$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY OF THE EL TENIENTE PORPHYRY COPPER DEPOSIT

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Chile's El Teniente deposit is the largest known porphyry Cu-Mo orebody (>70 Mt Cu[1]), and is genetically related to Late Miocene–Early Pliocene igneous activity on the western slopes of the Andean Cordillera (cf. Howell and Molloy, 1960, Camus, 1975, Cuadra, 1986, Skewes and Stern, 1995). The deposit is 2700 m long by 1000 to 1700 m wide and is elongated in a N-S direction, with a recognized vertical extent of about 1800 m.

Approximately 80% of the copper at El Teniente is distributed within a stockwork of mineralized veinlets and minor hydrothermal breccias within pervasively altered andesites, basalts and gabbros that are part of the Upper Miocene country rocks. Two intrusive bodies occur within the deposit, the Sewell Diorite (actually a tonalite) in the southeast part of the orebody and the dacitic Teniente Porphyry in its northern part. The Teniente Porphyry occurs as a north-south trending dike 1500 m long and 200 m wide. Minor quartz-diorite or tonalite intrusions known as the Central Diorite and the Northern Diorite occur along the eastern side of the deposit.

Hydrothermal breccias commonly occur along the contacts of intrusive bodies with the country rocks. The Braden Breccia is a conspicuous diatreme in the center of the deposit that forms a pipe 1200 m in diameter at the surface, narrowing to 600 m at a depth of 1800 m. The Braden diatreme pipe is poorly mineralized (~0.3% Cu), but it is surrounded by the copper-rich Marginal Breccia, a discontinuous rim of tourmaline-matrix hydrothermal breccia.

Latite dikes intrude El Teniente, some forming altered ring dikes that encircle the Braden breccia pipe. After mineralization had ceased, the southern section of the deposit was cut by a 3.8 ± 0.3 Ma lamprophyre dyke, marking the end of igneous activity (Cuadra, 1986). Biotite-dominated K-silicate alteration is widespread within the orebody. In contrast, pervasive phyllic alteration is restricted to 'diorite' intrusions, and to the Braden and Marginal breccias. Phyllic alteration primarily occurs as quartz-sericite haloes of quartz–sulfide-sulfate veinlets within the perimeter of the orebody, and slightly overprints potassic alteration. Propylitic alteration occurs largely peripheral to ore-grade rock. The relatively restricted development of phyllic alteration and the occurrence of the central breccia conflict with the classic porphyry copper model of Lowell and Gilbert (1970), but El Teniente may be regarded as a "variation on a theme" of the classic model, as suggested by Gustafson and Hunt (1975).

[1] The amount refers to the sum in metric tons of produced metal and present copper resources (ditto for other cited deposits).

The exceedingly large size of the El Teniente deposit, coupled with its apparently young mineralization age prompted us to initiate a systematic $^{40}Ar/^{39}Ar$ study whose goals are to determine the age(s) of the hydrothermal event(s) that produced such a remarkable copper concentration and ultimately to estimate the duration of the hydrothermal activity at El Teniente. This is particularly relevant to an understanding of the processes that formed super-giant high-grade copper deposits in the Chilean Andes and elsewhere. We report here 32 total fusion $^{40}Ar/^{39}Ar$ ages from sericite and biotite from different lithologic units of El Teniente and five step-heating ^{40}Ar-^{39}Ar ages of samples previously dated using conventional K-Ar methods (Cuadra, 1986).

Previous biotite K-Ar dating at El Teniente yielded radiometric ages of 4.6 to 4.7 Ma that were interpreted as the main mineralization event related to the Teniente Porphyry (Clark et al., 1983; Cuadra, 1986). Whole rock K-Ar ages of 4.7 and 4.5 Ma from the Braden and Marginal Breccias, respectively, were taken to suggest that Braden pipe was formed soon after mineralization. In addition, Cuadra (1986) ascribed older whole rock K-Ar ages of about 7 Ma to an early potassic alteration event related to the Sewell Diorite.

