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

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ABSTRACT Integrated studies carried out on the Proterozoic sediment-hosted Pb-Zn sulfide deposits of the São Francisco Craton, Brazil, allowed the estimation of (1) ages of the host sequences, (2) timing of mineralization, (3) possible sources of metal and sulfur, (4) temperature and salinity range of mineralizing solutions, (5) sources of fluids and (6) possible mechanisms of fluid flow. Contrary to the deposits from other Proterozoic basins, the Brazilian deposits do not contain world class metal reserves. This can probably be attributed to the lack of sufficient investments in exploration and mining development research activities. However, the sulfide deposits of the São Francisco Craton do share several important geological, structural, isotopic and fluid characteristics with some of the giant deposit types. Using these data we develop a more realistic metallogenic model for the Proterozoic sediment-hosted Pb-Zn sulfide deposits.

Keywords: metallogeny, lead-zinc, Proterozoic, Brazil

GEOTECTONIC SETTING

The lead zinc silver-rich deposits and their host Proterozoic sedimentary basins in the São Francisco Craton are distributed over more than 300.000 km^2 (Fig. 1). The majority of known deposits are hosted by Neoproterozoic dolomitic units of the Bambui Group and equivalents, with the exception of one small deposit (Caboclo) which is hosted by dolomitic lenses in the dominantly siliciclastic Caboclo Formation (1.2 Ga) of the Chapada Diamantina Group (Espinhaço Supergroup). Only two of the deposits studied are being mined: *Vazante*, 8 Mt (23% Zn) and *Morro Agudo*, 12 Mt (6,4% Zn, 2,2% Pb), respectively producing 650.000 t/year (ROM) with 13,5% Zn and 580.000 t/year (ROM) with 5% Zn and 2% Pb. They are hosted by dolostones of the Neoproterozoic Vazante Group, a folded counterpart of the Bambuí Group in the western border of the cratonic area.

The Mesoproterozoic basins of the Espinhaço Supergroup originated from a rifting structure, the Espinhaço Aulacogen, aligned NNW-SSE. The important geotectonic event is well defined by the typically anorogenic magmatism that occurs at the base of the Espinhaço Supergroup with age values of 1.76 to 1.8 Ga. The present configuration of the São Francisco Craton has been molded during the Brasiliano/Pan-African tectonic cycle (1.0 to 0.5 Ga). The fragmentation of the Rodinia supercontinent during this tectonic cycle and the subsequent inversion generated the Neoproterozoic extensional basins of São Francisco, Una and Una-Utinga, and the fold belts around the cratonic areas. It appears that the old extensional structures were active, even during this important compressional phase.

COMMON ATRIBUTES

The major characteristics of all the deposits studied are: **(1)** Host rocks are shallow water marine carbonates, mainly of dolomitic type, associated with organic-rich facies: stromatolitic structures, black micritic and oolithic carbonates, and black schists and marls, with disseminated pyrite. **(2)** For the Neoproterozoic deposits the presence of nodules of length-slow microquartz, gypsum, sulfides pseudomorphs of sulfates, teepee structures and dissolution breccias indicate their intimate association with evaporitic facies. The evaporite and dolomitic facies correspond to an end member of a regressive megacycle. These mineralized facies are superposed by organic-rich pelites, representing a rising sea level (Fig. 2). **(3)** The majority of the deposits studied show a very clear structural control with (a) normal faults aligned N30-40E for Caboclo (b) fractures and faults oriented N40 to N50W for Una-Utinga basins (c) normal faults (N15-50E) for the Vazante and Morro Agudo (d) At Irecê, intense folding masks any pronounced fault association. Figure 3 shows that some of these structures, apparently associated with the mineralization, crosscut the sedimentary basin and its basement, implying that they were active at least until the end of the basin filling. **(4)** With the exception of the Vazante mine, where primary mineralization is essentially silicatic (willemite), in all other deposits sulfides (pyrite, galena and sphalerite) represent the main mineral association, with (i) dominant sphalerite in Morro Agudo and Irecê (ii) dominant galena in Caboclo, Nova Redenção, Montalvânia, and Januária/Itacarambi. Silver is present in all deposits. **(5)** The most common gangue minerals are calcite, dolomite, quartz (mega and microquartz) and barite (absent in Caboclo). In Caboclo, there is also an important hydrothermal alteration zone surrounding the sulfide mineralization, with microcline, biotite, quartz and tourmaline. **(6)** In all deposits, mineralization is stratiform and sub-stratiform, along with irregular patches and veins of massive sulfides. In Morro Agudo, four main types of ore bodies have been described by Romagna & Costa (1988): N (stratiform), M (veins ?), JKL (massive, replacing oolitic dolostone) and GHI (massive, replacing brecciated dolostone).

