# Mineralization of La Salvadora deposit, Province of Mendoza, Argentina

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With 2 figures and 3 tables

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**Abstract:** La Salvadora ore deposit (35° 21′ 16″ S; 68° 23′ 22″ W), located in the Province of Mendoza, Argentina, is part of a group of polymetallic veins linked to a porphyry copper that shows a crude temperature zonation away from the potassic centre. This porphyry deposit is genetically related to Lower Permian volcanic rocks from a subduction tectonic setting. La Salvadora is a quartz and carbonate vein deposit hosted by a sericitized, silicified and carbonatized rhyolite. The ore paragenesis is composed of galena, chalcocite, native silver, chalcopyrite, and bornite, along with minor stromeyerite, tetrahedrite, sphalerite and hematite. Myrmekitic intergrowths of galena – rhombic chalcocite, with irregular stromeyerite inclusions in the rhombic chalcocite, are present. Ore mineral analyses show: (i) that the galena is free of silver and copper; (ii) the heterogeneities observed in Pb-free chalcocite are produced by variable contents of silver; (iii) stromeyerite has a very homogeneous composition despite its differences in origins; and, (iv) little copper is observed either in the native silver or in sphalerite. The myrmekitic intergrowths and the stromeyerite inclusions in the chalcocite suggest that they precipitated from fluids at temperatures between 150° and 67 °C, which is supported by the morphology of the fluid inclusions which suggest temperatures of formation below 120 °C, typical of epithermal systems.

Key words: La Salvadora, Argentina, silver mineralization, stromeyerite.

## Introduction

This paper examines the mineralogy of La Salvadora ore deposit, located in the San Rafael Massif, central-south Mendoza Province, Argentina, which

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is part of a group of polymetallic veins genetically related to the San Pedro porphyry copper deposit (DELPINO et al. 1993, RUBINSTEIN et al. 2001) in the Cerro San Pedro area (Fig. 1).

In the San Rafael Massif outcrops of Precambrian rocks are scarce and include Upper Proterozoic metamorphic rocks and granites. The area is dominated by Ordovician and Silurian carbonate and clastic sedimentary rocks deposited in a passive margin setting and subsequently metamorphosed and deformed during the Famatinian Orogeny.

During most of the Paleozoic, the southern portion of South America formed part of Gondwanaland. From the Carboniferous to the Triassic, a magmatic belt was active at the western margin of the continent. A foreland basin developed behind the Carboniferous arc was deformed during the San Rafael orogenic phase, which is related to the eastward migration of the magmatic arc in early Permian times. Volcanism started synchronously with this deformation event and ended in the Lower Triassic (KLEIMAN 1999). Two different suites can be distinguished within this volcanic sequence, termed the Choiyoi Group. An Early Permian suite (Lower Section), consisting of andesites and dacitic to low-silica rhyolitic ignimbrites with associated sedimentary rocks, has geochemical characteristics that point to a subduction zone tectonic setting (LLAMBÍAS et al. 1993, KOZLOWSKI et al. 1993, KLEIMAN 1999). The Late Permian – Early Triassic suite (Upper Section) is mainly composed of rhyolitic ignimbrites, andesitic dykes and lava flows, dacitic to rhyolitic subvolcanics and alkalic basaltic andesites, and shows transitional geochemical characteristics between subduction and continental intraplate conditions (MALVICINI & DELPINO 1989, KOZLOWSKI et al. 1993, KLEIMAN 1999). Thus, the volcanic character of the Choiyoi Group shows a progressive transition from a compressive to an extensional tectonic regime that ends with slightly alkaline and bimodal rifting magmatism in Middle Triassic times (MALVICINI & DELPINO 1989, KLEIMAN 1999).

From the Upper Cretaceous to the Pliocene, the geological record shows a sequence of continental sedimentary rocks and volcanic arc and back-arc products, including pyroclastic and silicic to basaltic volcanic rocks that were deformed by the different phases of the Andean Orogeny. Back-arc basaltic volcanism and sedimentation continued from the Pliocene to the Pleistocene (SELPÚLVEDA et al. 1997, SELPÚLVEDA et al. 2000, NARCISO et al. 2000). The overall stratigraphy of the San Rafael Massif is shown in Table 1.

