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Chapter 9

Gold-Rich Porphyry Deposits: Descriptive and Genetic Models and Their Role in Exploration and Discovery

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Abstract

Gold-rich porphyry deposits worldwide conform well to a generalized descriptive model. This model incorporates six main facies of hydrothermal alteration and mineralization, which are zoned upward and outward with respect to composite porphyry stocks of cylindrical form atop much larger parent plutons. This intrusive environment and its overlying advanced argillic lithocap span roughly 4 km vertically, an interval over which profound changes in the style and mineralogy of gold and associated copper mineralization are observed. The model predicts a number of geologic attributes to be expected in association with superior gold-rich porphyry deposits. Most features of the descriptive model are adequately explained by a genetic model that has developed progressively over the last century. This model is dominated by the consequences of the release and focused ascent of metalliferous fluid resulting from crystallization of the parent pluton. Within the porphyry system, gold- and copper-bearing brine and acidic volatiles interact in a complex manner with the stock, its wall rocks, and ambient meteoric and connate fluids. Although several processes involved in the evolution of gold-rich porphyry deposits remain to be fully clarified, the fundamental issues have been resolved to the satisfaction of most investigators. Exploration for gold-rich porphyry deposits worldwide involves geologic, geochemical, and geophysical work but generally employs the descriptive model in an unsophisticated manner and the genetic model hardly at all. Discovery of gold-rich porphyry deposits during the last 30 yr has resulted mainly from basic geologic observations and conventional geochemical surveys, and has often resulted from programs designed to explore for other mineral deposit types. The tried-and-tested approach is thought likely to provide most new discoveries for the forseeable future, although more rigorous and innovative application of the descriptive and genetic models can only improve the chances of success.

Introduction

GOLD-RICH porphyry systems possess all essential geologic attributes of gold-poor, commonly molybdenum-rich porphyry copper deposits (e.g., Lowell and Guilbert, 1970; Titley and Beane, 1981). Gold like copper is present within and immediately surrounding altered porphyry stocks. The stocks are focuses of more extensive hydrothermal systems, which may form other related mineralization styles, including high- and low-sulfidation epithermal deposits, skarns, and replacement deposits in carbonate and noncarbonate rocks (e.g., Sillitoe, 1991; Jones, 1992). The epithermal orebodies associated with the Far Southeast deposit, Philippines (Claveria et al., 1999), and the carbonate-hosted polymetallic orebodies alongside the Bingham deposit (Babcock et al., 1995) provide classic examples of zoning around gold-rich porphyry centers.

Porphyry deposits with average gold contents of ≥0.4 g/metric ton (t) Au may be defined, albeit arbitrarily, as gold rich (Sillitoe, 1979). These gold-rich porphyry deposits worldwide (Fig. 1) comprise a continuum of systems from copper plus by-product gold, through gold plus by-product copper, to gold-only end members (e.g., Kirkham and Sinclair, 1996; Fig. 2a). Average gold contents are generally <1 g/t, although a few deposits are richer (Fig. 2). Grasberg, for example, contains several hundred million metric tons (Mt) averaging >1.5 g/t Au. Typically, gold-rich porphyry deposits are deficient in molybdenum, but there are notable exceptions (e.g., Bingham, Ok Tedi, Skouries; Table 1). The size of the deposits varies markedly, from <50 to 4,500 Mt (Fig. 2b).

Bingham, the first porphyry copper deposit to be worked as a bulk-tonnage operation, is gold rich; however, the gold credit did not become economically important until the rise of the international gold price in the late 1970s. Other landmarks in the exploitation of gold-rich porphyry copper deposits include commissioning of Almalyk, Uzbekistan, in 1954, Santo Tomas II, Philippines, in 1958, Panguna, Papua New Guinea, in 1972, and Grasberg, Indonesia in 1989. Gold-only end members were first discovered in the Maricunga belt of northern Chile in 1982, with production commencing 7 yr later (Vila and Sillitoe, 1991).

The large size and high grade of the Grasberg deposit raised the profile of gold-rich porphyry deposits and led to their becoming prime exploration targets for companies interested in gold, copper, or both metals. The potential of gold-rich porphyry deposits is underscored by the fact that one-fifth of the world's giant gold deposits, defined as those containing ≥600 t Au, are porphyry type. The six giant deposits are Grasberg, Almalyk, Bingham, Panguna, Far Southeast, and Cerro Casale (Table 1).

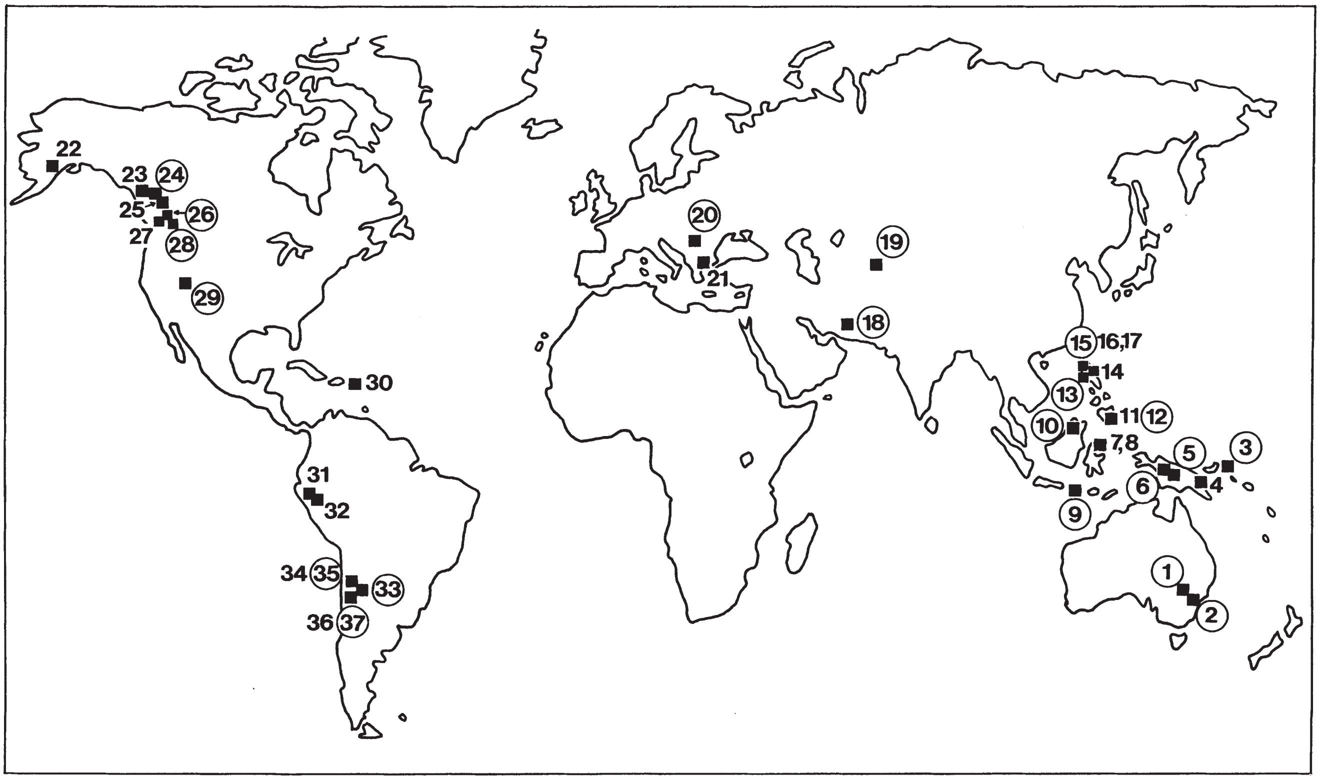

FIG. 1. Locations of principal gold-rich porphyry deposits. Note concentrations in western Pacific region and western Americas. Numbers keyed to deposit names in Table 1. Circled numbers indicate deposits with past or present production.

This article updates the generalized descriptive (empirical) model for gold-rich porphyry deposits presented previously (Sillitoe, 1993), emphasizing where certain examples differ from the norm. Historical advances in the understanding of porphyry copper systems are then briefly reviewed as a prelude to the currently preferred genetic model for gold-rich porphyry deposits. Methods used in exploration and discovery of gold-rich porphyry deposits are then discussed, with special attention paid to the relatively minor role played by descriptive and genetic models. Two typical discovery case histories are included. The article concludes with suggestions for further work and a series of questions and answers relating to the models described.

Descriptive Model

Regional tectonic setting

Gold-rich porphyry deposits are generated at convergent plate boundaries during or immediately following subduction of oceanic lithosphere. Many of these, as in Chile, Peru, and the Philippines, are parts of subduction-related volcanoplutonic arcs, in which epithermal gold deposits are also widespread. Elsewhere, however, including Bingham and Bajo de la Alumbrera (Table 1), gold-rich porphyry deposits formed in back-arc settings, above the downdip extremities of shallowly dipping lithospheric slabs.

Many gold-rich porphyry deposits are generated during intervals when arcs are subjected to periods of weak extension, as at Cerro Corona and Minas Conga in northern Peru (Petford and Atherton, 1994), and Marte, Lobo, Refugio, and Cerro Casale in the Maricunga belt, northern Chile (Kay et al., 1994). Elsewhere, extension progresses to produce interarc rifts like the Cagayan basin (Florendo, 1994), host to the Dinkidi deposit in Luzon, Philippines (Table 1). However, large high-grade deposits, in common with their gold-poor counterparts, are more typically emplaced during regional compression (Sillitoe, 1998). Compression may be a product of subduction of an aseismic ridge, as at Far Southeast (Yang et al., 1996), or arc-continent collision, as at Grasberg and Ok Tedi (Dewey and Bird, 1970). Indeed, eight deposits were emplaced in arcs either just before or after collisional events (Table 1). The giant Bingham deposit is an exception to this generalization, however, because it was generated during extension immediately following prolonged compressive tectonism (Presnell, 1997).

Crustal setting

Gold-rich porphyry deposits are present in Cordilleran arcs underlain by continental crust as well as in island arcs underlain by either continental or oceanic crust. Strict correlations between gold-rich porphyry deposits and oceanic settings and molybdenum-rich porphyry deposits and continental settings (e.g., Hollister, 1975) are clearly invalid.

Observations also do not support any clear relationship between gold-rich porphyry deposits and anomalously high gold contents in underlying crustal rocks, as proposed by

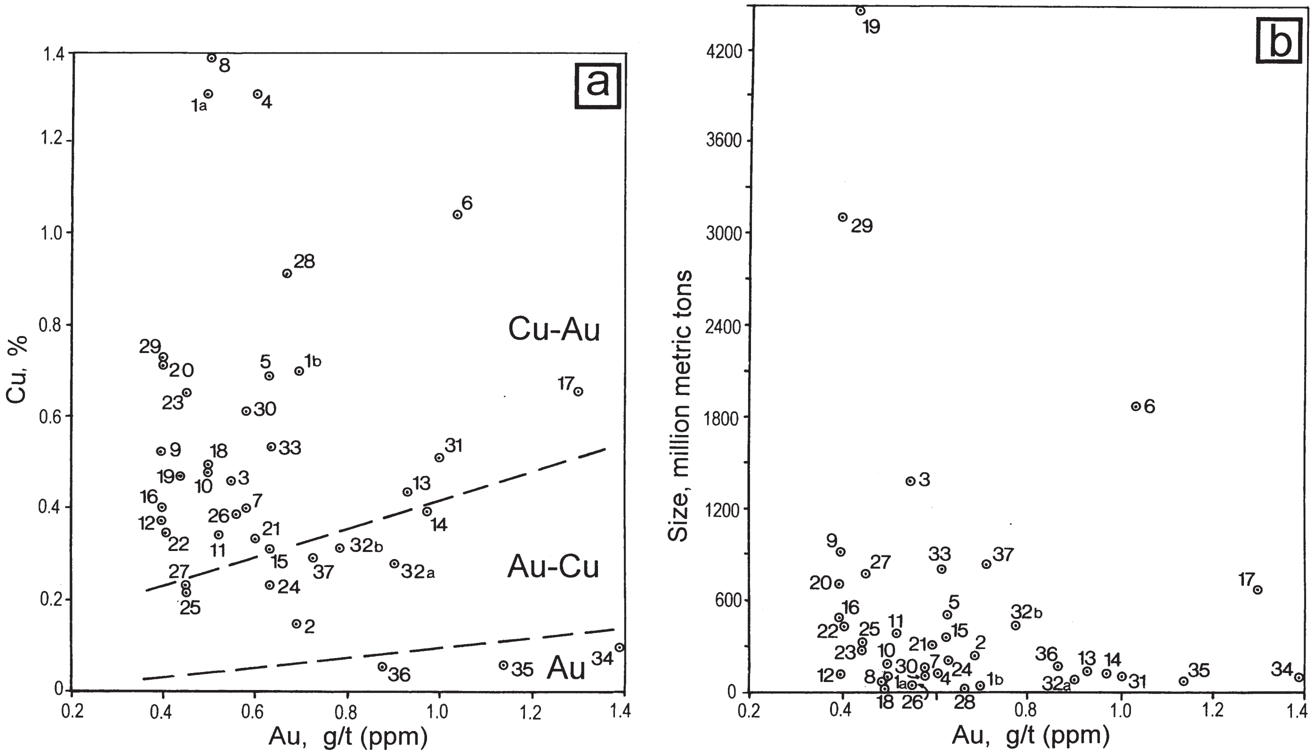

FIG. 2. Size and grade of principl gold-rich porphyry deposits: (a) copper versus gold content and (b) size (production + reserves) versus gold content. Note the broad spread of copper and gold values; informal subdivision into Cu-Au, Au-Cu, and Au-only categories; and predominance of deposits containing <300 Mt. Copper grades are dominantly hypogene except at Ok Tedi (5) and Sungai Mak (8), where important supergene chalcocite enrichment is included. Supergene oxidation affected Kingking (11), Almalyk (19), Mount Polley (26), and Afton (28) but without substantial changes in copper grades. Note that gold in leached capping at Ok Tedi (5) is not included. Numbers keyed to deposit names in Table 1. Data taken from references in Table 1 and the mining literature.

Titley (1990). Gold-rich porphyry deposits are widely distributed in volcanoplutonic arcs worldwide (Fig. 1); they can be isolated in otherwise gold-poor porphyry copper provinces (e.g., Dos Pobres in Arizona; Langton and Williams, 1982); and adjacent porphyry deposits may have markedly different gold contents (e.g., Saindak; Sillitoe and Khan, 1977). Nevertheless, there is a tendency for gold-rich porphyry deposits to be concentrated in geographically restricted belts, such as the Cajamarca belt of northern Peru, the Maricunga belt of northern Chile, and the Cordillera Central of Luzon, Philippines.

Volcanic setting

Gold-rich porphyry deposits are commonly emplaced at shallow (1–2 km) crustal levels (Cox and Singer, 1988) and, hence, are likely to be associated closely with coeval volcanic rocks. Indeed, Table 1 reveals that threequarters of deposits retain remnants of coeval volcanic sequences. The volcanic rocks are typically andesitic to dacitic or trachyandesitic to latitic in composition and, where volcanic landforms are partially preserved, they constitute stratovolcanoes. However, the existence of flow-dome complexes may be inferred above some gold-rich porphyry deposits, especially those associated with more felsic magmatism (e.g., Bingham; Waite et al., 1997).

A few deposits emplaced at shallow depths are hosted by coeval volcanics, a good example being Marte which formed at a depth of 500 to 700 m beneath a partly preserved stratovolcano (Vila et al., 1991). Generally, however, the surrounding country rocks comprise older lithologic units, as variable as serpentinite (Mamut; Kosaka and Wakita, 1978), schist (Skouries; Tobey et al., 1998), and limestone (e.g., Grasberg, Bingham, Ok Tedi, Cerro Corona).

Structural setting

Some gold-rich porphyry deposits are localized by major fault zones, whereas many have only relatively minor structures in their immediate vicinities. The former case is exemplified by Far Southeast, Guinaoang, Santo Tomas II, and Kingking (Fig. 1; Table 1), all localized by splays of the 1,500-km-long Philippine transcurrent fault system (Sillitoe and Gappe, 1984). A few gold-rich porphyry deposits are inferred to lie along deeply penetrating crustal lineaments, for example, Goonumbla and Cadia Hill on the Lachlan River lineament in New South Wales, Australia (Walshe et al., 1995). Deposits in compressive settings tend to occupy localized dilatant sites, such as that provided by strikeslip faulting in the fold-and-thrust belt at Grasberg (Sapiie and Cloos, 1995).