Fluid inclusions studies

Homogenization temperatures (T_H) and salinities obtained from primary fluid inclusions in sphalerite crystals from Morro Agudo, Vazante, Nova Redenção and Irecê indicate many similarities. In Morro Agudo, T_H and salinity varied according to the type of ore body and its location relative to the fault zone. There is a clear correlation between T_H and salinity distribution, and highest values being found close to the fault zone. For all the ore bodies, T_H ranges from 80 to 300°C (modal value of 160°C; n = 347) and salinity between 14% and 22% NaCl equiv. In Vazante, Dardenne and Freitas-Silva 1999 obtained from willemite crystals T_H values ranging from 159°C to 170°C and salinities from 3 to 15% wt Eq. Na Cl. In Nova Redenção, T_H values range from 80°C to 210°C, mode of 185°C (n = 165) and salinity ranges from 10% to 25% wt. Eq. NaCl. A limited number of analyses of sphalerites from Irecê mineralization indicated T_H ranging from 140 to 200°C and salinity from 3% to 10%wt Eq. NaCl (Kyle & Misi, 1997). A comparison of these data with those obtained for MVT, SEDEX and IRISH deposits (Fig. 4) suggests that Brazilian deposits are of the carbonate hosted and fault controlled type.

Isotopic data

Lead isotope data obtained by the present authors (Iyer *et al*., 1992; Misi, 1999) and others (Amaral, 1968; Cassedanne & Lassere, 1969) indicate the derivation of metals from upper crustal sources (Fig. 5). Despite an overall heterogenous distribution for different deposits, a near homogeneous distribution has been observed for some individual deposits. The deposits of Caboclo (Mesoproterozoic), Irecê and Nova Redenção, as well as the lead-zinc mineralizations of the São Francisco Basin (Neoproterozoic), show moderate to high radiogenic Pb isotope values, while the Pb isotope

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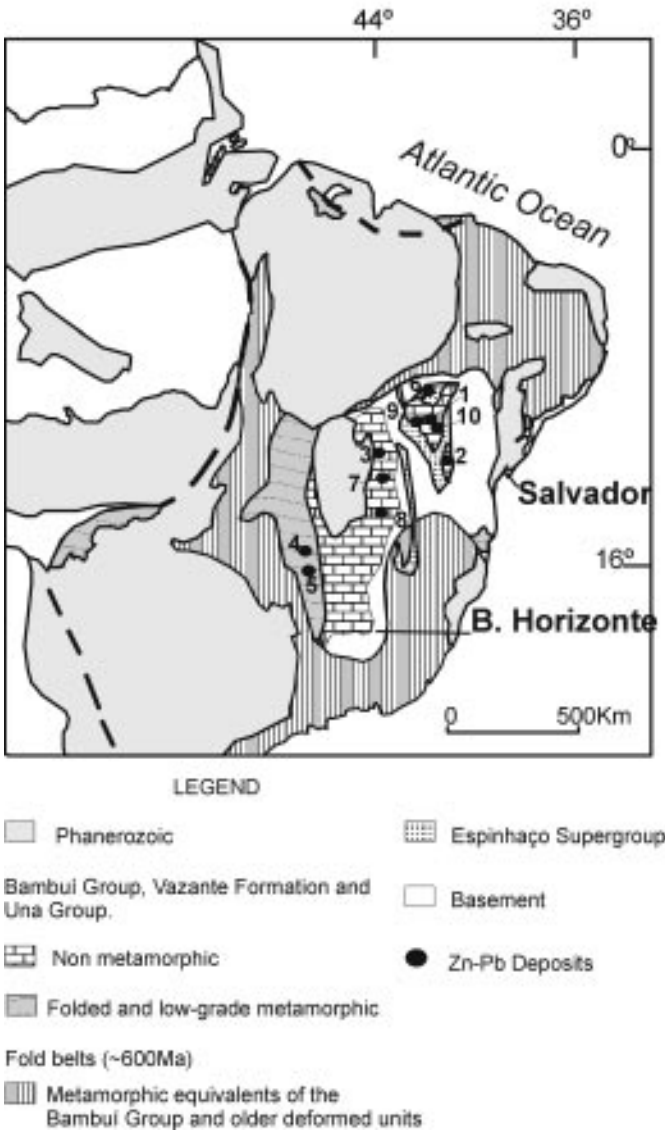

