# TECTONIC SETTING AND PRELIMINARY AGE OF HYDROTHERMAL SYSTEMS IN LOW GRADE METASEDIMENTARY SEQUENCES, SIERRA NORTE DE CÓRDOBA, ARGENTINA

**Millone, H.A[1]; O'Leary, M.S.[2]; Tassinari, C.C.G.[3] and Lira, R.[2]**

1. Gerencia de Minería de Córdoba, Celso Barrios 1712, 5016 Córdoba, Argentina. hmillone@hotmail.com
2. CONICET, Museo de Mineralogía y Geología Dr. A. Stelzner, V. Sarsfield 299, 5000 Córdoba, Argentina. soleary@com.uncor.edu, rlira@com.uncor.edu
3. Centro de Pesquisas Geocronológicas, Instituto de Geociências, Universidade de São Paulo, Brazil. ccgtassi@usp.br

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## INTRODUCTION

Alteration-mineralization systems hosted in low grade metasedimentary sequences in the Sierra Norte ranges, Córdoba, Argentina, were identified by Lira et al. (1995). Field and geochemical studies were performed during mining exploration tasks (Lira et al., 1997a) and subsequent work was oriented toward the investigation of genetic conditions of ore-bearing paragenesis ( O'Leary et al, 2001; Millone et al, 2002).

This contribution deals with the Pb-isotopic composition of galenas associated with other sulfides in quartz-veins. Isotopic data were treated according to Zartman & Doe (1981) and Stacey & Kramers (1975) models with the aim of establishing lead sources and the age of mineralization, respectively.

## REGIONAL GEOLOGY

The study area is located in the central-western portion of the Sierra Norte-Ambargasta batholith (SNAB), which is mainly composed of magmatic arc I-type calcalkaline granitoids of Neoproterozoic to Eopaleozoic ages, intruded in low grade metasedimentary sequences of probable Neoproterozic to Early Cambrian age. Dominant magmatic rocks are granodiorites and monzogranites which were intruded by a subvolcanic pluton of dacitic-rhyolitic composition. The whole sequence was afterwards intruded by small highly evolved subalkaline monzogranites and frequent rhyolite dikes. Latest intrusions correspond to thick syenogranitic aplites (Lira et al., 1997b). Neoproterozoic to Lower Cambrian ages have been registered for different plutonic and subvolcanic representative units (Rapela et al., 1998; Söllner et al., 2000; Millone et al., 2003).

Enclosing metasedimentary rocks occur as kilometer-sized roof-pendants that are well exposed in the western ranges of Sierra Norte. Main outcrops are known as Rodeíto, La Cañada-Nispo, El Tío-La Graciela, Agua del Río, La Salamanca (west of San Francisco del Chañar), San Jerónimo, and a few smaller ones. Some of them (for instance, Rodeíto, Agua del Río) are associated to structures of meridian strike.

## LOCAL GEOLOGY

Galena-bearing assemblages are present in a ~6 km $^2$ north-south elongated low grade metasedimentary roof-pendant that outcrops in the vicinities of Rodeíto locality (29°45'35" – 29°47'29S; 64°07'27" – 64°08'59"W). This outcrop is composed of phyllites (N40°E, near vertical dip) interbedded with metagreywackes (quartzites). Several rhyolite dikes (N-S to NE-SO) were intruded into the metasedimentary sequence roughly along regional schistosity. Both metamorphic rocks and dikes host a remarkably well-developed network system of ore-bearing quartz-rich veinlets.

## METASEDIMENTARY HOST ROCKS

The mineralized network was preferentially hosted by the multiple fractured metapsammitic facies. Veins and veinlets are 1 to 12 mm thick, though some can be as thick as 5 cm; drusy quartz growth and limonite boxworks are present. Some veins show thin selvages composed of fine grained aggregates of biotite and sericite.

