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Economic Geology, v. 105, pp. 1157–1162

SCIENTIFIC COMMUNICATIONS

LONGEVITY OF PORPHYRY COPPER FORMATION AT QUELLAVECO, PERU

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Abstract

Metal introduction at the late Paleocene to early Eocene Quellaveco porphyry copper-molybdenum deposit in southern Peru spans several phases of quartz monzonite porphyry emplacement and is bracketed by a precursor granodiorite pluton and a late-mineral porphyry body that postdates essentially all copper introduction. Together, the U-Pb ages of zircons from these intrusive rocks show that 1.08 ± 0.58 m.y. elapsed between the precursor pluton and initiation of stock emplacement; the porphyry system was active intermittently for at least 3.25 m.y. (4.07 ± 0.82 m.y.); and at least three-quarters of the copper inventory was deposited in a maximum of 3.12 m.y. (2.51 ± 0.61 m.y.). Recent U-Pb zircon dating of several other major central Andean porphyry copper deposits, in combination with other isotopic techniques, suggests that 2.5- to 4-m.y. life spans are commonplace. The longevity of porphyry copper systems implied by these studies appears to reflect the protracted time gaps between the multiple intrusions that intermittently replenished porphyry stocks. Other precise isotopic methods (Re-Os, $^{40}Ar/^{39}Ar$) typically document shorter life spans because it is more difficult, if not impossible, to date the full sequence of events involved in porphyry copper formation.

Introduction

Most, if not all, porphyry copper stocks are constructed by multiple intrusive events that commonly span at least part of the alteration and mineralization interval (e.g., Kirkham, 1971; Gustafson, 1978; Sillitoe, 2000, 2010), although the discrete porphyry phases commonly go unrecognized. This sequential intrusive history either maintains or, more likely, repeatedly raises the internal temperatures of the stocks so that they do not cool completely in <0.04 m.y., as predicted by theoretical modeling studies (Cathles et al., 1997), but are much longer lived.

It is precisely this multiphase character of porphyry copper stocks that offers a means of determining the total time required for deposit formation, from initial intrusion through to final sulfide deposition. If the porphyry phases contain suitable quantities of primary magmatic zircon, the actual crystallization age of each intrusive phase may be approximated using the U-Pb method because the closure temperature of zircon is >900°C (Lee et al., 1997). Recent studies using U-Pb zircon dating in combination with Re-Os molybdenite ages and $^{40}Ar/^{39}Ar$ or Rb-Sr ages of associated alteration minerals suggest life spans ranging from <1 to >4 m.y. for several porphyry copper systems (e.g., Ballard et al., 2001; von Quadt et al., 2002; Padilla-Garza et al., 2004), as discussed below.

Here, the life span of the major Quellaveco porphyry copper-molybdenum deposit in southern Peru, including the approximate duration of copper introduction, is determined by using exclusively U-Pb zircon dating. This approach is possible at Quellaveco because the results of drill-core logging and section construction, performed by one of the authors (RHS), showed that alteration and mineralization span a sequence of intrusive events, as well as being bracketed by a precursor pluton and a late, post-copper mineralization copper porphyry body.

Quellaveco Geology

The Quellaveco deposit, located near the northern end of the Paleocene to early Eocene porphyry copper belt of the central Andes (Sillitoe, 1988; Clark et al., 1990; Fig. 1a), is centered on a multiphase quartz monzonite porphyry stock emplaced into an equigranular granodiorite pluton, which itself cuts rhyolitic volcanic rocks assigned to the Late Cretaceous to early Paleocene Toquepala Group (Estrada, 1975; Guerrero and Candiotti, 1979; Candiotti, 1995; Fig. 1b). The pluton, which crops out over >3 km^2 in the vicinity of the Quellaveco stock, as well as extending northward beneath postmineral ignimbrite and gravel cover (Fig. 1b), is part of the granodioritic to monzogranitic Yarabamba superunit of the Coastal batholith (Pitcher, 1985). Phenocrysts in the porphyries are made up of abundant plagioclase, quartz, and biotite, plus scattered K-feldspar and hornblende, all surrounded by aplitic groundmass.

