From crucible to graben in 2.3 Ma: A high-resolution geochronological study of porphyry life cycles, Boyongan-Bayugo copper-gold deposits, Philippines

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ABSTRACT

The Boyongan and Bayugo porphyry copper-gold deposits are part of a belt of gold-rich copper deposits in the Surigao district of northeast Mindanao, Philippines. The detailed age relationships described in this study provide insight into the geologically short life cycles that characterize porphyry formation in dynamic arc environments. Since their late Pliocene emplacement (2.3–2.1 Ma; SHRIMP [sensitive high-resolution ion microprobe] U-Pb zircon dating) at depths of 1.2–2.0 km, these deposits were exhumed, deeply weathered, and buried. Weathering of these deposits led to the development of the world's deepest known porphyry oxidation profile (600 m thick) at Boyongan, and a modest (30–70 m) oxidation profile at adjacent Bayugo. This early-middle Pleistocene supergene event followed a period of rapid uplift and exhumation in northeast Mindanao (2.5 km/Ma; [U-Th]/He apatite age-elevation spectrum). Subsequent rapid subsidence (≥0.34 km/Ma; radiocarbon age-elevation spectrum) and burial of these deposits are attributed to a mid-Pleistocene shift from transpressional tectonics to the present-day transtensional setting in northeast Mindanao. During this period, debris flows, volcanic material, and fluviolacustrine sediments accumulating in the actively extending Mainit graben covered the weathered deposits, preserving the supergene profiles beneath 50–500 m of cover. This detailed geochronological study documents the geologically short (<2.3 Ma) time scales over which these major intrusion-centered mineral deposits evolved from emplacement, exhumation, deep oxidation, and burial, highlighting the dynamism of tectonic processes in environments such as the Philippine Mobile Belt.

INTRODUCTION

The Boyongan and Bayugo deposits are recent discoveries of porphyry copper-gold mineralization in the Surigao district of northeast Mindanao, southern Philippines, an area previously known primarily for epithermal gold mineralization. Pleistocene to Holocene volcanics and lake sediments cover the mid-Pliocene porphyry deposits, preserving the world's deepest known (>600 m) porphyry oxidation profile (Braxton et al., 2009). In this investigation, geochronological studies of the Boyongan and Bayugo systems focused on direct dating of the timing of magmatism, and hydrothermal activity (porphyry-style stockwork mineralization, and later phyllic alteration), low-temperature cooling (exhumation) history, and burial of the system. These data constrain the duration of the magmatic-hydrothermal systems at Boyongan and Bayugo, and the timing and rate of exhumation. In conjunction with existing geochronological constraints on the timing of burial, these data also constrain the duration of prior supergene oxidation.

Detailed geochronological studies of young porphyry systems, such as those found in the west Pacific, provide the opportunity to test numerical models describing the lifespans of these magmatic-hydrothermal systems. This is because the experimental errors are reduced relative to the theoretical longevity of shallow-level magmatic-hydrothermal systems (10^4–10^5 yr; e.g., Norton, 1982). In addition to dating intrusive emplacement and hydrothermal alteration, geochronological constraints on the absolute timing and duration of weathering enable direct estimates of the rate of supergene processes. Weathering of ore deposits affects profoundly the engineering strategy, cost, and efficiency of ore processing during mining (Sillitoe, 2005). Therefore, an improved understanding of the geological conditions and rates controlling sulfide oxidation has significant implications for mineral exploration and development of porphyry copper deposits.

GEOLOGICAL SETTING

Between the converging Philippine Sea plate (east) and the Eurasia plate (west), the Philippine archipelago mobile belt is an actively deforming tectonic collage of oceanic crustal blocks surrounded on most sides by destructive plate margins. Four subduction zones currently consume oceanic crust beneath the Philippines (Fig. 1). To the west, collision of the Philippines with the Eurasia plate is driving east- and northeast-directed subduction of south China, Sulu, and Celebes oceanic crust into the Manila, Negros-Sulu, and Cotabato Trenches, respectively. East of the central and southern Philippines, the Philippine Trench is consuming the Philippine Sea plate. Convergence between the Philippine Sea and Eurasia plates is highly oblique at the Philippine Trench; Aurelio (2000) attributed development of the major arc-parallel strike-slip faults affecting the archipelago to this configuration. One of the most important of these is the sinistral Philippine fault zone, extending over 1200 km north to south through the islands of Luzon, Masbate, Leyte, and Mindanao (Fig. 1). At the crustal scale, kinematics of the Philippine fault zone profoundly influence the stress distribution in the Philippine Mobile Belt, while at the regional scale, the Philippine fault zone has influenced the tectonic history of emplacement, exhumation, and burial of the Boyongan and Bayugo porphyry deposits in the Surigao Peninsula of northeast Mindanao.

