Precious metal-bearing epithermal deposits in western Patagonia (NE Lago Fontana region), Argentina

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ABSTRACT

Precious metal-bearing quartz veins occur at the northeastern sector of the Lago Fontana region in southwestern Argentina, within the context of the Andean continental magmatic arc environment. The deposits and their associated alteration zones are spatially related to a Cretaceous calc-alkaline magmatism represented by silicic dikes and hypabyssal intrusions, and hosted by a Late Jurassic to Cretaceous volcano-sedimentary sequence. The veins and related veinlets crop out discontinuously, in general terms in a NW-SE belt. The primary vein mineral assemblage is composed mostly of pyrite ± galena ± chalcopyrite > hematite ± arsenopyrite in silica gangue minerals. Chemical analyses of grab samples from selected quartz veins show as much as 5.7 ppm Au and 224 ppm Ag, as well as elevated Pb, Cu, and Zn. Hydrothermal fluids caused an innermost silicification and adularia-sericite alteration assemblage, and an external propylitic halo.

Sulfur isotope values measured for sulfides (δ34S from −1.90 to +1.56‰), and oxygen and hydrogen isotopes measured on quartz crystals and extracted primary fluid inclusion waters (δ18Ofl = −2.85 to +5.40‰; δDfl = −106.0 to −103.4‰) indicate that mineralization probably formed from magmatic fluids, which were mixed with meteoric waters. Also, fluid inclusion data from quartz veins point out that these fluids had low salinity (1.7–4.2 wt% NaCl equiv.), and temperatures of homogenization between 180 and 325 °C. Mineralogical, petrographic and geochemical features for mineralized surface exposures indicate a typical adularia-sericite, low sulfidation epithermal system in the Lago Fontana area that represents a promising target for further exploration programs.

1. Introduction

Epithermal deposits commonly develop in association with calc-alkaline magmatism in volcanic arcs at convergent plate margins (White and Hedenquist, 1990, 1995; Simmons et al., 2005). Many important ore deposits were concentrated around the Pacific Rim during the Cretaceous-Tertiary metallogenic epoch, among several regions, in the Cordillera de los Andes of South America (Sillitoe, 1997; Hedenquist et al., 2000). Some of these deposits, such as Huemules (Secretaría de Minería, 1984; Viera and Hughes, 1999), La Ferrocarrilera (Rolando, 2001), Mina Angela (Marquez, 1999b; Dejonghe et al., 2002), El Toqui (Wellmer and Reeve, 1990), and Cerro Bayo (Poblete et al., 2011) have been well studied in the Argentinian–Chilean part of the Cordillera Patagónica, but other prospective areas in the region have not been studied in detail. Among these are the epithermal precious metal-bearing quartz veins, and their related alteration zones, in the northeastern sector of the Lago Fontana area, southwestern Chubut Province (Fig. 1). The southern side of Lago Fontana area has been recognized for its conspicuous hydrothermal alteration zones and base and precious metals occurrences during the last decades of the 20th century (Domínguez, 1981; fondo Rotatorio de las Naciones Unidas para la exploración de los Recursos Naturales, 1982; Marquez, 1995; Marchionni et al., 1997; Japan International Cooperation Agency and Metal Mining Agency of Japan, 2000). Since then, there have been several exploration projects and research studies in the region.
In the northeastern Lago Fontana area, reconnaissance mapping, satellite image processing, field checking, and geochemical sampling resulted in the discovery of new quartz veins containing precious metals at levels worth of further exploration (Lanfranchini, 2002). This paper presents the results of reconnaissance studies at various scales of these precious metal vein occurrences and the geology of the region where they crop out, together with a preliminary metallogenic model for the region.

2. Previous work

Small placer gold deposits were mined in the Lago Fontana area in the early 20th century. The La Ferrocarrilera polymetallic vein deposit (Fig. 1) was also mined during the 1950s, but there is no geological information from that activity.

Regional geologic studies were conducted in the Lago Fontana and Lago La Plata areas as well as in the Aldea Apeleg region by Ploszkiewicz and Ramos (1977), Haller and Lapido (1980), Ramos (1981, 1983), and Ploszkiewicz (1987), who defined the main stratigraphical and morphostructural units. Later, Folguera et al. (2000), and Folguera and Iannizzotto (2004) proposed a tectonic evolution model for the Lagos Fontana and La Plata area. These authors defined extensional structure systems during the Mid-Late Jurassic to the Upper Cretaceous which allowed the generation of the quartz vein epithermal deposits.