TABLE 1. Selected Characteristics of Principal Gold-Rich Porphyry Deposits

No. in Figs. 1, 2	Name, location	Au (t)	Setting	Host porphyry	Petro-chemistry	Age (Ma)	Coeval volcanics	Alteration with Au ± Cu	Lithocap remnant preserved	Abundant magnetite ± hematite	A type quartz veinlets	Selected reference
1a	Endeavour 26 North and 48, Goonumbla, Australia	49	AIA	Qmonz	KCA	439	Yes	K	No	Yes	Yes	Heithersay and Walshe (1995)
1b	Endeavour 22 and 27, Goonumbla, Australia	22	AIA	Qmonz	KCA	439	Yes	K	No	Yes	Yes	Heithersay et al. (1990)
2	Cadia Hill, Australia	159	AIA	Qmonz	KCA	~440	Yes	K, Na, IA	No	Yes	Yes	Newcrest Mining Staff (1998)
3	Panguna, Papua New Guinea	768	IA	Di-Qdi	CA	3.4	Yes	K, IA, Ser	No	Yes	Yes	Clark (1990)
4	Wafi, Papua New Guinea	60	C	Di	CA	14	No	Ser, IA, AA, K	Yes	Yes	Yes	Tau-Loi and Andrew (1998)
5	Ok Tedi, Papua New Guinea	368	C (Col)	Monz	KCA	1.2	No	K, Sk	No	No	Yes	Rush and Seegers (1990)
6	Grasberg, Indonesia	1952	C (Col)	Monzdi	KCA	2.8	Yes	K, IA	No	Yes	Yes	MacDonald and Arnold (1994)
7	Cabang Kiri, Indonesia	81	IA (Col)	Qdi	CA	2.9	Yes	IA, K, Ca-Na	Yes	Yes	Yes	Carlile and Kirkegaard (1985)
8	Sungai Mak, Indonesia	32	IA (Col)	Di	CA	2.9	Yes	IA, AA, K	Yes	Yes	Yes	Carlile and Kirkegaard (1985)
9	Batu Hijau, Indonesia	368	IA	Ton	CA	5.1-4.9	Yes	K, IA	Yes	Yes	Yes	Clode et al. (1999)
10	Mamut, Malaysia	90	IA (Col)	Qmonz	KCA	5-9	No	K, Ser	No	Yes	Yes	Kosaka and Wakita (1978)
11	Kingking, Philippines	207	IA	Di	CA	Mio-Plio	Yes	K, Sk	No	Yes	Yes	Sillitoe and Gappe (1984)
12	Amacan, Philippines	46	IA	Qdi	CA	Mio-Plio	Yes	IA, K	No	No	Yes	Sillitoe and Gappe (1984)
13	Dizon, Philippines	130	IA	Qdi	CA	2.7	Yes	IA, K	Yes	Yes	Yes	Sillitoe and Gappe (1984)
14	Dinkidi, Philippines	117	IA (Rift)	Monz, Qmonz	A	23.2	Yes	K, IA	No	Yes	Yes	Garrett (1996)
15	Santo Tomas II, Philippines	230	IA	Di	CA	1.4	No	K	No	Yes	Yes	Serafica and Baluda (1977)
16	Ginaoang, Philippines	~200	IA	Qdi	CA	3.5	Yes	IA, Ser, AA, K	Yes	Yes	Yes	Sillitoe and Angeles (1985)
17	Far Southeast, Philippines	845	IA	Qdi	CA	1.5–1.2	Yes	K, IA	Yes	Yes	Yes	Hedenquist et al. (1998)
18	South body, Saindak, Pakistan	28	C	Qdi	CA	19–20	Yes	K	No	Yes	Yes	Sillitoe and Khan (1977)
19	Almalyk, Uzbekistan	1980	AIA	Qmonz	KCA	294–310	No	Ser, IA, K	No	Yes	Yes	Shayakubov et al. (1999)
20	Majdanpek, Yugoslavia	300	C	Qdi	CA	Late Cret	No	K, IA, CR, Sk	No	Yes	Yes	Herrington et al. (1998)
21	Skouries, Greece	>235	C (Col)	Syen	A	18	No	K, IA	No	Yes	Yes	Tobey et al. (1998)
22	Pebble Copper, Alaska	176	C	Gd	CA	90.5	No	K	No	Yes	Yes	Bouley et al. (1995)
23	Galore Creek, B. C., Canada	124	AIA (Col)	Syen	A	210	Yes	K, Ca-K	No	Yes	No	Enns et al. (1995)
24	Kemess South, B. C., Canada	126	AIA (Col)	Qmonzdi	CA	202	No	K, IA	No	Yes	Yes	Rebagliati et al. (1995)
25	Mount Milligan, B. C., Canada	134	AIA	Monz	A	183	Yes	K, IA	No	Yes	No	Sketchley et al. (1995)
26	Mount Polley, B. C., Canada	27	AIA	Monz	A	204.7	Yes	K, K-Na, Ca-K	No	Yes	No	Fraser et al. (1995)
27	Fish Lake, B. C., Canada	348	C	Qdi	CA	80	Yes	K, IA	No	Yes	Yes	Caira et al. (1995
28	Afton, B. C., Canada	18	AIA	Di	A	204	Yes	K, IA	No	Yes	No	Carr and Reed (1976)
29	Bingham, Utah	1256	C	Qmonz	KCA	37B38	Yes	K, Sk	No	No	Yes	Babcock et al. (1995)

TABLE 1. (*Cont.*)

No. in Figs. 1, 2	Name, location	Au (t)	Setting	Host porphyry	Petro chemistry	Age (Ma)	Coeval volcanics	Alteration with Au ± Cu	Lithocap remnant preserved	Abundant magnetite ± hematite	A type quartz veinlets	Selected reference
30	Tanamá, Puerto Rico	72	IA	Qdi	CA	41–44	Yes	K, IA	No	Yes	Yes	Cox (1985)
31	Cerro Corona, Peru	96	C	Qdi	CA	14.4	Yes	K, IA, Sk	No	Yes	Yes	James and Thompson (1997)
32a	Chailhuagon, Minas Conga, Peru	92	C	Gd	CA	23.2	Yes	K	No	Yes	Yes	Llosa et al. (2000)
32b	Perol, Minas Conga, Peru	335	C	Dac	CA	23.2 (?)	Yes	K, Ser, IA, Sk	Yes	Yes	Yes	Llosa et al. (2000)
33	Bajo de la Alumbrera, Argentina	516	C	Dac	KCA	7.1	Yes	K	No	Yes	Yes	Guilbert (2000)
34	Lobo, Chile	150	C	Di	CA	12.9	Yes	IA, K	Yes	Yes	Yes	Vila and Sillitoe (1991)
35	Marte, Chile	83	C	Di	CA	13.3	Yes	IA, K	Yes	Yes	Yes	Vila et al. (1991)
36	Refugio (Verde), Chile	190	C	Qdi	CA	23	Yes	Ca-Na, IA	Yes	Yes	Yes	Vila and Sillitoe (1991)
37	Cerro Casale, Chile	610	C	Di	CA	13.5	Yes	K, IA	Yes	Yes	Yes	Vila and Sillitoe (1991)

Abbreviations: setting: AIA = accreted island arc, C = continental margin, Col = during or following collision, IA = island arc; host porphyry: Dac = dacite, Di = diorite, Gd = granodiorite, Monz = monzonite, Monzdi = monzodiorite, Qdi = quartz diorite, Qmonz = quartz monzonite, Qmonzdi = quartz monzodiorite, Syen = syenite, Ton = tonalite; petrochemistry: A = alkaline, CA = calc-alkaline, KCA = high K calc-alkaline (shoshonite); age: Cret = Cretaceous, Mio = Miocene, Plio = Pliocene; alteration with Au ± Cu: AA = advanced argillic, Ca = Ca silicate, CR = carbonate replacement, IA = intermediate argillic, K = K silicate, Na = Na silicate, Ser = sericitic, Sk = skarn

In summary, though, there is no specific structural setting that favors the localization of gold-rich porphyry deposits. Rather, the impression is gained that deeply derived magmas are capable of attaining shallow levels appropriate for porphyry deposit generation whatever the structural state and preparation of the upper crust.

Intrusive rock compositions

The porphyry intrusions that are related genetically to all gold-rich porphyry deposits belong exclusively to I-type, magnetite series suites (e.g., Ishihara, 1981). Indeed, the abundance of hydrothermal magnetite in gold-rich porphyry deposits may be taken to suggest that their host intrusions are highly oxidized, sulfur-poor representatives of the magnetite series (Sillitoe, 1979). Bulk-tonnage gold deposits are also hosted by and related genetically to more reduced, either magnetite or ilmenite series intrusions, but these are of sheeted-vein rather than truly porphyry type (Thompson et al., 1999; Thompson and Newberry, 2000). Similarly, several "porphyry" copper-gold deposits related to ilmenite series intrusions (Rowins, 2000) are not considered to be porphyry type in the strict sense employed herein.

The porphyry stocks span a range of compositions, from low K calc-alkaline diorite, quartz diorite, and tonalite, through high K calc-alkaline quartz monzonite, to alkaline monzonite and syenite. The high K representatives generally meet the criteria for classification as shoshonites (e.g., Goonumbla and Cadia Hill; Walshe et al., 1995; Bajo de la Alumbrera; Müller and Forrestal, 1998). The alkaline rocks may be either saturated or undersaturated with respect to quartz (Lang et al., 1995a). Clearly, intrusive composition exerts little obvious influence on favorability for gold-rich porphyry genesis, although more highly fractionated intrusions of granitic composition are notably absent.

The ore-related porphyries contain feldspar and mafic minerals ± quartz phenocrysts in an aplitic to aphanitic groundmass. All the porphyries contain hornblende and/or biotite, to which pyroxene is commonly added in the case of the alkaline representatives. Some undersaturated alkaline intrusions contain pseudoleucite as a phenocryst phase (Lang et al., 1995a).

Intrusive rock geometries

Vertically extensive (1–>2 km) porphyry stocks of grossly cylindrical form are the focus of most gold-rich porphyry deposits and contain all or parts of the ore (Fig. 3). Their diameters range from <100 m to >1 km. Dike- and sill-like apophyses project outward from the sides and tops of stocks but are typically not abundant. Stocks are generally composite, with early porphyries being intruded by intermineral and late-mineral phases, a mechanism that causes episodic inflation of the stocks. Progressively younger porphyry phases are commonly intruded into axial portions of stocks, giving rise to nested geometries (Fig. 3). Intermineral and late-mineral phases commonly result in low-grade cores to deposits, as documented at Panguna (Clark, 1990), Grasberg (Van Nort et al., 1991), Santo Tomas II (Serafica and Baluda, 1977), and many other localities. These low-grade cores, which commonly constitute waste, may not attain the present surface and await definition by drilling (e.g., Perol at Minas Conga; Llosa et al., 2000).

Nevertheless, there are many exceptions to this stereotypical intrusion geometry. Early, marginally located porphyry intrusions may be lower in copper and gold contents than internal intermineral ones, as exemplified by Gras-

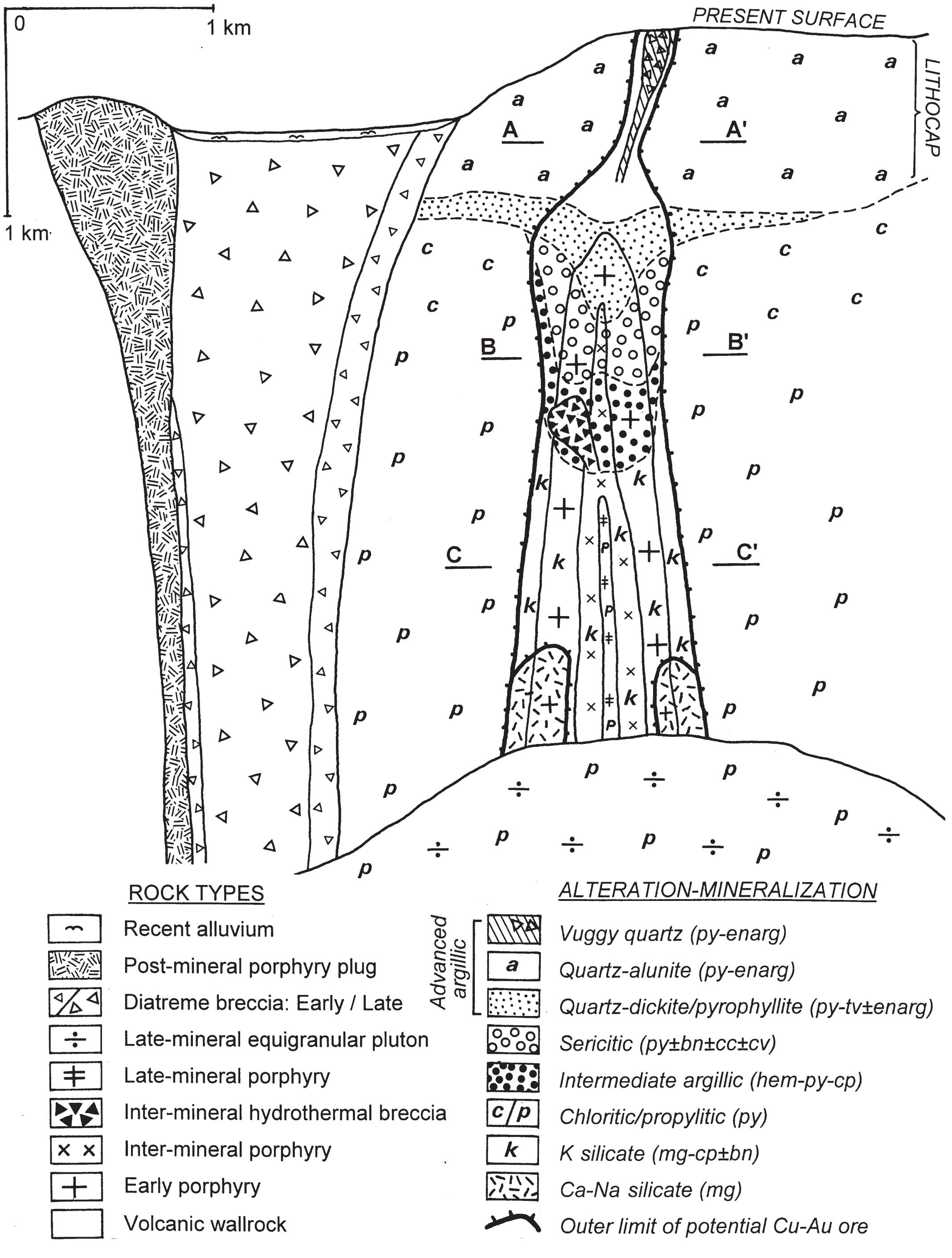

FIG. 3. Descriptive model of typical gold-rich porphyry system comprising composite porphyry stock and contiguous diatreme and porphyry plug, modified from Sillitoe (1993). Rock and alteration-mineralization types young upward in the respective legends, although advanced argillic zone is generated throughout the lifespan of the system. Characteristic opaque mineral assemblages are shown with alteration types. Abbreviations: bn = bornite, cc = chalcocite, cp = chalcopyrite, cv = covellite, enarg = enargite, hem = hematite, mg = magnetite, py = pyrite. Porphyry deposit is postdated and partly removed by axially positioned late-mineral porphyry and subjacent equigranular pluton. The system is telescoped, with base of lithocap superimposed on top of porphyry stock and its associated alteration and mineralization types. Outer limit of potential gold ± copper ore is shown, with deep Ca-Na silicate alteration remnant being essentially barren. The present surface, as shown, involved erosion of roughly the upper 500 m of the original system. Note contrast between high elevations over advanced argillic lithocap and recessive alluviated topography over soft diatreme breccia. A–A′, B–B′, and C–C′ are sections presented in Figure 10.

berg (MacDonald and Arnold, 1994). Loci of intrusion may migrate with time so that early, intermineral, and late-mineral phases lie alongside one another (e.g., Bajo de la Alumbrera; J. M. Proffett *in* Guilbert, 2000) or are complexly intermixed (e.g., Skouries; Tobey et al., 1998). Eccentric emplacement of the later intrusions gives rise to complex ore distribution patterns.

Intermineral and some late-mineral intrusions are texturally and compositionally very similar to the early stock phases, and so are often difficult to distinguish on appearance alone. A number of criteria, alone or in combination, need to be carefully applied if porphyry stocks are to be effectively subdivided. These criteria (Fig. 4) comprise (1) abrupt truncation of early veinlets, particularly quartz-dominated ones, in older phases at the contacts with younger phases (e.g., Kirkham, 1971); (2) narrow (<1 cm) zones of chilling in younger against older phases, implying that some stocks underwent appreciable internal cooling between intrusive pulses; (3) narrow (<2 cm) zones of flow-aligned phenocrysts in younger phases along contacts with older ones; (4) xenoliths of refractory veinlet quartz derived from older phases floating in younger phases within a few tens of centimeters of contacts with the older ones; (5) better texture preservation and lower fracture and veinlet densities in younger with respect to older phases; and (6) abrupt decreases in copper and gold contents on passing from older to younger phases. Early phases commonly approach or exceed twice the metal contents of intermineral phases, with copper and gold grades not necessarily changing in the same proportions. Late-mineral phases commonly contain <0.1 percent Cu.