Potassic (biotite-K-feldspar) and sericitic (quartz-sericite) alteration, the former generally overprinted and partly obliterated by the latter, developed extensively throughout much of the quartz monzonite porphyry stock and immediately surrounding granodiorite, and both contain veinlet and disseminated chalcopyrite. The potassic alteration is transitional outward in the precursor granodiorite to a pyrite-bearing propylitic assemblage, which defines the periphery of the system (Estrada, 1975; Candiotti, 1995; Kihien, 1995). Fluid inclusion studies showed that the main potassic and sericitic alteration and associated copper mineralization took place at temperatures of 590° to 340°C (Kihien, 1995). The Quellaveco deposit contains measured and indicated resources of 1,100 Mt, averaging 0.61 percent Cu (A.J. Wilson, written commun., 2009).

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[*] A digital supplement to this paper is available at <http://www.geoscienceworld.org/> or, for subscribers, on the SEG website, <http://www.segweb.org>.

0361-0128/10/3916/1157-6

Submitted: June 16, 2009
Accepted: June 8, 2010

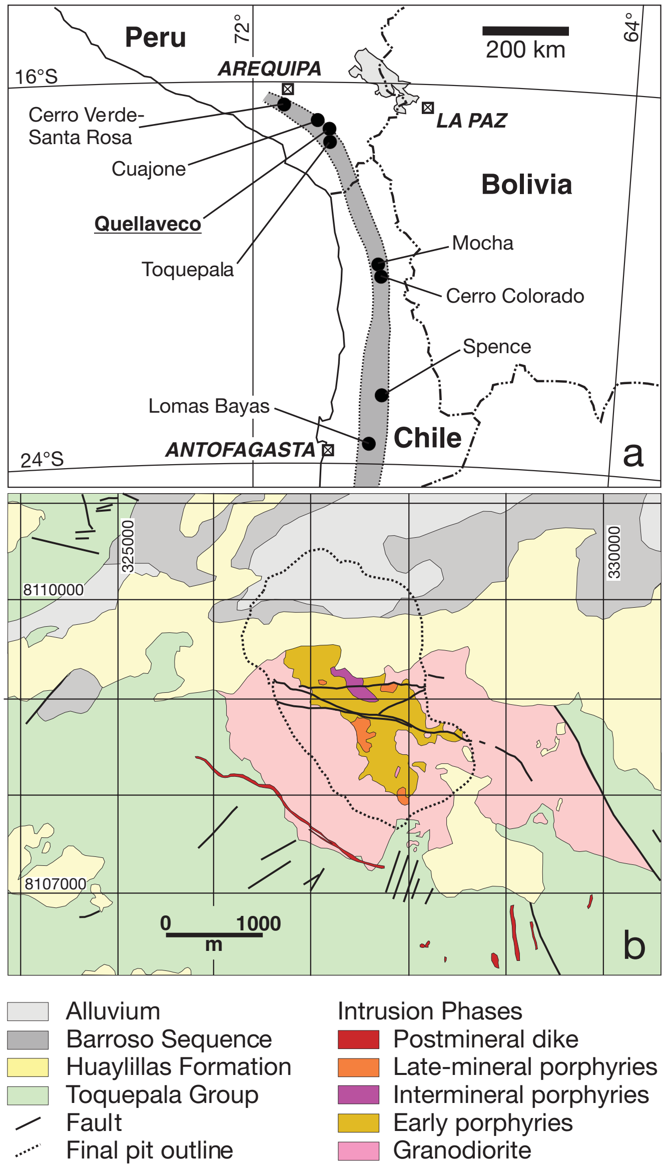

FIG. 1. Location and geology of the Quellaveco porphyry copper-molybdenum deposit, southern Peru. (a) Location map, showing the northern part of the Paleocene to early Eocene porphyry copper belt and its main deposits in northern Chile and southern Peru (adapted from Sillitoe and Perelló, 2005). (b) Simplified geologic map of the Quellaveco deposit and environs. Note that the northern third of the deposit is concealed beneath postmineral volcanic and subordinate sedimentary cover of early Miocene (Huaylillas Formation) and Plio-Pleistocene (Barroso Sequence) age. Geologic map supplied by Anglo American Exploration Perú S.A.