Arc magmatism associated with the eastward subduction of the Philippine Sea plate into the Philippine Trench produced a number of volcanic and intrusive complexes in northeast Mindanao, including the mid-Pliocene Boyongan Intrusive Complex. This complex contains at least nine discrete diorite intrusive phases. Intrusive activity began with the emplacement of a suite of three pre-mineralization porphyritic diorite stocks into an Oligocene to early Pliocene sequence of basalts, marine clastics, and carbonates. The development of an extensive pre-mineralization diatreme-like breccia body followed this early magmatism, resulting in the fragmentation of a large proportion of the earlier intrusions and the adjacent host rock.

Copper-gold mineralization followed the formation of the rock flour-matrix breccia body, in association with the emplacement of narrow, multiphase, pipe-like diorite porphyry stocks within the breccia complex at Boyongan, and within the pre-mineralization diorite stocks at Bayugo (Fig. 2). Mineralization developed in quartz vein stockworks concentrated in and around the cupolas of these early-mineralization

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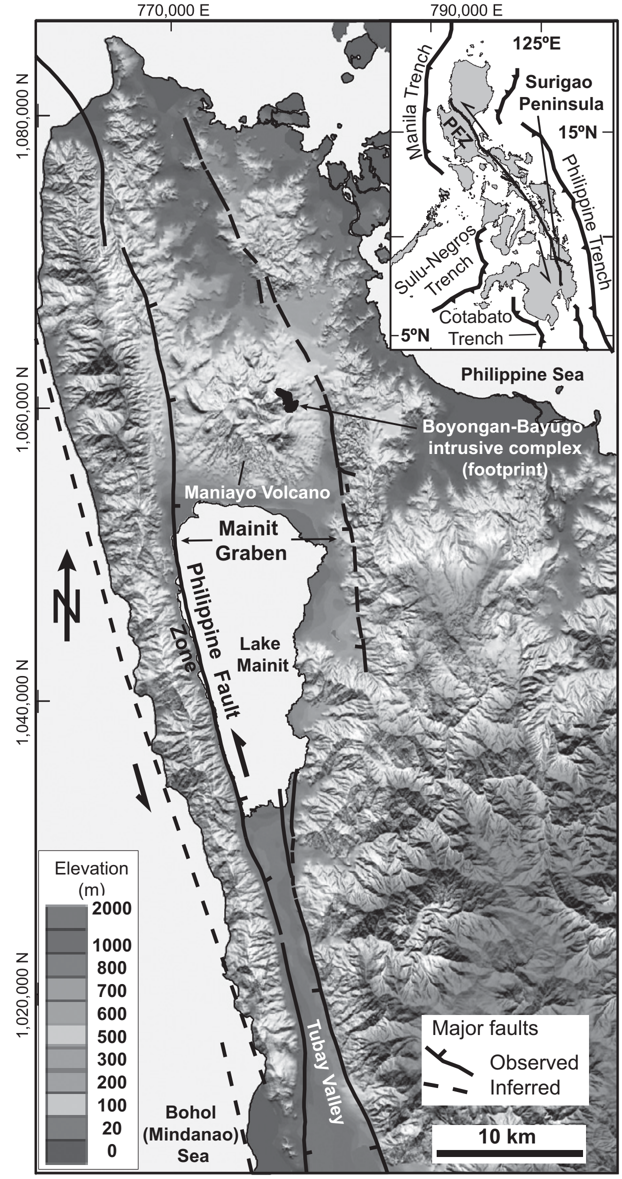