Pre- and postmineral intrusions are also encountered in and nearby some gold-rich porphyry systems. Premineral precursor intrusions are generally equigranular in texture and may be either genetically related to the porphyry stocks, as in the case of the monzonites at Bingham (Babcock et al., 1995), Ok Tedi (Bamford, 1972), and Goonumbla (Heithersay and Walshe, 1995), or constitute parts of substantially older plutons, as at Tanamá (Cox, 1985) and Santo Tomas II (Sillitoe and Gappe, 1984). There is a distinct tendency for porphyry stocks to intrude along the shoulders or edges of precursor plutons. Unaltered postmineral intrusions typically take the form of plugs or dikes. The plugs, generally composed of flow-banded dacite porphyry, occur either alone or in close association with diatremes (Fig. 3; see below). The dikes are normally andesitic in composition and their genetic affiliation, if any, with the main porphyry stocks remains unclear.

Ages and lifespans of porphyry deposits

Gold-rich porphyry deposits, like gold-poor ones, are predominantly Tertiary in age, with 25 (64%) of the deposits in Table 1 being Miocene or younger. The youthfulness of many deposits is ascribed to the rapid erosion rates in volcanoplutonic arcs, especially where pluvial climatic regimes prevail. Erosion is especially rapid in compressive arcs because of enhanced uplift rates, as documented for the vicinity of Grasberg (0.7 km/m.y.; Weiland and Cloos, 1996).

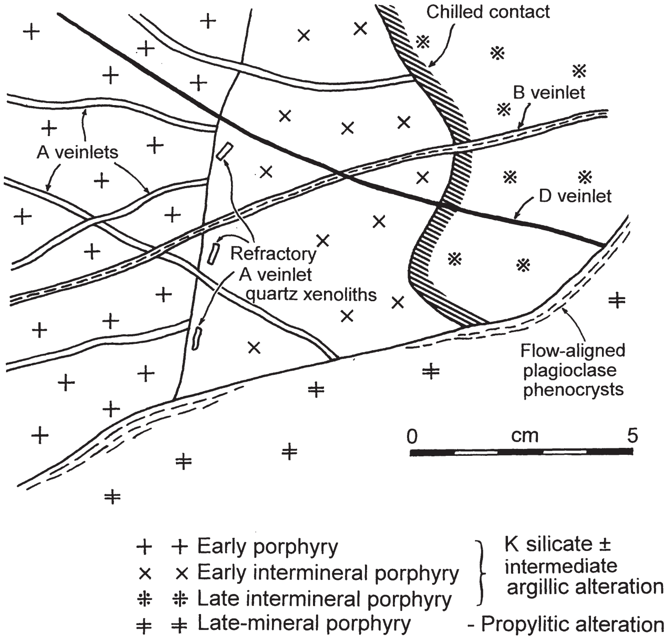

FIG. 4. Schema of geologic features used to discriminate between early, intermineral, and late-mineral porphyries in stocks hosting gold-rich porphyry deposits. Truncation of veinlets, quartz veinlet xenoliths, chilled contacts, and flow-aligned phenocrysts as well as textural and grade variations may denote contacts, albeit generally not all at the same contact. Early A, intermediate B, and late D veinlets are explained in the text and Figure 5. Note that early A veinlets are most abundant in early porphyry, less abundant in early intermineral porphyry, and absent in the two later porphyry phases. The late-mineral porphyry lacks veinlets and was subjected only to propylitic alteration. Note that stocks may comprise from two to at least 15 individually mappable phases, the four illustrated here serving simply as an example.

The generally younger ages of gold-rich porphyry deposits in western Pacific island arcs compared to those in the central Andean Cordillera mainly reflect more rapid unroofing and eventual erosion in tropical regions relative to arid environments (Sillitoe, 1997).

Notwithstanding the abundance of young gold-rich porphyry deposits, Mesozoic examples are widely preserved in British Columbia, Canada (Christopher and Carter, 1976), and there are Paleozoic examples in eastern Australia (Perkins et al., 1995) and central Asia (Zvezdov et al., 1993). Most of these older deposits appear to occur in island-arc terranes accreted to continental margins (Table 1). Several gold deposits of supposed porphyry type in Precambrian terranes (e.g., Boddington, Western Australia; Allibone et al., 1998) have been shown in the last few years to possess alternative genetic affiliations. However, the highly deformed and metamorphosed Troilus gold-copper deposit of Archean age in the Abitibi greenstone belt of Quebec, Canada, remains a good candidate for a gold-rich porphyry deposit (Fraser, 1993).

The combined intrusive and hydrothermal lifespans of gold-rich porphyry systems, as with porphyry systems in general, remain to be fully evaluated. Silberman (1985) summarized early radiometric dating studies of porphyry systems and concluded that 1 m.y. or so is a reasonable estimate. However, more recent work employing the $^{40}Ar/^{39}Ar$ technique has tended to shorten some inferred lifespans to <0.3 m.y., as at the gold-rich Far Southeast deposit (Arribas et al., 1995). Nevertheless, recent work at Bingham suggests that a lifespan of 1 m.y. or more may be valid (Parry et al., 1997).

It is critical to note that durations of intrusive plus hydrothermal activity in porphyry copper systems determined using either K-Ar or $^{40}Ar/^{39}Ar$ dating are minimum estimates because neither technique takes account of the early high-temperature histories of porphyry systems, above the blocking temperatures of the most commonly dated minerals (biotite, sericite). Furthermore, the repeated intrusion commonplace in porphyry stocks may lead to multiple pulses of temperature increase, each resulting in resetting of radiometric clocks. It is this repeated intrusion history that substantially prolongs the lifespans of porphyry systems compared to the brief time (~10,000 yr) required to cool single-pulse intrusions of roughly equivalent dimensions (Cathles, 1981).

Hydrothermal breccias

Hydrothermal breccias are commonly associated with gold-rich porphyry deposits and comprise early orthomagmatic as well as generally late phreatic and phreatomagmatic varieties, the last constituting diatremes (Sillitoe, 1985). Breccias that are generated relatively early in gold-rich porphyry systems are typically products of magmatic fluid discharge from intermineral porphyry phases (Fig. 3). As a consequnce, clast-restricted quartz veinlets of the A type (see below) are observed commonly. Orthomagmatic breccias tend to be volumetrically restricted, clast-supported, monolithologic, K silicate altered, and copper and gold bearing. In places, metal values attain double those in surrounding stockwork-disseminated mineralization. Examples include breccias at Panguna (Clark, 1990), Endeavour 27 at Goonumbla (Heithersay et al., 1990), and Mount Polley (Fraser et al., 1995). Late orthomagmatic breccias contain correspondingly less copper and gold and may be subore grade.

Minor (<10 m wide) pebble dikes of phreatic origin and large (>0.5 km wide) diatreme breccias (Fig. 3) conclude the evolution of some gold-rich porphyry systems, although they may both overlap with end-stage advanced argillic alteration and associated high-sulfidation epithermal mineralization, as at Dizon and Far Southeast. Diatreme breccias are generally low grade or barren, although exceptions occur (e.g., Galore Creek; Enns et al., 1995). Diatreme breccias have small, subrounded, polylithologic clasts, some of them polished, which are supported by abundant sandy or muddy rock-flour matrix containing broken juvenile crystals. The matrix contains crystals and clastic grains of pyrite and displays intermediate argillic alteration resulting from the hot meteoric water that permeates active diatremes. Blocks composed of lacustrine sediment or surge deposits and pieces of carbonized wood bear testimony to surface connections during diatreme formation (cf. Sillitoe, 1985). Diatreme formation may end with emplacement of porphyry plugs (e.g., Guinaoang; Sillitoe and Angeles, 1985). The soft, friable nature of diatreme breccias results in development of recessive topography (Fig. 3).

Hydrothermal alteration-mineralization types

Six broad alteration types are developed in silicate rocks in and surrounding gold-rich porphyry deposits (Fig. 3): Ca-Na silicate, K silicate (potassic), propylitic, intermediate argillic, sericitic (phyllic), and advanced argillic (cf. Meyer and Hemley, 1967). The various sulfide minerals present in gold-rich porphyry deposits are integral parts of these alteration assemblages, the only difference being that those rich in copper and associated gold (and locally molybdenite) may constitute ore. In addition, calcic (or magnesian) skarn may occur where carbonate rocks surround gold-rich porphyry systems (Ok Tedi, Kingking, Majdanpek, Bingham, Cerro Corona, Minas Conga; Table 1), as discussed by Meinert (2000).

Ca-Na silicate alteration is a somewhat informal name employed here for assemblages containing amphibole (actinolite, actinolitic hornbende, or hornblende), albite or oligoclase, and magnetite as both pervasive replacements and veinlets; however, diopside, with or without amphibole, may also occur. In some deposits, hydrothermal sodic plagioclase is developed without amphibole or pyroxene. The amphibole and magnetite typically occur as veinlets, either separately or together, whereas the sodic plagioclase most obviously occurs as veinlet selvages and replacements of feldspar phenocrysts. Quartz-magnetite ± amphibole veinlets are also prominent components of this alteration type in some deposits. The quartz is vitreous and granular, similar to that composing A type veinlets (see below). Early magnetite veinlets (Fig. 5) are denominated “M type” by Clark and Arancibia (1995).

Ca-Na silicate alteration is normally observed as the product of one or more early events in deep parts of gold-rich porphyry systems (Fig. 3), as at Mamut (Kosaka and Wakita, 1978) and Tanamá (Cox, 1985), and also occurs in some relatively gold-poor examples such as El Salvador, Chile (Gustafson and Quiroga, 1995). Alternatively, this alteration type may occur as difficult-to-recognize remnants within or alongside K silicate alteration zones (Clark and Arancibia, 1995). Ca-Na silicate alteration is not observed in many deposits because of either shallow exposure or obliteration by later K silicate alteration. Ca-Na silicate alteration assemblages are generally deficient in sulfides, although in a few prospects, where K silicate alteration is subordinate, it acts as the main host for copper and gold mineralization.

Some gold-rich porphyry deposits are characterized by hybrid Ca-Na and K silicate assemblages, in which biotite is abundant but albite or oligoclase accompany or substitute for K feldspar (e.g., Cabang Kiri; Lowder and Dow, 1978; Carlile and Kirkegaard, 1985). Moreover, amphibole and/or epidote are commonly observed as stable accompaniments to hydrothermal biotite, as noted below. In some of the porphyry copper-gold deposits hosted by Early Meso-

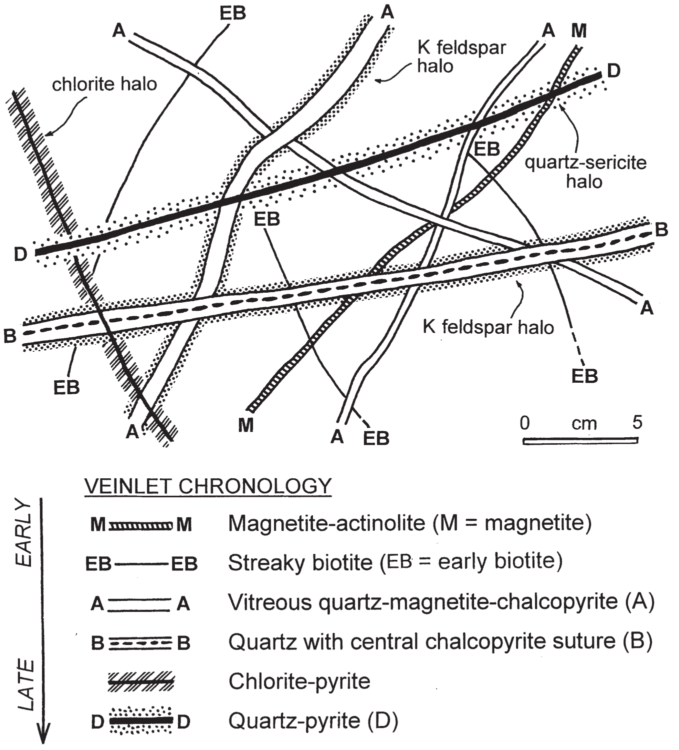

FIG. 5. Schema of typical dense veinlet stockwork in gold-rich porphyry deposit showing sequential formation of early M veinlets (Clark and Arancibia, 1995) with Ca-Na silicate alteration; early biotite (EB: Gustafson and Quiroga, 1995), A, and B veinlets (Gustafson and Hunt, 1975) with K silicate alteration; chlorite-pyrite veinlets with intermediate argillic alteration; and late D veinlets (Gustafson and Hunt, 1975) as the sole effect of sericitic alteration. Background alteration between veinlets is most likely to be K silicate, dominated by biotite-magnetite introduction, with partial intermediate argillic (sericite-illite-chlorite) overprint.

zoic alkaline intrusions in British Columbia, K silicate assemblages and calcic alteration minerals tend to be intimately mixed and difficult to resolve into separate alteration types (Lang et al., 1995b, c). Such Ca-K silicate assemblages, in which andraditic garnet may be a component (e.g., Galore Creek; Enns et al., 1995), are reminiscent of alteration in iron oxide-copper-gold deposits (e.g., Hitzman et al., 1992), with which convergence in certain other geologic features is also apparent. Ca-K silicate alteration in some gold-rich porphyry deposits linked to alkaline stocks displays coarse-grained pegmatoidal textures.

K silicate alteration, present in nearly all gold-rich porphyry deposits (Table 1; Fig. 3), is typically characterized by the presence of replacement and veinlet-filling biotite, commonly magnesium rich (phlogopitic) in composition. The biotite may be accompanied by hydrothermal K feldspar and/or actinolite. Early, typically deep biotite veinlets (Fig. 5) are denominated "EB type" by Gustafson and Quiroga (1995). K feldspar is more abundant in deposits associated with quartz monzonite, monzonite, and syenite porphyries, whereas actinolite shows a preference for, but is not restricted to, dioritic and quartz dioritic systems emplaced into cafemic, typically andesitic, host rocks. Epidote and carbonate also appear as minor alteration minerals in some such calcic systems. Anhydrite is a widespread and abundant disseminated and veinlet constituent in K silicate assemblages, as well as occurring in association with the other alteration types described below. Coarse-grained anhydrite veinlets are characteristically late and cut copper-gold mineralization.

A variety of quartz veinlets, introduced in several generations, typically comprises 10 to >90 vol percent of K silicate alteration. The veinlets may occur as multidirectional stockworks and/or subparallel arrays suggestive of enhanced structural control on emplacement. The most abundant veinlets, from a few millimeters to several centimeters in width, are composed of vitreous, granular quartz, are planar to slightly sinuous, and in places, discontinuous in form, and commonly lack prominent alteration halos, although K feldspar and/or biotite may be observable (Fig. 5); they are reminiscent of the A veinlets described by Gustafson and Hunt (1975) from the El Salvador porphyry copper deposit, Chile. Some veinlets are banded as a result of either repeated opening and quartz introduction or concentration of magnetite and/or pyrite in certain bands, giving them a dark-gray coloration. The latter variety, common in gold-only porphyry deposits in the Maricunga belt (Vila and Sillitoe, 1991; Vila et al., 1991), as well as elsewhere, may possess translucent centers and dark margins or vice versa. Laterally more extensive planar quartz veinlets, typically with center lines, are invariably later than A type veinlets but also lack prominent alteration selvages (Fig. 5); they possess similarities with Gustafson and Hunt's (1975) B veinlets but are not common in most gold-rich porphyry deposits. In contrast, however, some, but not all, gold-rich porphyry deposits associated with alkaline intrusions, such as those in British Columbia (Barr et al., 1976; Lang et al., 1995b), are deficient in quartz veining. This is presumably because the magmatic hydrothermal fluids were undersaturated with respect to quartz.

Hydrothermal magnetite, averaging 3 to 10 vol percent in many K silicate zones, occurs in veinlets with or without quartz, in irregular clots, and as disseminated grains and grain aggregates (Sillitoe, 1979; Cox and Singer, 1988). Magnetite-only veinlets may be considered as M type, whereas those containing quartz are essentially A type (Fig. 5). All but three deposits in Table 1 are estimated to contain ≥3 vol percent magnetite, a quantity exceeding that present in all but a very few gold-poor K silicate alteration zones. The magnetite both precedes and accompanies copper-bearing sulfide introduction but, contrary to recent claims (Clark and Arancibia, 1995), does not everywhere predate K silicate alteration.

Chalcopyrite and pyrite are the principal hypogene sulfides in K silicate alteration, although bornite is present in some deposits. Chalcopyrite typically occurs as finely disseminated grains in quartz veinlets, in association with magnetite, as well as alone in veinlet and disseminated forms. Pyrite contents are typically fairly low, with pyrite/chalcopyrite ratios ranging from <0.5 to 3. The core zones of some deposits, however, are essentially devoid of pyrite.

Substantially higher pyrite contents are generally the product of superimposed intermediate argillic alteration. Where bornite is present, preferentially in the deeper, central parts of K silicate alteration zones, chalcopyrite/bornite ratios can be <3 and bornite may be accompanied by hypogene digenite and chalcocite. Molybdenite is prominent in some deposits, especially those rich in magmatic and hydrothermal K feldspar, in later generations of quartz veinlets (B type), and as monomineralic veinlets and disseminated flakes.

