

## Fluid inclusion and isotopic compositions of Cordilleran polymetallic replacement bodies and veins at Cerro de Pasco, Peru

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### Introduction

Cerro de Pasco, located in central Peru and spatially related to a mid-Miocene (~16 Ma, Baumgartner et al., 2006), diatreme dome complex, is a world-class Zn-Pb-Ag-Cu-Bi deposit with past production plus known resources of at least 175 Mt @ 7% Zn and 2% Pb and 3 oz/t Ag. In addition, mining produced prior to 1950, 1200 Moz Ag, 2 Moz of Au and around 50 Mt @ 2% Cu (compiled from Jiménez, 1924, Cerro de Pasco Corporation, 1950; Einaudi, 1977; Fischer, 1977 and Cerro de Pasco geological staff, pers. com.)

At least two thirds of these metal concentrations consist of Cordilleran bodies replacing carbonate rocks in the central and eastern part of the deposit. The ores are sulfide-rich and are strongly zoned with internal portions having high sulfidation and oxidation assemblages. In the western part of the deposit, Cordilleran veins are present, hosted by the diatreme-dome complex. This work presents fluid inclusion and hydrogen and oxygen isotope data on the Cordilleran polymetallic replacement bodies and veins. The early pyrite quartz-body, the pyrrhotite pipes, and related iron-rich sphalerite - galena bodies are discussed elsewhere (Baumgartner et al., 2003; Einaudi, 1977).

### Alteration and Mineralization

In the eastern replacement bodies, the cores contain pyrite-famatinite and are accompanied by advanced alteration assemblages, including abundant alunite-quartz. This core grades out to an intermediate zone containing tetrahedrite, Bi- and Ag-rich phases, and pyrite; aluminum phosphate-sulfate minerals such as hinsdalite, as well as kaolinite-(dickite), are common constituents of this zone. The outer zone is the best developed and consists of sphalerite and galena plus abundant kaolinite and alunite group minerals such as hinsdalite. The Cordilleran veins on the western part of the deposit consist of an enargite-pyrite core, an intermediate zone with tennantite, stibnite, and Bi-minerals, and an outer zone that is poorly developed with small amounts of sphalerite and galena. The zoning observed in the Cordilleran ores in Cerro de Pasco is similar to that described by Bendezú et al. (2003) in Colquijirca, located 12 km to the South.

#### Fluid Inclusion and Stable Isotope Results

Cathodoluminescence (CL) imaging indicates multiple quartz generations in single grains. In general, commonly euhedral quartz grains associated with enargite in the core of the veins show three generations (Fig. 1a). The first one is a CL-bright luminescing core with complex oscillatory growth zones typical of magmatic quartz, as well as irregular margins indicating dissolution. The second generation is CL-dark and -bright luminescing with irregular banding and weak internal CL zoning; widespread dissolution borders and minute pyrite and anatase grains occur as inclusions. The third generation of quartz is characterized by marked oscillation with predominantly CL-dull to CL-dark luminescing and rare bright-luminescing growth zones. The first generation of quartz contains magmatic inclusions (~50µm glass inclusion with a shrinkage bubble) and liquid and vapor inclusions along cracks. The

second generation of quartz does not contain measurable fluid inclusions, mainly because of necking down. The third quartz generation contains abundant measurable fluid inclusions.

CL imaging in several quartz crystals from the center of replacement bodies shows only one generation of quartz, characterized by bright-CL oscillatory luminescence in the center of the crystal that becomes CL-darker toward the borders (Fig. 1b). No dissolution is visible. Some bands contain pyrite inclusions.

Fluid inclusions coexisting with vapor inclusions along cracks within magmatic quartz in diatreme-hosted veins have homogenization temperatures between 300 and 230°C and highly variable salinities, with up to 24 wt. percent NaCl eq. Salinities obtained in the other fluid inclusion assemblages, both in veins and replacement bodies, are always <10 wt. percent NaCl (Fig. 1). Fluid inclusion assemblages in growth zones in the third quartz generation from the diatreme-hosted veins yield homogenization temperatures from 200 to 270°C and salinities between 0.1 and 5.2 wt. percent NaCl eq. Those in quartz from the core of replacement bodies yield homogenization temperatures between 200 and 250°C and salinities from 0.1 to 9.5 wt. percent NaCl eq. Fluid inclusions in sphalerite from the outer zone of replacement bodies give slightly lower homogenization temperatures, between 170 and 220°C, and salinities between 0.5 and 10 wt percent NaCl eq.

