

# Amphibole Geochemistry of the Yanacocha Volcanic Rocks, Peru: Evidence for Diverse Sources of Magmatic Volatiles Related to Gold Ores

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The Yanacocha mining district, northern Peru, contains ~1,500 tonnes of gold resources hosted in quartz ± alunite altered rocks, in an area of relatively thick continental crust (~35 km) and long-lived Cenozoic subduction-related arc volcanism. Volcanism in the district began at ~20 Ma, and gold deposits are spatially and temporally associated with eruption of the ~80 km<sup>3</sup> Miocene Yanacocha Volcanics from 14.5 to 8.4 Ma. These volcanics are highly oxidized (~NNO +2), contain magmatic anhydrite, and range from andesite to dacite and minor rhyolite. The Yanacocha Volcanics consist of five successive eruptive groups: the Atazaico Andesite lavas, the Colorado Pyroclastics (andesite-dacite), the Azufre Andesite (and dacite) lavas, the San Jose Ignimbrite and related domes (dacite), and small volumes of Coriwachay Dacite dikes, domes, and (rhyolite) ignimbrite that are temporally associated with most gold mineralization.

The Atazaico and Azufre lavas contain one type of amphibole, but the Coriwachay Dacite ignimbrite units are characterized by two populations of amphiboles distinguished by aluminum content. On the basis of phase equilibrium, the low-aluminum (low-Al) amphiboles were formed at 750° to 840°C and 110 to 240 MPa (4–8 km depth), whereas high-aluminum (high-Al) amphibole is estimated to be the liquidus phase at 950° to 1,000°C and  $P_{H_2O} > 250$  MPa and total pressure of ~400 to 600 MPa (12–20 km depth). The content of rare earth and other trace elements of amphibole and whole rock suggests high-Al amphibole crystallized in equilibrium with bulk basaltic-andesite to andesite magma at low degrees of crystallization, whereas low-Al amphibole crystallized from dacite magma at high degrees of crystallization and a rhyolitic melt composition.

Hydrogen isotope compositions were analyzed by TCEA-IRMS (n = 77) and SIMS (n = 16) on both types of amphibole in order to determine the origin of the magmatic water. The  $\delta D_{Amph}$  via TCEA for 12.5 to 11.0 Ma andesite-dacite ranges from –40 to –120‰, whereas  $\delta D_{Amph}$  of younger dacitic volcanics and shallow intrusions (10.8 to 8.4 Ma) associated with gold mineralization is isotopically light and ranges from –100 to –112‰. The heaviest  $\delta D_{Amph}$  values (ca. –40‰) likely represent deep, subduction-derived water dissolved in a water-, fluorine-, and sulfate-rich but chlorine-poor basaltic andesite magma, whereas the lightest  $\delta D_{Amph}$  values (ca. –105‰) characterize the upper crustal chlorine-rich dacite magma chambers. Injection of the deep mafic magma into the shallow dacite magma may have triggered the Colorado and San Jose pyroclastic eruptions, and is supported by the short residence times (<1 yr) of high-Al amphibole admixed into dacite as estimated from dehydration rims and hydrogen diffusion lengths. The isotopically light values of the ore-associated Coriwachay dacitic magmas were produced by assimilation of earlier parts of the Yanacocha Volcanics affected by meteoric-hydrothermal alteration. These dacites contain low-Al amphibole that is zinc and chlorine rich whereas, in

comparison, the associated high-Al amphibole is copper and fluorine rich. Therefore, the deep hydrous oxidized mafic magmas may have supplied much of the sulfur, fluorine, copper, and, by inference, gold, whereas upper crustal recycling may have supplied most water and chlorine to late dacite magmas and ore fluids.