Propylitic alteration constitutes outer halos to gold-rich porphyry deposits and is generally confined to their wall rocks (Fig. 3). Chlorite, epidote, calcite, with or without subordinate albite, actinolite, and magnetite, coexist in propylitic assemblages. Internally, propylitic alteration grades into K silicate alteration as chlorite becomes subordinate to hydrothermal biotite. Externally, especially in andesitic volcanic sequences, propylitic alteration is often difficult to distinguish unambiguously from regionally extensive lower greenschist facies metamorphic assemblages. Upward transitions to chloritic alteration, lacking epidote, in the shallow peripheries of gold-rich porphyry systems reflect declining temperature (cf. Browne, 1978). Veinlet and disseminated pyrite, ranging from 3 to, locally, >20 vol percent, dominate the sulfide content of propylitic alteration which, with or without sericitic alteration (see below), constitutes pyrite halos to copper-gold zones. Minor amounts of chalcopyrite, tetrahedrite, sphalerite, and galena are common in propylitic zones, locally concentrated in faults or fractures as quartz-carbonate veins. Several hundred parts per million zinc and lead, in places accompanied by anomalous silver and manganese contents, form characteristic geochemical halos to copper-gold zones (e.g., Jerome, 1966).

Intermediate argillic alteration is widepread (Table 1), but underrecognized, as a pale-green overprint to K silicate assemblages, especially in the upper parts of porphyry stocks (Fig. 3). K silicate alteration is all but obliterated in the upper parts of some gold-rich porphyry deposits, for example, Dizon (Sillitoe and Gappe, 1984), Guinaoang (Sillitoe and Angeles, 1985), Marte (Vila et al., 1991), and Tanamá (Cox, 1985). Intermediate argillic alteration varies in both intensity and mineralogy. Assemblages may include sericite (fine-grained muscovite), illite, chlorite, calcite, and smectite, the last as a late-stage replacement of plagioclase in some deposits (e.g., Cerro Corona; James and Thompson, 1997). Hence the informal designation of intermediate argillic assemblages as sericite-clay-chlorite alteration by Sillitoe and Gappe (1984). Magnetite is variably martitized (transformed to hematite), and pyrite and specular hematite, with or without chalcopyrite, are introduced as veinlets (Fig. 5) and disseminated grains. Preexisting quartz veinlet stockworks survive, although their contained copper and/or gold are commonly partially to nearly completely removed. Locally, however, intermediate argillic alteration results in modest (say, <50%) increases in copper and/or gold contents over those in preexisting K silicate alteration, especially where monomineralic chalcopyrite veinlets are present. In deposits where intermediate argillic overprinting is intense, it is often impossible to determine whether preexisting copper and gold grades suffered modification.

Sericitic alteration in porphyry deposits is characterized by white to gray quartz-sericite-pyrite assemblages displaying partial to almost complete destruction of rock texture. Broad annuli of sericitic alteration, common around K silicate cores at many porphyry copper-molybdenum deposits (Lowell and Guilbert, 1970), are not widely developed in gold-rich porphyry deposits and are observed only at Bajo de la Alumbrera (Sillitoe, 1979), Fish Lake (Caira et al., 1995), Grasberg (Van Nort et al., 1991), and Saindak (Sillitoe and Kahn, 1977); however, more localized sericitic alteration, typically localized in the upper parts of porphyry stocks, is fairly common as an overprint to K silicate or intermediate argillic assemblages (Fig. 3) and may constitute copper-gold ore (e.g., Panguna, Wafi, Mamut, Guinaoang, Almalyk, Perol at Minas Conga; Table 1). Many gold-rich porphyry deposits lack appreciable sericitic alteration, including the D type quartz-pyrite veinlets with sericitic halos (Fig. 5) that are so common in many porphyry copper-molybdenum deposits (e.g., Gustafson and Hunt, 1975). Tourmaline is rarely developed in gold-rich porphyry deposits, despite its widespread appearance as a component of sericitic alteration in many parts of the world.

The sericitic zones of many gold-rich porphyry deposits possess pyrite as the sole sulfide mineral, in quantities ranging from 5 to >20 vol percent. Pyrite is typically in veinlets, some with minor quartz, or disseminated. Locally, however, copper (but not usually gold) values may be 10 to 20 percent higher in sericitic alteration than in preexisting alteration types (e.g., Guinaoang, Perol at Minas Conga). The copper may occur as the relatively low sulfidation state pyrite-chalcopyrite assemblage (e.g., Almalyk; Shayakubov et al., 1999) or as high sulfidation state assemblages like pyrite-bornite at Guinaoang (Sillitoe and Angeles, 1985) and pyrite-covellite at Wafi (Sillitoe, 1999). Hedenquist et al. (1998) and Sillitoe (1999) treat sericitic alteration carrying high sulfidation sulfide assemblages as the transition between the porphyry and advanced argillic lithocap environments.

Advanced argillic alteration is ubiquitous in the upper, commonly volcanic-hosted parts of gold-rich porphyry systems where it constitutes laterally extensive lithocaps as thick as 1 km (Sillitoe, 1995a; Fig. 3). This alteration is preserved as remnants within or nearby 12 deposits listed in Table 1. Advanced argillic assemblages can be coeval with early K silicate alteration, but in all deposits where lithocaps are preserved, they clearly overprint K silicate, propylitic, and intermediate argillic alteration. At some localities, sericitic alteration appears to be transitional upward to advanced argillic alteration (e.g., Wafi; Sillitoe, 1999). Advanced argillic alteration invariably continues after all other alteration processes have ceased in gold-rich porphyry systems, although in proximity to paleosurfaces the later stages may include steam-heated activity in addition to the deeply sourced advanced argillic alteration that dominates the early lives of systems. Where telescoping of high sulfidation epithermal and porphyry environments is extreme, advanced argillic alteration may pervasively overprint K silicate alteration, destroy all preexisting silicates and sulfides, and preserve only barren quartz veinlet stockwork (e.g., Wafi; Sillitoe, 1999). Advanced argillic alteration may also extend down faults for tens to hundreds of meters beneath the subhorizontal, roughly planar bases of lithocaps, as observed at Marte (Vila et al., 1991) and Guinaoang (Sillitoe and Angeles, 1985).

Chalcedonic quartz, alunite, pyrophyllite, diaspore, dickite, and kaolinite are abundant advanced argillic minerals. The chalcedonic quartz may comprise massive replacements or vuggy residual masses resulting from extreme base leaching (Stoffregen, 1987; Fig. 3). Barite and native sulfur are late-stage, open-space fillings. Pyrite ± marcasite, commonly as extremely finegrained (melnikovitic) aggregates, make up 10 to 20 vol percent of advanced argillic zones, especially as accompaniments to chalcedonic quartz and quartz-alunite. Locally, semimassive pyrite bodies are present. Enargite ± luzonite replaces the iron sulfides in restricted parts of some advanced argillic zones, especially along fault-localized feeder zones. High sufidation state pyrite-covellite, pyrite-chalcocite, and pyrite-bornite assemblages tend to increase at the expense of pyrite-enargite ± luzonite near the bottoms of advanced argillic zones, where pyrophyllite and/or dickite predominate over quartz-alunite (Fig. 3). Such mineralization may continue downward into sericitic alteration (Fig. 3). These high sulfidation state sulfides are intergrown with, coat, and partially replace disseminated pyrite grains which, in turn, are deposited after hypogene dissolution of low sulfidation state pyrite-chalcopyrite or chalcopyrite-bornite assemblages, as observed at Guinaoang and Wafi (Sillitoe, 1999).

Gold mineralization

Most of the gold in gold-rich porphyry deposits is introduced with copper during formation of K silicate alteration and, as a general rule, the gold and copper contents vary sympathetically. Gold contents also correlate well with the intensity of A type quartz veinlets. Ore zones are normally upright cylinders or bellshaped bodies. Intermediate argillic zones commonly also constitute ore where they overprint gold ± copper-bearing K silicate assemblages. Locally, as noted above, sericitic and advanced argillic alteration zones may also constitute gold ± copper ore. Gold contents (and Au/Cu ratios) tend to increase, even double, downward over distances of several hundred meters in some gold-rich porphyry deposits, at least in their upper and middle parts, as typified by Grasberg (MacDonald and Arnold, 1994) and Cabang Kiri (Carlile and Kirkegaard, 1985); however, they may also remain esssentially unchanged (e.g., Guinaoang; Sillitoe and Angeles, 1985) or even increase upward (e.g., Ok Tedi; Rush and Seegers, 1990).

Gold in gold-rich porphyry deposits is mainly fine grained (commonly <20 μm, generally <100 μm) and present as high-fineness (>800) native metal. Subsidiary amounts of coarse gold, recoverable in gravity circuits, is also present in a few deposits. Minor amounts of auriferous tellurides are also reported from several deposits, and the Almalyk deposit is reported to average 0.3 ppm Te (Shayakubov et al., 1999). Native gold is closely associated with copper-iron and iron sulfides (generally pyrite, but marcasite at Ok Tedi) as either intergrown, overgrown, or nearby quartz-encapsulated grains. As much as half the gold in pyritic deposits is generally associated with pyrite, whereas in pyrite-poor deposits it is commonly associated with chalcopyrite or bornite. In bornite-rich zones, bornite and gold are characteristically intergrown and gold grades tend to be higher than elsewhere (cf. Cuddy and Kesler, 1982).

Many gold-rich porphyry deposits are deficient in molybdenum (<20 ppm; e.g., Barr et al., 1976; Sillitoe and Gappe, 1984), whereas others possess recoverable amounts (>100 ppm) and fall within Cox and Singer's (1988) porphyry Cu-Au-Mo category. Molybdenum shows a distinct tendency to concentrate as halos to the molybdenum-poor, copper-gold core zones of many deposits (Ok Tedi, Batu Hijau, Santo Tomas II, Far Southeast, Bajo de la Alumbrera, Saindak), although the molybdenum-rich core to Bingham (>1,500 ppm Mo; Phillips et al., 1997) provides a notable exception. Silver in gold-rich porphyry deposits tends to correlate with gold, but the low average values (0.5–4 ppm) add little value. Platinoids, especially palladium in the form of merenskyite and sperrylite, are also reported in close association with gold and copper in several of the deposits (e.g, Mamut, Santo Tomas II, Ok Tedi, Skouries, Majdanpek; Tarkian and Stribrny, 1999; Economou-Eliopoulos and Eliopoulos, 2000). Palladium contents average as much as 0.05 g/t (Tarkian and Stribrny, 1999), hence providing appreciable added value at current world prices.

Supergene effects

Gold-rich porphyry copper deposits characteristically lack economically significant zones of supergene copper enrichment because of the relatively low pyrite contents and high neutralization capacities of most copper- and gold-bearing K silicate zones. Consequently, resultant leached cappings are goethitic and some contain appreciable copper as malachite, chrysocolla, neotocite, pitch limonite (cupreous goethite), and associated copper oxide minerals (cf. Anderson, 1982; Fig. 6a). However, notable exceptions are provided by the chalcocite blankets (Fig. 6b) at Bingham (Boutwell, 1905), Tanamá (Cox, 1985), Ok Tedi (Bamford, 1972), Sungai Mak, Almalyk (Shayakubov et al., 1999), and Majdanpek (Herrington et al., 1998). Leached cappings developed from intermediate argillic zones richer in pyrite contain more jarosite than goethite (e.g., Marte; Vila et al., 1991).

Gold enrichment is abnormal in leached cappings over gold-rich porphyry deposits but is claimed to have occurred at Bingham (Boutwell, 1905) and Ok Tedi (Danti et al., 1988). At Ok Tedi, a substantial proportion of the gold is coarser than that in subjacent sulfide zones (Rush and Seegers, 1990). Gold enrichment at Ok Tedi may have been appreciable, given that 46 Mt of leached capping averaged 2.7 g/t Au, more than four times greater than the average gold content of subjacent hypogene ore; however, the contribution from hypogene zoning remains uncertain.

In common with most porphyry copper deposits subjected to supergene alteration, leached cappings over gold-rich examples display widespread kaolinization of silicates (especially plagioclase), martitization of magnetite, and removal of anhydrite. Anhydrite hydration and eventual dissolution of the resulting gypsum take place to the lower limits of ground-water penetration, which is generally several hundred meters beneath the surface within hypogene ore (Fig. 6a, b). Blasting and caving characteristics of sulfide ore are markedly different beneath the sulfate front, which constitutes a roughly planar or trough-shaped interface (e.g., Sillitoe and Gappe, 1984; Clark, 1990; Fig. 6a, b). Supergene alunite is developed in and beneath leached cappings over more pyritic parts of some porphyry deposits (Sillitoe and McKee, 1996), except in tropical regions where excessive rainfall dilutes the sulfate concentrations of supergene solutions and inhibits alunite precipitation.

Genetic Model

Historical background

The genetic model for porphyry copper deposits, which is directly applicable to the gold-rich examples under consideration, developed progressively over the last century. As reviewed by Hunt (1991) and Hedenquist and Richards (1998), advances until about 1970 stemmed mainly from

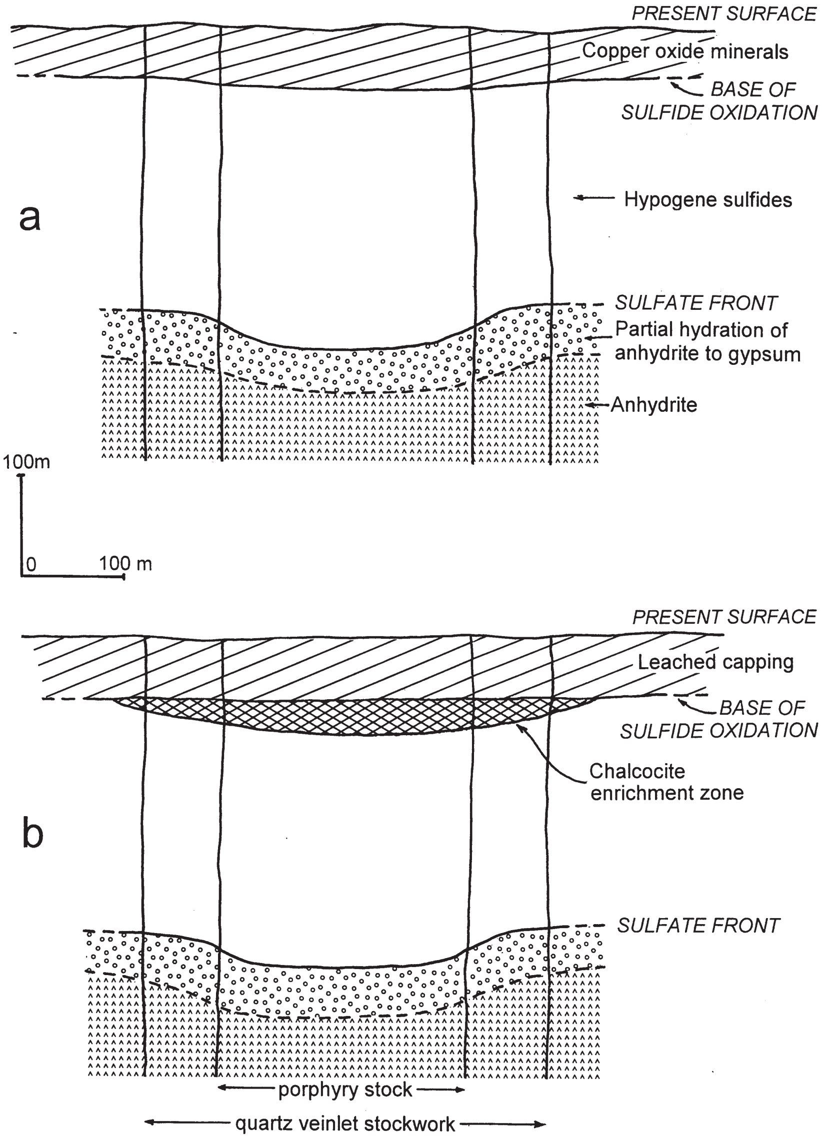

FIG. 6. Schematic supergene profiles over gold-rich porphyry deposits. a. Oxidized zone developed over pyrite-poor K silicate alteration without appreciable chalcocite enrichment. b. Copper-poor leached capping and underlying immature chalcocite enrichment zone developed over more pyritic alteration types, such as K silicate partially or completely overprinted by intermediate argillic or sericitic. A sulfate front resulting from anhydrite removal is present at depth within hypogene mineralization irrespective of details of supergene profile and sulfide content. See text for further explanation.

mining and scientific study of deposits in southwestern North America. Major tenets of the model were already in place by the 1920s, in particular, the fundamental realization that the ore-forming fluid is mainly magmatic in origin and derived from the altered and mineralized porphyry stocks and their subjacent parent plutons (e.g., Lindgren, 1905; Emmons, 1927). Investigations of porphyry copper deposits in southwestern North America were also instrumental in the elucidation of supergene processes responsible for sulfide oxidation and chalcocite enrichment (e.g., Emmons, 1917), the latter a prerequisite at the time for economic viability of most porphyry copper deposits.