Dated Intrusions

Three intrusive phases, representative of the three main families of quartz monzonite porphyries recognized in the Quellaveco stock, were selected and sampled for this study (Figs. 1b, 2, 3)—namely (1) a widespread early porphyry, displaying intense potassic alteration, including typical chalcopyrite-bearing A-type and molybdenite-bearing, B-type quartz veinlets, and cut by D-type quartz-pyrite-chalcopyrite veinlets with centimeter-scale sericitic halos (cf. Gustafson and Hunt, 1975; Fig. 3); (2) an intermineral porphyry cutting much of the potassic and sericitic alteration and its contained copper-molybdenum mineralization, but itself characterized by much weaker potassic alteration, sparse A-, B-, and D-type veinlets (Fig. 3), and approximately half the copper content (0.26%); and (3) a late-mineral porphyry postdating all potassic and sericitic alteration and displaying only weakly developed propylitic alteration, pyrite veining and dissemination, and containing <0.01 percent Cu. This propylitic assemblage is appreciably younger than that displayed by the dated sample of precursor granodiorite, which was collected from the propylitic halo (Fig. 2).

The early porphyry sampled for age determination was subjected to all except the very earliest pulse(s) of copper mineralization, which are confined to an even earlier, but volumetrically minor, porphyry phase. Based on rough estimates of the proportions (Fig. 1b) and average copper contents (Fig. 2) of the three porphyry families, the intermineral porphyry was emplaced after at least three-quarters of the copper had been precipitated. The late-mineral porphyry postdated essentially all copper introduction.

All the porphyry phases at Quellaveco are petrographically similar. Therefore, the following geologic criteria were used to separate them (cf. Sillitoe, 2000, 2010; Figs. 2, 3): (1) later phases truncated veinlets in earlier phases; (2) some later phases display fine-grained margins against earlier phases, which are interpreted as chilled contacts indicative of appreciable temperature decline between intrusive pulses; (3) later phases contain xenoliths of earlier phases, with early-generation A- and B-type veinlets either being confined to the xenoliths or occurring as discrete, isolated fragments; (4) later phases are characterized by less intense and, commonly, visually different alteration and veinlet development than earlier phases; and (5) later phases contain less copper than earlier phases, with the intrusive contacts marked by abrupt changes in copper tenor.

Geochronologic Methods and Results

Representative samples—each approximating 15 kg—of the precursor granodiorite and the three porphyry phases were collected from split drill core obtained from beneath the well-developed zone of weathering and supergene sulfide oxidation at Quellaveco. Uranium-lead dating of zircons separated from the four samples was done at the Pacific Center for Isotopic and Geochemical Research at the University of British Columbia. The zircons are all generally similar in appearance, comprising clear, colorless, stubby to elongate prisms with simple to multifaceted terminations and no evidence of inherited cores.

Conventional ID-TIMS U-Pb methods on air-abraded, multigrain zircon fractions were initially employed. The methods used are described by Mortensen et al. (2008); the analytical results are given in Table 1 (data repository) and shown on a conventional concordia plot in Figure 4. All the TIMS analyses lie on or near concordia, indicating that there is little or no inheritance of significantly older zircon cores or xenocrysts in any of the fractions analyzed. In general, the data are consistent with an age of ~59.2 Ma for the oldest unit dated (precursor granodiorite) and a substantially younger age of ~55 Ma for the late-mineral porphyry. However, there is considerable scatter in the data, which likely results from