Our new ^{40}Ar-^{39}Ar ages from hydrothermal sericite and biotite at El Teniente range from 12.26 to 4.39 Ma, with 28 total fusion ages concentrated in the interval from 5.58 to 4.39 Ma. Two peaks are clearly visible in the age distribution at 5.3 ± 0.1 Ma and 4.7 ± 0.1 Ma (Fig. 1). These peaks are statistically distinct (using the algorithm of Sambridge and Compston, 1994) and represent the time when rocks cooled below the mica closure temperature of approximately 300ºC. The peaks could correspond to two separate hydrothermal pulses, and since most of the samples were taken from mineralized rocks, the 5.3 and 4.7 Ma peaks may reflect distinct mineralization events. Molybdenite Re-Os ages of 5.6 and 4.8 Ma at El Teniente (Mathur et al., this volume) may provide support for this hypothesis.

These two putative thermal pulses are recognized in most of the lithologic units at El Teniente (andesites, Sewell Diorite, Teniente Porphyry, and Braden Breccia), suggesting that these lithologies had already been emplaced at about 5.3 Ma. Hydrothermal biotite from the Sewell Diorite was originally dated at 7.1 ± 1.0 by Cuadra (1986), but our step-heating experiments have yielded a total fusion age of 5.69 ± 0.08 Ma, and a U-shaped apparent age spectrum indicative of excess ^{40}Ar. After correcting for excess ^{40}Ar, our results indicate plateau and isochron ages at 4.69 ± 0.05 and 4.52 ± 0.19 Ma, respectively, for the Sewell Diorite. This suggests that the early potassic event of Cuadra (op. cit.) may be an artifact of excess ^{40}Ar. The absence of a clear correlation between radiometric ages with specific lithologies within El Teniente deposit suggests that our ages reflect hydrothermal/ mineralization events superposed on pre-existent lithologies, rather than the original age of the host rocks. Some of the lithologies reveal only the younger thermal event, such as the Central Diorite with total fusion dates of 4.66 ± 0.05 and 4.80 ± 0.07 Ma and the latite dikes dated at 4.80 ± 0.09 and 4.39 ± 0.17 Ma. Whether these rocks are young or were overprinted by the more recent thermal event cannot be resolved by our data at this time. The 4.39 Ma date comes from a weakly sericitized latite dike, possibly representative of the last hydrothermal activity within the deposit. This age may be correlated with molybdenite Re-Os dates from El Teniente at about 4.4 Ma (Mathur this volume).

Total fusion ^{40}Ar-^{39}Ar dates at 12.26 ± 0.37 and 10.07 ± 0.31 Ma obtained from a sericitized porphyritic facies of the Sewell Diorite (Blanco Porphyry) and the Northern Diorite respectively may represent earlier hydrothermal events that have been largely obliterated by younger thermal pulses. Further dating is planned to check this possibility. If accurate, the older total fusion ages would indicate that hydrothermal activity started at El Teniente during the Late Miocene at about the same time that Los Pelambres porphyry deposit was formed and the San Francisco Batholith was emplaced at the Río Blanco deposit (Atkinson et al., 1996, Serrano et al., 1996).

Although not fully conclusive, our new geochronologic data suggest that the conventional concepts of El Teniente's evolution may benefit from reexamination.

El Teniente appears to have been formed by superposed hydrothermal pulses that may have begun as early as the Late Miocene, but were later thermally obliterated by two main Early Pliocene alteration/ mineralization events. The occurrence of at least two distinct hydrothermal events within the same deposit may account for the richness and the anomalously large volume of El Teniente.