Early workers tended to link copper mineralization to sericitic and argillic alteration, and it was not until Gilluly's (1946) study at Ajo, Arizona, and a review by Schwartz (1947), that K silicate assemblages were widely recognized as early, centrally located parts of porphyry copper deposits. Sales (1954) was one of the first to report that K silicate alteration commonly accompanies introduction of major amounts of copper, although sericitic alteration dominates the copper-bearing zones in some deposits. Lateral and vertical zoning of alteration and mineralization assemblages in porphyry copper systems, appreciated by Creasey (1966) and others, was first generalized by Lowell and Guilbert (1970). They concluded that copper mineralization spans the interfaces between internal cores of K silicate alteration and shells of pyrite-rich sericitic alteration. However, as remarked by Hedenquist and Richards (1998), their influential scheme omits advanced argillic alteration despite its association with porphyry copper deposits having been recognized in southwestern North America by several earlier investigators (e.g., Schwartz, 1947). Sillitoe (1973, 1975) extended the Lowell and Guilbert (1970) porphyry copper model upward through a thick, widespread zone of argillic and advanced argillic alteration to the subaerial volcanic environment represented by high-temperature fumaroles atop stratovolcanoes.

Detailed studies of the El Salvador porphyry copper deposit in Chile documented several stages of porphyry intrusion, which spanned a sequence of alteration, veining, and metal introduction events (Gustafson and Hunt, 1975). Importantly, it was proposed that a late, nearly barren intrusion destroyed as much as one third of the preexisting hypogene copper mineralization. Gustafson and Hunt (1975) further proposed that about 75 percent of the copper was introduced during formation of K silicate alteration by a magmatic brine under lithostatic conditions, whereas the remainder accompanied superimposed sericitic alteration developed during influx of meteoric fluid under more brittle, hydrostatic conditions. Some of this later copper may have been remobilized from preexisting K silicate assemblages.

Several early workers, in particular Gilluly (1946), commented on the discharge of metal-bearing fluid from parent magma chambers and its ponding and eventual release during fracturing from beneath the early consolidated carapaces of porphyry stocks. Modeling by Burnham (1967) showed that once stocks become saturated by crystallization, the exsolved fluid creates pressures sufficient to generate the multidirectional veinlet stockworks and orthomagmatic breccias that host most of the metals in porphyry copper deposits. Experimental studies demonstrated that during magma crystallization copper partitions strongly in favor of the fluid phase (Whitney, 1975), in which it is transported as chloride complexes (Holland, 1972).

Experimental studies on mineral equilibria in the K_2O-Na_2O-Al_2O_3-SiO_2-H_2O system (Hemley, 1959; Hemley and Jones, 1964) formed the basis for interpretation of K silicate, sericitic, intermediate argillic, and advanced argillic assemblages in terms of redox state and acidity of hydrothermal fluids (Meyer and Hemley, 1967). Study of fluid inclusions in quartz veinlets from the Bingham porphyry copper deposit by Roedder (1971) showed that an early fluid responsible for the K silicate alteration comprised hypersaline liquid (>500°–700°C, 40–60 wt % NaCl equiv) coexisting with low-density vapor, whereas the later fluid that caused sericitic alteration was lower in both temperature (<350°C) and salinity (5–20 wt % NaCl equiv). Henley and McNabb (1978) concluded that the coexisting high- and low-density magmatic fluids are the products of phase separation during depressurization of a single moderately saline magmatic fluid that exsolved directly from the parent magma chamber at depths of 4 to 6 km (Burnham, 1979).

Results of early light stable isotope studies confirmed that K silicate alteration is formed from magmatic fluid whereas later feldspar-destructive alteration assemblages appeared to involve a substantial meteoric water component (Sheppard et al., 1971). This conclusion, in conjunction with modeling studies (e.g., Norton and Knight, 1977), led to the widely held notion that meteoric water is instrumental in copper precipitation (e.g., Taylor, 1974). Indeed, some workers extrapolated these results to imply that the copper is leached from the wall rocks of stocks by convectively circulating meteoric fluid cells, a conclusion nicely refuted on geologic grounds by Gustafson (1978). Subsequent oxygen, hydrogen, sulfur, lead, strontium-neodymium, and osmium isotope studies, reviewed by Hedenquist and Richards (1998), also support the original contention that the fluid and contained metals possess a dominantly magmatic origin.

Stimulated by the advent of plate tectonic theory, Sillitoe (1970, 1972) noted that porphyry copper deposits are integral parts of subduction-related volcanoplutonic arcs of calc-alkaline composition worldwide. He proposed that their copper and associated metal contents are extracted from hydrated tholeiitic basalt and pelagic sediment comprising the upper parts of downgoing slabs of oceanic lithosphere. The metal-bearing melt product then ascends into the overlying mantle wedge where it induces a second stage of partial melting to generate calc-alkaline magma. In contrast, the gold and molybdenum contents of porphyry copper deposits were assumed to reflect crustal composition and thickness (Kesler, 1973).

Petrogenesis

Numerous studies support the concept that volatiles, including water, chlorine, and boron, along with metals, associated with suprasubduction zone magmatism are recycled from the downgoing slab, especially from its veneer of pelagic sediments (e.g., Plank and Langmuir, 1993; Stolper and Newman, 1994; Noll et al., 1996; Fig. 7). The metal-bearing hydrous melt product derived from the subducted slab ascends into the mantle wedge where it causes flux melting to produce a variety of calc-alkaline magmas that construct principal arcs (Fig. 7). Much lower degrees of partial melting, especially of metasomatized lithospheric mantle, promote the generation of shoshonitic and alkaline magmas in back-arc and postsubduction-arc settings. Volatiles and metals contained in the mantle-derived partial melts are transported, with varying amounts of crustal interaction and assimilation, to the upper crust, where they are potentially available for concentration in gold-rich porphyry deposits. Gold and copper enrichment of magmas is not considered to be a prerequisite for formation of gold-rich porphyry deposits (Burnham, 1979; Cline and Bodnar, 1991), but, if present, their formation should be favored.

Several recent studies have emphasized the importance of very small degrees of partial melting of metasomatized portions of the lithospheric mantle wedge (Fig. 7) in the generation of mafic alkaline magma (e.g., Gibson et al., 1995). Such magma, which is both oxidized and enriched in volatiles, potassium, and chalcophile elements, appears to be parental to most "alkalic-type" gold deposits (Richards, 1995). Keith et al. (1995) and Waite et al. (1997) proposed that alkaline mafic magma is also critical in the generation of the gold-rich Bingham porphyry deposit. On this basis, gold-rich porphyry deposits elsewhere may be expected to reveal a similar linkage between abundant calc-alkaline or alkaline magma and small volumes of specialized mafic melt emplaced at the time of mineralization.

Solomon (1990) noted that arc reversal events, consequences of changes in subduction polarity, presaged formation of some gold-rich porphyry copper deposits (e.g., Panguna) in the southwestern Pacific region. He attributed this relationship to the remelting of a mantle wedge already partially melted during previous subduction, thereby oxidizing mantle sulfides to release their contained gold. McInnes and Cameron (1994) similarly suggested that oxidation of gold-bearing sulfide phases in metasomatized mantle by slab-derived alkaline melt is responsible for chalcophile element enrichment of magma parental to the alkalic-type epithermal gold deposit and precursor gold-rich porphyry copper mineralization at Ladolam on Lihir Island, Papua New Guinea (see Moyle et al., 1990). Subsequently, metasomatized mantle rocks enriched in gold, copper, platinum, and palladium were encountered as xenoliths derived from beneath the Lihir Island alkaline volcanic center (McInnes et al., 1999).

Subvolcanic magmatic evolution

Calc-alkaline and alkaline magmas accumulate in the upper crust to form the chambers (or systems of chambers) that are parental to gold-rich porphyry stocks. Field observations and theoretical calculations suggest that these chambers, represented by equigranular plutons, possess minimum sizes of ~50 km^3 (Cline and Bodnar, 1991; Dilles and Proffett, 1995; Shinohara and Hedenquist, 1997), although much larger sizes seem likely. For example, a >5,000-km^3 parent chamber is proposed at Bingham on the basis of an aeromagnetic anomaly (Ballantyne et al., 1995), although what percentage of this fed the Bingham stock and its associated gold-rich porphyry deposit is unknown. The cylindrical porphyry stocks are cupolas on the roofs, commonly the shoulders, of the parent plutons, through which magma and hydrothermal fluid are delivered to the volcanic environment: in essence, "exhaust valves" atop magma chambers. At depths of roughly 6 km, in the upper parts of parent chambers, a single-phase magmatic fluid separates, ascends, and is focused through the conduits provided by the overlying stocks.

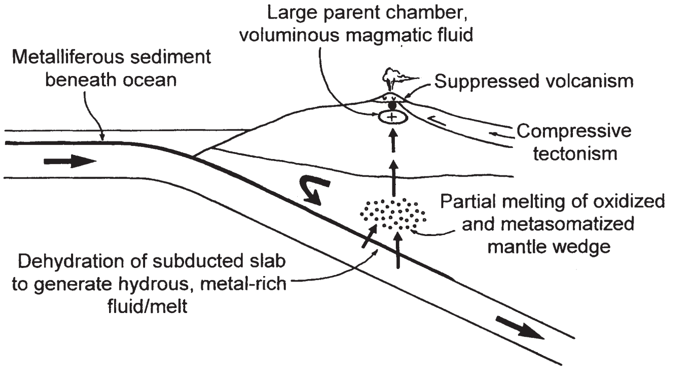

FIG. 7. Selected parameters influential in formation of large, high-grade, gold-rich porphyry deposits at convergent plate boundaries (modified from Sillitoe, 1972, 1998). Hydrous melt containing ligands and metals critical to gold-rich porphyry formation is extracted from the downgoing slab and rises into the mantle wedge causing metasomatism. Subsequent partial melting of this fertile, oxidized material generates calc-alkaline and alkaline magmas that carry the ligands and metals to the subvolcanic enviroment. There, under compressive tectonic conditions, volcanism tends to be suppressed and large parent magma chambers overlain by few or single stocks are able to form: an ideal situation for the efflux of voluminous magmatic fluid to create exceptionally large, high-grade deposits (black spot). See text for further explanation.

In compressional tectonic settings, Sillitoe (1998) speculated that parent chambers tend to be larger than in transtensional to extensional arcs because magma eruption to cause volcanoes is inhibited by a deficiency of steep extensional faults (Fig 7). The paucity of steep faults could also minimize the number of stocks on the roofs of parent chambers, implying that clusters of gold-rich porphyry deposits may be more typical of extensional tectonic settings (e.g., the 12 porphyry centers at Goonumbla; Heithersay and Walshe, 1995). All else being equal, larger parent chambers exsolve greater volumes of magmatic fluid which, if discharged through only a few stocks, or preferably a single stock, is theoretically able to generate larger and higher grade deposits. Grasberg may be cited as the classic example.

Field evidence shows clearly that magma and hydrothermal fluid, the latter in most cases probably already partitioned into high- and low-density phases, ascend into porphyry stocks either alternately or together for periods of several hundred thousand years and perhaps for >1 m.y. Since porphyry phases typically young horizontally inward from the margins, stocks must expand progressively during magma emplacement. In the absence of deformed wall rocks, expansion implies that the stocks occupy localized dilational sites even where the overall setting is compressional. Individual pulses of magma ascent and crystallization in stocks appear to be separated by restricted pauses because chilling is generally absent between porphyry phases; however, more extended cooling intervals are indicated locally by the presence of narrow chilled margins. Where observed (e.g., Guinaoang; Sillitoe and Angeles, 1985; Wafi; Sillitoe, 1999), the tops of porphyry stocks are domelike in overall form, implying that magma is not normally erupted from the cylindrical cupolas once gold-rich porphyry formation commences. Indeed, ponding of magmatic fluid beneath the tops of stocks may be a prerequisite for effective development of porphyry deposits. It may be suggested further that impermeable wall rocks cause additional fluid impoundment and, in extreme cases, may lead to development of abnormally high gold (>1 g/t) and copper (>0.8%) grades within stocks by minimizing lateral and vertical dissipation of magmatic fluid. The permeability of wall rocks is commonly reduced by contact metamorphism (hornfelsing, marbleization) consequent upon initial stock emplacement. In this manner, marbleized limestone in the upper preserved 1 km of the stock at Grasberg may have enhanced ore grades (Sillitoe, 1997).

Although there is local evidence for an absence of magma discharge from cylindrical cupolas once mineralization commences, a number of systems undergo late-stage resurgence of magmatism that may reach the paleosurface. The magmatic products are postmineral plugs and diatremes, which are thought to be represented at the paleosurface as dome complexes and maar volcanoes, respectively. Indeed, occurrence of subaerial products, including base surge deposits, lake beds, and carbonized wood, in diatremes confirms a surface connection (Sillitoe, 1985). Diatreme formation is typically late in the evolution of gold-rich porphyry systems because it is only then, once magmatic-hydrothermal activity has waned, that appreciable amounts of meteoric water are able to access magma bodies, a requirement for phreatomagmatic magmatism. Indeed, there is a strong suggestion that diatremes in mid to late Cenozoic gold-rich porphyry copper systems are more common in Southeast Asia and the southwestern Pacific region, where pluvial climatic regimes prevailed at that time.

Metal-enriched magmatic fluid generation

Magmatic fluid discharges from parent chambers either continuously or intermittently and tends to pond beneath the early consolidated apices of stocks and their enclosing wall rocks. Continued crystallization of stocks causes second boiling, fluid expulsion, and generation of the mechanical energy to create stockwork fracturing and hydrothermal brecciation (Burnham, 1967, 1979). Pressure quenching consequent upon second boiling creates the characteristic fine-grained groundmass of porphyry intrusions.

Formation of major gold-rich porphyry deposits, however, may be critically dependant upon external events that seriously perturb the stock environment and cause massive fluid expulsion. Such events might include the following:

1. Emplacement of a body of hot mafic magma into the parent chamber, possibly into the roots of the stock itself, causing heating and expansion of the contained volatiles and even introduction of additional sulfur and metal-rich volatiles (Hattori, 1993). This model is called upon to explain observations at Bingham (Keith et al., 1995; Waite et al., 1997) and elsewhere (Clark and Arancibia, 1995).
2. Catastrophic paleosurface degradation, either by landsliding or volcano sector collapse, resulting in dramatic depressurization of the stock and its parent chamber (Sillitoe, 1994). Sector collapse instantaneously removes rock masses ≥50 km^3 and is promoted by the weakening of volcanic edifices caused by argillic and advanced argillic alteration (e.g., López and Williams, 1993).
3. Rapid intrusion of magma from parent chambers into overlying stocks or eruption of magma from elsewhere on the roofs of the parent chambers, both of which would also cause abrupt depressurization (Lowenstern, 1993).
4. Seismic events which may be fault related or triggered by mechanisms (1), (2), or (3).

The magmatic fluid, whether expelled or sucked out of the parent chamber, is channeled upward through the magma as a bubble-rich plume to the cracking front along the roof of the magma body. Ascent of bubbles is most efficient where the water content is high relative to other volatiles, the degrees of magma crystallization is low, and the pressure is low (Candela, 1991).

Formation of gold-rich porphyry deposits requires that the gold (and copper) contents of upper crustal chambers partition efficiently into magmatic fluid. This requirement is fulfilled when the fluid is released before chalcophile elements (including platinum-group elements) are sequestered from the melt by segregation of immiscible sulfide liquid (Candela, 1992; Candela and Blevin, 1995). This condition is favored by one or more of the following: (1) magma with a fairly high water content, thereby attaining volatile saturation sooner; (2) magma with a high oxidation state, whereby sulfur is present mainly as sulfate rather than sulfide; and (3) magma that is relatively depleted in sulfur, therby suppressing the removal of appreciable quantities of metals. Gold and associated metals certainly are not sequestered by -immiscible sulfides if magma is highly oxidized and able to crystallize sulfates or sulfate-bearing feldspathoids (Thompson, 1995), an apparently common condition in calc-alkaline and alkaline arc magmas. Moreover, even if sulfide saturation does occur, loss of sulfur and water-rich fluid during eventual volatile saturation may cause oxidation and resorption of the magmatic sulfide droplets and release of the contained metals (Keith et al., 1995). Destabilization of magmatic sulfides causing metal liberation also may be caused by upward SO_2 fluxing of a magma chamber during intrusion of less fractionated, more mafic magma (Hattori, 1993) or simply to volatile release resulting from depressurization during magma acent (Lowenstern, 1993).

