MAGMA OXIDATION CONDITIONS RELATED TO GOLD AND COPPER MINERALIZATION IN THE HUALGAYOC MINING DISTRICT, PERU

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INTRODUCTION

The Hualgayoc mining district is located in the Andean Cordillera of northern Peru, 30 km north of the Yanacocha high-sulphidation Au deposit. The district hosts many Au ± Cu deposits, including the Cerro Corona Au-Cu porphyry, Tantahuatay high sulfidation Au, and AntaKori Cu skarn/high sulphidation Au-Cu deposits. In addition, the Cerro Jesus and Cerro San Jose intrusions host past-producing mines of Ag-rich intermediate sulfidation veins. The main objective of the study is to evaluate the characteristics of the intrusions associated with various mineralization.

The dominant phase of intrusive rocks in the Hualgayoc mining district is hornblende ± biotite-bearing porphyritic diorite with magnetite micro-phenocrysts. This includes the Cerro Corona complex, the Coymolache sill, the San Miguel diorite, and the San Nicolas, Cerro Quijote, Cerro Jesus, Cerro San Jose, Cerro Caballerisa and Cerro Choro Blanco intrusions. Volcanic rocks include the Hualgayoc rhyodacite north of Cerro Corona, the San Miguel andesite which contains clinopyroxene with rare xenocrysts of blue sapphire, and the andesitic to rhyolitic volcanic rocks of the Calipuy formation, host rocks to some of the AntaKori and Tantahuatay deposits.

All intrusions are hydrothermally altered except for the Coyomolache sill, the San Nicolas intrusion and the Hualgayoc rhyodacite. Variable chlorite ± epidote alteration affects the San Miguel diorite and Cerro Quijote intrusions. Intense alteration of white mica and clay minerals occurs at San Jose, Cerro Jesus, Tantahuatay and AntaKori. Acidic alteration of pyrophyllite ± alunite is present in Cerro Cienaga, Cerro Tantahuatay and AntaKori. Potassic alteration of K-feldspar + biotite + magnetite occurs in the Cerro Corona complex, and locally in the San Jose intrusion.

GEOCHRONOLOGY

We obtained new U-Pb zircon ages of 14 igneous rocks from the district. The data indicate that magmatic activity occurred from 15 to 9 Ma, which is similar to the ages of igneous rocks of the Yanacocha high-sulfidation Au deposit (16-8 Ma; Longo *et al.*, 2010), although most intrusions in the Hualgayoc District were emplaced between 14 and 15 Ma. Some of these intrusions are accompanied by Au-Cu mineralization (i.e., Cerro Corona), whereas