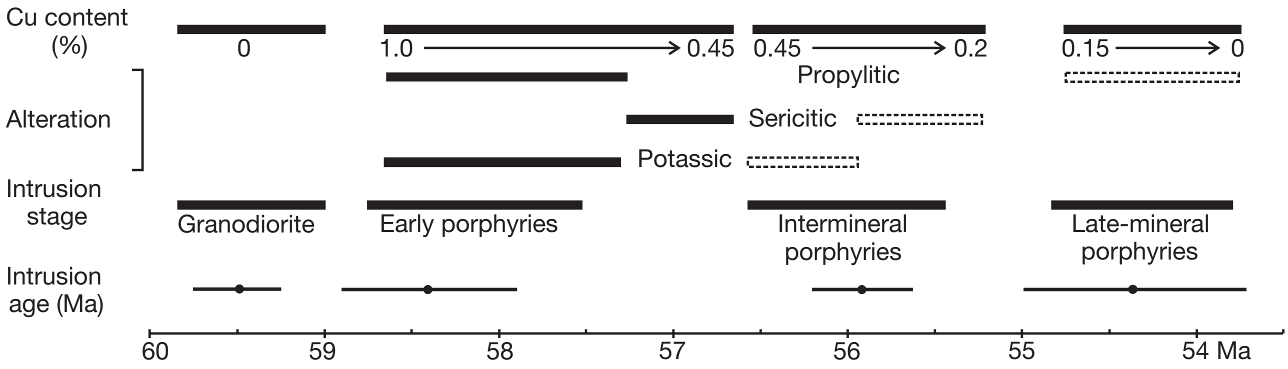

FIG. 2. Schematic time sequence of intrusion, hydrothermal alteration, and copper mineralization, Quellaveco porphyry copper-molybdenum deposit, Peru. Black bars represent main events, and dashed boxes represent subsidiary events. Time gaps shown between events are only approximate. The U-Pb ages and corresponding 2σ errors for the four dated samples (see text) provide a timeframe for the magmatic and hydrothermal evolution of the system.

variable postcrystallization lead-loss effects that were not completely avoided by the air abrasion of the zircon fractions prior to analysis, as well as incorporation of unknown amounts of xenocrystic zircon. This xenocrystic component may include grains incorporated from earlier phases of the intrusive complex (so-called antecrysts; see Miller et al., 2007, for discussion) or, possibly, from slightly older rock units (e.g., the Toquepala Group volcanic host rocks). The presence of such zircon xenocrysts is to be expected in multiphase intrusions like those at Quellaveco and renders high-precision chronology using multigrain ID-TIMS methods difficult, if not impossible.

In order to better constrain the emplacement ages of the four sampled intrusive phases at Quellaveco, laser-ablation (LA-) ICP-MS methods were used to date zircons from the same four samples used for the original ID-TIMS work. Tafti et al. (2009) described the analytical methods employed in the LA-ICP-MS study. Analytical data are reported in Table 2 (data repository) and the results shown graphically in Figure 5. Assigned ages are based on a weighted mean of ^{206}Pb/^{238}U ages (including decay constant errors) for between 24 and 44 individual analyses from each sample. Two analyses from sample 1 yielded slightly younger ^{206}Pb/^{238}U ages and are interpreted to reflect the effects of postcrystallization lead-loss.

Sample 1, the precursor equigranular granodiorite, yields an age of 59.49 ± 0.24 Ma based on 40 of 44 analyses (Fig. 5a). Sample 2 (early porphyry) gives an age of 58.41 ± 0.53 Ma (Fig. 5b), sample 3 (intermineral porphyry) an age of 55.90 ± 0.31 Ma (Fig. 5c), and sample 4 (late-mineral porphyry) an age of 54.34 ± 0.63 Ma (Fig. 5d). Within the 2σ error limits, there is no temporal overlap between these four ages (Fig. 2). All four of the dated samples contained a minor component of xenocrystic zircon, ranging in age from 60 to 68 Ma.

