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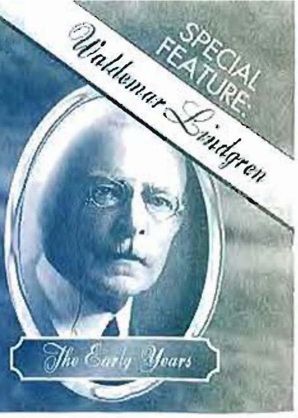

Discovery of a Jurassic Porphyry Copper Belt, Pangui Area, Southern Ecuador

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ABSTRACT

Grassroots exploration has led to discovery of 10 porphyry copper prospects in the previously unexplored Jurassic arc of southeastern Ecuador. The prospects are located in steep, wet, jungle-covered terrain in the Pangui area, part of the Cordillera del Cóndor. The exploration program, initially mounted in search of gold in the Oriente foreland basin, employed panned-concentrate drainage sampling. Follow-up of the resulting anomalies utilized soil sampling combined with rock-chip sampling and geologic mapping of the restricted creek outcrops. Scout and infill drilling of two of the prospects, San Carlos and Panantza, has shown hypogene mineralization averaging 0.5 to 0.7 percent Cu overlain by thin (averaging <30 m) zones of chalcocite enrichment or oxidized copper mineralization.

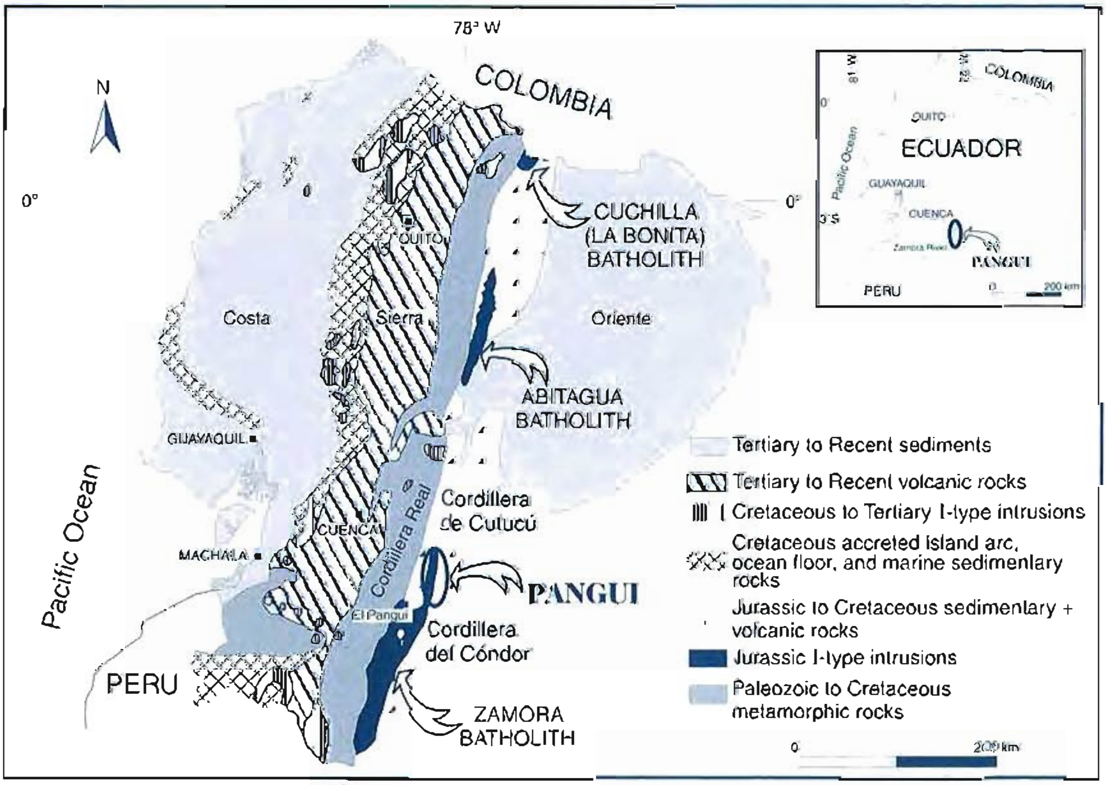

Figure 1. Simplified geology of Ecuador.

The prospects are centered on small, composite granodiorite to monzogranite porphyry stocks that cut the Zamora batholith or, in one case, a satellite pluton. The batholith is emplaced into Jurassic volcanosedimentary

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formations, which concealed Triassic extensional half-grabens before being incorporated into the Subandean fold-thrust belt along the western margin of the Oriente basin. North- and northwest-striking normal faults in the hanging wall of a major north-striking fault zone controlled the locations of most of the porphyry centers.

K silicate and variably overprinted intermediate argillic alteration, containing chalcopyrite as the principal sulfide mineral, characterize the central parts of most of the porphyry prospects and grade outward to pyrite-dominated propylitic halos. Overprinted sericitic alteration is generally less widely developed, although apparently shallower erosion at the Warintza and Wawame prospects resulted in preservation of extensive pyrite-rich sericitic zones. All the prospects contain appreciable (60–250 ppm) molybdenum, but gold tenors are low except at Panantza and Wawame (~0.15 and 0.2 g/t, respectively). Supergene oxidation and chalcocite enrichment zones are immature because of inhibition by the rapid erosion prevalent in the Pangui area. Supergene profiles attain their maximum development on ridge crests but are essentially absent along major creeks.

Discovery of the Pangui belt, along with other recently defined porphyry copper systems in northern Perú, Indonesia, and the Philippines, underscores yet again the efficacy of drainage geochemistry as an exploration technique in tropical and subtropical arc terranes as well as the outstanding potential for additional exposed deposits in poorly explored parts of the circum-Pacific region.

INTRODUCTION

A previously unknown porphyry copper belt has been discovered in the Pangui area, a 1,640 km² area of Morona-Santiago and Zamora-Chinchipe Provinces, southeastern Ecuador (Figs. 1 and 2). The 10 porphyry copper systems and one copper skarn define a 70-km-long, north-south-trending belt (Fig. 3, p. 10) in the Cordillera de Cutucú and Cordillera del Cóndor, parts of the Subandean belt bordering the Oriente basin in Perú (Fig. 1).