Fig. 1. Regional geology of the northeastern sector of the Lago Fontana area and surrounding zones (Modified from Ramos, 1981; Ploszkiewicz, 1987; Lanfranchini, 2002). Main study areas are marked with rectangles, and named as follows: A. Area of Fig. 5 that includes the southern portion of the Cordillera de Sakmata. B. Area of Fig. 7 that comprises the southern sector of the Sierra de Payaniyes, and Cerro Pepita. C. Area of Fig. 9, toward the eastern sector, includes the Cerros Teta, Colorado, and Pedrero.
Detailed metallogenic investigations in the southern part of the Lago Fontana area were carried out by Domínguez (1981), and Rolando et al. (2002), who studied the polymetallic mineralization of the La Ferrocarrilera mine region. Hayase et al. (1971) and Maiza and Tres Lagunas Formations. Toward the eastern sector the Tres Lagunas Formation is covered by marine transgressions represented by the Cotidiano Basalt Formation. This event was followed by WNW compression related to subduction of the Nazca Plate beneath the South American Plate (Sillitoe, 1974). Compression led to inversion of older faults and crustal shortening accommodated by folding and development of new faults (Volguera et al., 2000; Volguera and Ianizotto, 2004; Ianizotto et al., 2004).

3. Regional geological setting

An extensional structural regime characterized the Andes Patagónicos from the Mid-Late Jurassic to the Lower Cretaceous. In the Lago Fontana region, an extensive basic to andesitic volcanism was developed along a magmatic arc during the Middle to Upper Jurassic. It is represented by the lava flows of the Lago La Plata Formation (Ramos, 1976, 1981). At the end of this period, crustal stretching of the basement, controlled by regional NW striking subvertical normal faults, formed several basins associated with the opening of the Weddell Sea (Mpodozis and Ramos, 2008), that were inundated by marine transgressions represented by the Cotidiano and Tres Lagunas Formations. Toward the eastern sector the Tres Lagunas Formation reaches up to the Valanginian (Ramos, 1981). Later, during the Berriasian-Hauterivian, the fossiliferous black shales of the Katterfeld Formation were deposited. This event inducts by marine transgressions represented by the Cotidiano Basalt Formation. This event was followed by WNW compression related to subduction of the Nazca Plate beneath the South American Plate (Sillitoe, 1974). Compression led to inversion of older faults and crustal shortening accommodated by folding and development of new faults (Volguera et al., 2000; Volguera and Ianizotto, 2004; Ianizotto et al., 2004). A similar geological-metallogenic scheme is observed in the Cordillera Patagónica Chilena where geological investigations were conducted by several researchers during the last decade. These studies allowed establishing with precision the stratigraphy and their hydrothermal mineralizations associated (Parada et al., 2001; Hervé et al., 2007; Suárez et al., 2008). Therefore, the Chilean Jurassic-Cretaceous volcano-sedimentary stratigraphy can be well correlated with that of the Argentinian side. The Divisadero Group of Chile, which correlates with the Nirehuao and El Gato Formations in Argentina, was dated by Pankhurst et al. (2003) obtaining ages between 116 and 116 Ma for acid ignimbrites, while Suárez et al. (2008) got 118.5 ± 0.8 and 116.7 ± 0.7 Ma for similar rocks using U–Pb SHRIMP. The Nirehuao Formation was analyzed using ⁴⁰Ar–³⁹Ar method by Parada et al. (2001) who obtained an age of 96.3 ± 1 Ma. This Cretaceous magmatism is closely associated with several hydrothermal ore deposits in Chile, such as Cerro Bayo Mine in Laguna Verde area, where adularia from epithermal veins was dated at 114–111 Ma by the ⁴⁰Ar–³⁹Ar method (Poblete et al., 2011). In the argentinian side, Márquez (1999a) points out that there is a temporary relationship between the majority of the mineral occurrences in the Lago Fontana region and the acid to mesosilicic Cretaceous volcanism developed during the uppermost Lower Cretaceous and the beginning of the Upper Cretaceous.