Figure 1. Digital elevation model of Surigao Peninsula depicting location of Boyongan and Bayugo deposits in context of region's prominent tectonic and physiographic elements. Conspicuous Western Range and Mainit graben are products of transtensional deformation associated with differential sinistral displacement along discrete strands of Philippine fault zone (PFZ in inset). Boyongan and Bayugo intrusive complex now is within Mainit graben, and has been buried by younger sediments and volcanic material associated with Pleistocene–Holocene Maniayo volcanic complex. Map projection: Universal Transverse Mercator zone 51N, datum: Clark 1864 (Luzon exclusive of Palawan). Inset: Tectonic setting of Philippine archipelago, emphasizing configuration of opposed subduction zones flanking east and west, and regionally extensive Philippine fault zone.

intrusive centers. Large intermineralization diorite porphyry stocks truncated the early-mineralization intrusions at Boyongan and Bayugo at depth, developing weak copper-gold mineralization. Narrow, late-mineralization diorite porphyry dikes represent the last pulse of magmatism in the Boyongan Intrusive Complex.

Uplift, exhumation, and weathering followed the emplacement of the diorite porphyry suite. A supergene oxidation profile, exceeding 600 m in vertical extent at Boyongan, developed during this time. A localized extensional tectonic regime brought an end to supergene oxidation. Debris flows, andesitic flows, and volcaniclastic products associated with the nearby Maniayo volcanic complex shed into the Mainit graben, leading to burial of the deposits and preservation of the unusually thick supergene profile.

GEOCHRONOLOGICAL METHODS AND RESULTS

This section presents a summary of the sampling strategy employed to constrain the timing of magmatism, hydrothermal activity, exhumation, and burial of the Boyongan and Bayugo porphyry copper-gold deposits. Appendices DR1–DR3 in the GSA Data Repository[1] detail the sample location, preparation, and analytical methodologies followed; Figure 3 summarizes the geochronological findings.

U-Pb sensitive high-resolution ion microprobe (SHRIMP) dating of igneous zircon was employed to constrain the absolute timing and duration of magmatism. Sampling focused on a suite of four samples representing the earliest and latest intrusive phases in the complex, as determined by crosscutting relationships (Figs. DR1–DR4 in the Data Repository). U-Pb SHRIMP-2 dating of magmatic zircons separated from the two earliest pre-mineralization intrusions (2.31 ± 0.1 Ma for the "bird's-eye diorite porphyry" and 2.23 ± 0.1 Ma for the "medium-grained diorite porphyry") indicates an onset of magmatism in the late Pliocene. Similar SHRIMP-2 dating of the latest late-mineralization porphyry dikes (2.19 ± 0.16 Ma for the diorite porphyry 4, Bayugo; and 2.09 ± 0.20 Ma for the late-mineralization diorite porphyry, Boyongan) indicates a total duration of magmatism of <0.5 Ma at the 2σ level of uncertainty (Fig. 3). This estimate is comparable in magnitude to that gained by considering the difference in ages of the youngest zircon ages determined for each intrusive phase (0.39 Ma; Table DR1), following the approach of von Quadt et al. (2011) in evaluating the intrusive geochronology of the Bingham Canyon (Utah, USA) and Bajo de la Alumbrera (Argentina) porphyry systems.

A sample of hydrothermal molybdenite collected from the last K-silicate-stage quartz vein stage of volumetric significance at Boyongan (Fig. DR5) provided material for direct dating of the porphyry-stage mineralizing event. The replicate age determinations of 2.120 ± 0.007 and 2.115 ± 0.008 Ma are in close agreement (Fig. 3). Despite the young age, extremely high Re concentrations (>2000 ppm) contributed to small analytical uncertainties (Table DR3).

K-Ar age determinations of hydrothermal illite (postdating higher temperature molybdenite) constrain the waning stages of the Boyongan-Bayugo magmatic-hydrothermal system (Fig. DR5). K-Ar age determinations for two <2 µm illite separates (2.12 ± 0.03 Ma and 2.09 ± 0.03 Ma) indicate that the collapse of the final magmatic-hydrothermal system immediately followed the final stages of porphyry-style veining at Boyongan (Fig. 3).