The most representative mineral assemblages present in network veins are (after abbreviations of Kretz, 1983): Qtz-Chl, Qtz-Ep-Chl ± Bt ± Musc, Qtz-Cal-Chl ± Ms ± Ep, and Qtz-Kfs-Chl-Ep ± Plag. Two main quartz-textures were recognized: a) Fine-grained anhedral mosaic (5-20 μm); b) Comb texture (100 μm to 2 mm), prismatic crystals subparallel to vein walls, occasionally alternating with sericitized K-feldspar intergrown with plagioclase. Ore-bearing vein assemblages include: a) Galena, chalcopyrite, pyrite and minor bornite, partially transformed into malachite, goethite and hematite; b) Chalcopyrite and pyrite, with secondary assemblages of covellite, digenite, malachite, goethite and hematite; c) Sphalerite and galena partially altered to goethite and hematite; d) Sphalerite, chalcopyrite, galena and minor pyrite, with secondary association of covellite, digenite, malachite, goethite and hematite. Grain size of sulfides range from 0.1 to 5 mm, though sometimes cm-sized grains are present. Observed textures are intergrowths of chalcopyrite with bornite, chalcopyrite exsolutions in sphalerite and concentric replacement textures of Cpy→Dig→Cov→Goe. Pyrite is generally idiomorphic and frequently occurs as pseudomorphic replacements of hematite or goethite, sometimes associated to malachite, showing lattice textures.

Homogenization temperatures (Tht) obtained from fluid inclusion microthermometry in quartz from Qtz-Chl veins (Millone et al., 2000), fall in the range 300-400°C and estimated salinity range from 2.6 to 13.5 eq. wt % NaCl (n= 5, $\bar{X}$= 7.5).

Preliminary $\delta^{18}O$ data for the Qtz-Chl pair in equilibrium yielded temperatures in the range 600-



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650°C; these formation temperatures are ~200-250°C higher than fluid inclusion Tht. These values, concurrently with the lack of boiling evidences, suggest that a "pressure correction" would be applicable to the mineralizing system (Millone et al., 2000).

Mean and maximum contents of 77 chemical analyses of representative network veinlets in metapsammitic rocks (Lira et al., 1997a; Millone et al., 2002) are summarized below (values in ppm, except for Au in ppb): Au (6.8, 38.0); Ag (2.3, 47.7); Cu (290.9, 5475.0); Pb (372.1, 14667.0); Zn (423.8, 19220.0); Mo (2.0, 51.0); As (23.3, 468.0); Cd (1.7, 22.0); Sb (2.8, 42.0) and Bi (0.4, 13.0). Mineralogical data and geochemical correlation among analyzed elements indicate an Ag-Cu-Pb-Zn-(Au)-(As) principal association.

## RHYOLITE DIKES

Rodeíto metasedimentary roof-pendant is the country rock of several rhyolitic dike intrusions of submeridian strike. These bodies outcrop for hundreds of meters and have variable thickness (3 to >25 m). They have been classed into two categories, those of southern and central-western Rodeíto, which are characterized below.

Southern zone: 2 m thick dike crosscut by subhorizontal veins of drusy quartz up to 0.5 m thick. Observed sulfides include galena grains partially rimmed by covellite, small bornite grains with sporadically exsolved chalcopyrite and chalcopyrite with lamellar intergrowths of covellite included in pyrite; specular hematite is also present. Fluid inclusion Tht's cover the range 290-335°C and estimated salinity vary between 5.2 and 11.0 eq.wt. % NaCl (n= 7, $\overline{X}$= 8.4).

Central-western zone: 25 m thick dike, crosscut by two main vein systems: a) Subhorizontal quartz veins with polyhedral mosaic texture, some with jig-saw borders (up to 1 cm grain size), associated to chlorite and grey chalcocite altered to covellite-malachite and pyrite partially oxidized to goethite-hematite. This vein type hosts Cu-mineralization (~ 2.5 % Cu) and Ag, Au and Zn anomalies. Tht in quartz (O'Leary et al., 2001) are within the range 190-351°C (n= 37, $\overline{X}$= 289°C) and salinity vary from 0.5 to 4 eq. wt. % NaCl (n= 10, $\overline{X}$= 2.1). b) Quartz veins (N310° strike and 35° NE dip) that carry oxydized pyrite (goethite), bornite associated with chalcocite-covellite and minor chalcopyrite replaced by covellite. This vein type is anomalous in gold (up to 550 ppb). Fluid inclusion thermometry yielded Tht in the range 155- 366°C (n= 36, $\overline{X}$= 259°C) and estimated salinity vary from 0.6 to 8.5 eq. wt. % NaCl (n= 17, $\overline{X}$= 6.3) (O'Leary et al., 2001).