The climate of the Pangui area is humid subtropical, with annual rainfall of 1,000 to 2,500 mm and average temperatures ranging from 18° to 22°C. Elevations range from 600 to 3,000 m, with the deeply incised Zamora River forming the main drainage within the area. Much of the area is covered by jungle and characterized by slopes steeper than 25°. Soil cover varies in thickness from 10 cm to 20 m, with a thick (~1 m) layer of black humus typically overlying a well-developed, orange to red B horizon composed mostly of clay.

Nine of the 10 porphyry copper centers are located within the mapped limits of the Zamora batholith and the tenth, Warintza, is approximately 13 km east (Fig. 3). The Zamora batholith, extending from 3° to roughly 5° S, is bounded westward by Jurassic sedimentary and volcanic rocks and the Cordillera Real metamorphic belt, all cut by north-northeast-striking thrust faults (Figs. 1 and 2).

Until the mid-1990s, the Pangui area and its environs were largely unexplored. This article outlines the six-year exploration program initiated by Gencor Limited and continued, following corporate restructuring, by Billiton plc. General geologic features of the Pangui area are highlighted, with particular reference to the initial discoveries, the San Carlos and Panantza porphyry copper prospects.

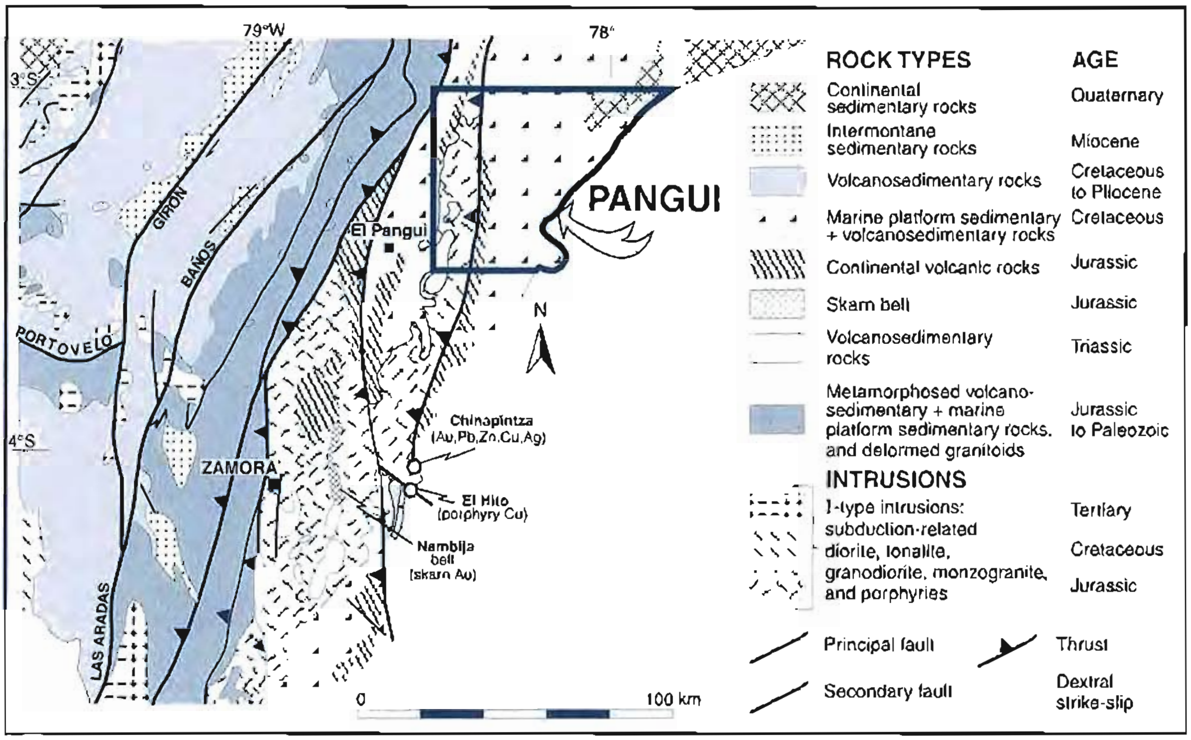

Figure 2. Simplified regional geology of part of southern Ecuador, modified from Zamora and Litherland (1993).

EXPLORATION HISTORY

Gencor, through its subsidiary Gatro Ecuador Minera S. A., initiated the Pangui project in 1994. Exploration was designed to test the perceived gold potential of the Oriente foreland basin by means of a regional reconnaissance panned-concentrate geochemical sampling program. The results outlined a number of gold and base-metal targets for follow-up, during which the first porphyry copper-molybdenum prospect, San Carlos, was identified in April 1995. Nine more porphyry copper centers were discovered by follow-up of other panned-concentrate anomalies over the next four years (Fig. 3).

Ridge-and-spur soil sampling effectively delineated the porphyry copper prospects. The soil sampling was accompanied by detailed rock-chip sampling of all mineralized rock exposures along streams and rivers, and was followed by scout diamond drilling of three of the identified porphyry copper targets. Infill evaluation drilling was completed on two of these targets, San Carlos and Panantza.

Airborne magnetic, electromagnetic, and radiometric data were collected over the Pangui belt and were complemented by ground induced-polarization surveys over most of the individual porphyry copper centers. Ground magnetic surveys were conducted solely at San Carlos and Panantza.

In mid-1999, Billiton scaled back its generative exploration effort and, shortly thereafter, concluded an agreement for further exploration of the Pangui area with Corriente Resources Inc. of Canada. Since late 1999, diamond drilling of two more porphyry copper prospects, Warintza and Wawame, has been funded by Corriente Resources and managed by Lowell Mineral Exploration.

REGIONAL SETTING

Ecuador may be divided into three physiographic units: the Costa, Sierra, and Oriente, from west to east (Fig. 1). The Oriente, or eastern region, is part of a foreland basin between the Guyana Shield and the Andean Cordillera (Baldock, 1982). It comprises the upper reaches of the Amazon basin and the Subandean zone. The Subandean zone in Ecuador is a back-arc fold-thrust belt, which encompasses the Cordillera de Cutucú and Cordillera del Cóndor frontal uplifts (Fig. 1).