3.1. Local geology

The Lago La Plata Formation is the oldest unit (Fig. 2) in the studied areas. It is composed of basalt and basaltic andesites which forms small and isolated outcrops with a poor topographic expression where it is difficult to recognize lava flow structures. In thin sections, these rocks contain pale green pyroxene and plagioclase (An₅₀–₅₂) phenocrysts, enclosed in a pilotaxitic groundmass. This sequence is overlain by the sedimentary rocks of the Tres Lagunas Formation. This unit is composed of thin greenish sandstone layers interbedded with dark grey marls and minor limestones. Usually, it is transitionally followed by the sandstones of the Apeleg Formation (Fig. 3A) which forms thick outcrops constituted mainly by light brown, fine to medium size quartz sandstone with a clast-supported texture, and minor conglomerate and shales with tabular layout.

Fig. 2. Stratigraphic section of the study area. Not to scale.
Ñirehuao volcanic rocks form rounded hills composed of strongly altered greenish to brown porphyritic andesite containing pyroxene and plagioclase phenocrysts in a pilotaxitic groundmass. The El Gato Formation crops out extensively constituting mainly numerous rhyolitic and dacitic dikes and small subvolcanic stocks. These igneous rocks form the Cerros Teta, Pedrero, and Colorado (Fig. 1), which are several kilometers in diameter. The predominant NW-striking rhyolitic dikes of the El Gato Formation appear as elongated crests 0.5–8.0 m-thick and as much as 1000 m-long (Fig. 3B and D). The rhyolitic rocks are light brown in color, and have a porphyritic texture, composed of bipyramidal quartz phenocrysts, up to 5 mm in length, as well as K-feldspar, plagioclase, euhedral biotite, and Fe-oxides, with accessory apatite and titanite in a felsitic groundmass.

Geochemical data of igneous rocks from the Ñirehuao and El Gato Formations indicate a generally subalkaline magmatism, mostly with
a calc-alkaline signature (Lanfranchini, 2002). Andesites of Ñirehuao Formation are meta-aluminous, while the El Gato volcanics are per-aluminous. According to the Rb vs Nb + Y tectonic discrimination diagram they correspond to a magmatic arc environment (Lanfranchini et al., 2006).

The Patagonian Batholith is poorly exposed in this region, only a few gabbroic to dioritic rocks of the Muzzio Formation (Upper Cretaceous, Ramos, 1976) which crop out as relatively small intrusions mainly within the sandstones of the Apeleg Formation (Fig. 3C). These intrusions formed low grade hornfels aureoles in the Apeleg sandstone at the Cerro del Finadito area (Figs. 1 and 5).

Finally, Pliocene–Pleistocene basalts and recent glaciofluvial–fluvial deposits overlie the older rocks. It conform extensively terraced levels essentially toward the eastern region.

4. Satellite image analysis

Several scenes of ascending and descending orbits of a georeferenced RADARSAT SAR image, with fine resolution, 37–40° angle of incidence, a pixel spacing of 6.25 m in both azimuth and coverage, and an image resolution of 10 × 10 m were used (Fig. 4A and B). These scenes, as well as the aerial photographs of the area, were rectified using a previously georeferenced LANDSAT-TM Image. RADAR image enhancement was performed by conventional methods and structural features extraction was done by visual interpretation (Marchionni et al., 1999). In the same area, LANDSAT TM satellite image analysis showed color alteration zones and also several linear morphological features with positive topographic expression. The complete satellite image processing allowed the identification of the main lineaments of the study area, which after been field checked, resulted in several mineralized structures and surrounding hydrothermal alteration zones. Linear structures have been effective exploration guides in the study area. These lineaments have a dominant NW-trending orientation and a subordinate NE-striking orientation. This structural scheme is consistent with that proposed by Ploszkiewicz and Ramos (1977), who recognized the lineaments defined block-faulting within the crystalline basement. The continuation of the lineaments into younger sedimentary rocks (Upper Miocene–Lower Pliocene) indicates a reactivation of the normal faults during recent times.