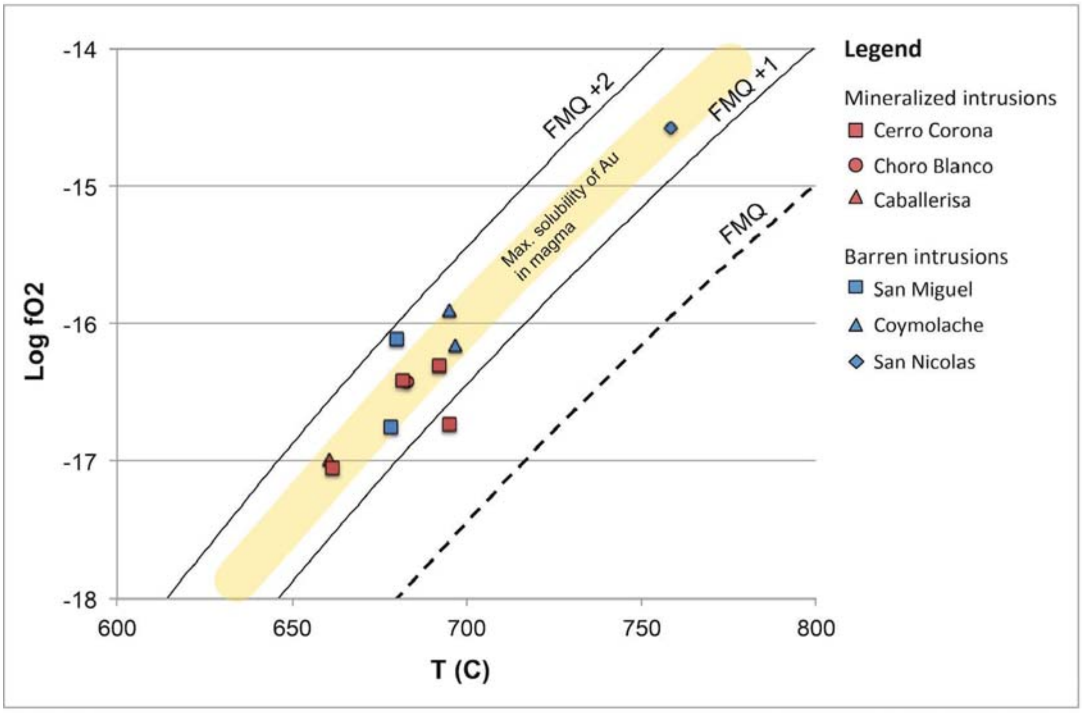

Figure 1. Temperature vs fO_2 relation for several barren and mineralized intrusions in the Hualgayoc District. Temperature was calculated from Ti content in zircon. Band of maximum solubility conditions for Au in hydrous sulfur-rich melt from Botcharnikov *et al.* (2010)

others appear to be barren (Coymolache). The volcanic rocks of the Calipuy formation which host the Tantahuatay high-sulphidation deposit are dated at 13 Ma. Late magmatism consists of barren rhyodacite-rhyolite domes intruded at 9.7 Ma.

BULK ROCK COMPOSITIONS

Igneous rocks in the district show high Sr/Y (40–90), moderately low Y concentration (8-16 ppm) and [La]n/[Yb]n ratio (9–18), and low [Dy] n/[Yb]n ratio (1.4-1.1). The geochemical signature is attributed to water-rich magmas formed by partial melting of an amphibole- bearing source. High water content in the magmas suppressed early crystallization of plagioclase to result in high Sr. Amphibole is responsible for low heavy rare earth elements and Y. All intrusions have relatively low Th content (3-7 ppm), indicating essentially no assimilation of siliciclastic rocks during magma ascent through the thick continental crust.

OXIDATION STATE OF MAGMAS

Using Ce4+/Ce3+ ratios in zircon and bulk rock compositions, fO_2 values of the parental melt for individual intrusions were calculated following the method of Smythe and Brenan (2016). All intrusions are moderately oxidized, FMQ +1 to +2 (logarithmic units above the fayalite-magnetite-quartz buffer) and the values are apparently independent of the association with mineralization (Figure 1). Oxidized melt can dissolve sulphides in the source and transport Au to the upper crust without precipitation of Au- and base metal- bearing sulphide melt (Botcharnikov *et al.* 2010). Au solubility in andesitic melt increases with increasing oxidation conditions and reaches its maximum value at around FMQ +1.5, beyond which the solubility of Au starts decreasing dramatically (Botcharnikov *et al.* 2010). In contrast, the solubility of Cu in andesitic melt increases steadily with increasing oxidation conditions (Zajacz *et al.* 2012). The median fO_2 value of magmas from the Hualgayoc mining district, FMQ +1.48, correspond to high Au solubility and appears to be consistent with the abundant Au mineralization in the district including the high Au/Cu ratio, ~1.7 x10-4, of the Cerro Corona deposit. If the magmas were more oxidized (FMQ e+2) we would expect to observe prevalent Cu mineralizations with minor Au mineralizations

CONCLUSION

Au-(Cu) mineralization in the Hualgayoc mining district is associated with hydrous, moderately oxidized magmas that originate from amphibole-bearing source rocks, with little to no crustal assimilation upon ascent and emplacement. Contemporaneous emplacement of mineralized and barren intrusions in the district suggest that an intrinsically high fO_2 value recorded by magmas does not necessarily imply the presence of Cu and Au mineralization. Other factors include the generation of a significant hydrothermal system upon magma crystallization in order to mobilize metals exsolved from magmas and and concentrate to economic values.

Our results also suggest that although the fO_2 value of magma may be of limited use to differentiate barren from mineralized intrusions across a district, this characteristic may be useful to identify potentially mineralized districts associated with high magmatic oxidation state (FMQ >+1) from barren districts with low magmatic oxidation state (FMQ <+1).

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