The isotopic composition of kaolinite (O and H) from the intermediate and outer zone of replacement bodies and of quartz (O) from veins and replacement bodies was measured (Fig. 2), as well as alunite (O and H) from the northwestern part of the district. Water compositions were calculated at equilibrium with kaolinite at 250°C for the intermediate zone and at 220°C for kaolinite from the outer zone. The  $\delta^{18}\text{O}$  and  $\delta\text{D}$  values range from 2 to 9 permil and -65 to -110 permil respectively.

Local meteoric water at Cerro de Pasco is assumed to be similar to that at Julcani (Deen et al., 1994), because of close age and elevation, with oxygen and hydrogen isotopic compositions of  $-17.5\text{ ‰}$  and  $-135\text{ ‰}$ , respectively. The isotopic compositions of water in equilibrium with kaolinite lie distinctly lower than the typical composition of magmatic waters (Fig. 2). One sample is particularly depleted in the heavy oxygen isotope relative to the other samples. Two populations can be distinguished and correspond to kaolinite from the intermediate zone (with higher  $\delta D$  values) and from the outer zone (with lower  $\delta D$  values). Unlike the waters in equilibrium with alunite, the trend depicted by the variations of isotopic compositions of water in equilibrium with kaolinite cannot be explained by simple mixing between magmatic and meteoric waters only. The measured values can be explained, however, with input of meteoric waters having exchanged with host rocks in an open convecting system in the manner proposed by (e.g. Field and Fifiarek, 1985). Models of isotopic exchange of meteoric water with (1) volcanic and (2) sedimentary rocks over a range of temperature from 25 to 400°C have been plotted in Figure 2. High water/rock ratios (0.3 and 0.9, respectively) have been chosen to explain the obtained  $\delta D$  and  $\delta O$  values. These water/rock ratios are in agreement with those estimated for many epithermal districts (Field and Fifiarek, 1985; Taylor, 1974). Therefore, the isotopic composition of the fluids that formed kaolinite (Fig. 2) suggests that magmatic water was mixed with exchanged meteoric water.

Calculated isotopic compositions of water in equilibrium with quartz from veins and replacement bodies, using equations of Zhang et al.(1989), are also shown in Figure 2. Water in equilibrium with quartz from replacement bodies has similar  $\delta^{18}O$  values as water in equilibrium with kaolinite. Only one sample has higher values, which could be explained by fluid interaction with carbonate rocks. O isotopic

compositions of water in equilibrium with veins are lower than those from the replacement bodies. However, these values must be interpreted with care because vein quartz crystals contain several generations of growth, as revealed by CL imaging.

### Conclusions

The fluid inclusion and stable isotope values obtained indicate several mineralization steps characterized by different fluid compositions:

- The alunite-related water appears to result from mixing between magmatic and meteoric water. The magmatic component likely represents oxidized vapors.
- The Cordilleran polymetallic bodies that replaced carbonate rocks in the eastern and central parts of the deposit formed from moderately saline fluids (<9 wt.% NaCl eq.). Their isotopic composition implies strong dilution of magmatic water by exchanged meteoric water and, possibly, minor input of non-exchanged meteoric water. Therefore, the original magmatic fluid had a high salinity. Temperatures of formation in the center of replacement bodies are between 200 and 250 °C, whereas in the outer zones temperatures were generally lower, 170 to- 220°C.
- The Cordilleran enargite-pyrite veins, principally hosted by the diatreme-dome complex, are characterized by moderately saline fluid (mainly <3.5 wt. % NaCl eq.) with homogenization temperatures of 200 to 270°C. The fluid  $\delta^{18}\text{O}$  values are similar but slightly  $^{18}\text{O}$  depleted compared to those forming the polymetallic replacement bodies. Dilution ratios cannot be estimated because of the lack of OH-bearing minerals.
- Vapor plus hotter and more saline fluids occur in inclusions along healed cracks within magmatic quartz, possibly representing early fluids from deeper parts of the system.