**Table 1.** Stratigraphy of the San Rafael Massif.

| | | | |
|---|---|---|---|
| Quaternary | Holocene | | Aragonite and travertine (Agua de Loyola Formation); Basalts (Tromen Formation); Gravels, sands, loess, silts, clays and salt deposits. |
| | Pleistocene | | Basaltic lavas, pyroclastitics and agglomerates (Chapúa and El Puente Group and Yaucha Formation); Conglomerates, sandstones and siltstones (Los Mesones and La Invernada Formation); Aragonite and travertine (Las Peñas Sur Formation); gravels, sands and silts (Colonia Los Coroneles Formation). |
| Tertiary | Pliocene | | Basalts, andesites, dacites and mesosilicic to acid dykes and breccias (Nevado and El Zaino Formation and Chapúa Group); Conglomerates, sandstones, siltstones, claystones and tuffs (Rio Seco del Zapallo Formation); gravels, sands and silts (Cajón de Mayo Formation). |
| | Miocene | | Sandstones, siltstones, claystones and tuffs (Aisol Formation); Andesites, dacites and rhyolites (Cortaderas Formation). |
| Mesozoic | Cretaceous | Upper | Conglomerates, sandstones, siltstones and claystones (Punta del Agua Formation). |
| | | Lower | Basic volcanic and hypabyssal rocks; ignimbritic, volcanic, intrusive and hypabyssal. |
| | Triassic | | Mesosilicic to acid rocks; sedimentary rocks (Quebrada del Pimiento and Puesto Viejo Formations, El Portillo Group). |
| Paleozoic | Permian | Upper | Basic volcanic and hypabyssal rocks; Rhyolitic lavas, ignimbrites, tuffs and breccias (Quebrada del Pimiento and Choique Mahuida Formation). |
| | | Lower | Mesosilicic to acid hypabyssal and volcanic rocks, ignimbrites, tuffs and sedimentary rocks (Cerro de Las Yeguas and Agua de los Burros Formation and Cochicó Group). |
| | Carboniferous | Upper | Quartzites, sandstones, siltstones, wackes and lutites (Agua Escondida and El Imperial Formation). |
| | | Lower | Granites, granodiorites and diorites (Piedra de Afilar and Plutonitas Agua de la Chilena Formations). |
| | Devonian | | Quartzites, sandstones, siltstones, wackes and lutites (Río Seco de los Castaños Formation). |
| | Silurian | | Metaquartzites and schists (La Horqueta Formation. |
| | Ordovician | | Gabbros, diorites and andesitic porphyries (Gabro Loma Alta and Plutonitas La Bordales Formations). |
| | | | Mudstones, metaquartzites, schists, quartzites, grainstones, sandstones, siltstones, (Ponon Trehue, Lindero and La Horqueta Formations). |
| Precambrian | Proterozoic | | Metaquartzites and intrusives (Cerro de la Ventana Formation). |

## Gondwanan mineralization in the San Rafael Massif

Based on stratigraphic constraints, the main ore deposits of the San Rafael Massif were genetically related to the Gondwanan magmatic cycle. Lead isotope analyses confirm this genetic link resulting in a model age of 279 Ma, considered to be the age of the deposits and re-mobilisation of lead through volcanism. This age is consistent with previous geochronological K–Ar and $^{40}Ar-^{39}Ar$ data, and also with the stratigraphic evidence. Lead isotope values also prove a mixing process between a mantle-derived component (probably a depleted mantle) and an upper crustal component (RUBINSTEIN et al. 2003).

The transition from a magmatic arc to a rift tectonic setting during the Gondwanan magmatic cycle leads to different mineralization styles (CARPIO et al. 2001). The subduction setting of the Lower Section of the Choiyoi Group led to the generation of Cu–(Mo) porphyry-type deposits such as Infiernillo, La Chilca, San Pedro and Cerro Tres Hermanos (FUSCHINI 1968, DELPINO et al. 1993, RUBINSTEIN et al. 2000 a, 2002 a, b). They are genetically related to dacitic to rhyolitic porphyritic rocks with potassic alteration surrounded by phyllic and propylitic alteration haloes developed in the country rock. Within the alteration zone polymetallic veins, mainly with galena mineralization and quartz gangue, crop out.