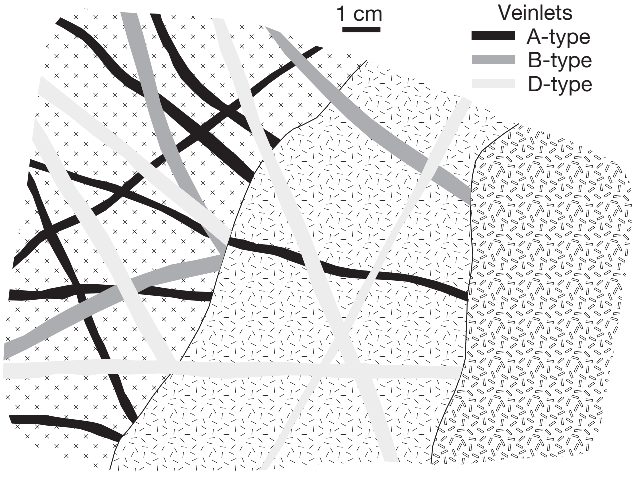

FIG. 3. Cartoon of intrusive contacts between early, intermineral, and late-mineral porphyries at Quellaveco to show the decreased veinlet intensity with time. The late-mineral porphyry is devoid of A-, B-, and D-type veinlets. Note that some D-type, as well as many A- and B-type, veinlets are truncated by the intermineral porphyry, a relatively unusual situation in porphyry copper deposits worldwide. Also note the change from background potassic in the early and intermineral porphyries to propylitic in the late-mineral phase.

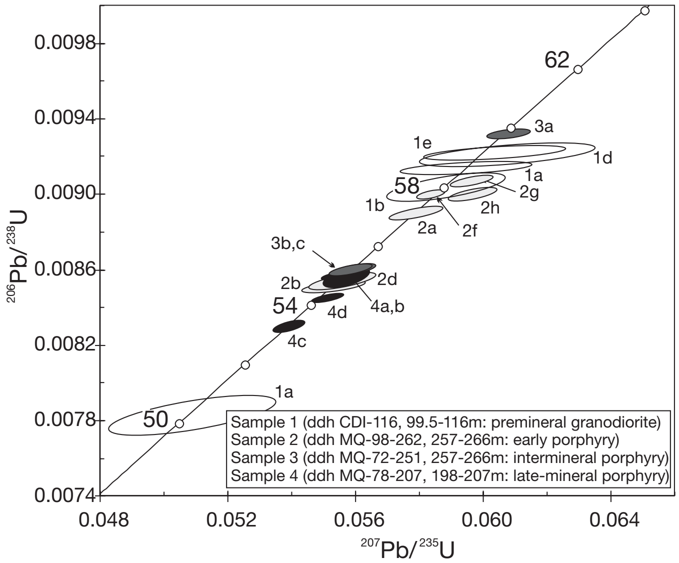

FIG. 4. Concordia plot for conventional ID-TIMS analyses of zircon from the precursor granodiorite (sample 1), early porphyry (sample 2), intermineral porphyry (sample 3), and late-mineral porphyry (sample 4), Quellaveco, Peru. The sample codes in parentheses begin with the drill-hole numbers and end with the depths in meters.