Apatite for dating the low-temperature cooling and exhumation history [single-crystal apatite (U-Th)/He thermochronology] came from 5 samples of the intrusive complex at Boyongan and Bayugo collected from drill core over a vertical interval of 630 m (Fig. DR6). Age determinations ranged between 1.98 ± 0.1 Ma and 1.49 ± 0.18 Ma; ages decrease systematically with increasing depth into the intrusive complex (Fig. 4; Table DR5).

To constrain the timing of graben formation and burial of the exhumed Boyongan-Bayugo intrusive complex, samples of wood, and mud containing abundant plant material, were collected for radiocarbon dating from drilling intersections of the Tugunan Formation near the basal unconformity (Fig. DR7). Of the nine samples dated, four contained essentially no detectable ^{14}C, and so are older than the detection limit for the method (41–45 ka). Age determinations for the remaining six samples were between 30 and 1.6 ka (Table DR6).

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[1] GSA Data Repository item 2012134, Appendix DR1 (geochronology of magmatism), Appendix DR2 (hydrothermal geochronology), Appendix DR3 (low-temperature geochronology), and Appendix DR4 (radiocarbon geochronology), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

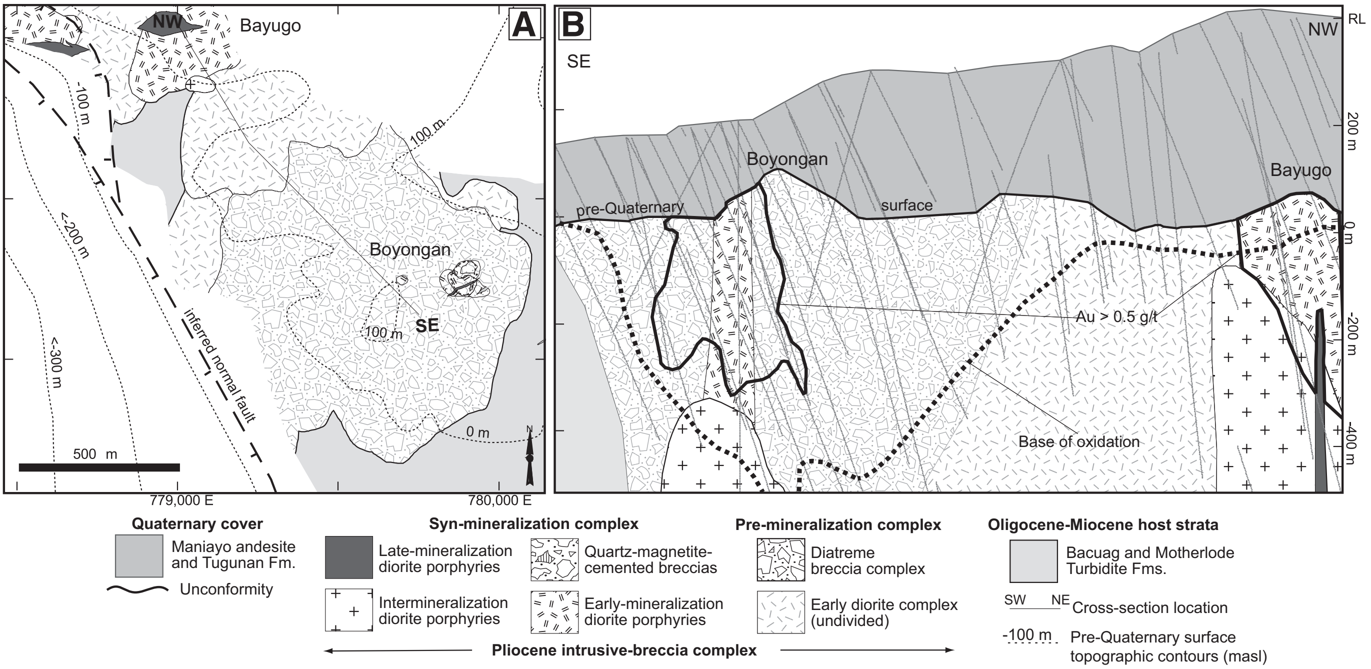

Figure 2. Map and cross section through Boyongan and Bayugo depicting the spatial relationship between gold grades and early-mineralization diorite porphyry stocks. A: Map projection (as in Fig. 1). B: Geological cross section (masl—meters above sea level). At Boyongan, vertically extensive oxidation profile coincides with diatreme breccia complex, compared with considerably thin profile at Bayugo. Relationships are based on interpretation from diamond drilling (gray lines).