Related to the intraplate magmatism from the Upper Section of the Choiyoi Group there are Mo porphyry-type deposits such as Germán and Elsiren (DELPINO 1997, CARPIO et al. 2001). They are quartz – molybdenite veins with phyllic alteration haloes which are emplaced in rhyolitic epizonal intrusions with potassic alteration. Fluorite and manganese vein systems, exclusively hosted by rocks from the Upper Section, are regionally distributed, while close to the Elsiren deposit scarce quartz – galena veins crop out. This style of mineralization was interpreted as a Climax-type deposit (DELPINO 1997, CARPIO et al. 2001). Also hosted by this Choiyoi Section is an epithermal, low sulphidation adularia – sericite type deposit with Au and Ag mineralization, which is probably related to a caldera structure (RUBINSTEIN et al. 2001).

## Geological setting

In the Cerro San Pedro area the Lower Section of the Choiyoi Group is termed the Cochicó Group (Fig. 1). It consists of intermediate to acidic sub-

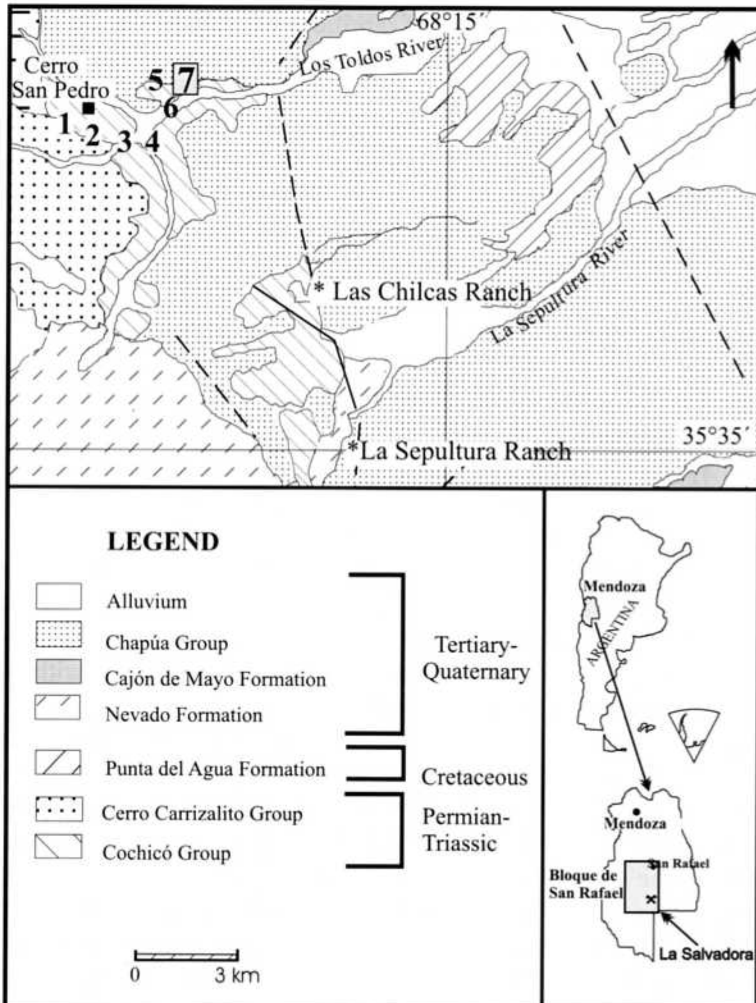


**Fig. 1.** Geology and location of vein deposits of the studied area: 1. La Julia; 2. San Pedro; 3. Santo Tomás; 4. La Margarita; 5. San Eduardo; 6. Juanita; 7. La Salvadora.

volcanic rocks, andesitic and dacitic lavas and minor sedimentary rocks (SEPÚLVEDA et al. 2000). Locally the Cochicó Group is represented by dacitic to rhyolitic hypabyssal rocks and minor andesitic debris flow deposits and dacitic tuffs. The hypabyssal rocks are intruded by moderately propyli-

tized subvolcanic and dyke rocks of dioritic composition. The Cerro Carrizalito Group (Fig. 1), equivalent to the Upper Section, includes rhyolitic lavas and dykes, subvolcanic intrusions, ignimbrites, breccias and minor dacitic ignimbrites and porphyritic diorites (SEPÚLVEDA et al. 2000).

The Punta del Agua Formation consists of conglomerates, sandstones, siltstones and argillites of Cretaceous age. Pliocene deposits are represented by the Nevado Formation which includes subvolcanics, lavas and pyroclastic rocks, basic to sub-silicic in composition, as well as conglomerates of the Cajón de Mayo Formation. Pliocene – Pleistocene basaltic lavas and pyroclastic rocks of the Chapúa Group also are found in the area (SEPÚLVEDA et al. 2000).

