid inclusion study of the Morro Agudo Pb–Zn deposits, Minas Gerais, Brazil. Revista Brasileira de Geociências 30, 318–321.

Dardenne, M.A., 1978. Zonação tectônica na borda Ocidental do Cráton do São Francisco. Congresso Brasileiro de Geologia, vol. 30. Sociedade Brasileira de Geologia, Anais, p. 299.

Dardenne, M.A., 1981. Os Grupos Paranoá e Bambuí na Faixa dobrada Brasília. Simpósio sobre o Cráton do São Francisco e suas Faixas Marginais, I, Salvador. COM/SBG, Anais, pp. 140–157.

Dardenne, M.A., 2000. The Brasília Fold Belt. In: Cordani, U.G., Thomaz Filho, A., Campos, D.A. (Eds.), Tectonic Evolution of South America. International Geological Congress, Rio de Janeiro, Brazil, vol. 31, pp. 231–263.

Dardenne, M.A., 2001. Lithostratigraphic sedimentary sequences of the Vazante Group. In: Misi, A. and Teixeira, J.B.G. (Orgs.), International Geological Correlation Programme 450, Proterozoic Base Metal Deposits of Africa and South America—First Field Workshop, Belo Horizonte, Brazil. Extended Abstracts, 48–50.

Dardenne, M.A., Freitas-Silva, F.H., Souza, J.C.F., Campos, J.E.G., 1998. Evolução tectono-sedimentar do Grupo Vazante no contexto da Faixa de Dobramentos Brasília. Congresso Brasileiro de Geologia, Belo Horizonte, Brazil, vol. 40, p. 26.

Doe, B.R., 1970. Lead Isotopes. Springer-Verlag, New York.

Folk, R.L., Pittman, J.S., 1971. Length-slow chalcedony: a new testament for vanished evaporites. Journal of Sedimentary Petrology 41, 1045–1058.

Freitas-Silva, F.H., Dardenne, M.A., 1997. Pb/Pb isotopic patterns of galenas from the Morro do Ouro (Paracatu Formation), Morro Agudo/Vazante (Vazante Formation) and Bambuí Group deposits. I South American Symposium on Isotope Geology, Campos do Jordão, Brazil, pp. 118–120.

Fuck, R.A., 1994. A Faixa Brasília e a compartimentação tectônica na Província Tocantins. IV Simpósio de Geologia do Centro-Oeste, Brasília, Brazil, pp. 184–187.

Goodfellow, W.D., Lydon, J.W., Turner, M.J.W., 1993. Geology and genesis of stratiform sediment-hosted (SEDEX) zinc–lead–silver sulfide deposits. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.J., Duke, J.J. (Eds.), Mineral Deposit Modelling. Special Paper, Geological Association of Canada, vol. 40, pp. 201–251.

Hitzman, M.W., 1995. Mineralization in the Irish carbonate-hosted Zn–Pb (Ba–Ag) orefield. In: Thompson, T.B. (Ed.), Irish Carbonate-Hosted Zn–Pb Deposits. Guidebook series, vol. 21. Society of Economic Geology (SEM).

Hitzman, M.W., 1997a. Sediment Hosted Zn–Pb and Au Deposits in the Proterozoic Paracatu Vazante Fold Belt, Minas Gerais, Brazil. Geological Society of America, Programs with Abstracts 27, A408.

Hitzman, M.W., 1997b. Observations from the Vazante Zinc Mine, Minas Gerais, Brazil. Report to Companhia Mineira de Metais.

Hitzman, M.W., 2003. Classification, genesis, and exploration guides for nonsulfide zinc deposits. Economic Geology 98, 685–714.

Hitzman, M.W., Beaty, D.W., 1996. The Irish Zn–Pb–(Ba) orefield. In: Sangster, D.F. (Ed.), Carbonate-Hosted Lead–Zinc Deposits. Society of Economic Geologists, Special Publication, vol. 4, pp. 112–143.

Iyer, S.S., 1984. A discussion on the lead isotope geochemistry of galenas from the Bambuí Group, Minas Gerais, Brazil. Mineralium Deposita 19, 132–137.

Iyer, S.S., Hoefs, J., Krouse, H.R., 1992. Sulfur and lead isotope geochemistry of galenas from the Bambuí Group, Minas Gerais, Brazil: implications for ore genesis. Economic Geology 87, 437–443.