The Subandean zone was part of an Early Mesozoic rift system (Jaillard et al., 1990; Aspden and Litherland, 1992) characterized by north-trending, nested half-grabens (Balkwill et al., 1995). Interpretation of unpublished seismic records for the Cordillera de Cutucú and Cordillera del Cóndor (C. Spencer, unpub. rept., 1995) shows that normal faults in the extensional system are curvilinear in form, with a dominant north-northwest strike and downthrow mostly to the west. The normal faults terminate against, or merge with, northeast-striking strike-slip transfer zones that consist of anastomosing or en-echelon fault sets. During the Early Jurassic, the rift basins were filled by marine limestone, sandstone, and shale (Santiago Formation), facies-equivalent red-bed sandstone and shale, with thin horizons of anhydrite, dolomite, and gypsum (Chapiza unit), and overlying arc-type basaltic and andesitic volcanic and volcaniclastic rocks (Misahuallí unit; Fig. 3), as documented by Tschopp (1953), Baldock (1982), and Litherland et al. (1994).

Middle to Late Jurassic batholiths and volcanic rocks (including the Misahuallí unit) along the eastern side of the Cordillera Real of Ecuador (Fig. 1) and in the Cordillera Oriental of Colombia are interpreted as remnants of a calc-alkaline volcanoplutonic arc constructed at an Andean-type continental margin (Sillitoe et al., 1982; Aspden et al., 1987). Jurassic plutons in Ecuador and neighboring Colombia, including the large Zamora, Abitagua, and Cuchilla batholiths (Fig. 1), range in age from ~190 to 150 Ma (Aspden et al., 1992; Litherland et al., 1994). Jurassic intrusions in the Cordillera Oriental of southern Colombia are associated with porphyry copper systems (Sillitoe et al., 1982, 1984; Fig. 4), but no such mineralization of this

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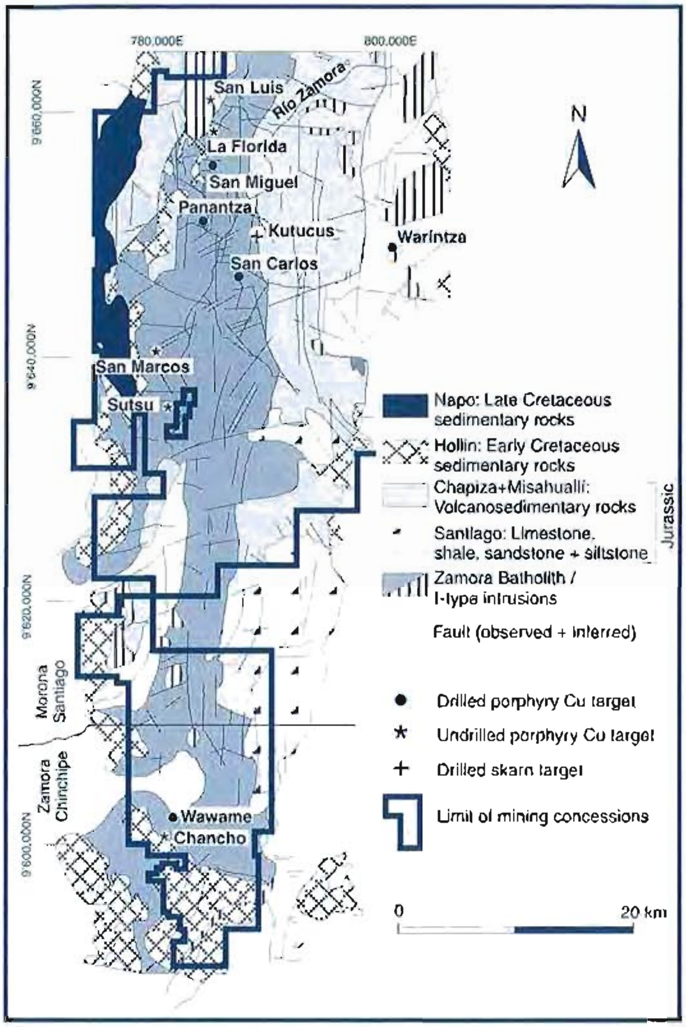

Figure 3. Summary geology of the Pangui district based on aerial photographs and reconnaissance mapping during follow-up drainage sampling. Locations of porphyry copper and skarn prospects are shown.

age had been documented farther south in Ecuador prior to the discoveries described herein.

Epicontinental quartzite of the Early Cretaceous Hollin Formation (Fig. 3) accumulated in a fluviatile environment over the erosionally planed Jurassic volcanosedimentary sequences and batholiths (Tschopp, 1953) following compressive tectonism induced by terrane accretion along the northern Andean margin (Aspden and Litherland, 1992). Back-arc extension during the late Early to Late Cretaceous allowed deposition of marine mudstone and limestone of the overlying Napo Formation (Tschopp, 1953). As a result of renewed collision along the northern Andean margin during the latest Cretaceous-Early Tertiary (Aspden and Litherland, 1992), the Early Mesozoic extensional faults underwent partial tectonic inversion. The Cordillera de Cutucú and Cordillera del Cóndor frontal uplifts were formed during this east-directed compression.

LOCAL METALLOGENY

Gold was exploited in pre-Colombian and Colonial times at several localities in the Cordillera del Cóndor. The Nambija and Chinapintza gold districts, approximately 70 km south of the Pangui area (Fig. 2), have attracted both artisanal miners and companies over the last two decades. Nambija is best known for gold in retrograde calcic skarn developed within a roof pendant in the Zamora batholith, whereas Chinapintza contains gold-bearing low-sulfidation epithermal polymetallic veins and hydrothermal breccias (Gemuts et al., 1992; Litherland et al., 1994; MEM-PRODEMINCA, 2000a). Porphyry copper-gold and related polymetallic mineralization along with placer gold occur nearby at El Hito (Fig. 2).