In the Cerro San Pedro area (Fig. 1) a porphyry copper deposit has been described (DELPINO et al. 1993, CARPIO et al. 2001, RUBINSTEIN et al. 2002 a). Spots of potassic alteration with an assemblage of biotite – K-feldspar – quartz affect the rhyolitic to dacitic hypabyssal rocks of Cerro San Pedro. Phyllic alteration (sericite–clay and quartz), widespread in the area, overprints and surrounds the potassic one. Finally there is a later carbonatization event. The random distribution of the hydrothermal alteration suggests that it corresponds to the upper part of the potassic zone of the system. Mineralization is scarce and consists of pyrite and magnetite, with minor chalcopyrite, galena, sphalerite, electrum and gold.

Veins and veinlets are abundant in the whole alteration area, with the larger ones hemyradially distributed around the San Pedro porphyry. Some of these larger vein deposits (Fig. 1) have been explored and even partially mined (RUBINSTEIN et al. 2002 a). La Julia and La Margarita veins have an ore paragenetic sequence of pyrite; sphalerite – galena – chalcopyrite; chalcopyrite; pyrite – molybdenite. They produce haloes in the host rock of intense phyllic alteration with muscovite, quartz, rutile and tourmaline. In the San Pedro and Santo Tomás veins only supergenic copper minerals (azurite, malachite) have been recognized. Phyllic alteration haloes consist of quartz, sericite and minor clays and chlorite. In Sin Nombre, a small vein croping out very close to a San Pedro vein, scarce pyrite and chalcopyrite and later hypogenic specular hematite are present. Here hydrothermal alteration of the country rock comprises sericitic–clay, chlorite and quartz. In the San Eduardo and Juanita deposits the paragenetic sequence consists of pyrite; Ag–galena; sphalerite – chalcopyrite. The alteration haloes comprise sericitic–clay and quartz overprinted by carbonatization. Chemical analyses of the described vein deposits are shown in Table 2.

**Table 2.** Chemical analyses (in ppm, except Au in ppb) from the veins by ICP (Ag, Bi, Cd, Cu, Mo, Pb, V, Zn) and INAA (As, Au, Sb, Th, U). Detection limit for Bi is 5 ppm and for Mo 1 ppm (bdl: below detection limit).

| | Ag | Bi | Cd | Cu | Mo | Pb | V | Zn | As | Au | Sb | Th | U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| La Salvadora | 12.9 | bdl | 6.7 | 25.5 | bdl | 585 | 58 | 844 | 11.8 | 15 | 11 | 2.5 | 2.8 |
| San Eduardo | 1 | bdl | 7.1 | 10.2 | 13 | 3140 | 72 | 812 | 19.9 | 34 | 6.3 | 1.8 | 7.7 |
| San Eduardo | >100 | bdl | 31.4 | 169 | bdl | 47300 | 16 | 6090 | 11.3 | 2630 | 20.5 | 0.9 | 3.5 |
| San Pedro | >100 | 60 | 81.1 | 12330 | 49 | 10380 | 74 | >10000 | 2620 | 136 | 26.6 | 8.8 | 6.2 |
| San Pedro | 17 | 26 | 22.9 | 3900 | 47 | 6010 | 98 | 5510 | 693 | 52 | 24.7 | 6 | 13 |
| Santo Tomás | 70.6 | 41 | 7.3 | 12560 | 9 | 183 | 44 | 1970 | 53.9 | 142 | 5.2 | 3.9 | 8.7 |
| Santo Tomás | 23.5 | 9 | 5.9 | 1800 | 11 | 396 | 83 | 2250 | 36.2 | 72 | 2.5 | 6.1 | 2.1 |
| La Julia | 4.7 | 36 | 3.3 | 12800 | 155 | 54 | 122 | 341 | 48 | 158 | 2.4 | 3.7 | 4.7 |
| La Julia | 19.1 | 65 | 1 | 28940 | 1610 | 192 | 30 | 417 | 60.3 | 279 | 10.5 | 1.5 | 9.7 |
| La Julia | 8 | bdl | 2 | 2060 | 63 | 126 | 81 | 162 | 34 | 109 | 2.7 | 8 | 3.6 |
| La Julia | 2.2 | bdl | 0.8 | 1420 | 5 | 21 | 70 | 177 | 16.2 | 48 | 1.5 | 10.1 | 5.5 |
| Juanita | 70.7 | 22 | 18.3 | 45.2 | 3 | 30180 | 47 | 2610 | 32.7 | 259 | 15.1 | 1.3 | 2 |
| Juanita | 14.5 | 9 | 9.5 | 17.8 | 2 | 5760 | 46 | 1060 | 22.6 | 54 | 14.7 | 0.4 | 3.4 |
| La Margarita | 6.1 | bdl | 13.8 | 1110 | 11 | 231 | 65 | 2120 | 12.8 | 48 | 2.8 | 6.6 | 8.3 |
| La Margarita | 18.8 | bdl | 19.1 | 1330 | 7 | 268 | 55 | 3370 | 118 | 182 | 30.8 | 6.6 | 6.2 |
| La Margarita | 1.5 | 7 | 2.1 | 51.9 | bdl | 67 | 77 | 357 | 13.5 | 27 | 2.3 | 4.4 | 3.5 |

