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LATE MIOCENE COPPER DEPOSITS, MAGMATISM AND TECTONICS IN THE ANDES OF CENTRAL CHILE

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Within the three Late Miocene to Pliocene Andean copper deposits Los Pelambres, Los Bronces-Río Blanco and El Teniente of central Chile (32-34°S), copper ore occurs both disseminated in association with altered porphyritic plutons, as well as in younger large mineralized breccia pipes emplaced explosively by the expansion of magmatic-hydrothermal fluids[1-3]. Some individual pipes are >2 km in vertical extent and with surface diameters >1 km. At Los Bonces-Río Blanco, a group of >10 distinct pipes, generated over 2.5 million years, form an elongated body >4 km in length and 1 km wide at the present erosional surface, and these breccias contain approximately 50% of the >50 million metric tons of Cu at this deposit[1,2].

Fluid inclusion and stable isotope data for breccia-matrix minerals indicate that these minerals, including copper ore, co-precipitated in open spaces from high-temperature, highly saline fluids exsolved from magmas[4-6]. Breccia-matrix minerals (tourmaline, biotite, anhydrite) have $^{87}Sr/^{86}Sr$ ratios which range from 0.7040 to 0.7049 and ϵ_{Nd} values which range from +3 to +1.1 [5,6]. These values are intermediate between those of the older Miocene host rocks ($^{87}Sr/^{86}Sr$ = 0.7037 to 0.7040; ϵ_{Nd} = +4.9 to +2.1) and younger Late Miocene and Pliocene igneous rocks ($^{87}Sr/^{86}Sr$ = 0.7043 to 0.7049; ϵ_{Nd} = +0.7 to -1.4) emplaced at each deposit after the formation of the breccias.

Various lines of evidence imply that the metal-rich magmatic fluids that generated the breccias were not derived from the Miocene plutons which host these breccias. First, the available chronological data indicate that the plutons are 1-3 million years older than the breccias[1-3]. Also, the angular nature of plutonic clasts in the breccias demonstrate that the host plutons were already crystallized at the time of breccia formation. Many clasts contain truncated quartz-sulfide veins, indicating that these host plutons had been hydrothermally altered and mineralized prior to breccia formation, and fluid inclusion data suggest that the host plutons had been uplifted and partially unroofed by erosion prior to breccia formation[7]. Finally, the Sr- and Nd-isotopic data indicate that the magmatic fluids that formed the breccia were in many cases isotopically distinct from the host plutons.

We conclude that the breccia-forming fluids were derived from plutons not yet

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exposed at the surface. This is consistent with the fact that the roots of the breccia pipes have not yet been encountered. For the case of Los Bronces-Río Blanco we estimate the approximate volume of unexposed plutons as follows: 1) the breccias form a body 4 km long, 1 km wide, and an estimated 1 km in vertical extent, implying a total volume of 4 km^3; 2) on the average breccias contain 75% clasts and 25% matrix, indicating 1 km^3 of total matrix material which was all deposited from the high-temperature, highly saline magmatic fluids which generated the breccias; 3) fluid inclusion data suggest that fluids carried at least 50% by weight total dissolved solids[5], implying that the total amount of fluid involved in breccia formation was twice the weight of the 1 km^3 of precipitated breccia-matrix material; 4) assuming that these fluids exsolved from magmas with 2 weight % dissolved water, the plutons were 50 times more massive than the exsolved breccia-forming fluids and thus 100 times more massive than the precipitated solids in the breccia matrix; and finally 5) assuming the breccia-matrix minerals have similar density as crystallized plutons, the volume of plutons from which the breccia-forming fluids exsolved were thus 100 times that of the total breccia matrix deposited, or 100 km^3. This volume of unexposed plutons, crystallized over the 2.5 million year period of breccia formation at Los Bronces-Río Blanco, represents only a relatively small proportion of the total volume of Miocene plutonic and volcanic rocks associated with this deposit.

We conceive of the generation of the Late Miocene and Pliocene copper deposits in the Andes of central Chile in the context of dynamic long-lived magmatic systems[5,6]. These systems were initiated in the Early Miocene with the eruption of over 3,000 meters of Farellones Formation lavas. Subsequently, these lavas were intruded by upper-crustal Early to Middle Miocene plutons. These lavas and plutons, which are the host rocks for the breccias, represent the upper and early portions of the same magmatic systems out of which the mineralized breccias were later generated. They were altered and mineralized prior to breccia formation. Younger plutons, not yet exposed at the surface, exsolved the metal-rich fluids that formed the mineralized breccias. The Sr- and Nd-isotopic variability among the mineralized breccias indicates that no single specific "copper porphyry magma" was required for their generation. Instead, the metal-rich fluids which formed the breccias were derived from magmas, cooling in the mid- to upper-crust, which had variable isotopic composition, including magmas isotopically similar to both older Miocene and younger Pliocene igneous rocks associated with each deposit. Finally, post-breccia porphyritic magmas were either erupted or emplaced at shallow levels in the vicinity of each deposit as these magmatic systems declined and magmatic activity migrated eastward[8] in the Late Miocene and Pliocene.

More than one mineralized breccia pipe occurs in each of the three Late Miocene Cu deposits in central Chile, and each of these individual breccias was generated by exsolution of metal-rich fluids exsolved from different individual plutons of distinct age, volume and composition. However, the formation of all the breccia pipes together as a group took place within the relatively restricted time period of the

Late Miocene, during the final phases of activity of the long-lived magmatic systems that were active in central Chile between the Early Miocene and Pliocene. The relatively rapid decline of these magmatic systems and the generation of the mineralized breccias in central Chile was tectonically triggered during the Late Miocene by decreasing subduction angle. Decreasing subduction angle caused 1) a decrease in the influx of mafic magmas and heat from the subarc mantle into the base of these systems and ultimately the eastwards migration of magmatic activity[8], and 2) crustal deformation, uplift and erosional unroofing of these systems[7]. Flattening of subduction angle below central Chile in the Late Miocene resulted from the subduction of the Juan Fernández Ridge[9]. Ridge subduction increased the rate of subduction of boron-rich pelagic sediment as well as the rate of subduction erosion[10], providing the boron to produce the tourmaline-rich breccias and causing the isotopic changes observed between the Late Miocene and Pliocene magmas in central Chile. The progressive southwards migration of the locus of subduction of the Juan Fernández Ridge[9] produced similar events of flattening of subduction angle, increased subduction erosion, eastwards migration of magmatism, crustal deformation combined with uplift and erosion, and the generation of Andean copper deposits north of 28°S before 20 Ma, north of 33°S before 7 Ma, and between 33-34°S around 5 Ma.

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