

DISTRICT OVERVIEW

**DATA
METALLOGENICA**

Batu Hijau Porphyry Copper-Gold Deposit

Steve Garwin, unpublished Ph.D. dissertation, 2000

ABSTRACT

The Geologic Setting of Intrusion-Related Hydrothermal Systems near the Batu Hijau Porphyry Copper-Gold Deposit, Sumbawa, Indonesia

The Batu Hijau porphyry copper-gold deposit, in south-western Sumbawa, Indonesia, lies within a 12 km by 6 km region that contains several mineralised centres. Batu Hijau contains a mineable reserve of 914 million tonnes at 0.53 % copper and 0.40g/t gold (4.84 million tonnes copper and 375 tonnes gold). The styles of peripheral mineral occurrences include porphyry and structurally controlled vein types.

The Batu Hijau district consists of a gently dipping, Early to Middle Miocene andesitic volcanoclastic succession ≥ 1500 m thick, which locally contains thin intercalations of limestone deposited in a fore-arc, mid-neritic palaeoenvironment. The volcanoclastic succession has been cut by several phases of intrusion, which include, sequentially: three types of hypabyssal andesite (Middle to Late Miocene), at least four quartz diorite plutons (Late Miocene to mid-Pliocene), and a series of porphyritic tonalite stocks and dykes (early- to mid-Pliocene). An andesitic diatreme and dyke complex, situated in the centre of the area, post-dates these intrusions. At Teluk Puna, about 8 km south of Batu Hijau, a Late Miocene, dacitic volcanoclastic sequence unconformably overlies andesitic basement rocks.

The volcanoclastic rocks and intrusions in the district, typically of low-K calc-alkaline affinity, comprise part of the Sunda-Banda magmatic arc, which is underlain by oceanic crust in the vicinity of Sumbawa. The isotopic signature of the igneous rocks, characterised by $^{143}\text{Nd}/^{144}\text{Nd} > 0.5129$, $^{87}\text{Sr}/^{86}\text{Sr} < 0.704$, $^{206}\text{Pb}/^{204}\text{Pb} < 18.7$, and γOs similar to that of the present-day mantle, is consistent with a sub-arc, MORB-like mantle wedge source.

The margins of easterly-elongate quartz diorite plutons have acted as a focus for brittle deformation, dyke emplacement and quartz vein deposition. The reactivation of pre-existing faults and zones of crustal weakness are inferred to have influenced the distribution of volcano-sedimentary facies and localised the emplacement of felsic intrusions. The intersection of fault and fracture zones with the complex margins of pre-mineral composite plutons controls, in part, the distribution of porphyry centres. Two major types of quartz vein are present: early, "A" and "B" veinlets and veins, and late, structurally controlled comb, massive and banded types.

Hydrothermal alteration is characterised by early alteration zones that are centred about tonalite intrusions at Batu Hijau, and tonalite, quartz diorite and minor granodiorite intrusions at three peripheral porphyry systems. Each of the four centres indicates a similar progression of alteration from central biotite-magnetite+oligoclase through proximal actinolite-magnetite and distal epidote-chlorite to background chlorite-calcite. Late, structurally controlled feldspar-destructive alteration zones extend for over 15 km through the area and overprint all types of early alteration. This later style of alteration includes intermediate argillic, sericitic (illitic) and advanced argillic types. The geometry and clay-mica mineral assemblages of these zones indicate higher temperatures and more acidic fluid conditions in the vicinity of Batu Hijau. The aerial extent of the late alteration zones is significantly greater than that of the secondary biotite or actinolite zones, and provides a larger exploration target. Pervasive carbonate-clay-chlorite alteration of the diatreme post-dates these other styles of alteration. The latest recorded hydrothermal event consists of zeolite-smectite veins and fracture-fillings.

At Batu Hijau, hypogene chalcocite, digenite, bornite and native gold partly comprise early "A" veinlets and chalcopyrite+bornite occur in transitional "B" veins. Late pyritic "D" veins contain chalcopyrite+minor bornite. The peripheral porphyry systems lack the early copper-sulfide assemblages, and are characterised by late-stage pyrite-chalcopyrite in the reopened portions of early-formed, copper-poor "A" and "B" veins. Anomalous Au and Ag concentrations are associated with pyrite+sphalerite+galena+chalcopyrite+tennantite bearing, comb and banded quartz veins that occur within late, structurally controlled zones. This style of mineralisation is associated with late-stage feldspar-destructive alteration, which has remobilised and depleted Cu in the upper levels of the Batu Hijau deposit. Auriferous quartz vein arrays extend for over 9 km from the flank of Batu Hijau into peripheral

base-metal sulfide-bearing quartz vein occurrences at Bambu and Teluk Puna, which indicate an increase in base-metal abundance proximal to Batu Hijau. The general patterns of metal zoning with respect to the porphyry centres indicate central Fe, Cu, Au and Ag, proximal Mo, and distal Pb, Zn, Ag, Au and As. Silver/gold ratios also displays a systematic variation with proximity to porphyry centres, ranging from ~1 to 2 in the Cu-Au core to >50 in the Pb-Zn halo for each centre.