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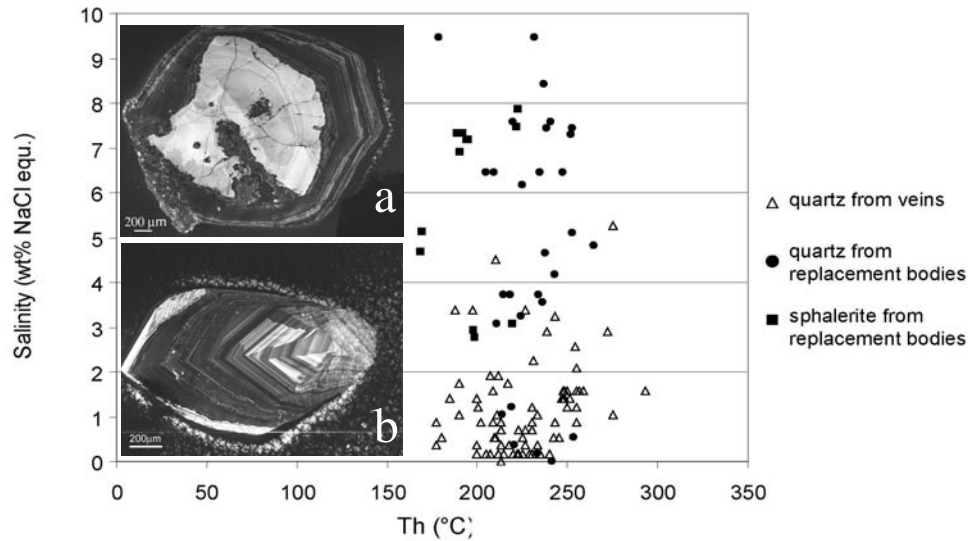


Figure 1: Fluid inclusion data in quartz from the core zone of replacement bodies in carbonate rocks and veins in the diatreme-dome complex. Inserts of cathodoluminescence images for quartz crystals are a) crystal from the center of a Cordilleran vein showing three quartz generations, and b) crystal from the center of a Cordilleran replacement body showing only one generation of quartz. Saline fluids are not present here.

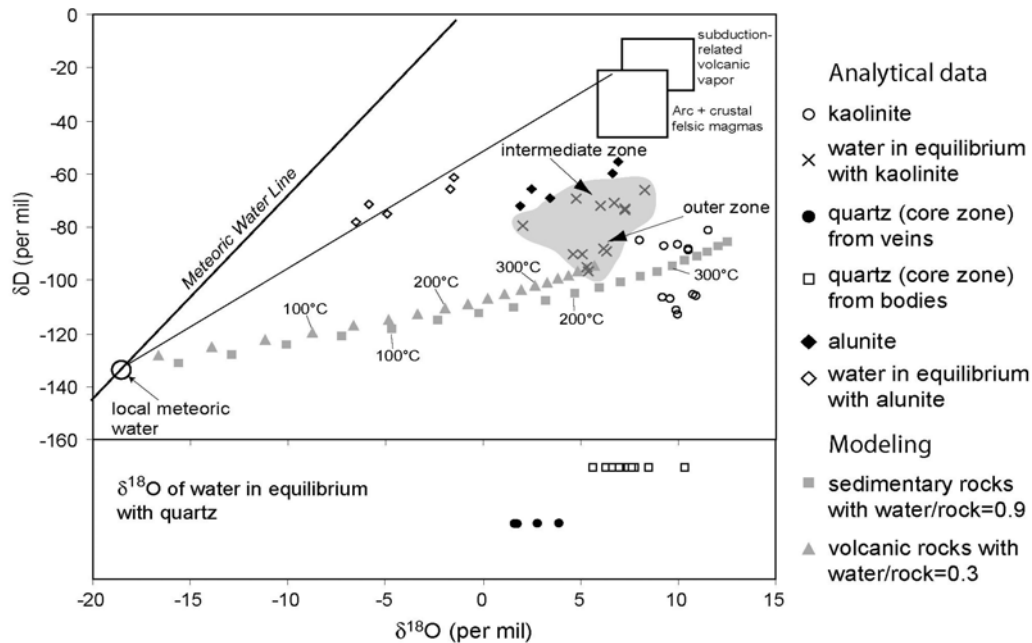


Figure 2: Oxygen and hydrogen isotopic data from Cordilleran veins and replacement bodies.  $\delta D$  and  $\delta^{18}O$  values have been calculated for water in equilibrium with

kaolinite from the Cordilleran replacement bodies using equations of Sheppard and Gilg (1996) for O and Gilg and Sheppard (1996) for H.  $\delta^{18}\text{O}$  values of water in equilibrium with quartz from Cordilleran veins and replacement bodies have been calculated using equation of Zhang et al. (1989).  $\delta\text{D}$  and  $\delta^{18}\text{O}$  values have been calculated for water in equilibrium with alunite from the northwestern part of the district using equations of Stoffregen et al. (1994) at 250°C. For modeling, see explanations in text.