Geological setting, mineralogy, and geochemistry of the Early Tertiary Au-rich volcanic-hosted massive sulfide deposit of La Plata (Western Cordillera, Ecuador)

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ABSTRACT: The Au-rich (4.8 g/t Au) volcanic-hosted massive sulfide (VHMS) deposit of La Plata (Western Cordillera of Ecuador) is hosted by Early Tertiary volcanic rocks of the Macuchi Unit, which represents an intraoceanic island arc sequence, now accreted to the continent. This study presents the first detailed description of the geology, mineralogy, and geochemistry of this deposit.

1 INTRODUCTION

The volcanic-hosted massive sulfide (VHMS) deposit of La Plata is situated in the province of Pichincha (central Ecuador), about 57 km SW of Quito and 32 km SE of Santo Domingo de los Colorados (longitude: 78°56'E – latitude: 00°23'S), on the western slope of the Cordillera Occidental, at an altitude ranging from 1350 to 1700 meters.

A preliminary resource of 840,000 tons @ 4.8 g/t Au, 54 g/t Ag, 4.1% Cu, 0.7% Pb and 4.2% Zn has been measured (Cambior 1998). The high gold grade of the La Plata deposit allows its classification as a Au-rich VHMS deposit (Hannington et al. 1999).

La Plata belongs, together with the deposits of Macuchi and El Patiño to the south (Fig. 1), to an Early Tertiary Au-bearing VHMS metallogenic province within the island arc terrane of Macuchi. In this study we provide the first detailed geological, mineralogical, and geochemical description of the La Plata deposit.

2 GEOLOGICAL SETTING

Ecuador consists of several oceanic and continental terranes accreted to the Amazon craton between Early Cretaceous and Early Tertiary times (Fig. 1). The oceanic island arc terrane of Macuchi, host to the La Plata deposit, consists of a Paleocene-Eocene submarine volcanosedimentary sequence with pillow lavas and intrusions of basaltic to andesitic composition.