## La Salvadora ore deposit

La Salvadora was mined, together with other vein deposits of the district, from the begining of the 19th century up to the begining of the 20th century (SALAZAR 1974). This ore deposit (RUBINSTEIN et al. 2000b) consists of a group of anastomosing veins up to 15 cm wide that result in a subhorizontal N–S lode of about 1 m in width. The gangue is chalcedonic quartz which encloses the mineralization, and which in turn is brecciated and cemented by later carbonate. The ore body is hosted by a porphyritic to glomeroporphyritic rhyolite with plagiolcase and minor amphibole, biotite and quartz phenocrysts in an alkali feldspar – quartz groundmass. The surrounding country rock shows moderate to high degrees of sericitization and silicification, both mainly pervasive and minor in veinlets, and also moderate carbonatization in veinlets and clusters.

### *Mineralization*

In the oxidation zone at La Salvadora limonite is dominant and appears together with minor malachite, jarosite and cerussite with galena relicts. Primary mineralization consists of galena, rhombic chalcocite, native silver,

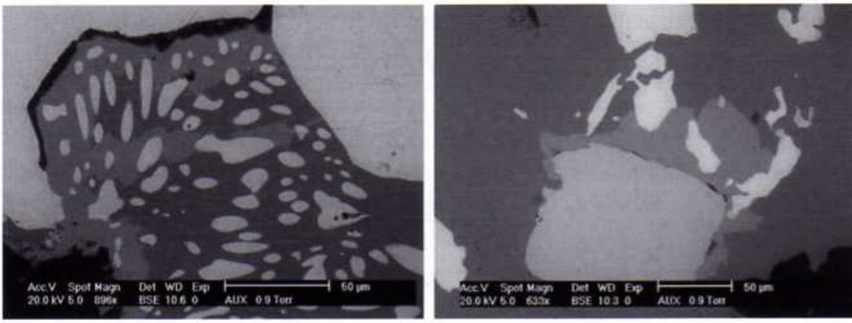


**Fig. 2.** a) Chalcocite (dark gray) – galena (white) myrmekitic intergrowth; b) Native silver (light gray) grain in chalcocite (dark gray) with an irregular stromeyerite rim (medium gray).

chalcopyrite and bornite, and minor stromeyerite, tetrahedrite, sphalerite and specular hematite. The ore minerals occur as:

- Intergrowths of galena, rhombic chalcocite, stromeyerite, native silver and, occasionally, tetrahedrite;
- Myrmekitic intergrowths of galena and rhombic chalcocite (Fig. 2 a);
- Intergrowths of rhombic chalcocite and stromeyerite (pseudomyrmekite);
- Stromeyerite at the contact between rhombic chalcocite and native silver (Fig. 2 b);
- Intergrowths of bornite, chalcopyrite, native silver and minor sphalerite, with the silver usually in the center of the assemblage;
- Tabular specular hematite.

*Composition of the ore minerals*

Mineral analyses (Table 3) were determined utilising a Cambridge Instruments scanning electron microscope (CamScan) equipped with an Oxford Instruments energy dispersive X-ray analytical facility, operated at 20 kv. Standards utilised were: pyrite for S, lead telluride for Pb and pure metals for Zn, Cu, Ag and Fe. Analytical errors were determined to be ± 1.5 %. Galena analyses show a very constant composition and are free of silver and copper. Heterogeneities observed in Pb-free chalcocite (Fig. 2 a) are produced by variable contents of silver. Despite its differences in origins, stromeyerite has a very homogeneous composition. Little copper is observed either in the native silver or notably in the pure sphalerite.