5. Hydrothermal alteration

Narrow hydrothermal alteration zones surround the mineralized veins. Silification, the most common alteration type, is well developed in the sandstones of the Apeleg Formation. Silification is evident both as pervasive replacement (Fig. 6a and b) composed of minute quartz andchalcedony grains, and as numerous very thin veinlets that are accompanied by minor sericite patches. Within these veinlets, minor amounts of euhedral rhombic adularia crystals (Fig. 6h), as much as 350 μm in length, are intergrown with quartz. Sericite frequently forms small patches in the wall rock. Scarce, 50 μm to 1 mm in diameter, xenomorphic grains of disseminated pyrite are associated with the patchy sericite alteration. Veinlet walls are locally coated with radiating sprays of iron oxide tinted sericite.

Argillically altered rocks are not easily recognized, because they are frequently buried by thin detrital cover due to weathering of soft argillically altered rocks. Argillic alteration is weakly developed adjacent to many of the veins and extends a few meters into the wall rocks. It is mainly characterized by kaolinite replacement of feldspars and pervasive illite-smectite.

Strong propylitic alteration, defined by dark greyish-greenish rock, several meters in width, forms distal to the veins, mainly in the andesitic flows of the Ñirehuao Formation. It is characterized by calcite and epidote replacement of plagioclase, and chlorite (rapidiolite-brunsvigite) both pervasive (Fig. 6g) as replacement of pyroxene.

In the Cordillera del Gato, at the west of the study area, there is an extensive alteration zone. It forms an kaolinite–alunite–siliceous blanket that is mainly replacing acid volcanics of El Gato Formation. Despite this area is not the aim of this study we consider, preliminarily, that this deposit would correspond to a steam heated system related to the Cretaceous magmatic activity, according to the observed mineralogical and textural features. This interpretation is also supported by some stable isotope (∆18O) data, calculated in dickite from Susana Mine (Lanfranchini, 2002) that yielded values between −2.81‰ and −2.71‰ (at 230 °C, Hayase and Maiza, 1973).

6. Vein deposits

Epithermal quartz veins occur in several places of the Payaniyeu region within the Late Jurassic-Cretaceous volcano-sedimentary
sequence. They are spatially related to rhyolitic and rhyodacitic dikes of the El Gato Formation. Although the quartz veins constitute discontinuous outcrops, they form a sinuous outcrop pattern that generally trends NW-SE in an approximately 30-km-long by 15-km-wide belt. The veins are near vertical, ranging from centimeters up to several meters thick, and tens to hundreds of meters long (Fig. 3E and F). The main veins locally contain anomalous concentrations of precious and base metals (Table 1).

The principal quartz veins crop out at the Lote 15 sector in the Sierra de Payaniyeu (Figs. 1B and 7) and at the Mina de Plomo sector in the Cordillera de Sakmata (Figs. 1A and 5). They are near vertical, and have N 30°–40°W and minor N 50°E (Mina de Plomo) strikes.
The veins crop out discontinuously for almost 900 m, are as much as 5 m wide, and are commonly hosted by rhyodacitic dikes of the El Gato Formation, which intruded the volcano-sedimentary succession. Wall rocks immediately adjacent to the vein system, mostly rhyodacite, andesite and sedimentary rocks, have been altered to a quartz-sericite assemblage, and are locally brecciated and cut by microcrystalline quartz veins (Fig. 8). This alteration extends for at least 15 m from the veins, where it grades outward to a propylitic assemblage.

The veins are composed of milky to translucent quartz with lesser sparry carbonate. The most frequent microscopic primary textures are massive, comb and zoned crystals (Fig. 6e and f); evidence of recrystallization includes mosaic and flamboyant textures. Banded and breccia textures (Fig. 6c and d) are developed

Fig. 6. Field photographs showing silicified structures at Mina de Plomo (a) and Cerro Teta (b). c. Quartz banded texture in Lote 15 vein. d. Hand specimen photograph of breccia texture from the Cerro Pepita, coin diameter - 25 mm. e-f. Photographs of thin sections showing vein quartz textures in Lote 15. e. Mosaic texture. f. Drusy texture toward the crystal rim and recrystallized amorphous silica (chalcedony). g. Chlorite aggregates at Lote 15 veins. h. Rhombic adularia crystals in quartz veinlets from Lote 15. Abbreviations: adul = adularia, cal = calcite, qz = quartz.
Table 1
Variations in geochemical analyses of main quartz veins from Lote 15, Mina de Plomo, Sierra de Payaniyeu, Cerro del Finadito and Cerro Teta, Western Patagonia Argentina.