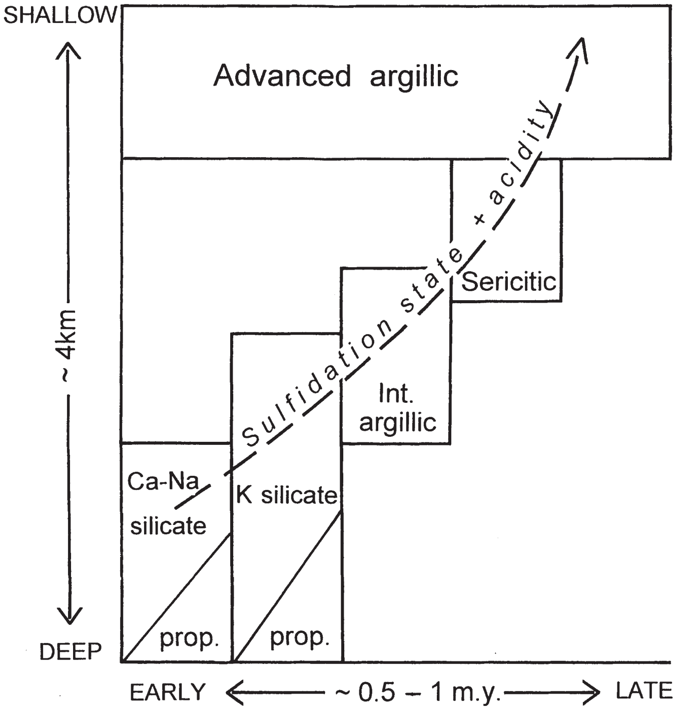

FIG. 8. Schematic depth-time plot to show typical observed sequence and positions of Ca-Na silicate, K silicate (including propylitic halos), intermediate argillic, sericitic, and advanced argillic alteration. The dashed arrow generalizes the progressive increase in sulfidation state and acidity of the fluids responsible.

Hydrothermal alteration processes

Alteration zones in gold-rich porphyry deposits are typically zoned upward and become progressively younger in the sequence: Ca-Na silicate, K silicate, intermediate argillic, sericitic, and advanced argillic, although the last can begin to form at shallow depths in the early, K silicate stage (Figs. 8 and 9). Propylitic alteration is the lateral equivalent of both Ca-Na silicate and K silicate zones, with which it is transitional. With the exception of propylitic, Ca-Na silicate, possibly some K silicate alteration, and the shallower parts of advanced argillic lithocaps, the other alteration types develop at the expense of previously altered, as opposed to unaltered, porphyry and wall rocks (Fig. 9). Hence the alteration minerals, including sulfides, in preexisting assemblages are reconstituted under different, generally progressively lower temperature, more acidic, and higher sulfidation state conditions (Fig. 8) to form the successively younger alteration types. Therefore, a rock volume affected by deeply penetrating advanced argillic alteration may have consisted previously, in turn, of sericitic, intermediate argillic, K silicate, and Ca-Na silicate assemblages. This progressive overprinting of alteration type—telescoping—may be due to continued degradation of the paleosurface during alteration and mineralization or simply to waning of the magmatic hydrothermal system that would accompany downward propagation of the brittle-ductile boundary as temperatures fall (Fournier, 1999). However, massive telescoping of advanced argillic over K silicate alteration, as observed at Marte, Wafi, and elsewhere (Sillitoe, 1999), is thought likely to require more than just natural waning of systems and seems best interpreted as a consequence of exceptionally rapid surface erosion with or without gravitationally induced collapse (Sillitoe, 1994; Fig. 9).

Different investigators have claimed that most of the gold and associated copper in gold-rich porphyry deposits is introduced either early during K silicate alteration (e.g., Bingham; Babcock et al., 1995; Batu Hijau; Clode et al., 1999) or later with intermediate argillic alteration (Corbett and Leach, 1998; Leach, 1999) and/or sericitic alteration (e.g., Far Southeast; Hedenquist et al., 1998). At Guinaoang (Sillitoe and Angeles, 1985) and Wafi (Tau-Loi and Andrews, 1998; Sillitoe, 1999), however, broadly similar ore-grade copper and gold contents span the deep K silicate through intermediate argillic and sericitic to shallow advanced argillic zones, albeit constituting distinctive sulfide assemblages dictated principally by sulfidation state in association with each of the alteration types (see above).

There is general agreement that the gold and copper in K silicate assemblages are introduced by magmatic brine (e.g., Candela, 1989; Bodnar, 1995); however, there is still minority support for metal scavenging from upper crustal rocks by surface-derived fluid (Sheets et al., 1996), a notion that fits poorly with geologic observations, as noted previously (Gustafson, 1978). Propylitic halos result by dilution of the outwardmoving magmatic brine with meteoric or connate fluids circulating through wall rocks (e.g., Bowman et al., 1987). However, the lower temperature and lower salinity fluid responsible for copper and gold precipitation within intermediate argillic or sericitic assemblages is considered on the basis of light stable isotope data, fluid inclusion studies, and geologic considerations to be either an admixture of magmatic and meteoric fluids (e.g., Bodnar, 1995), or a late-stage, lower temperature magmatic fluid (Hedenquist et al., 1998) that ascends directly from the parent chamber as crystallization advances and the contained magma stagnates (Shinohara and Hedenquist, 1997). Whichever explanation is correct should be compatible with the observations that intermediate argillic and/or sericitic alteration is transitional downward to K silicate alteration in all gold-rich porphyry deposits, and that K silicate alteration formed under lower redox conditions than prevailed during the overprinted intermediate argillic alteration, which ubiquitously contains martitized magnetite ± specular hematite.

Notwithstanding which of these alternative fluid sources proves to be correct, I support the concept that gold and copper in the shallower, later, lower temperature alteration zones are successively reconstituted and variably remobilized from their original sites in K silicate alteration, as proposed and modeled for Butte, Montana, by Brimhall (1980). Little variation in copper and, in some cases, gold contents over vertical intervals of approximately 1,000 m, spanning transitional K silicate, intermediate argillic, sericitic, and advanced argillic zones (Fig. 3; see above),

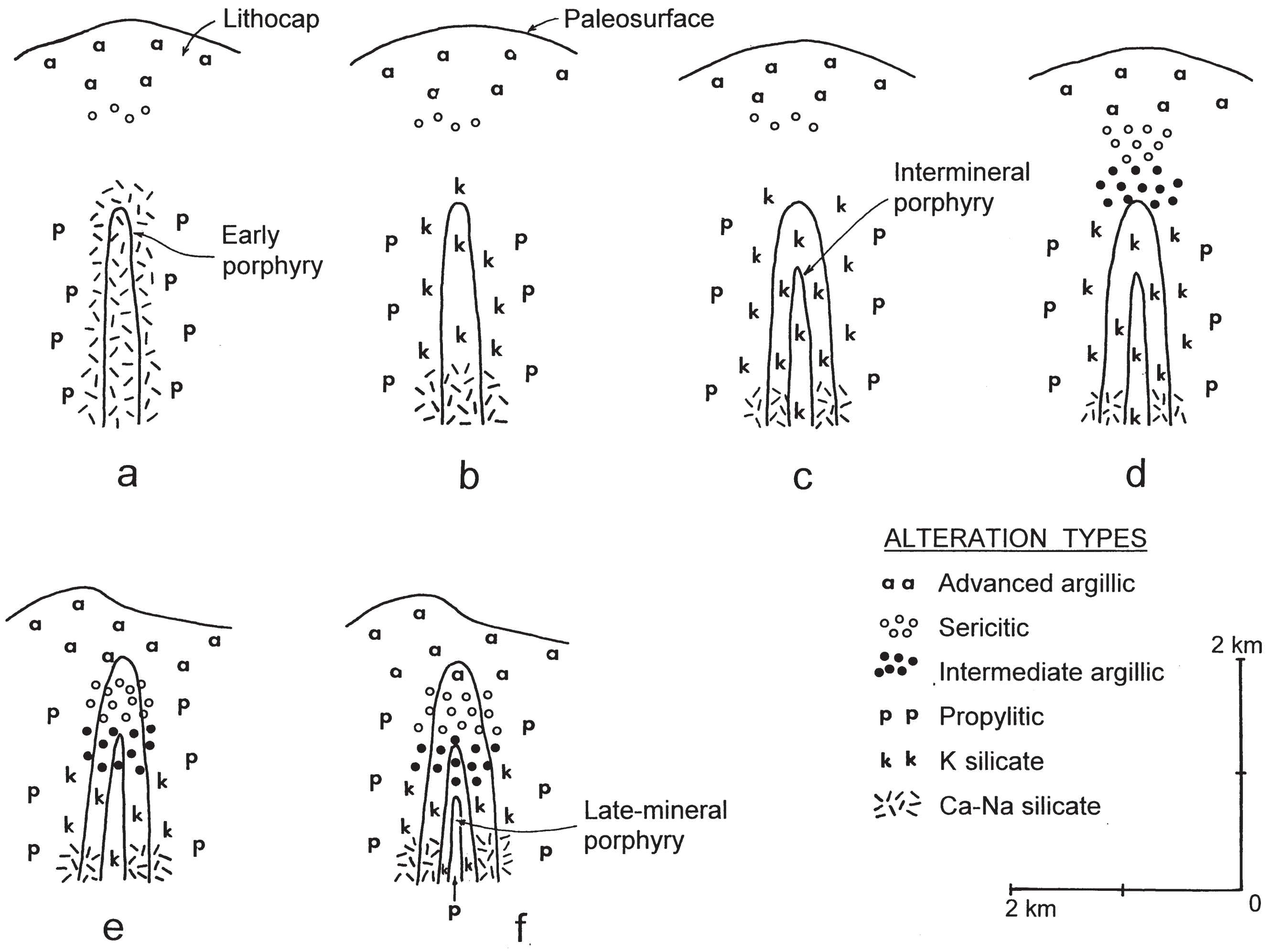

FIG. 9. Simplified genetic model to show interpreted evolution of typical gold-rich porphyry system. a. Early porphyry intrusion with development of barren Ca-Na silicate alteration from high-temperature magmatic brine, propylitic alteration on margins, and early lithocap by condensation of magmatic volatiles. b. Magmatic brine cools to form K silicate alteration, with introduction of most of gold and copper into the system, while propylitic halo and lithocap continue to develop. c. Intermineral porphyry intrusion causes stock inflation and continued K silicate alteration and gold-copper mineralization but with resulting intensity and grades lower than in early porphyry and its immediate wall rocks. d. Progressive cooling of system, probably with initial meteoric water incursion, causes development of intermediate argillic alteration at expense of upper parts of K silicate zone. e. Catastrophic paleosurface degradation causes telescoping of the system, with advanced argillic, sericitic, and intermediate argillic alteration progressively overprinted on to K silicate zone causing major reconstitution and partial remobilization of preexisting sulfide assemblages. f. Late-mineral porphyry intrusion causes further stock inflation and development of a barren propylitic core. See text for further explanation.

argues strongly for reconstitution of initial metal inventories rather than development of similar metal tenors during four different alteration events. Furthermore, metal remobilization seems to be the simplest means of explaining why intermediate argillic, sericitic, and advanced argillic alteration may be essentially barren or either lower or higher in grade with respect to the preceding K silicate alteration, even within the confines of single deposits. Alternatively, however, the relative timing of metal release from the magma could be called upon to account for the association of metals with either early K silicate or late intermediate argillic and sericitic alteration. Nevertheless, gold and copper remobilization is assured in many deposits where K silicate alteration containing chalcopyrite and bornite is overprinted by patches of barren pyritic intermediate argillic or sericitic alteration, or where porphyry cut by barren A type quartz veinlets showing evidence for removal of sulfide grains is pervasively sericitized and contains disseminated pyrite, chalcocite, and covellite.

Controversy also surrounds the cause of Ca-Na silicate alteration that formed during the early stages of at least some gold-rich and other porphyry deposits. Lang et al. (1995c) advocated magmatic fluid as the cause of sodic and calcic alteration in the gold-rich porphyry copper deposits associated with alkaline intrusions in British Columbia. Clark and Arancibia (1995) shared this opinion for gold-rich porphyry copper deposits elsewhere. In contrast, Dilles and Einaudi (1992) and Dilles et al. (1995) proposed the early influx and heating of connate brine from sedimentary wall rocks to account for apparently similar alteration at Yerington, Nevada. Certainly, heating of a fluid is capable of generating sodic alteration as opposed to potassic alteration during cooling (e.g., Giggenbach, 1984). Such external fluid might be viable if Ca-Na silicate alteration were everywhere barren of metals, but in some of the alkaline porphyry deposits of British Columbia, as well as elsewhere, it is closely and complexly related to K silicate alteration and contains ore-grade gold and copper. Moreover, Ca-Na silicate alteration is common in volcanic-hosted deposits where connate brine is most unlikely to have been available.

For these reasons, a magmatic brine capable of Ca-Na metasomatism is the preferred fluid for early Ca-Na silicate alteration. Pollard (1999) proposed an elegant explanation for albitization followed by potassic metasomatism in felsic magmatic systems. In his model, CO_2-rich aqueous fluid contains more sodium than an equivalent CO_2-poor fluid so, on phase separation and partitioning of CO_2 into vapor, the sodium content of the resulting brine exceeds the equilibrium value, thereby promoting albitization and, on cooling, K feldspar alteration, the sequence observed most commonly in gold-rich porphyry deposits. Theoretically, the sodic to potassic sequence may be repetitive to explain local postpotassic sodic alteration in some gold-rich porphyry deposits (e.g., Mount Milligan; Sketchley et al., 1995). It seems likely that the CO_2 content of early magmatic fluid at depth in porphyry stocks (25–30 mole % in the Pine Grove porphyry molybdenum system, Utah; Lowenstern, 1994) is high enough to create the desired effect. Although mineralized in some cases, early Ca-Na silicate assemblages are typically deficient in gold and copper, a situation which may reflect (Sillitoe, 1993) (1) that temperatures were too high for breakdown of metal chloride complexes, other than that of iron to form magnetite, and/or (2) that essentially all sulfur was in solution in the oxidized state and therefore unavailable for metal precipitation (Arancibia and Clark, 1996; Clark and Arancibia, 1995).

Two mechanisms for development of advanced argillic alteration assemblages appear to be feasible in gold-rich porphyry deposits (Hemley and Hunt, 1992; Hedenquist et al., 1998): (1) cooling and progressive ionization of acidic constituents contained within the dominantly magmatic brine; and (2) absorption of ascendant magmatic volatiles contained in the low-density magmatic fluid phase into meteoric water aquifers, with condensation of HCl plus disproportionation of SO_2 to H_2SO_4 to generate acidity (e.g., Giggenbach, 1997). Formation of pyrophyllite, dickite, and perhaps other advanced argillic minerals in the vicinities of porphyry stocks may result from the former mechanism, whereas areally extensive quartz-alunite alteration in the main lithocap environment is more likely to be a product of the latter, as shown at the Far Southeast gold-rich porphyry and topographically higher Lepanto enargite gold deposits (Hedenquist et al., 1998). Ionization of acids is a progressive process, whereas volatile condensation is characterized by sharp chemical fronts. This contrast should translate into gradational as opposed to sharp contacts between alteration assemblages as one moves from the roots of lithocaps upward (Fig. 3).

The origin of gold and copper concentrations in advanced argillic zones remains highly uncertain but may include one or more of: (1) remobilization from preexisting alteration types; (2) the late-stage, low-temperature, low-salinity magmatic fluid proposed by Hedenquist et al. (1998); and (3) volatile metal species carried in low-density magmatic volatiles (Sillitoe, 1983; Heinrich et al., 1999). Recent analysis of fluid inclusions from quartz veinlets in the K silicate alteration zone at Grasberg showed that the low-density vapor phase is capable of carrying ten times more copper and gold than the coexisting brine, at least under high-pressure conditions (Heinrich et al., 1999). This phase may, therefore, reasonably be invoked as a supplier of metals to the lithocap environment. Indeed, the fact that the vapor contains essentially all the arsenic (Heinrich et al., 1999) strongly implicates it in the formation of high sulfidation epithermal deposits containing the arsenic bearing sulfosalts, enargite and luzonite. Yet the low-salinity (5–15 wt % NaCl equiv) fluid present in inclusions from the Lepanto high sulfidation enargite-gold deposit (Hedenquist et al., 1998) accords poorly with this mechanism.

Metal distribution

Transport of gold and copper in magmatic brine is widely accepted to be in the form of chloride complexes (Hayashi and Ohmoto, 1991; Seward, 1991). Nevertheless, recent experimental work suggests that sulfide species may be an effective transporting agent of gold in brine under high-pressure (100–400 MPa), high-temperature (550°–725°C) conditions appropriate for initial separation of magmatic fluid from chambers parental to porphyry stocks (Loucks and Mavrogenes, 1999). If this were so, however, it would be difficult to explain the good correlation of gold and copper in the K silicate alteration zones of most gold-rich porphyry deposits, unless the copper were also carried as sulfur complexes. The gold-copper correlation suggests cotransport and codeposition from the same fluid under nearly identical conditions, thereby implying a common transport mechanism. The close association of gold with chalcopyrite and, especially, bornite, as a result of unmixing of gold from solid solution in these sulfides during cooling to 500°C (Simon et al., 2000), leads to the same conclusion. Fluid cooling is the most likely cause of gold and copper precipitation from brine in K silicate zones (Gammons and Williams-Jones, 1997). The cooling may be assisted by mixing of ascendant and refluxed brine (cf. Fournier, 1999).