Kinnaird, J.A., Ixer, R.A., Barreiro, B., Nex, A.M., 2002. Contrasting sources for lead in Cu-polymetallic and ZnPb mineralization in Ireland: constraints from lead isotopes. Mineralium Deposita 37, 495–511.

Kyle, J.R., Misi, A., 1997. Origin of Zn–Pb–Ag sulfide mineralization within Upper Proterozoic phosphate-rich carbonate strata, Irecê Basin, Bahia, Brazil. International Geology Review 39, 383–399.

Leach, D.L., Sangster, D.F., 1993. Mississippi Valley-type lead–zinc deposits. In: Kirkhan, R.V, Sinclair, W.D., Thorpe, R.I., Duke, J.M. (Eds.), Mineral Deposit Modeling. Geological Association of Canada, Special Papers, vol. 40, pp. 289–314.

Marini, O.J., Fuck, R.A., Danni, J.C., Dardenne, M.A., 1981. A evolução geotectônica da Faixa de Brasília e de seu embasamento. In: COM/SBG. I Simpósio sobre o Cráton do São Francisco e suas Faixas Marginais, Salvador, Brazil, pp. 100–115.

Marini, O.J., Fuck, R.A., Danni, J.C., Dardenne, M.A., Loguercio, S.O.C., Ramalho, R., 1984. As faixas de dobramentos Brasília, Uruaçu e Paraguai-Araguaia e o Maciço Mediano de Goiás. In: Schobbenhaus, C., Campos, D.A., Derze, G.R., Asmus, H.E. (Eds.), Geologia do Brasil. Texto Explicativo do Mapa Geológico do Brasil e da Área Oceânica Adjacente Incluindo Depósitos Minerais. Ministério da Minas e Energia Departamento Nacional da Produção Mineral, Brasília, Brazil, pp. 251–303.

Misi, A., 2001. Estratigrafia isotópica das seqüências do Supergrupo São Francisco, coberturas neoproterozóicas do Cráton do São Francisco. Idade e correlações. In: Pinto, C.P., Martins-Neto, M.A. (Eds.), Bacia do São Francisco. Geologia e Recursos Naturais. Sociedade Brasileira de Geologia, Belo Horizonte, Brazil, pp. 67–92.

Misi, A., Iyer, S.S., Tassinari, C.C.G., 1996. Boquira (2.5 Ga) and Morro Agudo (0,65 Ga) Lead–Zinc Deposits, Brazil: New SEDEX Subtypes? XXXIX Congresso Brasileiro de Geologia, Salvador, Brazil, Extended Abstracts, pp. 251–253.

Misi, A., Veizer, J., Kawashita, K., Dardenne, M.A., 1997. The age of Neoproterozoic carbonate platform sedimentation based on $^{87}Sr/^{86}Sr$ determinations, Bambuí and Uma Groups, Brazil. I South American Symposium on Isotope Geology, Campos do Jordão, São Paulo, Brazil, Extended Abstracts, pp. 199–200.

Misi, A., Iyer, S.S., Tassinari, C.C.G., Kyle, J.R., Coelho, C.E.S., Franca Rocha, W.J.S.F., Gomes, A.S.R., Cunha, I.A., Carvalho, I.G., 1999. Geological and isotopic constrains on the metallogenic evolution of the Proterozoic sediment-hosted Pb–Zn (Ag) deposits of Brazil. Gondwana Research 2, 47–65.

Misi, A., Iyer, S.S.S., Kyle, J.R., Coelho, C.E.S., Tassinari, C.G.G., Franca-Rocha, W.J.S., Gomes, A.S.R., Cunha, I.A., Toulkeridis, T., Sanches, A.L., 2000. A metallogenic evolution model for the lead–zinc deposits of the Meso and Neoproterozoic sedimentary basins of the São Francisco Craton, Bahia and Minas Gerais, Brazil. Revista Brasileira de Geociências 30, 302–305.

Misi, A., Iyer, S.S., Tassinari, C.G.C., Franca-Rocha, W.J.S., Coelho, C.E.S., Cunha, I.A., Gomes, A.S.R., 2004. Dados isotópicos de chumbo em sulfetos e a evolução metalogenética dos depósitos de zinco e chumbo das coberturas neoproterozóicas do Cráton do São Francisco. Revista Brasileira de Geociências 34, 263–274.