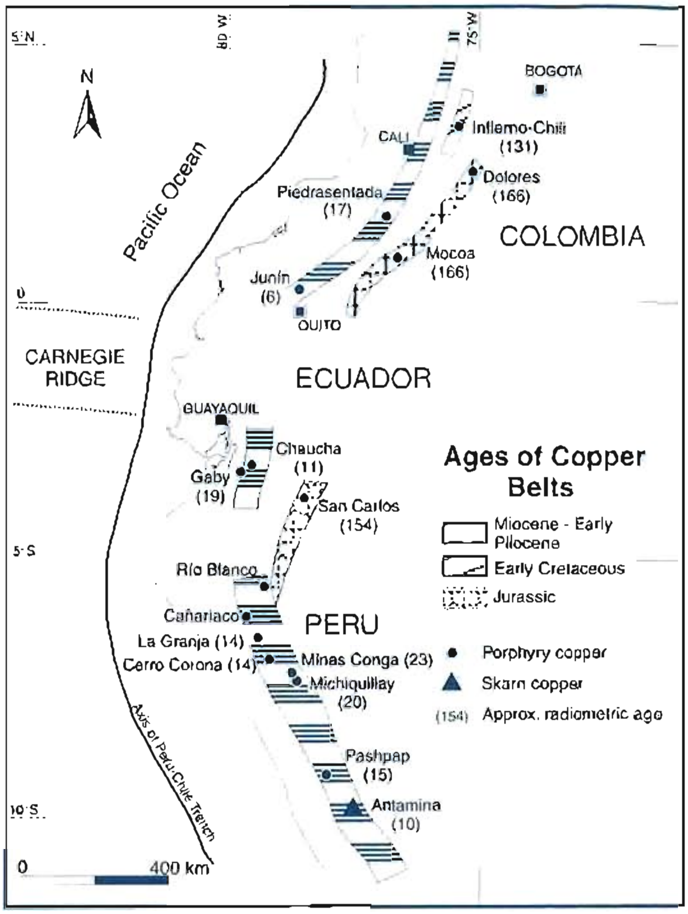

Figure 4. Copper belts of the Andes of southern Colombia, Ecuador, and northern Perú showing the main porphyry and skarn copper deposits and prospects, modified from Sillitoe (1988) using radiometric ages from Noble and McKee (1999), MMAJ-JICA (1997), MEM-PRODEMINCA (2000b), and this study.

The gold mineralization of porphyry, skarn, and epithermal types in the Cordillera del Cóndor has been dated as mid-Cretaceous to early Tertiary by the K-Ar method (MEM-PRODEMINCA, 2000a), although a Jurassic age was assumed by Gemuts et al. (1992).

LOCAL GEOLOGY

The Zamora batholith comprises I-type, calc-alkaline diorite, tonalite, granodiorite, and monzogranite intrusions characterized by a general lack of ductile fabrics and relatively low Sr_i values (0.7046–0.7051; Litherland et al., 1994). The batholith, dated at Middle to Late Jurassic (~190 to 150 Ma; Aspden et al., 1992; Litherland et al., 1994), cuts the Santiago, Chapiza, and Misahualli sequences and is intruded by the stocks related to nine of the Pangui porphyry copper centers (Fig. 3).

K-Ar ages of 154 ± 5 Ma (SERNAGEOMIN, Chile, unpub. rept., 1997) for a whole-rock sample of intensely sericitized porphyry and 157± 5 Ma for hornblende separated from a late intermineral porphyry (MEM-PRODEMINCA, 2000a), both from San Carlos, confirm that the Pangui porphyry copper belt is also Late Jurassic in age (Fig. 4).

The Zamora batholith and associated stocks are unconformably overlain by the Hollin quartzite (Fig. 3), which attains a thickness of approximately 150 m in the Pangui belt where it forms flat-lying outliers. Mudstone and subsidiary limestone of the overlying Napo Formation are exposed on the western flanks of the Cordillera del Cóndor (Fig. 3).

The Zamora batholith is interpreted to have been intruded into the hanging wall of a north-striking zone of Jurassic normal faults that was tectonically inverted in the Tertiary to produce the Cordillera del Cóndor uplift (Fig. 3). Nine of the porphyry copper prospects are located adjacent to subsidiary faults cutting the batholith, especially those striking north and northwesterly.

The porphyry copper prospects identified through late 1999 are centered on composite granodiorite to monzogranite porphyry stocks. At San Carlos, Panantza, and elsewhere, the porphyries are the foci of K silicate alteration and chalcopyrite mineralization. Intermediate argillic and sericitic alteration overprint the K silicate assemblages, except at Warintza and Wawaine, where sericitization is limited in extent. Propylitic alteration, containing anomalously high zinc, constitutes halos to all the porphyry centers. Quartz veinlets are poorly developed in all the porphyry prospects compared to many such systems elsewhere. Sulfide zoning, from pyrite/chalcopyrite ratios as low as 1:10 in the cores to >10:1 on the peripheries, clearly defines the prospects.

PORPHYRY COPPER PROSPECTS

San Carlos

The composite granodiorite porphyry stock at San Carlos intrudes equigranular monzogranite of the Zamora batholith. The porphyries contain prominent plagioclase and hornblende with subordinate quartz phenocrysts. Early, intermineral, and postmineral phases are recognized, each with its own diagnostic copper content. Progressively younger porphyries truncate veinlets in earlier phases (cf., Kirkham, 1971).

The early porphyry is characterized by relatively low intensities of quartz veining and typically 0.5 to 0.7 percent hypogene Cu, mainly in the form of dispersed grains and fracture coatings of chalcopyrite. The intermineral porphyries are subdivided into three phases containing progressively lower copper contents (Figs. 5 and 6). These three phases also display progressively lower fracture and veinlet intensities, with the last two lacking molybdenite-bearing B veinlets (as defined by Gustafson and Hunt, 1975). The intermineral porphyries constitute two north-northwest-striking dike-like bodies, the western one possessing a shallowly southeast-dipping roof (Figs. 5 and 7). The postmineral porphyry is volumetrically minor, comprises narrow northeast-striking dikes, and lacks veinlets and sulfides.

A northeast-striking fault separates the early porphyry in the south from the intermineral porphyries farther north (Figs. 5 and 7). The fault is observed to have been active during mineralization and to have undergone north-side-down, postmineral displacement approaching 400 m (Fig. 7).