The results of $^{206}\text{Pb}/^{238}\text{U}$ SHRIMP (zircon rims) and $^{40}\text{Ar}/^{39}\text{Ar}$ (hydrothermal biotite) geochronology indicate that, within each porphyry centre, the emplacement of the causative intrusions and early hydrothermal alteration were nearly contemporaneous. The SHRIMP results indicate four major felsic intrusive episodes, each separated by ~ 0.6 to 0.9 m.y. and related to a distinct porphyry centre (dates are given $\pm 2\sigma$):

- 5.88 ± 0.14 Ma for a syn-mineral dyke in the oldest porphyry centre (Sekongkang);
- 4.99 ± 0.16 Ma and 4.43 ± 0.14 Ma for plutons and stocks in the intermediate centres (Arung Ara and Katala, respectively);
- 3.76 ± 0.10 Ma to 3.67 ± 0.12 Ma for the early-, syn- and late-mineral tonalite stocks and dykes that comprise Batu Hijau; all three intrusions are emplaced within 90 ± 160 k.y.

The multiple phases of intrusion within each porphyry centre are not distinguished by the SHRIMP zircon ages. The emplacement of the intrusions in each porphyry system was evidently rapid, falling within the limits of precision of this dating method.

The Late Miocene ages of sericite from fault-controlled zones of feldspar-destructive alteration and comb quartz veins southeast of Batu Hijau indicate that hydrothermal activity began as early as ~ 7.1 Ma. This expands the series of distinct hydrothermal events to at least five, constrained to have developed over a period of ~ 3.5 m.y. The duration of the Batu Hijau hydrothermal system is 80 ± 80 k.y., as determined from the argon closure of early biotite and late sericite (3.73 ± 0.08 Ma vs. 3.65 ± 0.02 Ma).

The causative intrusions in the porphyry centres were emplaced at progressively higher crustal-levels through time, as indicated by plagioclase-amphibole thermobarometry and (U-Th)/He apatite thermochronometry results. The estimated depths of crystallisation within the felsic intrusions range from ~ 6 to 9 km for phenocrysts in the porphyritic tonalites at Arung Ara and Katala (5.0 to 4.7 Ma), which constrain the depth of the causative magma chamber(s) to a minimum of 8 km. The solidus emplacement of porphyritic intrusions ranges from ~3 to 5 km at Arung Ara and Katala to as shallow as ≤ 2 km for the tonalite porphyry stocks at Batu Hijau (3.7 Ma) and late-stage porphyritic andesite dykes in the vicinity of the diatreme. The intensity of hydrothermal alteration and metal tenor of the porphyry systems increase with causal intrusion emplacement at progressively higher levels, with the most efficient release of metal-bearing volatiles occurring early in the crystallisation sequence of the tonalite porphyry complex at Batu Hijau.

The majority of the porphyry centres, including Batu Hijau, and the peripheral vein systems at Bambu and Teluk Puna, probably developed under stress-states imposed by nearly arc-orthogonal compression related to subduction of the Indian Plate beneath the Banda arc, characterised by a north-north-easterly directed, maximum compressive stress (σ_1). In contrast, the west-north-westerly zones of comb quartz veins, and related feldspar-destructive alteration, in the vicinity of Batu Hijau are inferred to be related to subsequent relaxation events, characterised by a north-north-easterly trending, minimum compressive stress (σ_3). Average exhumation rates during, and subsequent to, Pliocene porphyry development, determined from (U-Th)/He apatite thermochronometry, range from about 0.5 ± 0.2 mm/yr. for the mid-Pliocene (3.7 Ma) to present, to 1.5 ± 1.0 mm/yr. for the mid-Pleistocene (~1.0 Ma) to present.

The ~3.5 m.y. period, defined by felsic magmatism and related hydrothermal systems in the district (~7.1 through 3.7 Ma), is attributed to the onset of arc-parallel expansion and tensional reactivation of north-easterly trending, crustal-scale strike-slip fault networks in western Sumbawa. The dilatant movement on these faults is probably related to the collision of the leading edge of the Australian shelf, or a microcontinent, with the Banda arc in the vicinity of Timor (~8 Ma) and the subsequent collision of the Australian Craton (~4.0 to 2.5 Ma). The arc-transverse faults localised the rapid ascent of magma, which facilitated the efficient release of mineralising fluids at high crustal-levels. The subduction of the buoyant, Roo Rise oceanic plateau, south of Sumbawa, is inferred to have caused a kink, or tear, in the down-going slab, which enhanced the delivery of mantle-derived melts to the overlying arc, where the episodic reactivation of crustal-scale fault- and fracture-systems increased crustal permeability.

The Batu Hijau deposit displays many of the characteristics of global porphyry copper systems. However, significant differences are related to the low-K calc-alkaline composition of the tonalitic melts at Batu Hijau. The resultant magmatic-hydrothermal fluids are responsible for the K-poor alteration types that

distinguish this deposit from others, particularly those porphyry systems associated with quartz monzonite in continental settings. At Batu Hijau, secondary oligoclase supplants K-feldspar in the central biotite zone, and paragonite proxies for sericite locally. In addition, the abundance of advanced argillic alteration at Batu Hijau exceeds that which typically characterises late-stage alteration in many other porphyry systems.

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