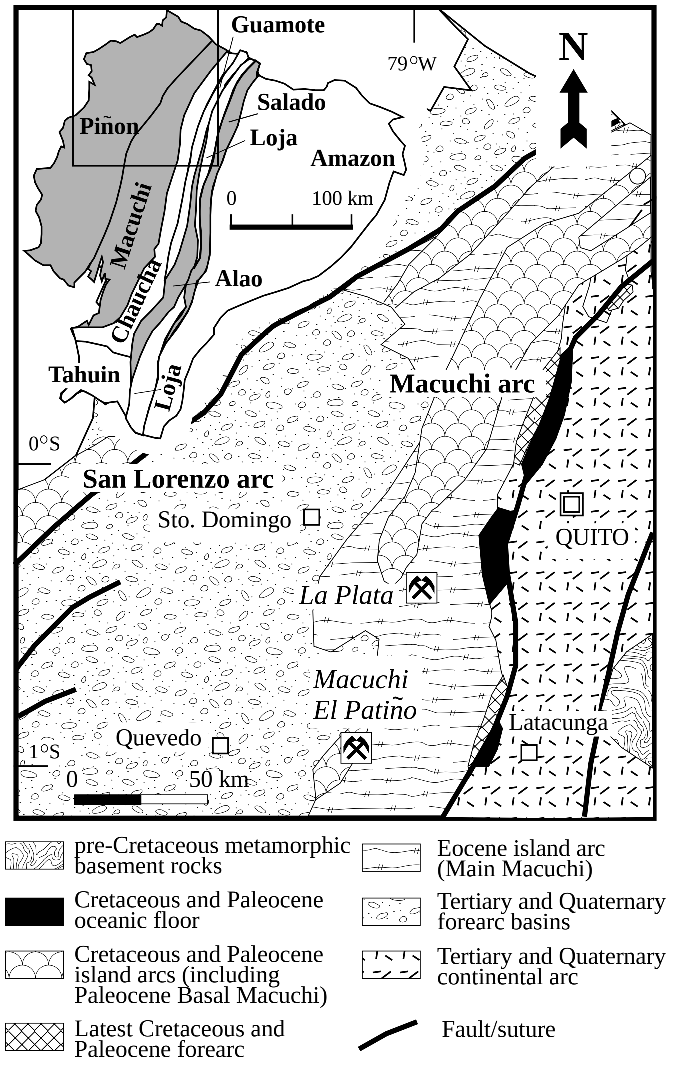

Figure 1. Geological map of the northern Western Cordillera. Inset: geoteconic map of Ecuador (grey=oceanic terrane; white=continental terrane) (from Chiaradia & Fontboté, 2001).

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Within the Macuchi Unit, Chiaradia & Fontboté (2001) distinguish the Paleocene *Basal Macuchi* (lower part of the arc pile, MgO-, Ni- and Cr-rich primitive volcanics, SiO_2 = 47.5-55.0 wt%, MgO = 12.5-4.0 wt%) characterized by abundant basaltic pillow lavas intercalated with mudstones, and the Eocene *Main Macuchi* which is the higher part of the arc pile. The *Main Macuchi* consists mostly of basaltic andesites and andesitic pillow lavas, breccias and volcanic sandstones, but also comprises more evolved and SiO_2-rich rocks (SiO_2 as high as 69.0 wt%, MgO as low as 1.0 wt%), probably resulting from longer magma residence times at shallow crustal levels. The *Main Macuchi* would represent a younger arc superimposed on the older one represented by the *Basal Macuchi*. The La Plata deposit is hosted by the *Main Macuchi* sequence.

3 MINE GEOLOGY AND ORE MINERALOGY

The mine zone consists of an easterly inclined anticline of north-south direction, plunging 45° to the south (Fig. 2). Most of the sulfide mineralization is found on the eastern flank of the anticline, at the transition between felsic and mafic rocks (Fig. 2). The mineralization and host sequence have undergone only weak zeolite facies burial metamorphism and the geometric relationships between orebody and host rocks are close to the original ones except in areas affected by fracturing. The footwall is composed of highly altered dacite crosscut by a mineralized stockwork, while the hanging wall encompasses basaltic to andesitic volcanic rocks, partly massive, partly brecciated. Cambior’s geologists and Prodeminca (2000) describe the occurrence of rhyodactic intrusive bodies (dikes or sills) on the eastern flank of the anticline. A ubiquitous level of massive jasper (<10 cm thick) is found directly atop of or less than 5 meters above the mineralization (Fig. 2). The Al-Fe-Mn concentrations suggest a hydrothermal exhalative origin for this level.

The geochemistry of the volcanic rocks reveals a tholeiitic affinity and an ensimatic island arc setting in agreement with previous studies (e.g., BGS & CODIGEM 1999; Chiaradia & Fontboté 2001). Perlitic textures found in footwall lithologies are consistent with a submarine volcanic environment. On the other hand no traces of explosive activity (e.g., pyroclasts) have been found.

The host rocks are altered to various degrees due to the occurrence of the zeolite-facies burial metamorphism and to the hydrothermalism associated with the mineralization. The hydrothermal alteration phases are essentially quartz, sericite, pyrite, ± chlorite, ± illite in the footwall, and hematite, ± pyrite, ± sericite, ± ankerite in the hanging wall.