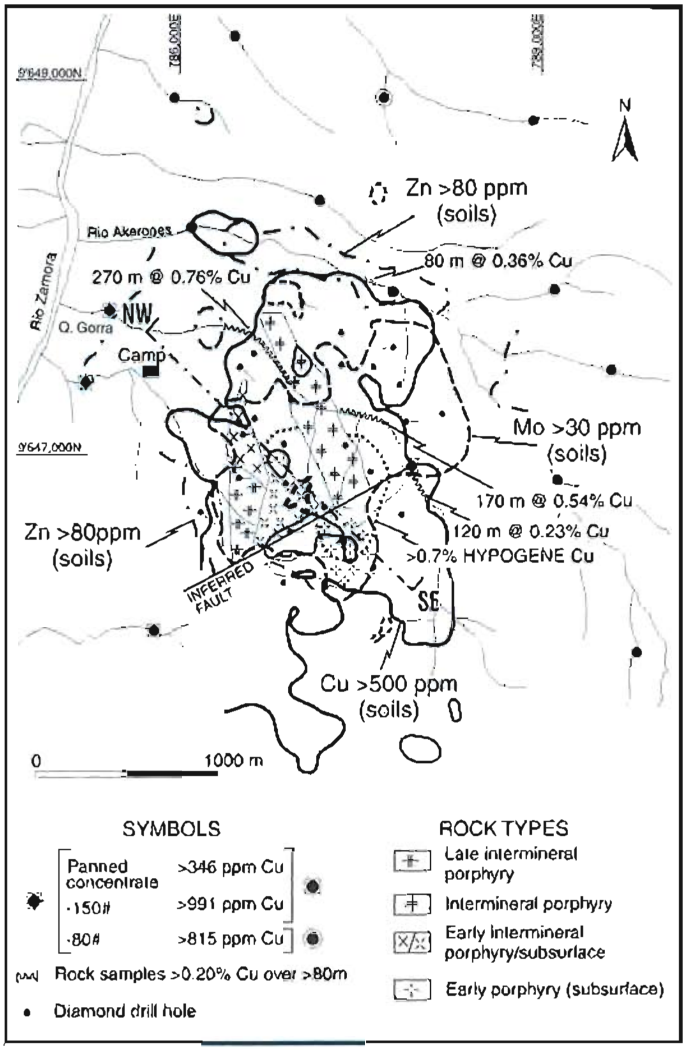

Figure 5. Selected geologic and geochemical features of the San Carlos porphyry copper prospect. Note panned-concentrate results obtained during the reorientation survey, rock-chip sample results along the main creek through the prospect (with total sampling lengths and average copper grades), and outer limits of copper, molybdenum, and zinc soil geochemical anomalies. NW–SE is line of section in Figure 7.

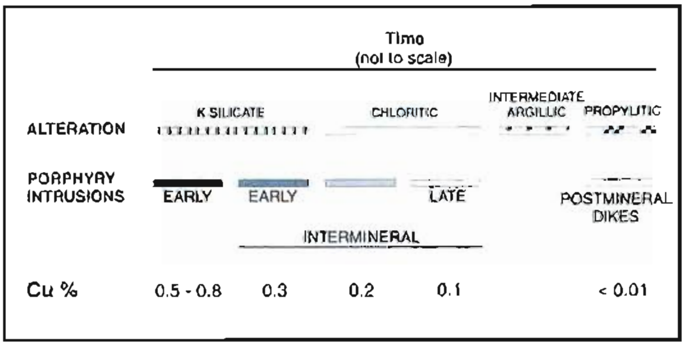

Figure 6. Schematic plot showing temporal relations between porphyry intrusion, alteration, and average copper grades, San Carlos porphyry copper prospect.

The early porphyry and the first of the intermineral porphyries, along with the adjoining host monzogranite, were subjected to K silicate (biotite-K feldspar) alteration and associated chalcopyrite mineralization. The two latest intermineral porphyries were emplaced after the completion of K silicate alteration (Fig. 6), as shown by direct

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replacement of hornblende phenocrysts by chlorite rather than biotite. Alteration as well as mineralization intensities diminish as the porphyry phases become younger. The central copper-bearing parts of the system are characterized by pyrite/chalcopyrite ratios of ≤1:1; ratios increase abruptly outward to exceed 10:1 in the southwest and 50:1 in the northeast, where peripheral sericitic alteration is located.

Intermediate argillic alteration overprints all the intrusive rocks, excepting the postmineral dikes (Fig. 6). This alteration event is characterized by partial transformation of mafic minerals to chlorite, replacement of plagioclase by illite or smectite, hematite pseudomorphs (martite) after magnetite, and some pyrite and calcite introduction, but does not appear to have materially changed the overall copper content. Small, irregularly distributed patches of K silicate alteration remain within the predominant intermediate argillic assemblages, but larger remnants also occur locally (Fig. 7). The barren postmineral porphyry dikes display only weak propylitic (chlorite-epidote) alteration.

A roughly 600 x 600-m zone in the south-central part of the San Carlos prospect contains >0.7 percent hypogene copper in the early granodiorite porphyry and its host monzogranite (Fig. 5). Hypogene copper content decreases progressively outward, although the decrease is modest toward the north. Emplacement of the intermineral porphyries partly destroyed this higher-grade hypogene core zone.

An immature supergene profile, thickest beneath ridge crests and essentially absent from creek beds, is developed at San Carlos. The chalcocite enrichment zone, which averages ~25 m thick, is best developed where high hypogene copper values and pyrite/chalcopyrite ratios of ≥1:1 in monzogranite underlie the main ridge (Figs. 5 and 7). The best vertical drill intersection of enriched material is 1.34 percent Cu over 68 m. A thin mixed zone of chalcocite partly transformed to copper oxide minerals separates the enriched zone and the overlying 50- to 150-m thick goethitic leached capping (Fig. 7).

Where pyrite/chalcopyrite ratios are <1:1, insufficient acid was generated to mobilize much copper. Neotocite (amorphous copper-manganese-iron silicate), copper clay (fine-grained chrysocolla impregnating supergene kaolinized plagioclase phenocrysts), and minor pitch limonite (cupriferous goethite) and chrysocolla developed extensively in the oxidized zone. The relatively high neutralization capacities of the intermineral porphyries resulted in fixation of exotic copper, mainly as copper clay, in the oxidized zones.