The reason for marked variations of Au/Cu ratios between gold-rich porphyry deposits (Fig. 2a) is another parameter that remains poorly understood. Recent analysis of magmatic brine (>60 wt % NaCl equiv) in fluid inclusions in quartz veinlets from the gold-rich Grasberg and Bajo de la Alumbrera porphyry copper deposits suggests that Au/Cu ratios at the deposit scale may reflect the original metal budget of the magmatic fluid itself, which is controlled by conditions and processes in parent chambers (Ulrich et al., 1999). Nevertheless, the suppression of copper deposition in gold-only porphyry deposits, such as those in the Maricunga belt, remains contentious. Based on geologic evidence for unusually shallow emplacement of some of the diorite to quartz diorite porphyry stocks in the Maricunga belt, for example, only 500 to 700 m beneath a stratovolcano summit at Marte (Vila et al., 1991; Sillitoe, 1994), gold rather than copper may have been preferentially transported and precipitated (Sillitoe, 1992). This is because early magmatic fluid liberated at low pressures (shallow depths) is likely to be of relatively low salinity (Cline and Bodnar, 1991; Cline, 1995) and, therefore, less capable of carrying copper in chloride form but able to transport gold efficiently as a bisulfide complex (Seward, 1991). This proposal is supported further by the fact that low-salinity vapor rather than brine exists under lithostatic conditions at depths of <~1 km (Candela and Blevin, 1995), in keeping with preliminary fluid inclusion results from Marte (Vila et al., 1991). An alternate explanation would simply invoke a copper-deficient magmatic fluid.

Overprinting of K silicate assemblages by intermediate argillic or sericitic alteration may cause differential remobilization of copper and gold, with the latter apparently more commonly depleted than the former. This observation is perhaps not surprising given that late fluids are more likely to be dilute and, therefore, better able to redissolve gold rather than copper. Such remobilized gold is available for concentration in epithermal deposits beyond the main porphyry deposits, either in the suprajacent high sulfidation lithocap or in marginal, lower sulfidation zones (Sillitoe, 1989).

The close correlation between gold and PGE, especially palladium, in gold-rich porphyry copper deposits and the sympathetic relationship between gold, PGE, and chalopyrite provide good evidence that PGE are transported by chloride complexes and precipitated under similar conditions of K silicate stability, including high oxidation states, to gold and copper. This conclusion is supported by theoretical and experimental evidence (e.g., Wood et al., 1992).

Molybdenum halos, which partially overlap the outer limits of the copper-gold cores of some gold-rich porphyry deposits, give the impression of being zoned with respect to copper and gold. Therefore, it seems reasonable to assume that the three metals precipitated from the same overall magmatic fluid, in keeping with the presence of molybdenum, copper, and gold in brine from the same fluid inclusions (Ulrich et al., 1999). However, little is known about the paragenetic position of the molybdenite concerned. In contrast, the exceptional molybdenum-rich core at Bingham appears to be the product of a relatively late, partly superimposed event characterized by B type veinlets (Phillips et al., 1997).

Study of fluid inclusions from quartz veinlets in the K silicate alteration zones at Grasberg and Bajo de la Alumbrera shows that high-salinity brine, and not the coexisting vapor, contains most of the zinc, lead, and silver, in concentrations greater even than that of copper (Ulrich et al., 1999). However, none of these metals is appreciably concentrated in the deposits themselves. Cooling of magmatic brine as it reacts with wall rocks and becomes diluted with convectively circulated meteoric or connate fluids in propylitic halos may be the main cause of the zinc, lead, and silver precipitation (Hemley and Hunt, 1992), giving rise to geochemical halos of these metals and, in some cases, localized vein concentrations. More substantial concentrations of zinc, lead, and silver are confined to some systems with receptive carbonate host rocks, such as Bingham and Cerro Corona, where fluid neutralization induces precipitation of the base metal sulfides (Seward and Barnes, 1997).

Exploration and Discovery

Models in exploration

Thompson (1993) argued that a combination of descriptive and genetic models is used more widely in porphyry copper exploration, including that for gold-rich examples, than in the search for many other mineral deposit types. This situation stems from the fact that the genesis of porphyry deposits is reasonably well understood, leading to effective underpinning of the descriptive model by relatively unambiguous genetic parameters. This state of affairs is very different from that of many gold deposit types, for which there exist multiple competing genetic hypotheses.

Notwithstanding this favorable situation, the descriptive model for gold-rich porphyry deposits has been applied in a generally unsophisticated manner to exploration. Only very generalized geologic features are widely employed. For example, gold-rich porphyry exploration is conducted in well-defined volcanoplutonic arcs, typically in belts or districts with known deposits and prospects and, therefore, demonstrated potential. Zinc-lead occurrences and geochemical anomalies are often interpreted to suggest the peripheries of porphyry systems. More detailed exploration attention is focused on altered porphyry stocks, in which characteristic quartz veinlet stockworks are used to confirm the presence of porphyry-type mineralization and outline principal targets (e.g., Leggo, 1977). Zoning of alteration inward from propylitic to K silicate assemblages, possibly with an intervening sericitic zone (Lowell and Gulbert, 1970), is used commonly as a broadscale vector. Enrichment of stocks and their immediate wall rocks in hydrothermal magnetite is a sign that systems are likely to be gold rich (Sillitoe, 1979).

More recently, it has become quite widely accepted that advanced argillic lithocaps may overlie and conceal porphyry deposits, including gold-rich ones (e.g., Sillitoe, 1995a). Lithocaps have become increasingly popular exploration targets since opportunities to encounter outcropping porphyry deposits have decreased. Telescoped systems are required if gold-rich porphyry mineralization is to be found at economically viable depths. Nevertheless, unless quartz veinlet stockworks in advanced argillic-altered rock are observed in outcrop, it is generally difficult to determine the degree of telescoping without considerable drilling.

Although explorationists are usually familiar with some or all aspects of the genetic model for gold-rich porphyry deposits, these are rarely brought to bear directly during exploration. Genetic interpretation simply provides a measure of intellectual support for field observations and acts as a comfort factor for the explorationist.

Influence of models on geochemistry and geophysics

Geochemistry and geophysics are widely used in exploration for porphyry copper deposits, including gold-rich ones. The interpretation of geochemical and geophysical responses depends heavily on the erosion level of the porphyry system and, hence, the mineralogy of the alteration zones exposed and concealed at shallow depths (Fig. 10).

Conventional geochemistry is normally very effective in defining outcropping gold-rich porphyry prospects, especially where pyrite-poor K silicate alteration is exposed. Geochemical values in rocks and soils (including talus fines in arid regions; Maranzana, 1972) typically exceed 500 ppm Cu and 100 ppb Au. Copper anomalies may attain several thousand ppm where pyrite contents are extremely low, but they become progressively more subdued as pyrite/copper-bearing sulfide ratios increase (e.g., Leggo, 1977). Nevertheless, gold remains equally effective as a pathfinder in pyrite-rich and pyrite-poor situations (e.g., Learned and Boisson, 1973). Molybdenum tends to define partially overlapping geochemical halos to many gold-rich porphyry deposits (Fig. 10b, c), whereas zinc and lead constitute patchily developed outer halos. Arsenic values are not normally anomalous unless enargite- or luzonite-bearing sericitic and/or advanced argillic alteration in the roots of or within lithocaps are preserved.

Drainage geochemistry, using –80# to –200# silts, bulk leach extractable gold (BLEG), or panned heavy mineral concentrates also highlights most gold-rich porphyry deposits. In tropical regions, where drainage geochemistry is especially effective, stream silts in high-order drainages commonly contain hundreds of ppm Cu and hundreds of ppb Au within 2 km or so of gold-rich porphyry deposits. Copper transport may be largely mechanical over and around oxidizing systems characterized by extremely low pyrite contents, but partly in solution and potentially over greater distances in the case of systems containing more abundant pyrite. The fine grain size of much of the gold in porphyry deposits implies that stream silts provide an effective sample medium. By the same token, placer gold accumulations are not widely developed downstream from gold-rich porphyry deposits, although small examples are reported at Panguna, Ok Tedi, Kemess South, and Bingham.

Several gold-rich porphyry deposits generate prominent bulls-eye aeromagnetic anomalies (Fig. 10c), as at Grasberg (Potter, 1996) and Batu Hijau (Maula and Levet, 1996), as well as clearly defined ground magnetic highs (e.g., South body at Saindak, Sillitoe and Khan, 1977; Skouries, Tobey et al., 1998; Chailhuagon at Minas Conga, Llosa et al., 2000), because of the abundance of hydrothermal magnetite in K silicate zones. Nevertheless, other deposits generate magnetic rims to central lows (e.g., Endeavour 48 at

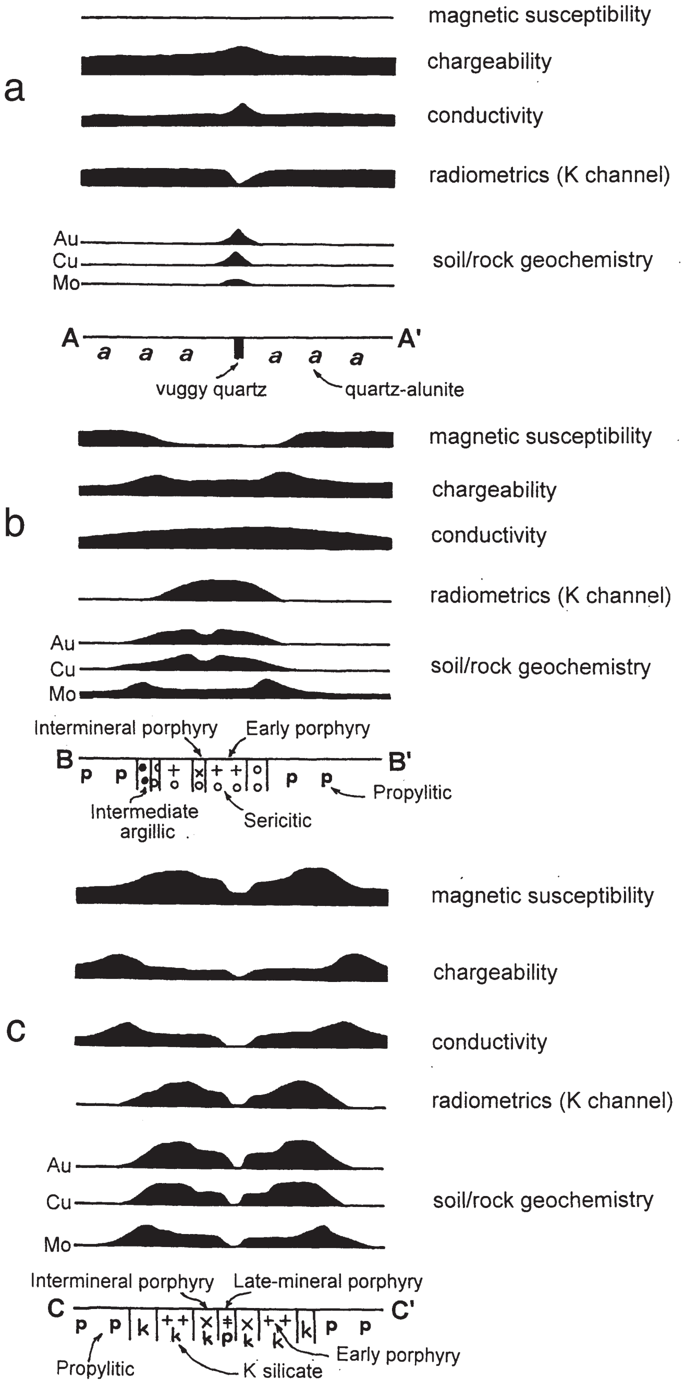

FIG. 10. Idealized geophysical and geochemical responses at three levels (A–A′, B–B′, and C–C′ in Figure 3) of a typical gold-rich porphyry deposit: (a) within the lithocap where pyrite contents are high; (b) within the upper parts of the underlying porphyry stock overprinted by sericitic and intermediate argillic alteration, also with appreciable pyrite contents; and (c) within deeper levels of the porphyry stock dominated by pyrite-poor K silicate alteration but containing low-grade and barren porphyry phases in its axial parts. Thickness of bars depicting magnetic, chargeability, conductivity, radiometric, and geochemical responses is roughly proportional to intensity of predicted anomalies. Section legends correspond to those in Figure 3.

Goonumbla; Heithersay et al., 1996) or no readily identifiable anomaly at all. Intermediate argillic, sericitic, and advanced argillic overprints will all cause magnetite destruction and, hence, suppress magnetic susceptibility, with the recorded response depending on the depth to magnetite-bearing K silicate zones. It is difficult to use regional aeromagnetic surveys to explore effectively for even magnetite-rich porphyry deposits, however, because the areally restricted magnetic signatures are difficult to distinguish from responses given by numerous other geologic features common to arc terranes. Indeed, extensive aeromagnetic surveys in the central Andes, southwestern Pacific region, and elsewhere have so far failed to discover a gold-rich porphyry deposit. Nevertheless, the first recognition of copper mineralization at the Mount Polley porphyry copper-gold deposit resulted from followup of an aeromagnetic anomaly (Fraser et al., 1995).

Parts of gold-rich porphyry systems commonly give rise to chargeability highs or act as conductors or resistors. However, as illustrated schematically in Figure 10, the response provided by electrical geophysical surveys must be correlated carefully with geologic and alteration features before valid drilling targets can be selected. For example, depending on erosion level and, hence, total sulfide content and distribution, a chargeability high may encompass an entire porphyry system (e.g., Saindak; Sillitoe and Khan, 1977) or simply denote its pyritic halo (e.g., Mount Milligan; Sketchley et al., 1995; Fig. 10), whereas pyrite-poor systems may lack an appreciable response altogether. Deposits characterized near surface by extensive intermediate argillic alteration (e.g., Perol at Minas Conga; Llosa et al., 2000) or supergene kaolinization accompanying oxidation and chalcocite enrichment may give rise to resistivity lows (conductivity highs), although the opposite effect is commonplace, especially in lithocap settings, where quartz introduction is important. The semimassive sulfide accumulations that accompany silicic rocks in lithocaps would, however, act as conductors.

Where altered rock or rock fragments occur at surface, gold-rich porphyry systems may give rise to ground or airborne radiometric anomalies in response to potassium additions during K silicate, sericitic, or alunite-rich advanced argillic alteration (Fig. 10). However, concealment of deposits by dense vegetation or even under thin postmineral cover results in suppression or elimination of the potassium count.

Model predictions

The descriptive model for gold-rich porphyry deposits has predictive power that may be brought to bear in discriminating between economically attractive and unattractive exploration plays. As a consequence, exploration funding may be focused on more promising systems.

The best gold-rich porphyry deposits are those that possess wide, coherent, single-phase, well-mineralized intrusions spanning several hundred vertical meters. Normally, these are the early intrusions containing the highest copper and gold values, which have suffered minimal dilution by lower grade inter- and late-mineral phases. Recognition and mapping of inter- and late-mineral phases, using the criteria summarized above, are prerequisites for selection of systems with the greatest potential. Furthermore, delimitation of inter- and late-mineral intrusive phases is important if reconnaissance drilling is to avoid lower grade, commonly centrally located parts of systems. These are commonly not well defined with soil and, sometimes, even rock-chip geochemistry, which are the techniques often used to site initial drill holes. Late- to postmineral diatreme emplacement may also result in destruction of parts of porphyry deposits (e.g., Dizon; Sillitoe and Gappe, 1984), thereby reducing the amount of available ore.

Porphyry stocks emplaced into rocks of relatively low permeability, especially marbleized limestone and poorly fractured hornfels, are believed to be particularly favorable targets for high-grade gold-rich porphyry deposits because of their capacity to prevent lateral and, in some cases, also vertical dissipation of metalliferous fluid. Gold and copper grades also seem likely to be higher in deposits generated beneath, rather than within, volcanic edifices because of more efficient retention of magmatic fluid.

Gold-rich porphyry prospects in which bornite (± digenite and chalcocite) is a dominant sulfide in K silicate zones are particularly attractive exploration objectives both because gold contents tend to be higher and because the close bornite-gold association leads to high gold recoveries, commonly >80 percent, by conventional flotation (Sillitoe, 1993; Simon et al., 2000). In contrast, less deeply eroded prospects, in which intermediate argillic and/or sericitic alteration assemblages are developed both pervasively and intensely, are commonly less attractive propositions than those dominated by K silicate assemblages. This is because intermediate argillic and sericitic overprints cause reconstitution of sulfide assemblages and result in close association of some of the gold with introduced pyrite. As a result, gold recoveries tend to be <60 percent compared to >70 percent in ore dominated by pyrite-poor, K silicate assemblages, because of loss of auriferous pyrite to the tails. Nevertheless, where intermediate argillic or sericitic alteration dominates, the likelihood always exists that K silicate alteration containing higher metal, especially gold, values may exist at depth (e.g., Wafi).