Thirty three analyzed samples of mineralized rhyolitic porphyries yielded the following results (same units as in metamorphites): Au (24.4, 550.0); Ag (4.8, 85.3); Cu (983.4, 24157.0); Pb (280.9, 1067.0); Zn (344.7, 2508.0); Mo (4.4, 9.0); As (27.6, 191.0); Cd (1.0, 6.0); Sb (1.0, 6.0) and Bi (9.1, 199.0). Geochemical correlation show an association characterized by Ag – Au – Cu – Pb - (Zn) – Bi – As.

## METHODOLOGY

Galena grains from vein quartz hosted in metagreywackes were handpicked under stereoscopic microscope (samples # 24032, 24082, 20105 and 24389); an additional galena sample was collected from quartz veins that cut a rhyolitic dike from the southern zone of Rodeíto (sample # 24078). Pb isotopic analyses were carried out at the Centro de Pesquisas Geocronológicas, Universidade de São Paulo, Brazil.

The Pb isotopic analyses on galenas included the use of HCl+HNO3 for washing and HCl for dissolution. Only in impure samples (galena + others sulfides) the Pb was extracted by HCl and HBr in an AG1-X8 (200-400#) column. The Pb isotopic analysis were carried out on a multicollector VG 354 Micromass mass spectrometer. The procedural blank for Pb was 70 pg. Pb isotope ratios were corrected relative to the values of the NBS981 standard, by 1.0024 for $^{206}Pb/^{204}Pb$, 1.0038 for $^{207}Pb/^{204}Pb$ and 1.0051 for $^{208}Pb/^{204}Pb$. The analytical error for these isotopic ratios was 0.15-0.48%, 0.13-1.07% and 0.104-0.45%, respectively. The isotopic data were regressed using the program of Ludwig (1999). The ages were calculated using the decay constants established in Steiger & Jäger (1977); for $^{235}U$ and $^{238}U$ the decay constants were $9.8485 \times 10^{-10}\ yr^{-1}$ and $1.55125 \times 10^{-10}\ yr^{-1}$.

## ISOTOPE RATIOS

Measured ratios are listed in table 1 and plotted in the Stacey & Kramers (1975) two-stage model diagram (Fig. 1).

**Table 1.** Lead isotope ratios of galenas from Rodeíto. Sample 24078 is located in a rhyolite dike, remainder are hosted by low grade metasedimentary rocks.

| Sample # | 24078 | 24032 | 24082 | 24105 | 24389 |
|---|---|---|---|---|---|
| $^{206}Pb/^{204}Pb$ | 18.048 | 18.028 | 18.004 | 18.006 | 18.030 |
| Error (1 σ) | 0.023 | 0.051 | 0.030 | 0.447 | 0.010 |
| $^{207}Pb/^{204}Pb$ | 15.642 | 15.634 | 15.597 | 15.589 | 15.609 |
| Error (1 σ) | 0.023 | 0.053 | 0.030 | 0.464 | 0.010 |
| $^{208}Pb/^{204}Pb$ | 38.024 | 37.955 | 37.854 | 37.844 | 37.917 |
| Error (1 σ) | 0.024 | 0.056 | 0.031 | 0.476 | 0.010 |
| T (Ma) | 514.9 | 515.0 | 460.6 | 444.6 | 466.2 |
| μ | 9.964 | 9.935 | 9.771 | 9.737 | 9.821 |

From figure 1 an age of 433 Ma can be depicted from the intersection of the isochrone with the modeled curve. Ages computed according to the two-stage Pb-Pb evolution model of Stacey & Kramers (1975) would be within the range 445-515 Ma. Despite the fact that these are model ages, the age of the mineralizing event could be preliminarily assigned to the Eopalaeozoic, most likely to the Upper Ordovician-Lower Silurian .