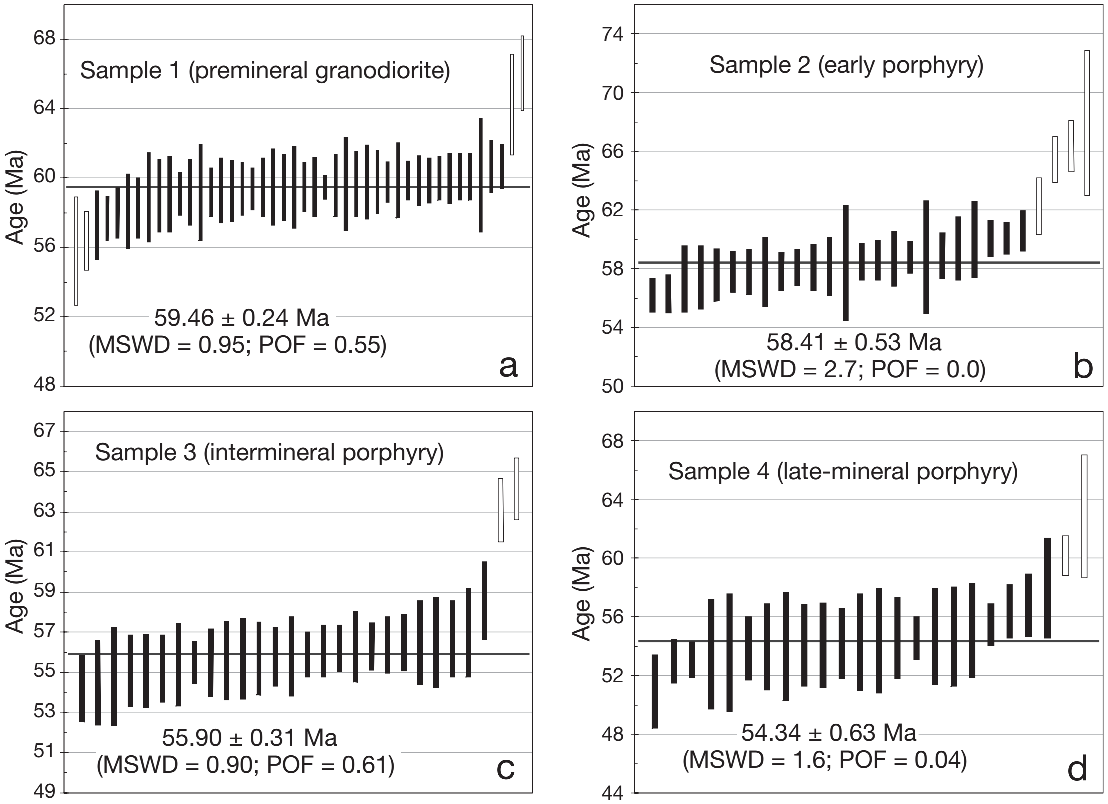

FIG. 5. Plots of $^{206}Pb/^{238}U$ ages for zircon analyses from the Quellaveco intrusions. (a) Sample 1, premineral granodiorite. (b) Sample 2, early porphyry. (c) Sample 3, intermineral porphyry. (d) Sample 4, late-mineral porphyry. Error bars (including decay constant errors) for individual analyses are shown at the 2σ level. Assigned ages are based on a weighted $^{206}Pb/^{238}U$ age for each sample. Rejected analyses are shown as open bars. MSWD = mean square of weighted deviates; POF = probability of fit.

The data show that the precursor pluton, or at least one pulse of it, was emplaced 1.08 ± 0.58 m.y. before the Quellaveco stock (calculated using the addition in quadrature method for estimating the relevant errors). This restricted time gap between intrusion of the precursor pluton and Quellaveco stock is comparable to the 1 to 2 m.y. interval suggested by $^{40}Ar/^{39}Ar$ dating to separate the nearby early Eocene Toquepala porphyry copper deposit (Fig. 1a) and its host pluton, also part of the Yarabamba superunit (Clark et al., 1990). The temporal proximity of the precursor intrusions and porphyry copper stocks in this part of the Paleocene to early Eocene belt suggests derivation from a common, parental magma chamber. The late Paleocene to early Eocene ages for the three porphyry phases are in reasonable agreement with a previous K-Ar age of 54.1 ± 2.1 Ma for alteration sericite (Estrada, 1975) and, in general terms, with a broad spread of imprecise whole-rock K-Ar ages averaging 53.6 ± 11.6 Ma (Zimmermann and Kihien, 1983).

The entire Quellaveco porphyry copper system, including the precursor pluton, developed over an interval of 5.15 ± 0.67 m.y., whereas the porphyry stock and its associated copper-molybdenum mineralization were generated in a minimum of 3.25 m.y. (4.07 ± 0.82 m.y.; Fig. 2). The main copper introduction events, which account for at least three-quarters of the contained metal, predated intrusion of the intermineral porphyry and therefore must have been completed in a minimum of 1.90 and a maximum of 3.12 m.y. (2.51 ± 0.61 m.y.; Fig. 2).