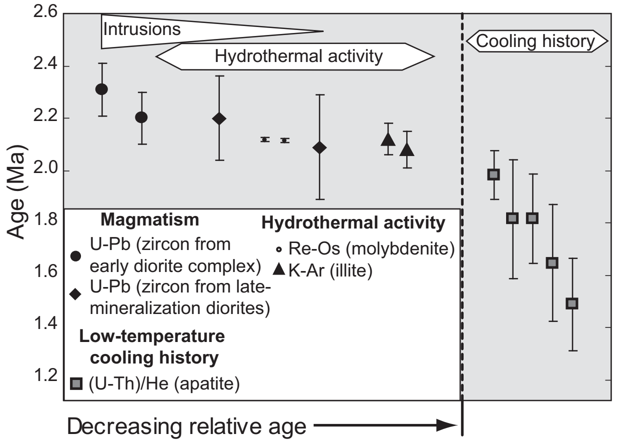

Figure 3. Results of thermochronology in context of igneous and hydrothermal geochronology at Boyongan and Bayugo. Data describe protracted cooling history of ~0.5 Ma following igneous and hydrothermal activity. All age determinations are shown with 2σ uncertainty.

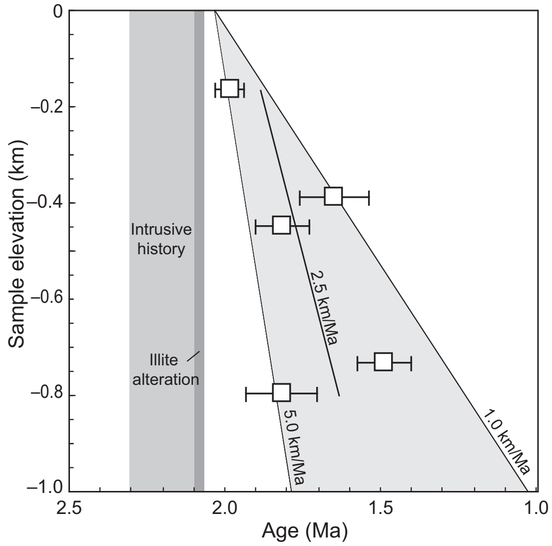

Figure 4. Age-elevation diagram for apatite (U-Th)/He dating results (1σ) from Boyongan and Bayugo. Data describe general younging trend with increasing depth, consistent with exhumation between 1 and 5 km/Ma. Error-weighted slope of 2.5 km/Ma best fits existing data.

TIMING AND DURATION OF SUPERGENE OXIDATION

The (U-Th)/He data show that by ca. 2 Ma, rocks near the current top of the igneous complex had cooled to the apatite He closure temperature. This temperature corresponds to ~1 km depth, assuming a geothermal gradient of 50 °C/km, a surface temperature of 25 °C, and an apatite closure temperature of 75 °C. If exhumation continued at the rate of 2.5 km/Ma (projecting from the apatite age-elevation spectrum in Fig. 4), exposure and weathering of the current pre-mineralization surface initiated ca. 1.6 Ma. Burial of the complex by volcanism and sedimentation associated with extensional basin development curtailed oxidation, and preserved the supergene profile. Existing age determinations suggest that burial began as early as 0.6 Ma (Ar-Ar hornblende in postmineralization volcanics; A. Camacho, 2001, personal commun.), and final burial of the complex by debris flows occurred as late as 1600 ^{14}C yr B.P. (^{14}C date on wood in debris flows; Table DR6). The >600 m oxidation profile at Boyongan therefore developed between ca. 1.6 Ma and 1.6 ka, and the majority of oxidation likely occurred before the onset of burial at 0.6 Ma.