*Figure 1 – Geotectonic setting and location of the main zinc-lead deposits of the Proterozoic sedimentary cover of the São Francisco Craton. **1** – Vazante **2** – Morro Agudo **3** – Januária/Itacarambí **4** – Montalvânia **5** – Serra do Ramalho **6** – Nova Redenção **7** – Irecê **8** – Morro do Gomes **9** – Melancias **10** – Caboclo (Mesoproterozoic).*

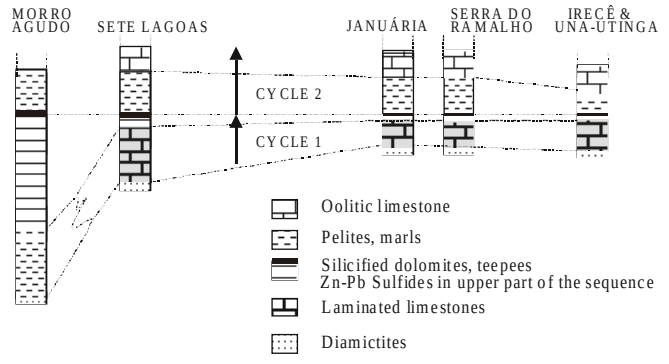

Figure 2 – Lithostratigraphic and chemostratigraphic correlations between the Neoproterozic sequences of the São Francisco Craton and the location of the Zn-Pb deposits at the end of a regressive megacycle.

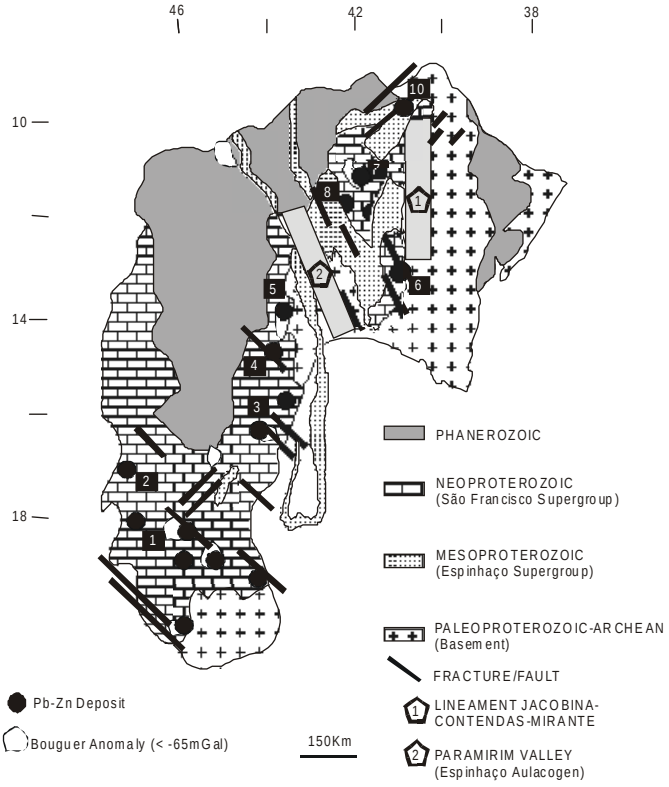

Figure 3 – Distribution of Zn-Pb deposits in the São Francisco Craton and its association with fractures/faults and with oval shaped negative Bouguer anomalies. See Fig. 1 for the names of the main deposits.