Misi, A., Iyer, S.S.S., Coelho, C.E.S., Tassinari, C.C.G., Fanca-Rocha, W.J.S., Cunha, I.A., Gomes, A.S.R., Oliveira, T.F., Teixeira, J.B.G., 2005. Sediment-hosted lead–zinc deposits of the Neoproterozoic Bambuí Group and Correlative Sequences, São Francisco Craton, Brazil: a review and a possible metallogenic evolution model. Ore Geology Reviews 26, 263–304.

Moeri, E., 1972. On a columnar stromatolite in the Precambrian Bambuí Group of central Brazil. Eclogae Geologicae Helvetiae 65, 185–195.

Monteiro, L.V.S., 2002. Modelamento Metalogenético dos depósitos de Zn de Vazante, Fagundes e Ambrósia, associados ao Grupo Vazante, Minas Gerais. Ph.D. thesis, Universidade de São Paulo, Brazil.

Monteiro, L.V.S., Bettencourt, J.S., Spiro, B., Graça, R., Oliveira, T.F., 1999. The Vazante Zinc Mine, Minas Gerais, Brazil: constraints on fluid evolution and willemític mineralization. Exploration and Mining Geology 8, 21–42.

O'Keefe, W.G., 1986. Age and postulated source rocks for mineralization in central Ireland, as indicated by lead isotopes. In: Andrew, C.J., Crowe, R.W.E., Finlay, S., Pyne, J.F. (Eds.), Geology and Genesis of Mineral Deposits in Ireland. Irish Association of Economic Geology, Dublin, pp. 617–624.

Parenti Couto, J.G., Cordani, U.G., Kawashita, K., Iyer, S.S., Moraes, N.M.P.P., 1981. Considerações sobre a idade do Grupo Bambuí com base em análises isotópicas de Sr e Pb. Revista Brasileira de Geociências 1, 5–16.

Pimentel, M.M., Dardenne, M.A., Viana, M.G., Costa Lima Goia, S.M.C.L., Jungle, S., Seer, H.J., 2001. Nd Isotopes and the provenance of the sediments of the Neoproterozoic Brasília Belt, central Brazil. Journal of South American Earth Sciences 14, 571–585.

Rigobello, A.E., Branquinho, J.A., Dantas, M.G.S., Oliveira, T.F., Neves Filho, W., 1988. Mina de zinco de Vazante. In: Schobbenhaus, C., Coelho, C.E.S. (Eds.), Principais Depósitos Minerais do Brasil, vol. 3. Departamento Nacional da Produção Mineral, pp. 101–110.

Rohl, B.M., 1996. Lead isotope data from the Isotrace Laboratory, Oxford: archeometry database 2, Galena from Britain and Ireland. Archeometry 38, 165–180.

Romagna, G., Costa, R.R., 1988. Jazida de zinco e chumbo de Morro Agudo, Paracatu, Minas Gerais. In: Schobbenhaus, C., Coelho, C.E. (Eds.), Departamento Nacional da Produção Mineral/Companhia Vale do Rio Doce, Principais Depósitos Minerais do Brasil, vol. 3, pp. 111–121.

Russel, M.J., 1986. Extension and convection: a genetic model for the Irish Carboniferous base metal and barite deposits. In: Andrew, C.J., Crowe, R.W.A., Finlay, S., Pennel, W.M., Pyne, J.F. (Eds.), Geology and Genesis of Mineral Deposits in Ireland. Irish Association of Economic Geologists, Dublin, pp. 545–554.

Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters 26, 207–221.

Strauss, H., 1997. The isotope composition of sedimentary sulfur through time. Palaeogeography, Palaeoclimatology, Palaeoecology 132, 97–118.

Valeriano, C.M., Dardenne, M.A., Fonseca, M.A., Simões, L.S.A., Seer, H.J., 2004. A evolução geotectônica da Faixa Brasília. In: Mantesso-Neto, V., Bartorelli, A., Carneiro, C.D., Brito-Neves, B.B. (Eds.), Geologia do Continente Sul-Americano. Evolução da Obra de Fernando Flávio Marques de Almeida. Beca Produções Culturais Ltda, São Paulo, Brazil, pp. 575–592.

Zartman, R.E., Doe, B.R., 1981. Plumbotectonics the model. Tectonophysics 75, 135–162.