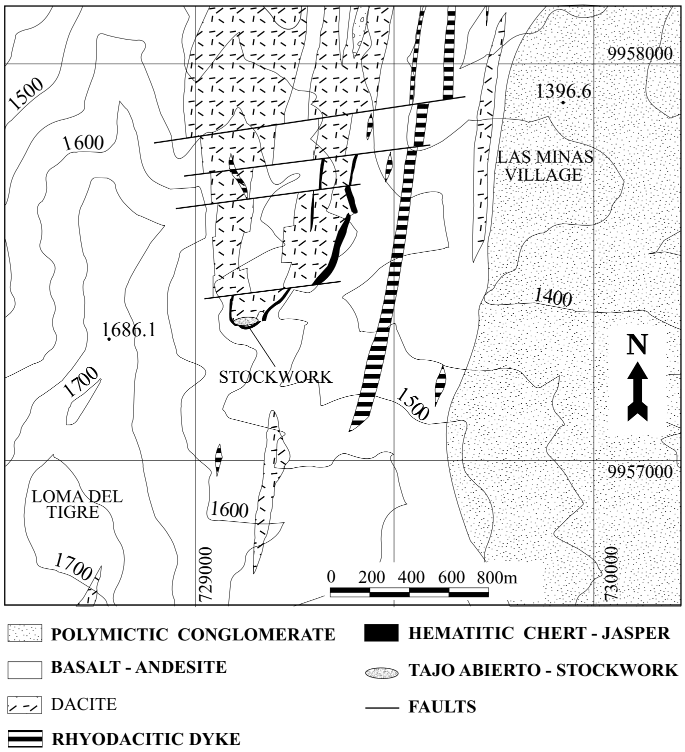


Figure 2. Geological map of the La Plata concession (modified after Cambior’s mapping). See http://www.unige.ch/sciences/terre/mineral/seminars/quito03_terreno/quito03_terreno.html for a more detailed colour map.

The orebodies are massive to semi-massive lenses forming a well defined stratigraphic horizon. Their thickness varies from several decimeters to a few meters, rarely exceeding 10 meters, and their lateral extent can reach 100 meters. The main ore minerals are chalcopyrite, pyrite, sphalerite, bornite, and galena, with subordinate fahlore (identified as tennantite by electron microprobe analysis) and covellite, accessory digenite, chalcocite, and native gold. Gangue minerals are barite and, to a lesser extent, quartz. Ore minerals often display fine laminated textures. Resedimented ore breccias (e.g., from mound erosion) are absent at La Plata. The mutual relationships of the ore phases permit to divide the mineralization events into three principal stages (Fig. 3) although overlapping between stages occurs due to the dynamic nature of the VHMS formation process. The *Early ore stage* is characterized by the deposition of massive pyrite. It is followed by the *Main ore stage* characterized by the deposition of almost all economic ore minerals: chalcopyrite, sphalerite, and subordinate bornite and galena. Bornite and sphalerite seem to be cogenetic, while chalcopyrite and galena are later phases. Chalcopyrite replacing pyrite, sphalerite, bornite, and galena, as well as chalcopyrite filling fractures within these minerals are common features. No traces of significant recrystallization nor mobilization of ore minerals have been observed.

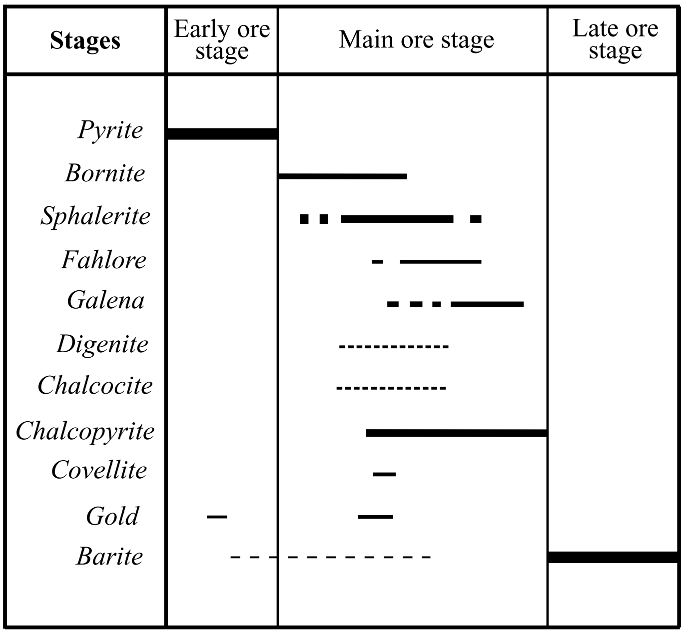


Figure 3. Paragenetic mineral sequence at La Plata.