**Table 3.** Chemical compositions of the ore minerals.

| | S | Cu | Pb | Ag | Fe | Zn | Total |
|---|---|---|---|---|---|---|---|
| Chalcocite | 19.16 | 78.34 | | 1.45 | | | 98.95 |
| | 19.57 | 80.30 | | 0 | | | 99.87 |
| | 19.99 | 79.96 | | 0.80 | | | 100.75 |
| | 19.45 | 80.01 | | 1.03 | | | 100.49 |
| | 19.08 | 79.33 | | 0.70 | | | 99.11 |
| Stromeyerite | 15.15 | 31.95 | | 52.86 | | | 99.96 |
| | 15.07 | 32.10 | | 52.49 | | | 99.66 |
| | 15.30 | 30.53 | | 52.94 | | | 98.77 |
| | 15.36 | 32.33 | | 53.68 | | | 101.37 |
| | 15.07 | 32.10 | | 52.49 | | | 99.66 |
| Galena | 13.06 | | 88.11 | 0 | | | 101.17 |
| | 13.00 | | 88.45 | 0 | | | 101.45 |
| | 12.86 | | 88.25 | 0 | | | 101.11 |
| | 12.57 | | 88.19 | 0.12 | | | 100.88 |
| | 12.39 | | 88.58 | 0.06 | | | 101.03 |
| Bornite | 25.50 | 63.37 | | 0 | 11.06 | | 99.93 |
| | 24.84 | 63.07 | | 0 | 11.15 | | 99.06 |
| | 25.59 | 63.29 | | 0.56 | 10.89 | | 100.33 |
| | 25.83 | 63.42 | | 0 | 11.04 | | 100.29 |
| | 26.29 | 63.53 | | 0 | 10.96 | | 100.78 |
| Native silver | | 0.51 | | 99.14 | | | 99.65 |
| | | 0.47 | | 99.87 | | | 100.34 |
| | | 0.60 | | 99.34 | | | 99.94 |
| | | 0 | | 99.98 | | | 99.98 |
| | | 0 | | 99.03 | | | 99.03 |
| Sphalerite | 32.16 | 1.57 | | | | 65.92 | 99.65 |

## Discussion

Myrmekitic intergrowth between chalcocite and galena, chalcocite and stromeyerite, and stromeyerite and galena are only rarely found in natural ore parageneses (SCHWARTZ & PARK 1932, RAMDOHR 1985, PARR & CHEN 1986). At the Erasmus mine, Leogang, Austria, PARR & CHEN (1986) described two ore parageneses. The first consists of bornite, chalcopyrite, tetrahedrite, galena and pyrite, along with minor Ni-, Ge-, Sn- and V-bear-

ing minerals. The second paragenesis consists of Ag- and Hg-bearing minerals that include kongsbergite (mercurian silver), balkanite, betekhtinite, rhombic chalcocite, stromeyerite, furutobeite, bornite, chalcopyrite, cinnabar, galena and tennantite with frequent stromeyerite–galena, stromeyerite–chalcocite, and chalcocite–galena myrmekitic intergrowths. These intergrowths precipitated from oversaturated fluids at temperatures between 150° and 67 °C at the end of the paragenetic sequence.

In La Salvadora ore deposit myrmekitic chalcocite–galena and pseudomyrmekitic stromeyerite–chalcocite intergrowths occur, so that a temperature range of formation similar to that of Erasmus mine can be reasonably assumed. This assumption is supported by the morphology of La Salvadora fluid inclusions which suggests temperatures of formation below 120 °C (I. Korseniewsky, pers. comm.), typical of epithermal systems.

Considering the ore parageneses, metal contents and the hydrothermal alteration assemblages of the studied veins from the San Pedro district, a crude temperature zonation away from the potassic centre of the porphyry deposit has been inferred (Carpio et al. 2001); La Salvadora would represent the most distal part of this vein system. Based on the fact that mineralizations considered to be of lower temperature origin (La Juanita, La Salvadora, San Eduardo veins) are at lower altitudes than ones of higher temperature, tellescoping was also suggested (Carpio et al. 2001). This hypothesis is consistent with uplift related to relaxation when the compressive tectonic regime ceased at the end of the Early Permian.

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