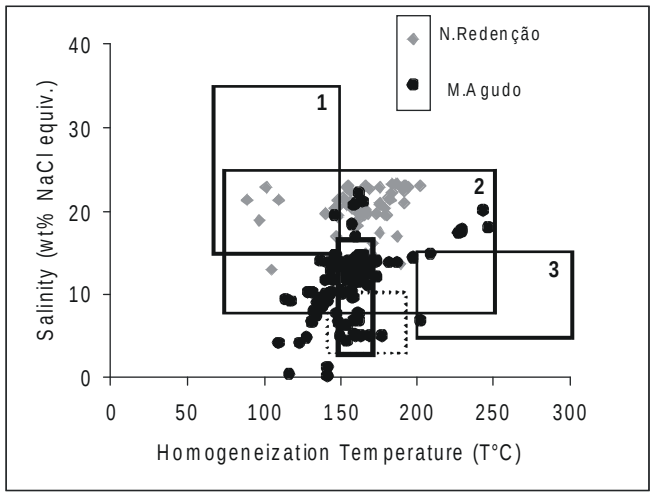

*Figure 4 – Homogeneization temperatures (T_H) and salinities from primary and pseudosecondary fluid inclusions in sphalerite from some Neoproterozoic Zn-Pb deposits of the São Francisco Craton and comparison with classical sedimentogenic types. **1** - Mississipi Valley Type (MVT) **2** – Irish **3** – SEDEX. Area within dotted lines: data of primary fluid inclusions from Irecê sphalerite. Area within dark lines: fluid inclusions in willemite from Vazante (Dardenne and Freitas Silva, 1999).*

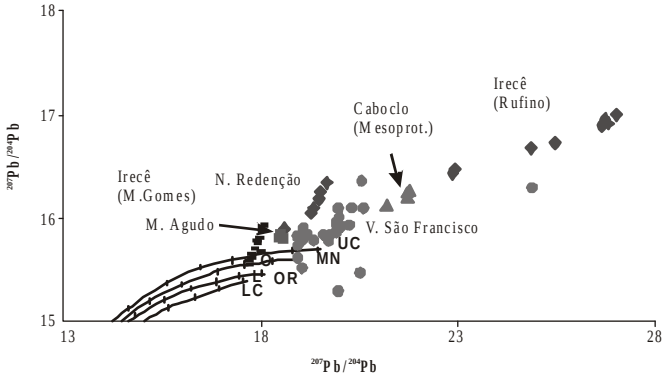

Figure 5 – Lead isotope composition of sulfides from the deposits studied. Evolution curve according to the plumbotectonic model of Zartman and Doe (1981). ***UC*** *– Upper Crust* ***MN*** *– Mantle* ***OR*** *– Orogen* ***LC*** *– Lower Crust.*

data for the deposits of Vazante and Morro Agudo are less radiogenic. The mean values obtained for $^{206}Pb/^{204}Pb$ ratios in these deposits are shown in table 1.

Sulfur isotopic values were determined by the present authors for stratiform + nodular sulfates (barite and gypsum) and sulfides (mainly sphalerite, galena and pyrite) from the deposits of Irecê, Nova Redenção, Vazante and Morro Agudo and on galena crystals from the Caboclo deposit (Mesoproterozoic). The overlapping of $\delta^{34}S$ values for sulfates of the Neoproterozoic deposits with the data of coeval seawater sulfate (Claypool *et al.*, 1980) indicate the derivation of the sulfur from seawater (Tab. 2).

The majority of the inclusion data and isotopic studies are from the MSc dissertations of W. Franca-Rocha, A. S. R. Gomes, A. L. Sanches, I. A. Cunha and other members of our research group. The database used here is available in Misi (1999) and is expected to be available soon in the following site: "http://www.cpgg.ufba.br/metalogenese/".