The possible Pb sources were examined through the use of the plumbotectonic diagrams of Zartman & Doe (1981) who established different evolutionary models of Pb isotopes dependent on the reservoir.

In the diagram of figure 2a ($^{207}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$), analyzed data are distributed along a trend drawn oblique to modeled curves, which suggest an heterogeneous source for Pb. Data points are located between the "Upper Crust" and "Orogen" curves, though closer to the orogenic reservoir. Similarly, in the case of the diagram of figure 2b ($^{208}Pb/^{204}Pb$ *vs.* $^{206}Pb/^{204}Pb$), data points plot close to the "Orogen" curve, between it and the curve representative of "Lower Crust".

On the other hand, computed μ values for galena ($^{238}U/^{204}Pb$) range from 9.7 to 9.9 (Table 1). These values suggest that Pb was predominantly derived from rocks with high U/Pb ratios, typical of the upper crust. In this sense, Pb isotopic data suggest an heterogeneous source for Pb, composed of rocks with high U/Pb and Th/Pb ratios.

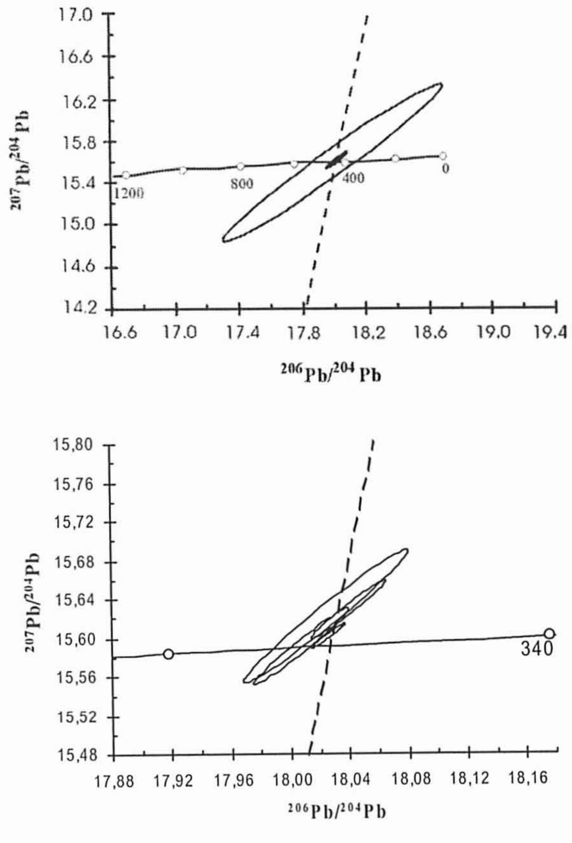


**Figure 1.** (a) Pb/Pb isotopic data for galenas of Rodeíto plotted in the "two-stage" Pb-Pb evolution model of Stacey & Kramers (1975). Intersection of the isochrone with the modeled curve indicates an age of 433 Ma. Data point error ellipses are 68.3 % confident. (b) Enlargement of figure 1 at the intersection zone.

## DISCUSSION AND CONCLUSIONS

If the origin of fluids involved in Rodeíto mineralization are considered to be of metamorphic remobilization (Millone et al., 2000, 2002), the system might be classified as mesothermal following the scheme of Nesbitt (1988). Groves et al. (1998) proposed to designate this type of deposits as "orogenic gold deposits" considering that the tectonic setting was the unique feature common for the whole group. These deposits are associated with regional metamorphic terranes of all ages. Ore is formed during compressional or transpressional stages, where hydrated sediments and/or volcanic rocks are subducted facing continental margins. Heat derived from subduction increases the thermal gradient within the accretional prism, initiating hydrothermal fluid migration channeled along megastructures through long distances (Groves et al., 1998).