Panantza

The Panantza prospect is characterized by a suite of intrusive rocks similar to those at San Carlos. An equigranular monzogranite host rock, intruded by aplogranite, is cut by an early and two intermineral monzogranite porphyries. The three porphyries have grade signatures of 0.6 to 0.8, 0.3, and 0.15 percent hypogene Cu, respectively. All the porphyries contain prominent plagioclase and hornblende phenocrysts plus variable amounts of quartz phenocrysts and orthoclase megacrysts. The early porphyry has notably less phenocrystic quartz and orthoclase than the early intermineral phase. The early porphyry constitutes an elongate, northwest-trending body (Fig. 8). Several narrow, barren postmineral porphyry dikes were intersected in the drilling, all suspected to be genetically unrelated to

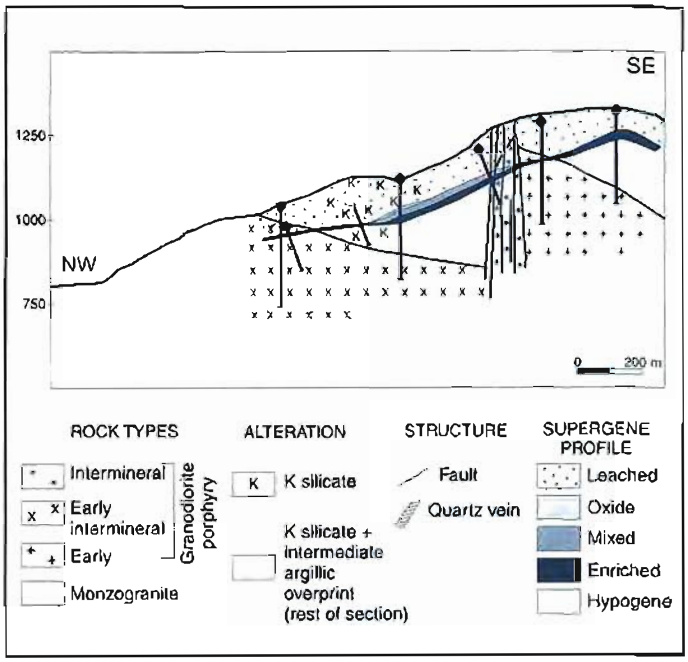

Figure 7. Geologic section of San Carlos porphyry copper prospect, along line NW–SE in Figure 5.

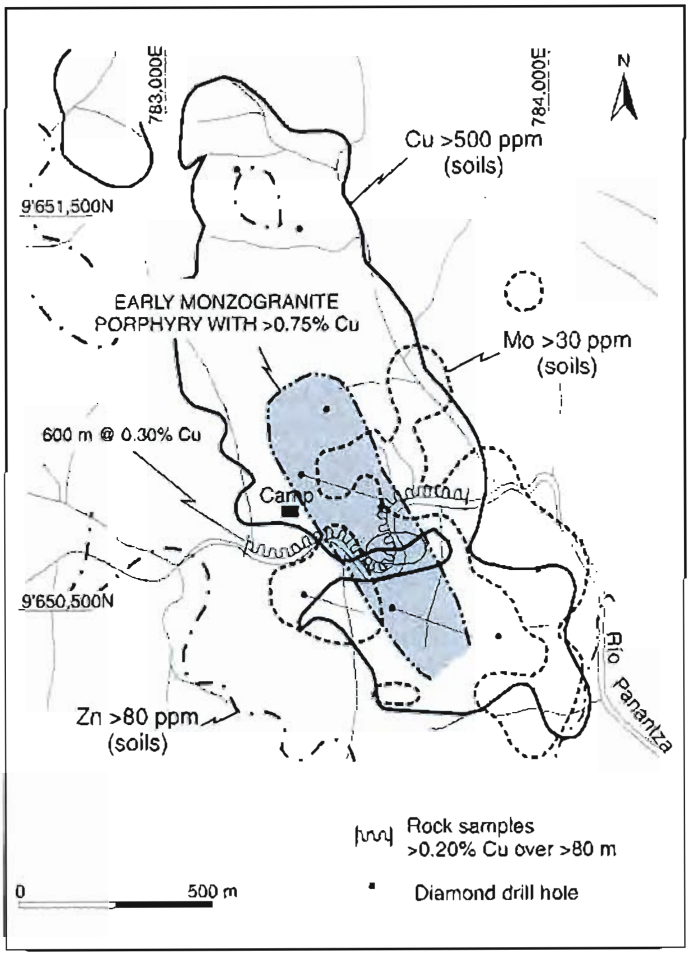

Figure 8. Selected geologic and geochemical features of the Panantza porphyry copper prospect. Note rock-chip sample results along the main creek through the prospect (with total sampling length and average copper grade) and outer limits of copper, molybdenum, and zinc soil geochemical anomalies.

porphyry copper formation. An earlier dike generation is andesitic (microdioritic), a later one dacitic or rhyodacitic.

Monzogranite and aplogranite host rocks, early porphyry, and early intermineral porphyry all underwent K silicate alteration, accompanied by chalcopyrite as disseminated grains in mafic sites and fracture fillings. Pyrite/chalcopyrite ratios in the central parts of the system do not exceed 1/1, but pyrite content increases appreciably as the periphery of the system is approached.

K silicate alteration in the core of the system passes outward to a partial halo of sericitic alteration which is deficient in chalcopyrite. The K silicate core is patchily overprinted by intermediate argillic and less widespread sericitic alteration. Although the intermediate argillic overprint caused local redistribution of copper and addition of pyrite, it does not have any consistent effect on the average copper content of the pre-existing K silicate alteration. It does, however, cause a 30 to 60 percent reduction of the initial (~0.15 g/t) gold content.

The most southerly drill hole intersected a major, possibly northwest-striking fault zone defined by sheared and brecciated monzogranite. The fault zone is characterized by pervasive sericitic alteration and contains late-stage sphalerite (up to 0.8% Zn), from which it is inferred that the faulting was active at least during late-stage hydrothermal activity.

The highest hypogene copper values, >0.75 percent, are concentrated in and immediately surrounding the early porphyry body in a northwest-trending zone some 800 m long and 200 m wide (Fig. 8). Copper values decrease progressively outward beyond this early porphyry zone, which is confined to the southern half of the Panantza copper-in-soil anomaly (Fig. 8).