<table>
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<th></th>
<th>Au (ppb)</th>
<th>Ag (ppm)</th>
<th>Cu (ppm)</th>
<th>Pb (ppm)</th>
<th>Zn (ppm)</th>
<th>Fe (pct)</th>
<th>As (ppm)</th>
<th>Sb (ppm)</th>
<th>Hg (ppb)</th>
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<td>4.6</td>
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<td>1950.0</td>
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<td>0.5</td>
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Fig. 7. Geologic map of the southern sector of the Sierra de Payaniyeu and the Cerro Pepita. Modified from Ploszkiewicz, 1987; Lanfranchini, 2002.
surrounding rhyodacite and andesite wall rock fragments, each a few centimeters in diameter, that are located near both the centers and the margins of the quartz veins. In addition, several thin quartz veinlet systems cross-cut the mineralized zones.

The hypogene mineral assemblage is composed of pyrite ± galena ± chalcopyrite > hematite ± arsenopyrite ± chlorite ± fluorite, with variable amounts of gold and silver. Gold appears as native grains as long as 10 μm or as micro-inclusions in the sulfide minerals. Pyrite forms several generations of crystals, which show euhedral square cross sections, up to 5 mm in diameter. It occurs disseminated in quartz veins or in the adjacent wall rocks and is commonly oxidized to Fe-oxide boxworks. Galena crystals are as much as 3 cm in diameter and frequently contain exsolved chalcopyrite. Some galena partially replaces pyrite crystals (Fig. 3H) and is intergrown with quartz grains. Chalcopyrite is scarce and erratically distributed as irregular masses of anhedral crystals (anglesite, cerusite, and Fe-oxides) in veinlets, and particular replacing hypogene chalcopyrite and galena grains.

In the Cerro Teta area (Fig. 9), several near vertical quartz veins, each as much as 5 m-wide, strike approximately E–W. At Cerro Colorado, the silicified zones are also near vertical, and reach up to 4 m-wide but have a variable strike between N–S and NW–SE. Despite the absence of visible sulfides in the outcrops of milky quartz veins, geochemical analyses reveal up to 524 ppb Au and 76 ppm Ag.

The general sulfide mineral paragenetic sequence has 3 main stages: (1) an early formation of euhedral pyrite that precipitated before the generation of scarce irregular chalcopyrite grains, (2) afterward, main galena deposition occurred, sometimes including chalcopyrite, and (3) a second generation of cubic pyrite crystals. In addition, fine-grained pyrite appears frequently disseminated toward the vein margins and in adjacent wall rocks but there are no clear evidences about its paragenetic relationship.

Two hydrothermal quartz vein systems related to a Ca–Fe–magnetite skarn (Lanfranchini et al., 2007), named El Abuelo, and El Solcito are located at Cerro Pepita, in the southern part of the study area. Ore grades vary between 40 and 63 wt% Fe. Anomalous metal contents of >1% Cu and as much as 81 ppm Ag have been measured.

7. Sample selection and analytical methods

Representative quartz veins and altered wall rocks were sampled for whole rock geochemical analysis in order to detect the presence of metal anomalies. Minor and trace element contents were analyzed on 63 selected samples by inductively coupled plasma-mass spectrometry (ICP-MS), and by instrumental neutron activation analysis (INAA) at Actlabs Ltd. (Canada).

Electron microprobe analyses were carried out on sulfide minerals with the aim of establishing anomalous contents of precious metals, using a Cameca Camebax SX-100 at the Departamento de Geología, Universidad de Oviedo, Spain. Operating conditions were 15–20 kV accelerating voltage, beam current of 15–20 mA, and beam width of 1—2 μm. Natural mineral standards certificated by MAC (Micro Analysis Consultants Ltd., United Kingdom) were used for calculating element concentrations.

