

PROGRESS REPORT ON A PETRO-GEOCHEMICAL AND MINERALOGICAL STUDY OF THE “EL TENIENTE BELT”, CENTRAL CHILE: IMPLICATIONS OF LOWER CRUSTAL MELTING PROCESSES AND THE LINKS TO GIANT ANDEAN PORPHYRY Cu-Mo MINERALIZATION

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OVERVIEW

Over the past few years, our research group has been actively engaged in the study of magma genesis in subductive regimes and on the use of resistate minerals as a monitor of environment of formation. A major portion of this research has been funded by CONICYT-Chile through Fondecyt research grants. This present Fondecyt Lineas Complementarias project builds on these accomplishments and a much broader scale project has emerged to further develop the scientific understanding of deep crustal/subduction zone-related magmatism associated with active continental margins and its constraints on the formation of economic porphyry Cu-Mo systems.

INTRODUCTION

The main objective of the project is to evaluate processes that took place deep in or below the Andean crust of the El Teniente Belt of Central Chile and link them to those processes that formed some of the giant to supergiant Miocene-Pliocene porphyry copper deposits characteristic of this belt. This presentation outlines findings to date on several fronts of the project. The majority of the works focuses on the El Teniente supergiant porphyry copper deposits as data from the other two systems (Los Pelambres and Río Blanco-Los Bronces) are still being collected at the time of writing.

HIGH-AL TTG ANALOGOUS INTRUSIVE ROCKS IN THE SUPERGIANT EL TENIENTE PORPHYRY COPPER DEPOSIT.

The main igneous units at the El Teniente deposit are: the pre-ore “Andesitas de la mina” (subvolcanic mafic bodies), “Diorita Sewell” (leuco-quartz-diorite to trondhjemite stock) and the syn-ore “Pórfido Teniente” (leuco-dacite porphyry) and minor leuco-tonalitic apophyses.

The distinctive petrographic and geochemical features of the felsic intrusive units include: leucocratic character, high Na_2O (>4.5wt%) and Al_2O_3 (>15.5wt%) contents, high Sr/Y (>80), La/Sm (>5) and La/Yb (>25) ratios with low HREE_{chn} (~2x), Y (<7ppm) and Sc (<10ppm) contents, sub-alkaline (calc-alkaline) affinity and metaluminous character ($\text{ASI}<1$). The evidence suggest that these rocks were mainly derived from a garnet(\pm pyroxene \pm amphibole)-bearing basaltic source. Additionally, the lack of a negative Eu anomaly in conjunction with high Sr (550-1050 ppm) content for a silica range of 60 to 70wt%, preclude significant plagioclase in the source residue. Furthermore, #Mg <0.55 coupled with relatively low Ni (\approx 10 ppm) and Cr (\approx 20 ppm) contents of these rocks, preclude any significant interaction of the silicic magmas with the mantle wedge.

From the isotopic point of view, these porphyries have less radiogenic $\text{Sr}_{(i)}$ values (\approx 0.7040) and higher $\epsilon\text{Nd}_{(i)}$ values (+3.4 to +3.9) than those exhibited in Quaternary volcanics at the same latitude, but are almost identical to modern lavas erupted through the thinnest SVZ crust. The Pb isotopes, are clearly more radiogenic than Nazca Plate Basalts, but less radiogenic than those from the Juan Fernández aseismic Ridge.

Overall, petrographic, geochemical and isotopic evidence points to a general petrogenetic model based on high pressure partial melting of young mafic Andean lower crust, as the main magma source from which this high-Al TTG analogous suite associated with the El Teniente porphyry Cu-Mo deposit was derived.

BORON BEHAVIOUR IN SVZ ROCKS: IMPLICATION OF BORON, CRUSTAL/ SUBDUCTION PROCESSES AND SUPERGIANT COPPER MINERALIZATIONS

In order to understand the origin of the large amounts of B associated with the supergiant porphyry copper deposits of the Central Chile Andes, we have investigated the behaviour of B in simpler basaltic to basaltic andesite systems belonging to the central and southern provinces of the southern volcanic zone of the Andes (CSVZ, 33°-41.5°S; SSVZ 41.5°-46°S). Samples are from small eruptive centers (SEC) and large stratovolcanoes. While SEC are controlled by the 1000 km long, N10°E, Liquiñe-Ofqui Fault Zone (LOFZ), which is located behind the volcanic front, the stratovolcanoes in contrast are controlled by fractures tranverse to this fault. Volcanic front stratovolcanoes are richer in B (12.8-16.2 ppm) than SEC. With the exception of Huellemolle and Mirador (12.1 and 11.5 ppm B respectively), the studied SEC have B contents < 10 ppm. The lowest value (1.6 ppm) is found in a basalt (48.8% SiO_2) from the Puyuhuapi volcanic group, which is located well behind the volcanic front. Puntagudo stratovolcano, also located behind the front and controlled by the LOFZ, has low B content (2.9 ppm)

similar to SECs. The affinity of B to aqueous fluids phases and its positive correlation with ^{10}Be suggests that B is firstly controlled by the amount of aqueous fluids liberated from the slab which, in turn, is related to its surface temperature and position of centers with respect to depth of the slab, and secondly to the evolution styles of magmas and eruptive behaviour of each center. This, together with the low concentrations of B in the lower crust suggest that B increases as the hydrothermal solutions increase during the rise of the magmas through the crust. Thus, it is expected higher concentrations of B in deposits emplaced in a thick crust.