Chalcocite enrichment is weakly developed at Panantza as a result of either unduly low pyrite/chalcopyrite ratios or insufficient initial copper content in the intermineral porphyries. The oxidized zone at Panantza averages only about 50 m thick because the system is centered on the broad Rio Panantza valley (Fig. 8). Where pyrite/chalcopyrite ratios are ≤1:1, copper oxide mineralization, underlain by a thin zone of chalcocite-bearing mixed material, is developed. The main copper oxide minerals are copper clay, malachite, chrysocolla, and pitch limonite.

Other prospects

More recently discovered porphyry copper prospects in the Pangui belt include Warintza and Chancho-Wawame (Fig. 3). The Warintza area is underlain by an equigranular granodiorite pluton located east of the Zamora batholith. The pluton intrudes a sequence of andesitic volcanic and minor intercalated sedimentary rocks, locally calcareous in composition, the affiliation of which remains uncertain (Fig. 3). Part of the contact between the pluton and its host rocks is cut by a composite granodiorite or monzogranite porphyry stock, the focus of the main Warintza porphyry copper system. Small volumes of hydrothermal breccia occur locally. The Warintza prospect is characterized by a 10-km^2 zone of intense and pervasive sericitic alteration. The sericitic zone is interpreted to be underlain by K silicate alteration, which is exposed at the lowest elevations around the margins of the prospect. On the basis of the results of rock-chip sampling along creeks, the high pyrite content (pyrite/chalcopyrite >5/1), and the existence of a broad high ridge at Warintza, chalcocite enrichment is predicted to be as good as, if not better than, that at San Carlos. Results announced (May 2, 2000) by Corriente Resources suggest a broadly similar thickness and degree of enrichment beneath the area selected for initial drill testing.

At the Chancho-Wawame porphyry copper prospect, granodiorite of the Zamora batholith intrudes Misahuallí andesitic volcanics and siltstone and is overlain by Hollín quartzite. The granodiorite and its host rocks at Wawame are cut by several porphyry phases, the most important of which is tentatively assigned a quartz diorite composition. Smaller intermineral diorite porphyries are also observed, along with bodies of hydrothermal breccia. Sericitic alteration is predominant, although remnants of K silicate alteration are present. Rock-chip sampling along the numerous creeks at Wawame suggests that the mineralization consists of >0.5 percent hypogene Cu and ~0.2 g/t Au, values that were confirmed (July 6, 2000) by Corriente Resources' initial drilling results.

RESOURCES

San Carlos was tested by 26 diamond drill holes totaling 5,933 m, from which an inferred hypogene mineral resource of about 850 million tonnes at 0.5 percent Cu was estimated (B. Kirk and J. Ford, unpub. rept., 1999). Although a zero cutoff grade was applied, the calculation refers only to the higher-grade early porphyry and contiguous monzogranite, with the lower-grade intermineral and late-mineral porphyries being excluded from consideration. Supergene sulfide and copper oxide resources are far more limited, albeit higher in grade, with the main chalcocite enrichment zone averaging >0.7 percent Cu.

At Panantza, a total of 2,983 m of diamond drilling was completed in 11 holes, but data are insufficient to estimate mineral resources. Drill holes in the central part of the prospect cut hypogene mineralization averaging about 0.7 percent hypogene Cu, similar to that in the higher-grade zone at San Carlos. Copper oxide mineralization in two holes averages about 1.2 percent Cu over 27 to 50 m vertically, although continuity of the mineralization remains to be determined. No significant chalcocite enrichment was encountered at Panantza.

EXPLORATION REVIEW

When exploration commenced in the Pangui area, a lack of suitable topographic and geologic maps provided the rationale for an aerial photographic interpretation in 1994. This interpretation identified a number of the principal north- and northwest-striking faults that later proved to control the locations of porphyry copper prospects. Our experience suggests that aerial photography, RADARSAT (synthetic aperture radar imagery), and Landsat TM imagery may be used as effective aids to selecting prospective ground in the Pangui area.

Panned-concentrate sampling was the main technique used during the reconnaissance exploration stage, and proved to be the critical element in the program. Sample density, at one per ~0.4 km^2, was high. Panned-concentrate samples were analyzed for gold (30–50 g fire assay with AA finish) and a suite of 34 elements by ICP at Bondar Clegg's laboratory in Vancouver, Canada. Geologic mapping during the reconnaissance phase also proved useful, but cannot be relied upon as a basic exploration tool because of the lack of outcrip.

Orientation studies, which had the specific aim of detecting coarse gold, showed that panned-concentrate sampling was the most suitable geochemical method for regional screening. A further orientation study was

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undertaken following recognition of the first porphyry copper prospect at San Carlos. This reorientation sampling revealed no significant difference between anomaly definition achieved using –80# and –150# silt fractions and the panned concentrates (Fig. 5). Both stream-sediment and panned-concentrate sampling would have showed the San Carlos drainages to be anomalous with respect to a suite of elements, including Cu (Fig. 5), Mo, Zn, Pb, As, and Au.

Follow-up work, comprising semidetailed geologic mapping and ridge-and-spur soil sampling, outlined the general extent and characteristics of the porphyry copper prospects. Subsequent infill soil sampling on lines 200 m apart is sufficient to fully delimit the mineralization. The main prospects are overlain by >500 ppm Cu and >30 ppm Mo in soil (Figs. 5 and 8). Several orientation studies were conducted to define the optimal soil-sampling procedure. This involved collection of samples from the B horizon at a depth of 50 cm to 1 m and at 50- to 100-m intervals along lines. Duplicate samples were taken at every twentieth site. No augering was necessary for sample collection. Soil samples weighing 800 to 1000 g were collected for shipment to Intertek Testing Services, Bondar Clegg's preparation facility in Quito, where the samples were dried, disaggregated with pestle and mortar, and sieved to –80#. The –80# fraction was analyzed for Au and a suite of 34 elements in the same manner as described above for the panned-concentrate samples.

During target definition using grid soil sampling, detailed chip-channel sampling of all well-mineralized outcrops along creek beds was carried out at 5- to 20-m intervals (Figs. 5 and 8). Where samples were largely free of supergene chalcocite, the analytical results approximate the hypogene copper content of underlying rocks. Generally, where mineralization crops out and possesses pyrite/chalcopyrite ratios of ≤1:1, the core of the system is exposed. This conclusion would be confirmed by mapping K silicate-altered early porphyry intrusions. In contrast, if a creek displays pyrite/chalcopyrite ratios substantially >1:1, it suggests that the high-grade core of the system may be concealed elsewhere within the soil anomaly, and hence, requires scout drilling to locate it. Alternatively, the K silicate core may underlie pyrite-rich sericitic alteration.