Rodeíto hydrothermal system gathers some of the typical parameters of these deposits, such as the host rock type, the mineral paragenesis, the textural features of the veins and the structural relationships.

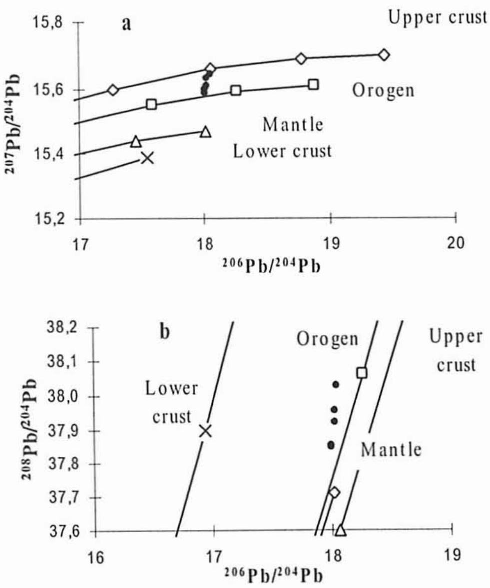


**Figure 2.** (a-b) Galenas from Rodeíto plotted in plumbotectonic diagrams (Zartman & Doe,1981).

Preliminary oxygen isotope geothermometric calculations using the Qtz-Chl pair yielded formational temperatures of 600 - 650 °C (Millone et al., 2000), which are higher than those strictly characteristic of phanerozoic mesothermal deposits, but are still possible (Groves et al., 1998). Fluid salinity varies from 13.5 to 0.5 eq. wt. % NaCl (Millone et al., 2000; O´Leary et al., 2001), which is too low for expected purely magmatic fluids. $\delta^{18}O_{H2O}$ computed at 600° varies between 9.8‰ (from quartz) and 8.5‰ (from chlorite); $\delta D_{H2O}$ computed from chlorite at 600° varies from -56.2‰ to ~-26‰, depending on the equation used. These values suggest that the isotopic composition of water involved in Rodeíto mineral deposition could be of metamorphic origin (Millone et al., 2000).

Lead isotope data presented in this contribution show a crustal source possibly formed by mixing of crustal and successively recycled orogenic rocks, which is in line with the proposed metallogenetic model. On the other hand, there are important facts that do not rigorously meet typical features of the orogenic model, among them, the relatively high contents of Ag, Cu, Pb and Zn and the erratic distribution of Au in the system, as well as the apparent absence of nearly ubiquitous carbonic fluids ($CO_2$, $CH_4$) as indicated by fluid inclusion microthermometry.

It has been stated that Rodeíto Pb-isotope signature in plumbotectonic plots favors a mesothermal or orogenic origin in the sense of Groves et al. (1998). The common fact that thermal events linked to subduction could extend over periods greater than 100 Ma, makes it difficult to unequivocally assign the mineralizing event (430 to 515 Ma) to the ultimate stages of the Pampean cycle or to any specifical evolutionary stage of the Famatinian orogeny.

Compared to other geological units related to this ore deposit type in Argentina, to our knowledge, no other Middle Cambrian to Lower Silurian ages have been registered within the Sierras Pampeanas system. Ore deposits that keep some analogies with Rodeíto are those located in the Ordovician sequences of Sierra de Rinconada, in the Puna high plateau, Jujuy province (Rodriguez et al., 2001) and those of Incahuasi mine in Catamarca province (González, 1999). Most outstanding similarities are the characteristics of host rocks and the ages attributed to mineralization which span the Ordovician-Silurian boundary, coincident with the Ocloyic orogeny.

In relationship to worldwide occurrences of phanerozoic orogenic deposits, Rodeíto shares common features with the Bendigo-Ballarat district, in central Victoria, Australia (Bierlein & Crowe, 2000); most remarkable comparable parameters are the isotopic composition of mineralizing fluids, the structures of vein systems, the possible age and lithology of host rocks, the age of mineralization and the age of associated magmatic rocks.

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