A METALLOGENIC EVOLUTION MODEL FOR THE LEAD-ZINC DEPOSITS OF THE MESO AND NEO PROTEROZOIC SEDIMENTARY BASINS OF THE SÃO FRANCISCO CRATON, BAHIA AND MINAS GERAIS, BRAZIL

AROLDO MISI 1, SUNDARAM S. IYER 2, CARLOS E. SILVA COELHO 3, COLOMBO C.G. TASSINARI 3, WASHINGTON J. S. FRANCA-ROCHA 4, 5, ADRIANA S. ROCHA GOMES 3, 4, IONÁ ABREU CUNHA 4, 5, TEOPHILOUS TOULKERIDIS 6 AND ANDREIA LIMA SANCHES 7

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 investigations in exploration and mining development research activities. However, the sulfide deposits of the São Francisco Craton do share several important geological, structural 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 km2 (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 Caboçao 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 Bambui 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 anogenic 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 ATTRIBUTES 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, teeppee structures and dissolution breccias indicate their intimate association with evaporitic facies. The evaporite and dolomitic facies correspond with those obtained for MVT, SEDEX and IRISH deposits (Fig. 4) indicating that Brazilian deposits are of the carbonate hosted and fault controlled type.

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. NaCl. 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; Cassidy & Lassere, 1969) indicate the derivation of metals from upper crustal sources (Fig. 5). Despite an overall heterogeneous 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
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/Tucarambi 4 – Montalvânia 5 – Serra do Ramalho 6 – Nova Redenção 7 – Irecê 8 – Morro do Gomes 9 – Melancias 10 – Cuboclo (Mesoproterozoic).

Figure 2 – Lithostratigraphic and chemostratigraphic correlations between the Neoproterozoic 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 – Homogenization 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 - Mississippi 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 (Durdenne and Freitas Silva, 1999).
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 δ^{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 Missi (1999) and is expected to be available soon in the following site: http://www.cppg.uba.br/metallogenese/.

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 mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits the sulfur isotopic data and the association of part of the mineralization with evaporitic features suggest the derivation of sulfur deposits.

The mean values obtained for ^{206}Pb/^{204}Pb ratios in these deposits are shown in Table 1.

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

<table>
<thead>
<tr>
<th>DEPOSIT</th>
<th>^{206}Pb/^{204}Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morro Agudo</td>
<td>17.8 ± 0.08</td>
</tr>
<tr>
<td>Vazante</td>
<td>17.7 ± 0.09</td>
</tr>
<tr>
<td>Vale do São Francisco</td>
<td>21.2 ± 4.18</td>
</tr>
<tr>
<td>Nova Redenção</td>
<td>19.4 ± 0.32</td>
</tr>
<tr>
<td>Irecê</td>
<td>25.4 ± 1.50</td>
</tr>
<tr>
<td>Cabo­clo (Mesoproterozoic)</td>
<td>21.6 ± 0.26</td>
</tr>
</tbody>
</table>

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°C) 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 Mesos and Neoproterozoic mineralizations.

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

<table>
<thead>
<tr>
<th></th>
<th>SULFATES (‰ CDT)</th>
<th>SULFIDES (‰ CDT)</th>
<th>δ^{34}S sulfate-sulfide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irecê</td>
<td>+24,6 (n = 19)</td>
<td>+29 (n = 13)</td>
<td>-3.7 (n = 13)</td>
</tr>
<tr>
<td>Vazante</td>
<td>+23 (n = 18)</td>
<td>-3.7 (n = 13)</td>
<td>-</td>
</tr>
<tr>
<td>Nova Redenção</td>
<td>+21,7 (n = 19)</td>
<td>+21,7 (n = 19)</td>
<td>+29 (n = 6)</td>
</tr>
<tr>
<td>Morro Agudo</td>
<td>+29 (n = 13)</td>
<td>+29 (n = 13)</td>
<td>+29 (n = 6)</td>
</tr>
<tr>
<td></td>
<td>+23 (n = 18)</td>
<td>+23 (n = 18)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>+15,2 (n = 5)</td>
<td>+15,2 (n = 5)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>-3,2 (n = 8)</td>
<td>-3,2 (n = 8)</td>
<td>-</td>
</tr>
</tbody>
</table>

The isotopic data are also consistent with an origin related to subduction processes in the Late Neoproterozoic (1.7 Ga) as suggested by the characteristics of the U-Th-K rich granites (Sangster et al., 1998) and by the high geothermal gradient calculated for the upper and middle crust of the São Francisco Craton. 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°C) 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 Mesos and Neoproterozoic mineralizations.

**Acknowledgements** This study is part of our contribution to the IGCP Project 450 “Proterozoic sediment-hosted base metal deposits of Western Gondwana”. We are grateful to John Ross for his valuable comments. This research is supported by FINEP/PADCT and CNPq grants to A.M. It is also partially supported by CBPM, CMM, SGM and CPRM.
Figure 6 – A possible evolution model (simplified) for the Proterozoic sediment-hosted Zn-Pb deposits of the São Francisco Craton.

References