Heating and freezing analyses of fluid inclusions were obtained from approximately 50- to 100-μm-thick doubly polished thin sections using a LINKAM THM 560 heating-freezing stage in the Fluid Inclusion Laboratory at the Centro de Desenvolvimento de
9. Fluid inclusions

9.1. Petrography

Different textural varieties of euhedral to subhedral quartz crystals were studied for Fi. Eighteen quartz samples from the Lote 15 and Mina de Plomo occurrences in the Sierra de Payaniyeu were examined to estimate the temperature and composition of hydrothermal fluids. Quartz from the main veins and silicified wall rocks contained zones of primary Fi, and planes of secondary and pseudosecondary Fi. Primary Fi data from euhedral, 1- to 3-cm-long quartz crystals, which are intergrown with sulfide grains and small rhombic adularia crystals with 90 μm average length, were analyzed. These quartz crystals contain growth zones (Fig. 10) mainly defined by an abundant two-phase Fi association, and a few small monophase (<5 μm) primary Fi that are not suitable for microthermometric analysis. Primary Fi also occur as isolated clusters in these crystals. Pseudosecondary and secondary Fi are distributed along healed and late fracture planes; no microthermometric analyses were performed on them.

Primary two-phase Fi (LH₂O + VH₂O) range between 10 and 50 μm in size. They have irregular, almost polygonal, elongated shapes, occasionally showing “necking down” features. Vapor phase volume varies from 10 to 20% of total Fi volume (Fig. 10). Locally, some groups of primary Fi exhibit variability from 10 to 50%
in vapor phase volume. Although these FI have different proportions of vapor phase, they homogenize at the same temperature to the liquid phase, suggesting trapping of boiling fluid.

9.2. Microthermometric measurements

Microthermometric measurements were restricted to quartz-hosted inclusions, because these inclusions are large and a primary origin could be assigned to them, and phase changes are easy to observe. During freezing measurements no phase changes that would indicate the presence of carbon-bearing volatile phases in the vapor were observed in any of the vein systems studied. The fluid inclusions had first melting temperatures (T_e) between −22 and −24 °C, similar to the eutectic for the system NaCl–H_2O, with minor K^+ that would have been responsible for lowering the eutectic point of the system below the theoretical −20.8 °C (Shepherd et al., 1985). The final melting temperatures (T_m) for ice range between 2.5 to 1.0 °C, indicating low salinities that vary between 1.7 and 4.8 wt % NaCl equiv., with a mode in the range of 3.5 to 4.5 wt % NaCl equiv. (Fig. 11 and Table 2).

During heating experiments, the two-phase FI homogenized into the liquid phase at temperatures between 180–300 °C, with two modes at 200–220 °C and 260–280 °C. The first mode corresponds to the FI in the peripheral sectors of crystals, whereas the second mode relates to the cores (Fig. 11).

10. Stable isotope

Stable isotope (O, H, S) results are summarized in Table 3. The samples analyzed were those that had been in contact with sulfides throughout the exposed vein system; these sulfides comprise less than about 1 percent of the total vein.

δ^{18}O_H_2O values range between 5.3 and 5.4‰ in quartz crystals, and between −2.85 and −0.91‰ in fluid inclusions of quartz. δD_H_2O yielded values of −106.4 to −103.4‰ in fluid inclusions of quartz crystals. Reference meteoric waters, used to infer metallogenic environment, were selected from the pluviometric data base of the International Atomic Energy Agency (Vienna) using waters

### Table 2

Summary of primary fluid inclusion microthermometric data in quartz grains from representative veins at Lote 15, and Mina de Plomo.

<table>
<thead>
<tr>
<th>Location</th>
<th>Type of mineralization</th>
<th>Th (L + V)</th>
<th>Te</th>
<th>Tm</th>
<th>Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lote 15</td>
<td>Quartz vein</td>
<td>180–325</td>
<td>−24</td>
<td>−2.5</td>
<td>1.0/4.8</td>
</tr>
<tr>
<td></td>
<td>Quartz veinlet-wall rock</td>
<td>180–290</td>
<td>−23</td>
<td>−3.1</td>
<td>1.7/3.8</td>
</tr>
<tr>
<td>Mina de Plomo</td>
<td>Quartz vein</td>
<td>190–310</td>
<td>−22</td>
<td>−2.4</td>
<td>1.5/4.0</td>
</tr>
</tbody>
</table>

Temperatures are °C units: Th (L + V) homogenization temperature of vapor phase, Te: eutectic temperature, Tm: melting temperature of ice. Salinities (wt % NaCl equiv.) are calculated from ice-melting temperatures.