Discussion

The use of LA-ICP-MS dating methods on large numbers of zircon grains from intrusions associated with porphyry copper mineralization at Quellaveco makes it possible to confidently assign high-precision crystallization ages to the various intrusive units. Our new U-Pb ages completely resolve the timing of the three main porphyry intrusion events, and indicate that there are finite time gaps of at least 0.3 to 1.7 m.y. between each of them (Fig. 2). A more detailed dating study, including additional Quellaveco porphyry phases, is being carried out by A. Simmons (personal commun., 2009) and will likely help to fill in some of these time gaps. Nonetheless, incontrovertible geologic evidence for amagmatic pauses, characterized by stock cooling, is provided by the chilled porphyry contacts and recurrent development of the potassic to sericitic alteration sequence following both early and intermineral porphyry intrusion (Figs. 2 and 3). Hence, porphyry copper systems can be long-lived loci of intermittent magma injection, within which the individual magma batches may be separated by appreciable time gaps and, as a consequence, not be thermally and mechanically related to one another. Alteration and mineralization were active in the amagmatic intervals between porphyry emplacement, although not necessarily continuously (cf. Maksaev et al., 2004).

The 4.07 ± 0.82 m.y. required for porphyry stock emplacement, alteration, and mineralization at Quellaveco is comparable to the full duration of porphyry copper formation elsewhere in the central Andes, as determined using combinations of U-Pb and other isotopic methods (Fig. 6): Antapaccay 5.2 ± 0.7 m.y. (Jones et al., 2007; B. Jones, written commun., 2008), Escondida 4.2 ± 1.0 m.y. (Padilla-Garza et al., 2004), Los Pelambres 3.68 ± 0.15 m.y. (Perelló et al., 2009), Chuquicamata 3.5 ± 0.4 m.y. (Ballard et al., 2001), Bajo de la Alumbrera ~3 m.y. (Harris et al., 2008), El Teniente 2.8 ± 0.6 m.y. (Maksaev et al., 2004), and Río Blanco ~2 m.y. (Deckart et al., 2005); the last, however, is a minimum because the earliest porphyry phases were not dated. Two of the porphyry phases at Chuquicamata are separated by 1.3 ± 0.4 m.y. (Ballard et al., 2001), at Escondida by ≥2 m.y. (Padilla-Garza et al., 2004), and at Bajo de la Alumbrera by ~1.0 m.y. (Harris et al., 2008)—time gaps comparable to those (at least 0.3 and 1.7 m.y.) determined between the three dated phases at Quellaveco. Elsewhere, however, U-Pb zircon dating of porphyry copper stocks, including their late-mineral porphyry phases, suggests variably shorter life spans (Fig. 6). These include 1.7 ± 2.3 m.y. at La Caridad in Mexico (Valencia et al., 2005), 0.7 ± 0.3 m.y. at Elatsite in Bulgaria (von Quadt et al., 2002), and only 0.09 ± 0.16 m.y. at Batu Hijau in Indonesia (Garwin, 2002).

Together, these geochronologic results show that several major, central Andean porphyry copper systems, irrespective of their absolute size and grade, were at least intermittently magmatically and hydrothermally active for 2.5 to 4 m.y. and, in some cases, perhaps longer (Fig. 6). The duration of individual porphyry copper life spans appears to be mainly dictated by the total time that elapsed between emplacement of the first and last porphyry phases. Nevertheless, the bulk of the copper and associated metals may be introduced during the early stages of these life spans: 2.5 ± 0.6 m.y. in the case of Quellaveco.