The superposition of at least two temporally distinct magmatic-hydrothermal systems has been documented in the super-giant (66 Mt Cu) porphyry copper at Chuquicamata (Ballard et al., 2001, Reynolds et al., 1998, Ossandon et al., 2001). Overprinting of the hydrothermal system was an important factor in the formation of the enormous La Escondida deposit (26 Mt Cu; Padilla et el., 2001). In contrast, the detailed ^{40}Ar-^{39}Ar study of the smaller Potrerillos porphyry copper (4 Mt Cu) revealed only one relatively brief mineralizing event (Marsh et al., 1997). While multiple mineralization events have been documented in the Indio Muerto District, but these are distributed within seven centers aligned for 4 km (Gustafson et al, 2001). Overlapping mineralizing events formed the El Salvador deposit (6 Mt Cu) at this district (Gustafson and Hunt, 1975; Gustafson et al, 2001). However, the smaller size of El Salvador relative to the mentioned super-giant deposits may be due to the physical separation of the magmatic-hydrothermal systems at Indio Muerto.

The formation of super-giant porphyry copper deposits in the Chilean Andes appears to require the superposition of temporally distinct magmatic-hydrothermal mineralizing systems within a single orebody.

The exceedingly large size of El Teniente and high hypogene grades probably would not be possible without the hydrothermal overprinting inferred from the radiometric data.

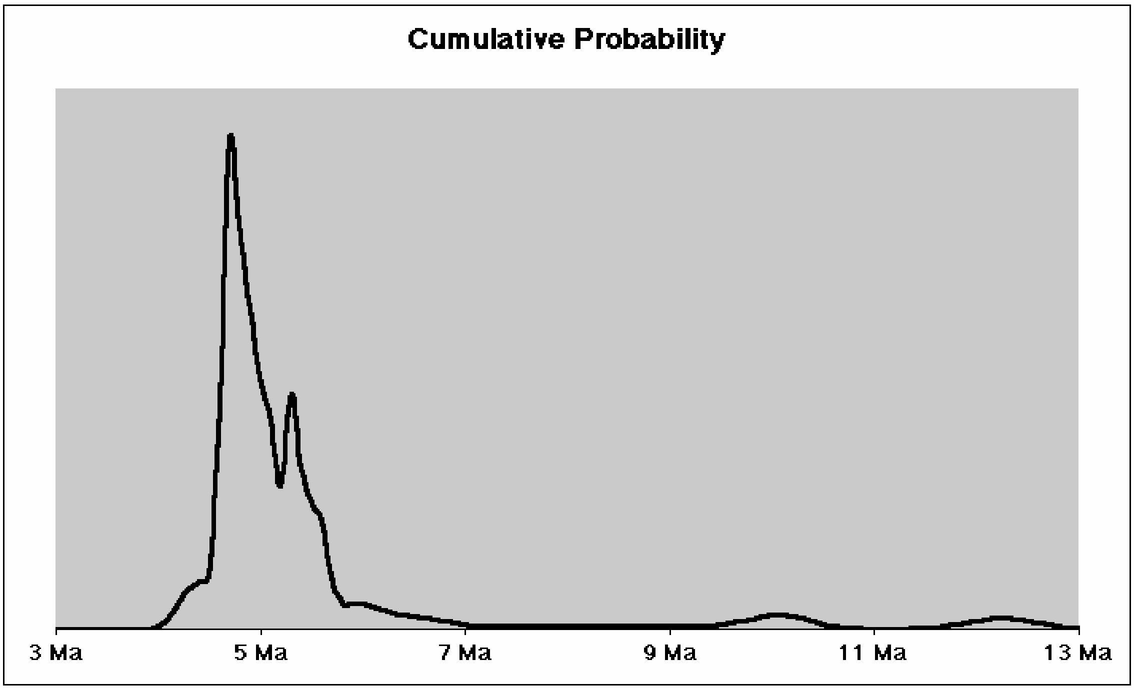

Fig. 1. Probability plot showing summed total fusion $^{40}Ar/^{39}Ar$ according to their uncertainties from hydrothermal sericites and biotites of El Teniente. Two statistically distinct peaks at 4.7 ± 0.1 and 5.3 ± 0.1 Ma represent the time when rocks cooled below the mica closure temperature of approximately 300ºC. These peaks represent two alteration/mineralization events at El Teniente (see text for explanation).

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