### Table 3

Stable isotope data from Lote 15, Cerro Pepita (El Abuelo skarn and El Solcito vein), and Mina de Plomo sectors.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Location</th>
<th>Mineral</th>
<th>δ^{18}O_{min} (‰)</th>
<th>δ^{18}O_{H_2O} (‰)</th>
<th>δD_{min} (‰)</th>
<th>δD_{H_2O} (‰)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L15 1</td>
<td>Lote 15 sector</td>
<td>Quartz</td>
<td>5.3</td>
<td>−2.43</td>
<td>−2.85</td>
<td>−106.4</td>
</tr>
<tr>
<td>L15 2</td>
<td>Lote 15 sector</td>
<td>Quartz</td>
<td>5.4</td>
<td>−2.33</td>
<td>−2.85</td>
<td>−106.4</td>
</tr>
<tr>
<td>L15 11</td>
<td>Lote 15 sector</td>
<td>Quartz</td>
<td>5.3</td>
<td>−2.43</td>
<td>−2.85</td>
<td>−106.4</td>
</tr>
<tr>
<td>L15 21</td>
<td>Lote 15 sector</td>
<td>Quartz</td>
<td>5.3</td>
<td>−2.43</td>
<td>−2.85</td>
<td>−106.4</td>
</tr>
<tr>
<td>4231a</td>
<td>El Abuelo skarn</td>
<td>Pyrite</td>
<td>0.1</td>
<td>−1.21</td>
<td>0.2</td>
<td>−0.11</td>
</tr>
<tr>
<td>4247a*</td>
<td>El Solcito Vein</td>
<td>Pyrite</td>
<td>0.2</td>
<td>−0.11</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Data from Lanfranchini et al. (2007).
considered to have similar latitude, altitude, and continental conditions than those prevailing during the Cretaceous in the area of study (Fig. 12). In general it is assumed that the current meteoric water line is analogous to possible meteoric water in the geologic past, as the isotopic value of the oceans is buffered by interaction of seawater with oceanic crustal material in ridge areas (Muehlenbachs, 1986).

Sulfide sulfur isotopes ($\delta^{34}S_{\text{min}}$) from the Lote 15, Cerro Pepita (El Abuelo skarn and El Solcito vein) and Mina de Plomo quartz veins and veinlets, yielded values from $-1.90^\circ_{\text{oo}}$ to $+1.56^\circ_{\text{oo}}$ (Table 3).

10.1. Stable isotope thermometry

Oxygen isotope systematics were used to get an independent estimate of the conditions of vein formation. The measured $\delta^{18}O$ values of quartz and fluid phase extracted from quartz crystal pairs give vein temperatures of about 265 °C, using experimental coefficients from Clayton et al. (1972). This estimate agrees very well with the range of 220–280 °C estimated from fluid inclusion homogenization temperatures for the quartz deposition.

Sulfur isotope thermometry was attempted without much success on pyrite-galena pairs. Galena and intergrown pyrite pairs give reasonable temperatures, but even these do not unequivocally meet textural criteria for equilibrium deposition. Similarly, in rare pyrite-galena contact associations, the galena involved is a younger generation overgrown on older pyrite. Of all the associations examined, only two (samples P8 and 1187) seem to coexist with sulfides that are products of the same paragenetic stage and, even in these, the pyrite appears somewhat older. These samples give $\delta^{34}S_{\text{py}} = \delta^{34}S_{\text{ga}}$ values corresponding to equilibrium temperatures in the range of 345–485 °C (from the equations of Ohmoto and Rye, 1979; Li and Liu, 2006), clearly higher than the fluid inclusion data. We infer that these two carefully selected specimens represent nonequilibrium phases, probably as a result of non-contemporaneous deposition.

11. Discussion

Precious metal-bearing quartz vein formation in the Lago Fontana area occurred during the Cretaceous magmatic activity. This magmatism is represented by basic to acid subvolcanic bodies and lava flows into the Late Jurassic to Cretaceous volcano-sedimentary sequence.