Airborne electromagnetic and magnetic surveys are useful in recognizing porphyry copper alteration zones within the Zamora batholith and satellite plutons. High conductivity responses are obtained over sericitic and propylitic halos of the San Carlos, Sutsu, and Panantza prospects, whereas at Warintza a high conductivity anomaly outlines the main mineralized zone characterized by sericitic alteration. Analytical signal lows due to magnetite destruction define porphyry centers where intermediate argillic or sericitic alteration is intensely developed (P. Mills and B. Kirk, unpub. rept., 1999). The ground and airborne geophysical results were not used for locating the initial scout drill holes, but proved a valuable backup to geochemistry when siting the subsequent infill holes at San Carlos and Panantza.

DISCUSSION

The Jurassic metallogenic belt along the eastern edge of the Andean Cordillera, host to the Zamora batholith and Pangui porphyry copper systems, is well-defined southward from Colombia to the vicinity of the Ecuador-Perú border, where it appears to terminate (Fig. 4). The cessation of Jurassic magmatism at this position, coincident with the change in Andean strike from northeast to northwest at the Huancabamba Deflection, may be attributed to the fact that subduction of oceanic lithosphere was directed southeastward (Aspden et al., 1987; Jaillard et al., 1990). Hence, orthogonal subduction with associated magmatism and copper mineralization along the northern Andes gave way to roughly trench-parallel motion and amagmatic conditions along the central Andes of Perú.

The available radiometric ages suggest that the Pangui porphyry copper stocks were intruded during the final stages of Zamora batholith emplacement. Hence, the confinement of the porphyry copper systems to the Zamora batholith. However, at Warintza, an equigranular satellite pluton suggests that batholith and stock intrusion and copper mineralization took place during—and followed by—uplift and erosion. The postmineral erosion must have largely predated deposition of the unconformably overlying Hollin Formation and, therefore, been a consequence of the latest Jurassic collisional event (Aspden and Litherland, 1992). Notwithstanding the typically small sizes of the mineralized stocks (Figs. 5 and 8), the predominance of pyrite-poor K silicate alteration and paucity of sericitic alteration and hydrothermal brecciation at most prospects may be taken to suggest that a relatively deep (say, >3 km) environment is exposed.

Nevertheless, the predominance of pyrite-rich sericitic over K silicate alteration at both Warintza and Wawame, as well as at the Jurassic Mocoa prospect in southern Colombia (Sillitoe et al., 1984; Fig. 4), implies that erosion levels may be substantially shallower locally. Preservation of these shallower systems, as well as the Pangui belt in general, owes much to concealment in a back-arc setting beneath the Cretaceous Hollin and Napo Formations as well as now-eroded younger formations.

Hypogene copper content of 0.7 to 0.8 percent in the cores of the best-studied prospects—San Carlos and Panantza—is relatively high by world standards. Such high values are somewhat surprising when the relatively low intensity of quartz-veinlet stockworks is recalled. Most of the Pangui prospects contain 60 to 70 ppm (and, at Warintza, ~250 ppm) Mo and, hence, are classifiable as copper-molybdenum systems, although none has a molybdenum content approaching that of Mocoa (>600 ppm; Sillitoe et al., 1984). Low-grade gold (<0.1 g/t), is generally present except at Panantza and Wawame where available analyses suggest averages of ~0.15 and 0.2 g/t, respectively.

The steep terrain, copious rainfall, and consequent high erosion rates in the Pangui area seem to have inhibited development of deep supergene profiles and generation of thick leached, oxidized, and attendant chalcocite enrichment zones like those in southern Perú and northern Chile (e.g., Sillitoe, 1990). Rather, supergene profiles are relatively thin and immature, ranging from maxima of ~150 m beneath ridge crests to zero beneath major drainages. Such modest supergene profiles typify porphyry copper systems in similar geomorphic and climatic regimes elsewhere in the northern Andes (e.g., Mocoa; Sillitoe et al., 1984; Río Blanco; Braun et al., 2000; Fig. 4). Nevertheless, substantially thicker zones of chalcocite enrichment locally developed rapidly under comparable conditions (e.g., Ok Tedi, Papua New Guinea: Bamford, 1972), thereby implying that the full supergene potential of the Pangui belt must await completion of further drilling. Any supergene profiles developed before Hollin sedimentation in the Early Cretaceous appear to have been eroded, although this remains to be ascertained at Chancho, which is partially concealed beneath flat-lying quartzite.

CONCLUDING REMARKS

Discovery of the Pangui porphyry copper belt was an unexpected outcome of a somewhat unorthodox gold exploration program. Panned-concentrate sampling proved to be extremely effective in identifying copper and molybdenum anomalies associated with the porphyry copper centers, although this sample medium would not be the one normally selected for base-metal exploration. The difficult terrain, limited access, and extreme climatic conditions were the main challenges to both the regional geochemical sampling and subsequent follow-up work, as they are in some other jungle-covered arcs throughout the circum-Pacific region. Mapping and sampling of creek outcrops combined with soil geochemistry proved an efficient means of delimiting the porphyry copper systems and selecting drill targets—procedures used widely in similar environments elsewhere.

The Pangui discoveries emphasize yet again the effectiveness of grassroots exploration using tried-and-tested geologic and geochemical techniques in poorly explored areas. In the case of the Pangui area, proximity to the disputed frontier with Perú hindered exploration activities for 57 years. It is hoped that the permanent settlement of the border dispute in 1999 will promote exploration and lead to further discoveries both in southern Ecuador and neighboring northern Perú. Furthermore, the success of the Pangui project should encourage application of similar basic grassroots programs elsewhere in underexplored tropical and subtropical regions around the Pacific Rim. Comparable programs, based on drainage geochemistry, have resulted in discovery of porphyry copper systems in steep jungle terrain at Río Blanco in northern Perú (Braun et al., 2000), Batu Hijau in Indonesia (Meldrum et al., 1994), and Tampakan in the Philippines (Rohrlach et al., 1999) during the last decade. Río Blanco and Batu Hijau, like the Pangui porphyry copper systems, were the unplanned outcomes of exploration for gold.

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