During the *Main ore stage*, accessory phases such as fahlore, primary covellite, and very little chalcocite and digenite were also formed, with ambiguous relationships with the other ore phases. Fahlore is spatially associated and cogenetic with sphalerite. The *Late ore stage* is characterized by the precipitation of abundant barite infilling the voids between preexisting minerals. No massive bedded barite has been identified. Gold occurs in small grains ranging in size from 5 to 50 microns, but a large grain reaching 350 microns was also observed. The smaller grains are often rounded and occur within other ore phases of the *Main ore stage*, in particular bornite, chalcopyrite, galena, and digenite. The bigger gold grains fill open spaces within the boundaries of surrounding minerals. Gold inclusions within early pyrite were also observed and might suggest an early gold stage, but this should be verified by additional work. In a similar way, it is not clear whether the gold occurring as single grains in barite is cogenetic with this mineral. Electron microprobe analysis reveals Au-contents ranging from 79.6 to 97.0 wt.%, the remainder being represented essentially by Ag with minor amounts (<1%) of Hg and Cu.

4 ORE GEOCHEMISTRY

The $\delta^{34}S$ values of the sulfides range between -2.2 and +1.6 ‰ (N=16: Fig. 4). As in other VHMS deposits, the results do not allow to discriminate between (i) leaching of basaltic sulfur from underlying volcanic rocks, and (ii) non-bacteriogenic reduction of marine sulfate at temperatures of 250° to 300 °C. The sulfur isotopic composition of barites ($\delta^{34}S$ = 20 to 21.4 ‰: Fig. 4) exhibits the signature of marine sulfate at mid- to upper Eocene times and argue against a direct magmatic contribution of volcanic SO_2 to the hydrothermal system. Even if the use of sulfur isotope pairs as a geothermometer is problematic in VHMS because isotope equilibrium is rarely attained, the calculated temperatures (250-365 °C for sulfate-sulfide, 205-310 °C for sulfide-sulfide) are in general agreement with the accepted temperature ranges of Cu-bearing VHMS deposits. The effects of a possible re-equilibration during low-grade metamorphism should nevertheless be considered.

The $^{87}Sr/^{86}Sr$ compositions of barites show that, whereas seawater probably provided the major part of sulfur contained in barite, Sr (as well as Ba) was mainly derived by the interaction of the hydrothermal fluid with footwall volcanic rocks (Fig. 5).

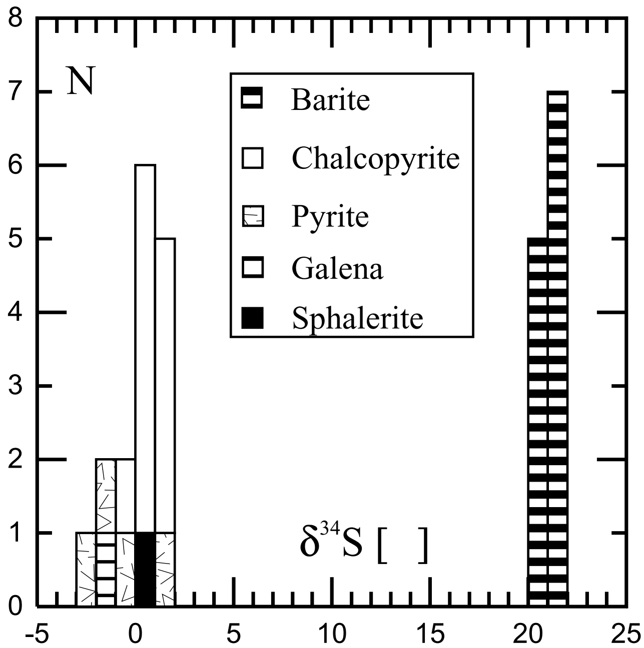
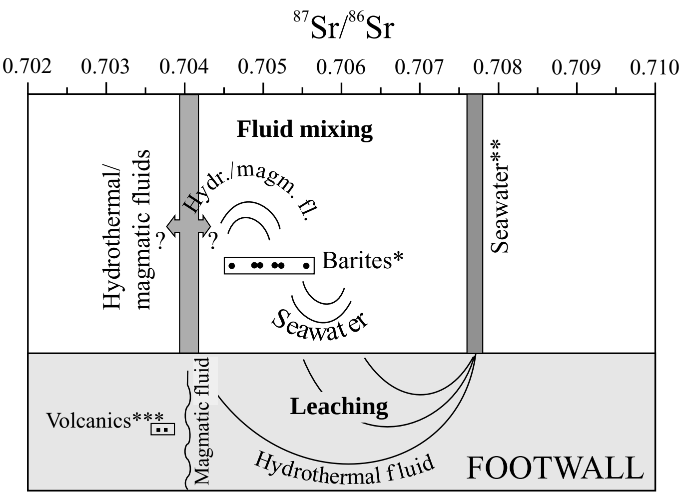