These vein deposits extend mainly along a N30° to 60° W direction, suggesting a structural control for the circulation of hydrothermal fluids along older faults that were reactivated later in the Lower Cretaceous. These vein systems are interpreted to have formed at relatively high levels. The depth at which they formed can be inferred from fluid inclusion data, considering that they were trapped during boiling processes and therefore do not require a pressure correction (Haas, 1971; Bodnar et al., 1985). Indirect evidence for boiling is the existence of primary fluid inclusions with different proportions of vapor phase homogenized at the same temperatures in some groups (Fig. 13). Pressures of about 60–70 bars can be calculated for these solutions, from data obtained for the NaCl–H$_2$O system, assuming $<5$ wt% NaCl equiv. salinity, a density of 0.62–0.65 g/cm$^3$, and an upper limit of the temperature of homogenization of about 280 °C. Under hydrostatic conditions, these pressures should be equivalent to a maximum depth of 600 m below the paleosurface. In addition, the presence of quartz and chalcedony, with lesser adularia and carbonate, the occurrence of distinctive vein textures, including colloform and crustiform banding and comb quartz, and the low temperature FI that lack detectable CO$_2$, also suggest a high level of emplacement.

A magmatic origin for the sulfur in the vein-forming fluids is assumed due to the close spatial relationship between the rhyolitic to dacitic subvolcanic bodies and the quartz veins, as well as by the sulfur isotope data. The analyzed samples are typical of sulfides throughout the exposed vein system. Sulfide minerals show a very narrow range of $\delta^{34}S$ values from $-1.90$ to $+1.56$ per mil. This tight range indicates that the sulfides were deposited from hydrothermal solutions whose sulfur was derived from a single source. These hydrothermal fluids may have derived their sulfur directly from magma or from the leaching of sulfides in igneous host rocks.

The $\delta^{18}O_{\text{H}_2\text{O}}/\delta^{18}O_{\text{H}_2\text{O}}$ diagram (Fig. 12, after Sheppard, 1986) shows that there are two main possibilities for the origin of the water: (1) water was derived from a magmatic system and probably mixed with meteoric waters. Even though isotopic data do not plot exactly on a mixing line between the two end members, it could be assumed that the origin of the mineralizing fluid could be compatible with heated meteoric water, in which case $\delta^{18}O_{\text{H}_2\text{O}}$ value would increase while $\delta^{18}O_{\text{H}_2\text{O}}$ composition would remain constant, or (2) these waters also contain water trapped in the sediment at the time of its formation. The extent of isotopic exchange of water is not really known, as there are diverse processes that change the isotopic composition of a hydrothermal water.

Fluid pressure decreased during upwelling of the hydrothermal fluid, resulting in boiling and partial degassing, and pH increase by H$_2$S loss to the vapor phase. This model is supported by the presence of rhombic adularia in quartz veins that is very common in areas of boiling geothermal systems, because a pH increase favors the precipitation of that feldspar (Hedenquist and Henley, 1985a, 1985b).
This increase in pH could also have favored base metal sulfide precipitation. The resulting H₂S depletion in the hydrothermal fluids would destabilize Au and Ag bisulfide complexes, resulting in the precipitation of precious metals together with sulfides (Reed and Spycher, 1985).

An intrusion-related model of this epithermal deposits is schematically shown in Fig. 14, through cross sections that illustrate the metallogenic evolution at the Lago Fontana area during the Mid-Upper Jurassic to Upper Cretaceous, beginning with the formation of a volcanic arc, followed by deposition of a sedimentary sequence and by the emplacement of rhyolitic bodies, corresponding to a late arc in the area, and related quartz veins.

12. Conclusions

Widespread calc-alkaline magmatism, part of a N−S-trending volcanic arc, occurred during the Jurassic – Cretaceous in southwestern South America. In the NE Lago Fontana area, this igneous activity formed several intrusive bodies that are spatially and genetically associated with precious metal-bearing low sulfidation epithermal systems. This magmatism represents a useful guide for explorationists because it is linked to a considerable area of mineralization described in this paper.

Although current knowledge of these epithermal deposits in the study area is incomplete, in particular due to lack of drilling to define deeper levels, our surface geological studies allow some generalizations. These include: (1) the presence of an evident regional geochemical signal, with anomalous contents of Au, Ag, As, and Hg, (2) a significant distribution of quartz veins which conform different epithermal systems located across a 450 km² area, and (3) mineralogical and textural features that suggest relatively shallow paleodepths of the exposed veins.

The presence of a favorable scenario like the NE Lago Fontana region, with clear and defined metallotects represented mainly by the existence of several mineral occurrences and related hydrothermal alteration zones allows to encourage further exploration programs with promising expectation.

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