MINERAL CHEMISTRY OF TOURMALINE, RUTILE AND APATITE FROM THE SUPERGIANT EL TENIENTE PORPHYRY COPPER DEPOSIT: IMPLICATIONS FOR SOURCE REGIONS, MAGMATIC AND HYDROTHERMAL PROCESSES

a. Tourmaline

A survey of tourmaline from the El Teniente porphyry copper deposit is reported with emphasis on distribution, texture, compositional varieties, minor, trace and REE abundances, together with stable isotope (O, H, B) signatures. Tourmaline occurs 1) as a trace constituent in veins and wallrocks associated with stockwork mineralization and alteration and 2) as the primary matrix material associated with tourmaline breccia pipes. Texturally, the tourmaline occurs as scattered needles, as radial groups of crystals, as massive granular aggregates and as intergrown aggregates of fine-grained fibrous needles.

The tourmaline have characteristic major and trace element compositions. SiO_2 and B_2O_3 contents generally display little variations, whereas Al_2O_3 (36.9 to 18.7 wt%), FeO (19.3 to 1.9 wt.%) and MgO (10.0 to 5.7 wt%) have significant compositional ranges. Abundances of K_2O (0.10 to 0.02 wt%), and CaO (0.95 to 0.19 wt%) are systematically low, while Na_2O varies from 2.7 to 1.9 wt. %. Contents of MnO and Cr_2O_3 are commonly below detection limits. TiO_2 varies widely between 3.89 to 0.06 wt%. On the Al-Fe-Mg ternary diagram, the tourmaline plots within the schorl-dravite solid solution series, with a tendency for Mg-rich members (dravite) to dominate. Calculation of the structural formula indicates Fe^{3+} substitution for Al^{3+} is common. Zonation in the tourmaline can be either optically and chemically distinct or non existent. Two styles of chemical zonation have been observed including a Fe-Mg zonation were the Al content remains uniform and a Fe-Al zonation with a stable Mg content.

The results are discussed in terms of the significance of tourmaline in the copper forming system, as well as its relevance as a potential pathfinder for source regions and crustal/subduction processes.

b. Rutile

At the El Teniente deposit, rutile is the main Ti mineral in the hydrothermal alteration envelopes, particularly in the potassic core. Rutile is formed under hydrothermal conditions from the breakdown of Ti-bearing

minerals. Minor anatase was also identified, yet it tends to occur in distal carbonate veins in the deposit fringe. Sampling covered the main hydrothermal alteration zones and lithologies present in the ore deposit.

EPMA (n=326) and PIXE (n=85) analyses of rutile(-anatase) show relatively high minor and trace elements contents (~3 wt%), where Fe, W and V account for almost 90% of the impurities. The remaining ~10% includes traces of Mn, Cr, Si, Al, Nb, Ta, Sn, Sc, Mo, Cu, Zn, Sb, Pb, As, Ni, Zr and U.

Results shows that in spite of the super-giant nature of this deposit and its complex history of alteration and mineralization, rutile(-anatase) composition changes systematically with position in the deposit. Most indicative elements are: Mo, Zr, Nb, Ta, U, As and Pb. Molybdenum is high (186 ppm) in rutiles from porphyries but very low (~5 ppm) in rutiles from the wallrock. In the same way total HFSE content is almost 5 time higher in rutiles from the porphyries (1307 ppm) than in those from the wallrock (269 ppm). Uranium in rutile shows a similar, but less marked, concentration contrast, with 49 ppm in the porphyries and 18 ppm in wallrock rutiles. One exception is anatase, which is enriched in U (78 ppm) and also in lead. Arsenic is enriched in rutile(-anatase) from the marginal low ore-grade propylitic zone (46 ppm), while it is very low (6 ppm) in rutile from the potassic core.

The fact that rutile produced by mineralizing fluid alteration can allocate a broad spectrum of different cations makes this Ti-oxide a potential “monitor” of the chemical evolution of hydrothermal fluids.

c. Apatite

Sulfur is an essential component in magmatic and hydrothermal fluids that produce porphyry copper deposits. Its speciation ($S^=$ or S^{+6}) is strongly dependent on the oxygen fugacity of the magma, being $S^=$ dominant at low fO_2 , and S^{+6} at high fO_2 . Oxydized magmas prevent early sulfide fractionation, producing S and metals concentration towards the later stage of magmatic crystallization, favoring in turn, ore deposit formation.

From the crystal chemistry point of view, S can enter in apatite structure when it is as S^{+6} . Therefore its content in apatite could be a good monitor of magma oxydation state. We have analyzed apatites from the silicic porphyries at El Teniente (“Porfido Teniente” (PT), “Diorita Sewell ” (DS) and “Diorita La Huifa” (LH)).

Preliminary results based on EPMA analyses allow us to establish: 1) All analyzed grains have measurable SO_3 content. 2) It varies within a) the same grain (generally lower toward rims), b) between different grains (depending on the texture: apatite inclusions are richer than microphenocrysts and groundmass grains), and c) between different rock-units (apatites from the PT (related to Cu mineralization), have the highest values (0.69wt% compared to DS (0.55wt%) and LH (0.37wt%). 3) In LH, two apatite populations have been identified: one with a turbid appearance, and low minor element content, and another, clear in appearance, with characteristically high chlorine content (up to 2.8wt% Cl, while the highest value in PT and DS is 0.9wt%). 4) S enters into the studied apatite by the following coupled substitution mechanisms: a) $S^{+6} + Si^{+4} _ 2P^{+5}$ and/or b) $S^{+6} + Na^+ _ P^{+5} + Ca^{+2}$. 5) Additionally Si and Na also participate in other coupled exchange reactions to explain the main chemical features of the studied apatites: a) $REE^{+3} + Si^{+4} _ P^{+5} + Ca^{+2}$ and b) $REE^{+3} + Na^+ _ 2 Ca^{+2}$.

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