DISCUSSION AND CONCLUSION For the Neoproterozoic deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur from a dominant seawater source. There is no clear evidence for a seawater sulfur source for the Mesoproterozoic deposit of Caboclo. Lack of correlation between the $\delta^{34}S$ and $^{206}Pb/^{204}Pb$ for samples from the Neoproterozoic deposits indicates the derivation of sulfur and metals from different sources. Temperatures above 120°C, obtained from fluid inclusion study of sphalerite crystals in the deposits investigated, indicate thermochemical reduction of sulfates to be the dominant mechanism in the formation of the sulfides. However, in the Morro Agudo deposit, the sulfides may have formed by a more complex process: We observed a zoning pattern in sulfur isotopic data, with respect to the fault zone, whereby the heaviest $\delta^{34}S$ values (mean of +34 ‰ CDT in the M ore body) are closer to the fault zone. The values drop to -3.7‰ CDT in the N ore body, 120m away from the fault in the same stratigraphic zone. Two different sulfur sources, one of them probably related to the addition of isotopically heavy sulfur from the hydrothermal fluid circulating in the fault zone, may be invoked to explain the zoning.

The Vazante deposit is mainly formed by willemite (zinc silicate) with minor amounts of sphalerite and galena. The near absence of sulfide minerals is attributed to a high oxygen fugacity during the mineralization event (Monteiro, 1998), a suggestion supported by the presence of abundant hematite and silica associated with the mineralization. In Vazante, sphalerite and galena yield relatively heavy $\delta^{34}S$ values, although much lower than the data from the Morro Agudo deposit.

The textures and features displayed by the deposits indicate a dominant process of replacement of the carbonate host rocks during the mineralization. Some features of the mineralization at Morro Agudo, Vazante, Nova Redenção and Irecê indicate a syngenetic or syndiagenetic mineralization, e.g. the presence of millimetric beds of ultra fine sphalerite in the N orebody at Morro Agudo, and the plastic deformation of the host carbonate by syn-sedimentary faults and by the growing of sulfide nodules in the other deposits.

Table 1 - Pb isotopic data of Pb-Zn deposits of São Francisco Craton

DEPOSIT	$^{206}Pb/^{204}Pb$
Morro Agudo	17,8 ± 0,08
Vazante	17,7 ± 0,09
Vale do São Francisco	21,2 ± 4,18
Nova Redenção	19,4 ± 0,32
Irecê	25,4 ± 1,50
Caboclo (Mesoproterozoic)	21,6 ± 0,26

Table 2 - Sulfur Isotope data of sulfates and sulfides from Pb-Zn deposits of the São Francisco Craton

	SULFATES (‰ CDT)	SULFIDES (‰ CDT)	$\delta^{34}S_{sulfate-sulfide}$
Irecê	+29 (n = 13)	+23 (n = 18)	6
Nova Redenção	+37,5 (n = 4)	+14,5 (n = 18)	23
Morro Agudo/ Vazante	+24,6 (n = 19)	*Orebody N* -3,7 (n = 13)	28,3
		Orebody M +34 (n = 3)	-
		Orebody JKL +21,7 (n = 19)	2,9
		Orebody GHI +29 (n = 6)	-
		Vazante +15,2 (n = 5)	9,4
Caboclo	-	-3,2 (n = 8)	-