Figure 4. $\delta^{34}S$ values in sulfides and barite of La Plata.

Therefore, the combination of sulfur isotopes and $^{87}Sr/^{86}Sr$ ratios ($^{87}Sr/^{86}Sr$ = 0.704601±9 to 0.705549±8) of the barite favors a mixing model for the precipitation of this mineral (Fig. 5).

The lead isotopic compositions of ore minerals (Chiaradia & Fontboté 2001) are very homogenous and overlap the compositional field of the *Main Macuchi* rocks, suggesting derivation of the majority of ore lead from leaching of the *Main Macuchi*.

The $^{207}Pb/^{204}Pb$ values (~15.67) of ore minerals and associated magmatic rocks of La Plata are anomalously high for an intraoceanic island arc setting and possibly result from spiking of a depleted mantle source by radiogenic lead from pelagic sediments (Chiaradia & Fontboté 2001).



* Analyzed in the present study *** After Cosma et al. (1998)
** After Burke et al. (1982)

Figure 5. Model of Sr isotope signatures of La Plata barites.

5 CONCLUSIONS

Currently, the major factors attributed to high gold grades in VHMS deposits are a peculiar fluid chemistry, the direct involvement of magmatic volatiles, a petrogenetic enrichment in the source rocks, and boiling at shallow-water depth (Hannington et al. 1999). With regard to fluid chemistry, isotope analyses (sulfur, strontium and lead) emphasize the involvement of several fluid and metal sources at La Plata. The ore chemistry (0.27 mole% FeS in sphalerite, As-rich tennantite), the bornite + pyrite assemblage and the presence of primary covellite could indicate relatively high conditions of sulfidation. Nevertheless, the absence of acid alteration assemblages comparable to those observed in certain Au-rich VHMS deposits (e.g., Sillitoe et al. 1996), does not support circulation of hot and acidic fluids during ore formation. Shallow level boiling could not be tested in this study. On the other hand, Chiaradia & Fontboté (2001) propose a possible petrogenetic control of the high gold grades, whereby magmatic extraction from a residual source might play a role in the formation of Au-rich VHMS deposits of the Western Cordillera.

In conclusion, paragenetic, geotectonic, petrographic, and geochemical considerations suggest that La Plata belongs to the Kuroko-type VHMS of Sawkins (1976), or to the bimodal mafic VHMS-type of Barrie & Hannington (1999). The fact that the massive sulfides form a stratigraphically well defined horizon, the presence of textures showing fine lamination, the proximity of the exhalite jasper horizon, and the absence of breccias related to mounds are features that could be used to support a brine-pool model for the La Plata VHMS deposit, although more data (including fluid inclusions) are necessary and other interpretations are possible.

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