DISCUSSION

Porphyry deposits are especially useful in studies of exhumation and uplift because their emplacement at discrete shallow crustal levels provides a marker for subsequent tectonic events. Neogene tectonic reconstructions for the southern Philippines suggest that a protracted period of compression, wrench tectonics, and thrusting between the Late Miocene and late Pliocene characterized the collision and docking of the Philippine arc in Mindanao with the Eurasian plate (Pubellier et al., 1996). Transtensional features, such as the active Mainit graben (Fig. 1), document a change in structural style. Volcanic rocks of the Maniayo complex cover the graben floor (Figs. 1 and 2; Fig. DR7), and the earliest consistent dates for the andesites suggest that transtension had initiated by the mid-Pleistocene.

Applied to one of the geologically youngest known porphyry systems, the high-resolution geochronology presented herein provides quantitative constraints on the duration of porphyry formation (2.3–2.1 Ma), rates of exhumation, supergene profile development, and burial within this evolving tectonic context. The exhumation rate (~2.5 km/Ma) defined in this study for the Boyongan and Bayugo porphyry deposits exceeds by an order of magnitude the global average exhumation rate for porphyry deposits (0.158 km/Ma) estimated by Kesler and Wilkinson (2006). However, the findings in our study are consistent with estimates of uplift, exhumation, and erosion rates for regions of comparably intense compressive tectonic activity and high precipitation such as the Southern Alps (Little et al., 2005; Tippett and Kamp, 1995) and Taiwan (Liu et al., 2000; Willett et al., 2003).

Absolute geochronological constraints for the timing of supergene processes suggest that at Boyongan, the world's deepest known supergene porphyry oxidation profile developed over a period lasting <1.6 Ma. These data are comparable to duration estimates for the supergene profile development at Ok Tedi (Papua New Guinea), and are considerably shorter than supergene cycles documented for older porphyry systems in the United States and Chile (Table 1). The rapid supergene development documented herein is consistent with the observation of Sillitoe (2005), who inferred from the young hypogene ages reported for the Ok Tedi (1.1–1.2 Ma) and Boyongan (2.5 Ma) porphyries that well-developed porphyry supergene profiles can form over short (<1 Ma) periods. Sillitoe (2005) also emphasized the role of geological and physiographic characteristics that influence the extent and character of supergene profiles produced. Paleophysiographic reconstructions from the Surigao Peninsula (Braxton et al., 2009) suggest that elevated permeability in the diatreme breccia complex at Boyongan promoted drainage of groundwater to the lowlands to the west, producing the vertically extensive (>600 m) vadose zone of oxidation.

TABLE 1. MINIMUM DURATION OF PORPHYRY SUPERGENE OXIDATION

Deposit, country	Age range (Ma)	Duration (Ma)	Basis*	Reference[†]
Boyongan-Bayugo, Philippines	<1.6–0.3	<1.3	(U-Th)/He, ^{14}C	1
Ok Tedi, Papua New Guinea	<1.1	<1.1	K-Ar wr, K-Ar bi	2, 3
Morenci, USA[§]	13.4–4.3	9–9.2	Ar-Ar al, jar, MnO	4
Chuquicamata, Chile	19–15.2	2.6–5.0	Ar-Ar al	5
Escondida, Chile	18–14.7	2.0–3.4	Ar-Ar al	6

Note: Table presents timing relationships described for principal supergene oxidation and/or enrichment events.

*Interpretation of geological context with geochronological constraints: Ar-Ar—supergene alunite (al) jarosite (jar), or cryptomelane-hollandite Mn oxides (MnO); ^{14}C—radiocarbon dating; K-Ar wr—whole rock; K-Ar bi—hydrothermal biotite; U-Pb—SHRIMP (sensitive high-resolution ion microprobe) magmatic zircon; (U-Th)/He—apatite thermochronometry.

[†] References: 1—this study; 2—Chivas et al. (1984); 3—Page (1975); 4—Enders (2000, and references therein); 5—Sillitoe and McKee (1996); 6—Alpers and Brimhall (1988).

[§] Three principal cycles of enrichment.

The geological relations and age constraints presented in this study highlight the rapidity with which major porphyry districts can evolve in dynamic arc environments, and illustrate the fortuitous constellation of circumstances that dictate their potential for preservation or removal from the geological record.

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