The strong influence of underlying basement rocks in the supply of metals to the deposits is suggested by Pb isotope data (Table 1) and this aspect is discussed by Iyer et al. (2000). Approximate ages of the source rocks calculated from the Pb-Pb secondary isochrons obtained from galena of the Caboclo deposit and from sulfides of the Irecê mineralization (Figure 5) are respectively 2.2 and 1.7 Ga. These ages correspond to two important events (see Figure 3) that formed U-Th-K rich granites: a) The peraluminous leucogranites at 2-2.2 Ga in the *Jacobina-Contendas Lineament*, with U = 4-40 ppm and Th = 6-32 ppm (Sabaté *et al.*, 1990) and the alkaline to sub-alkaline magmatism, at ~1.7 Ga, with U = 4-20 ppm and Th = 15-76 ppm (Maruéjol *et al.*, 1987). On a Bouguer gravity map of the São Francisco Craton (Ussami, 1993), the deposits of Irecê, Nova Redenção, Serra do Ramalho, Itacarambi and some other Pb-Zn occurrences of the São Francisco Basin appear to be associated with circular to oval-shaped negative anomalies with amplitude below – 65 mGal (Figure 3), suggesting that these deposits are genetically linked with the underlying rock bodies causing the anomalies. This kind of anomalies are normally associated with uranium-rich granites (Sangster et al, 1998) and thermal perturbation (Fehn *et al.*, 1978). The high temperature values obtained from fluid inclusions of sphalerites in the deposits of Nova Redenção and Irecê (up to 250°) and an unusually high paleo-geothermal gradient calculated for the upper and middle crust of the São Francisco Craton (Iyer *et al.*, in prep.) suggest the participation of a high temperature source in the formation of the deposits. The high geothermal gradient could have generated a convective system inducing the circulation of the mineralizing hydrothermal fluids for the Meso and Neoproterozoic mineralizations. In addition to the high permeability of the basement rocks and the low thermal conductivity of the sediments, the presence of pelitic cap rocks of low permeability helped reducing cooling of the system by rapid ingress of meteoric water, a condition considered essential by Sangster *et al.*, 1998. This condition is satisfied by the deposits studied, which are capped by pelitic sediments. Figure 6 illustrates the proposed model discussed above.

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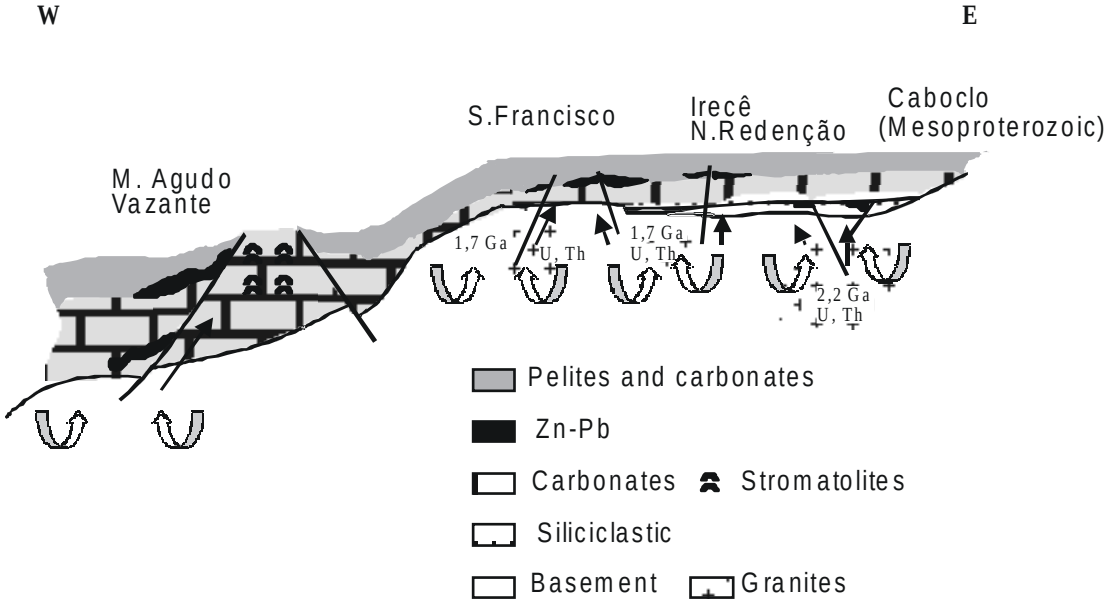

Figure 6 – A possible evolution model (simplified) for the Proterozoic sediment-hosted Zn-Pb deposits of the São Francisco Craton.

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