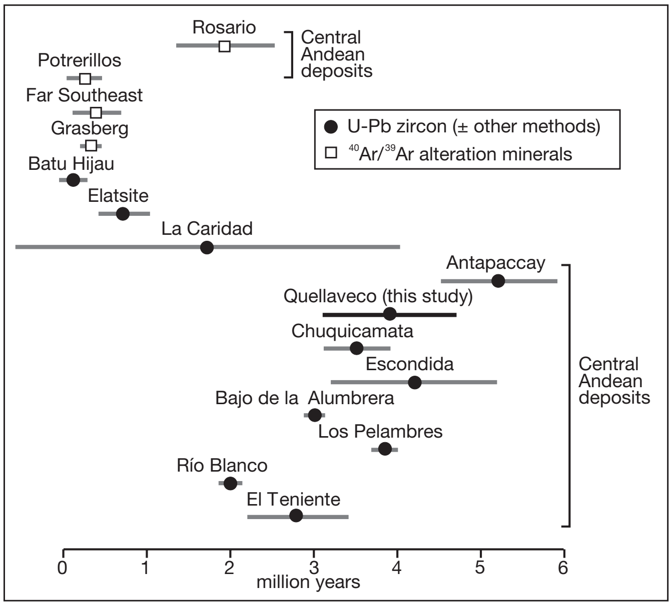

FIG. 6. Schematic representation of the durations of porphyry copper formation at selected deposits determined using U-Pb, Re-Os, and ^{40}Ar/^{39}Ar methods, either alone or in combination. Note the longevity of many (but not all) porphyry copper life spans estimated using U-Pb zircon dating, and the generally shorter apparent life spans suggested by the ^{40}Ar/^{39}Ar method. Data from Arribas et al. (1995), Marsh et al. (1997), Ballard et al. (2001), Garwin (2002), von Quadt et al. (2002), Maksaev et al. (2004), Masterman et al. (2004), Padilla-Garza et al. (2004), Deckart et al. (2005), Pollard et al. (2005), Valencia et al. (2005), Jones et al. (2007), Harris et al. (2008), B. Jones (written commun., 2008), Perelló et al. (2009), and this study.

Porphyry copper life spans determined using U-Pb zircon dating alone or in combination with other chronometers are commonly, but not always, longer by a factor of two or more (Fig. 6) than those based on Re-Os molybdenite ages (e.g., 0.5–1.0 m.y.; Zimmerman et al., 2008) and/or ^{40}Ar/^{39}Ar ages of alteration minerals—typically biotite, K-feldspar, sericite, and/or alunite (e.g., 0.2–1.9 m.y.; Arribas et al., 1995; Marsh et al., 1997; Masterman et al., 2004; Pollard et al., 2005). This age disparity reflects the fact that porphyry copper life spans based on Re-Os and ^{40}Ar/^{39}Ar dating are only minima, but for different reasons (cf. Zimmerman et al., 2008). Re-Os ages underestimate life spans because molybdenite generations rarely, if ever, span the entire porphyry copper event, including late-mineral porphyry intrusion. In contrast, alteration ages are likely to record only the later stages of porphyry copper formation, after systems cooled through the blocking temperatures for biotite, K-feldspar, and sericite (250°–400°C; Richards and Noble, 1998), thereby taking no account of the early, higher-temperature (400°–>800°C) events during which all porphyry intrusion and major copper introduction took place (cf. von Quadt et al., 2002). However, Re-Os molybdenite dating of some porphyry copper deposits also suggests protracted, albeit probably minimum, life spans similar to those determined by the U-Pb method (e.g., Barra et al., 2005).

Acknowledgments

This report is an outgrowth of work carried out for Minorco in 1996 and Anglo American in 2007, and is published with the permission of Graham Brown, the late Nigel Grant, and Vicente Irarrázaval. Luís Calienes and Nigel Grant facilitated the fieldwork. Tim Beale, Nigel Grant, Ben Jones, Pepe Perelló, John Thompson, Dick Tosdal, and Alan Wilson commented on various versions of the manuscript, and Dave Cooke, Bruce Eglington, and Larry Meinert acted as *Economic Geology* reviewers.

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