Shallowly exposed gold-rich porphyry prospects showing appreciable degrees of telescoping commonly preserve the roots of lithocaps, in the form of sericitic and/or advanced argillic alteration, superimposed on preexisting K silicate and intermediate argillic assemblages containing quartz veinlet stockwork (Figs. 3 and 8). Such zones, especially the shallowest parts of them, commonly contain enargite ± luzonite as a major sulfide mineral (e.g., Wafi, Guinaoang), thereby downgrading economic potential because of the dirty arsenic-rich flotation concentrate that would result. Enargite-bearing zones could become of interest in the future, however, if copper and gold grades were sufficiently high to justify bioleaching of the flotation concentrates.

The economic potential of gold-rich porphyry deposits, like that of all other porphyry deposits, is profoundly influenced by the interplay between alteration type and depth of supergene weathering. Where oxidation is deep (>200 m), as is commonly the case in the western United States and the central Andes, the copper-bearing sulfides plus minor pyrite typical of K silicate alteration zones oxidize essentially in situ, resulting in widespread development of copper oxide minerals. The copper may be readily recovered from such material using heap leaching-electrowinning (SX-EW), but gold would be lost. Conversely, the copper oxide content would preclude effective gold recovery by cyanidation. Therefore, where prospects are dominated by K silicate alteration, limited sulfide oxidation is advantageous, implying that systems in tropical environments (western Pacific region, Southeast Asia, northern Andes, central America) or glaciated regions (British Columbia, Alaska, southern Andes) possess the greatest potential. Nevertheless, even there, problems may result because of admixed copper oxide minerals and gold in shallow ore zones to be mined first. Exploitation of gold from the leached capping at Ok Tedi was less than successful because remnant oxide copper caused serious problems during cyanidation (Rush and Seegers, 1990). Still higher copper contents (>0.5%) in oxidized rock at Kingking (Sillitoe and Gappe, 1984) may entirely prevent extraction of the associated gold.

If pyrite-rich sericitic or advanced argillic alteration is widely developed, however, deep oxidation may induce total copper leaching and, if gold contents are high enough (>~0.8 g/t), result in gold ore suitable for cyanidation. Leaching is favored by high acid-generating capacity caused by high pyrite/copper-bearing sulfide ratios combined with low neutralization capacity stemming from deficiency of feldspars and mafic minerals. The leached copper would accumulate at the top of the underlying sulfide zone to generate a zone of chalcocite enrichment, in which gold contents would approximate hypogene values. Such gold-bearing chalcocite enrichment comprises much of the ore at Ok Tedi (Rush and Seegers, 1990).

Discovery methods

Notwithstanding the existence of fairly sophisticated descriptive and genetic models for porphyry deposits, discovery of gold-rich examples during the modern era, say the last 30 yr, is generally marked by a lack of sophistication. Rather, the tried-and-tested methods—geologic observation and geochemistry, either separately or in conjunction—have been most instrumental in discovery (Table 2). Remote sensing studies did not result in discovery, although six deposits were first spotted from the air or the ground because of prominent color anomalies. Geophysics, which contributed to just two discoveries, also played a surprisingly minor role. Two deposits (Wafi, Guinaoang), both concealed, were discovered by drilling with a different sort of target in mind. Indeed, nine (36%) of the discoveries stemmed from programs designed to explore for deposit types other than gold-rich porphyries (Table 2). These conclusions mirror those for discoveries of porphyry copper and a variety of gold deposit types in general (Sillitoe, 1995b).

It is anticipated that future discoveries of gold-rich porphyry deposits will follow the same pattern. Certainly, no evolution of the discovery process is apparent over the last 30 yr (Table 2). If this prognosis is accepted, the exploration methodology to be employed is clearcut. Nevertheless, application of some smarter geology, dictated by current descriptive and genetic models for gold-rich porphyry deposits, should help to discriminate between well- and poorly endowed prospects and thereby maximize the chances of exploration success.

Discovery case histories

Two case histories are summarized as typical examples of the discovery of gold-rich porphyry deposits: (1) Cerro Casale at high altitudes in the arid Maricunga belt of northern Chile, which entailed initial recognition as a color anomaly during an overflight, followed by geologic mapping, geochemistry, and drilling; and (2) Batu Hijau in the tropical rain forest environment of Indonesia, which involved drainage geochemistry followed by soil geochemistry, restricted geologic mapping, trench sampling, and drilling. Both programs were designed primarily to search for epithermal gold deposits!

Cerro Casale: An extensive zone of hydrothermal alteration was recognized in 1980–1981 during fixed-wing overflying of an extensive area in the high Cordillera of northern Chile. Ground followup revealed an area of potential interest, denominated Aldebarán, which grid soil (talus-fines) and rock-chip geochemistry showed to contain three separate areas anomalous with respect to gold-copper-molybdenum, zinc-lead-silver, and arsenic-antimony-mercury, respectively. The gold, copper, and molybdenum anomalies in talus fines exceeded 0.1, 100, and 9 ppm, respectively (Vila and Sillitoe, 1991; Fig. 11). Geologic inspection of the gold-copper target, Cerro Casale, at the lowest elevations (maximum: 4,430 m asl), determined it to be a gold-rich porphyry prospect, based on recognition of an outcropping porphyry stock containing K silicate alteration and stockwork quartz-specular hematite-magnetite veining (Vila and Sillitoe, 1991). In contrast, the arsenic-antimony-mercury anomaly coincided with an advanced argillic lithocap >500 m higher in elevation, with the zinc-lead-silver anomaly being caused by a vein zone at the base of the lithocap and alongside the porphyry target (Vila and Sillitoe, 1991). Trenching of the exposed quartz-specular hematite-magnetite stockwork outlined an area for testing by means of reverse-circulation drilling. The drilling was restricted to the oxidized zone, in which an average grade of ~0.6 g/t Au and ~0.06 percent Cu was determined. After several years of inactivity, the major company controlling the property optioned it to a junior, which proceeded to delimit and drill off the oxide gold zone, resulting in an expanded geologic resource of 56 Mt at 0.84 g/t Au. Since holes drilled to appraise the oxidized zone bottomed in sulfides containing copper as well as gold values, the junior explorer took the decision to drill a deep hole to test the gold and copper potential at depth. The hole intersected extensive gold- and copper-bearing K silicate alter-

TABLE 2. Discovery of Gold-Rich Porphyry Deposits since 1969

Name, location	Date of discovery by drilling	Main discovery method	Exploration rationale	Reference
Endeavour 22 and 27, Goonumbla, Australia	1977 (22), 1979 (27)	Auger geochemistry	Perceived VMS potential	Heithersay et al. (1996)
Endeavour 26 North and 48, Goonumbla, Australia	1979 (26 North), 1992 (48)	RAB drilling (26 North), aeromagnetics and RAB drilling (48)	Search for additional deposits in porphyry copper-gold cluster (48)	Heithersay et al. (1996)
Cadia Hill, Australia	1992	Geologic reappraial and soil geochemistry	Investigation of old mining district	Wood and Holliday (1995)
Wafi, Papu New Guinea	1990	Core drilling	Testing high-grade epithermal gold target in epithermal gold prospect	Tau-Loi and Andrew (1998)
Ok Tedi, Papua New Guinea	1969	Drainage geochemistry (float and –80# anomalies) and geology	Porphyry copper exploration in virgin rain forest terrain	Bamford (1972)
Grasberg, Indonesia	1988	Renewed geologic inspection and rock-chip geochemistry	Testing long-known porphyry copper prospect	Potter (1996)
Cabang Kiri, Indonesia	1975	Drainage (–80#) geochemistry, geology, and soil and rock-chip geochemistry	Proposed extension of Philippines porphyry copper province into North Sulawesi	Lowder and Dow (1978)
Sungai Mak, Indonesia	1981	Drainage (–80#) geochemistry, geology, and soil and rock-chip geochemistry	Further exploration of known porphyry copper-gold district	Carlile and Kirkegaard (1985)
Batu Hijau, Indonesia	1991	Drainage (BLEG and –80# anomalies) and auger geochemistry	Epithermal gold exploration in poorly explored rain forest terrain	Meldrum et al. (1994)
Dinkidi, Philippines	1989	Inspection of high-grader gold workings	Prospecting in Luzon, Philippines	Garrett (1996)
Guinaoang, Philippines	1971	Core drilling	Testing hypothetical fault intersection for lode copper-gold	Sillitoe and Angeles (1985)
Far Southeast, Philippines	1980	Testing geologic concept	Search for porphyry copper-gold deposits in old mining district	Sillitoe (1995b)
Saindak, Pakistan	1974	Geologic mapping and rock-chip geochemistry	Investigation of outcropping copper oxide mineralization	Sillitoe and Khan (1977)
Pebble Copper, Alaska	1990	Follow-up of color anomaly identified from aircraft, rock-chip sampling (gold anomaly)	Area perceived to be metallogenically favorable for epithermal and intrusion-related gold	Bouley et al. (1995)
Kemess South, B. C., Canada	1984	Soil geochemistry	Exploration in vicinity of Kemess North porphyry copper-gold prospect	Rebagliati et al. (1995)
Mount Milligan, B. C., Canada	1987	Soil geochemistry, magnetics, IP	Perceived favorability of region for gold-rich porphyry deposits	Sketchley et al. (1995)
Cerro Corona, Peru	~1980	Geologic inspection and geochemistry	Part of long-known Hualgayoc mining district	
Minas Conga, Peru	1995	Drainage (–75#) geochemistry, geology, and soil and rock-chip geochemistry	Exploration for gold within 20 km of Yanacocha high sulfidation gold deposit	Llosa et al. (2000)
Bajo de la Alumbrera, Argentina	1969	Geologic mapping and rock-chip geochemsitry	Investigation of prominent color anomaly	Sillitoe (1995b)

TABLE 2. (*Cont.*)

Name, location	Date of discovery by drilling	Main discovery method	Exploration rationale	Reference
Lobo, Chile	1983	Follow-up of color anomaly identified from aircraft, geology, rock-chip and talus-fines (–80#) geochemistry	Exploration for El Indio high sulfidation vein-type gold deposits in virgin volcanic terrain	Vila and Sillitoe (1991)
Marte, Chile	1983	Follow-up of color anomaly identified from aircraft, geology, rock-chip and talus-fines (–80#) geochemistry	Exploration for El Indio high sulfidation vein-type gold deposits in virgin volcanic terrain	Vila and Sillitoe (1991)
Refugio, Chile	1985	Follow-up of color anomaly identified from aircraft, geology, rock-chip and talus-fines (–80#) geochemistry	Exploration for El Indio high sulfidation vein-type gold deposits in virgin volcanic terrain	Vila and Sillitoe (1991)
Cerro Casale, Chile	1986	Follow-up of color anomaly identified from aircraft, geology, rock-chip and talus-fines (–80#) geochemistry	Exploration for El Indio high sulfidation vein-type gold deposits in virgin volcanic terrain	Vila and Sillitoe (1991)

ation and led to a major program of core drilling to investigate the size and grade of the gold-copper resource. The program led to estimation of 791 Mt at 0.71 g/t Au and 0.29 percent Cu. The original owner had by this time been diluted out and the junior optioned the property to one of the major gold companies which undertook additionl drilling to bring the resource to 847 Mt at 0.72 g/t Au and 0.29 percent Cu. A feasibility study is completed, but the future plans for Cerro Casale have yet to be announced.

Batu Hijau: A major gold company commenced systematic drainage geochemistry in the rain forest terrane of Sumbawa Island, Indonesia, in 1986. The BLEG technique was combined with –80# stream silt, panned-concentrate, and float sampling. The first-priority BLEG anomalies did not include Batu Hijau, which gave rise to a second-order response (10 and 15.3 ppb Au) along with 135 ppm Cu in the correponding –80# stream silt samples (Meldrum et al., 1994). Eventual follow-up drainage sampling in 1989 revealed a 5-km^2 anomaly (Fig. 12), including 169 ppb Au in BLEG and 580 ppm Cu in stream silt samples taken 1 km north of the discovery outcrop (Meldrum et al., 1994). Weakly copper-mineralized bedrock and copper-rich intrusive float samples were also found. In fact, as early as 1987, field crews had identified copper-bearing sulfides in diorite float from near the island's southern coast in a creek draining the Batu Hijau area (Meldrum et al., 1994). When the drainage anomaly was followed up in 1990, spectacular malachite-stained outcrops were encountered in an area of sparse forest vegetation (Meldrum et al., 1994). The surface extent of the mineralization at Batu Hijau was outlined by alteration mapping and ridge-and-spur auger geochemistry to the top of bedrock (Meldrum et al., 1994). A large zone of K silicate alteration contained >1,000 ppm Cu at the top of bedrock. Detailed sampling of 629 randomly oriented, 5-m-long trenches dug within this anomalous zone revealed >3,000 ppm Cu and >0.2 ppm Au over upper parts of the Batu Hijau hill. Molybdenum values define an annulus around the copper-gold core. Drilling commenced in 1991 to generate a geologic resource of 334 Mt averaging 0.80 percent Cu and 0.69 g/t Au. Further drilling resulted in an expanded mineable reserve of 914 Mt grading 0.53 percent Cu and 0.40 g/t Au, which was the basis for open-pit mine development and first production of gold-bearing copper concentrate in late 1999.

Some Outstanding Questions

The descriptive and genetic models for gold-rich porphyry deposits are reasonably well defined so that major knowledge gaps do not exist. Nevertheless, continued high-quality field mapping of geologic relations, especially intrusion, alteration, and veinlet relationships, complemented by petrographic, fluid inclusion, and isotopic studies will further refine our understanding of this important deposit type.

At a practical level, we need to document the following situations better:

1. Why gold-rich porphyry deposits occur in discrete belts or districts, although also existing as isolated centers in generally gold-poor regions. If the formation of gold-rich deposits reflects emplacement of highly oxidized magma, as supported herein, how do relatively isolated intrusions differ so markedly in redox state from neighboring ones? Is the redox state of magma determined at the mantle wedge source, following Carmichael (1991), or can crustal composition cause redox states to change?
2. Any contrasts between gold-rich porphyry deposits formed in extensional versus compressive settings at convergent plate boundaries. How do transverse across-arc lineaments influence deposit localization under different regional stress regimes?
3. The nature of the deep, commonly uneconomic parts of gold-rich porphyry deposits, as carried out in gold-poor systems at Yerington (Dilles and Einaudi, 1992) and El Salvador (Gustafson and Quiroga, 1995). Results will help in recognition of root zone characteristics for use in exploration as well as throw more light on the Ca-Na silicate alteration type and the nature of early, high-temperature

magmatic fluid. For example, is single-phase supercritical fluid commonly present as proposed for Island Copper, British Columbia, by Arancibia and Clark (1996)?

4. The details of alteration and mineralization in the zone of transition between the main porphyry deposit and the base of the overlying lithocap, in situations that display different degrees of telescoping (e.g., Sillitoe, 1999).

5. The mineralogic and geochemical parameters of advanced argillic lithocaps that may denote proximity to underlying gold-rich porphyry deposits. For example, does molybdenum concentrate above porphyry centers? More precise means of targeting porphyry-type mineralization beneath areally extensive lithocaps are urgently needed.

At an academic level, it would be useful to know more about the following points:

1. The true intrusive plus hydrothermal lifespans of gold-rich porphyry systems, from first intrusion through to end-stage advanced argillic alteration. Employment of the U-Pb method on zircons and Re-Os method on molybdenite should, in combination, be capable of solving the problem. The latter method discriminated between the timing of B and D veinlet events at El Salvador, Chile (Watanabe et al., 1999).

2. Causes of fluid discharge from parent chambers to generate gold-rich porphyry deposits. Is the Burnham (1967, 1979) model adequate and necessary, or are external triggers required? Theoretical modeling studies on the effects of various proposed external causes, such as intrusion of mafic magma, catastrophic paleosurface degradation, rapid magma ascent, or seismic events (see above), would provide a useful start.

3. Whether fluid ascends continuously or as intermittent pulses from the parent chamber into composite porphyry

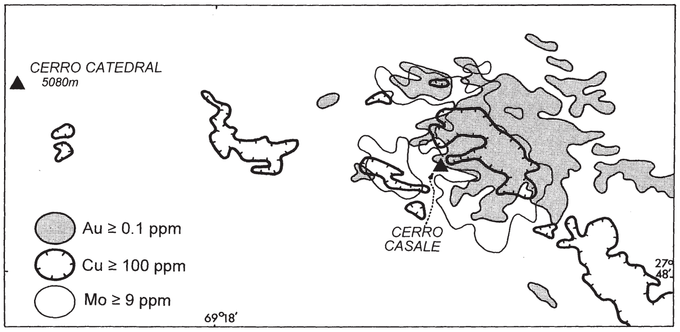

FIG. 11. Soil (–80# talus-fines) geochemistry for gold, copper, and molybdenum over the Cerro Casale gold-rich porphyry deposit at Aldebarán, Maricunga belt, northern Chile (taken from Vila and Sillitoe, 1991). Zinc, lead, silver, arsenic, antimony, and mercury contents are largely below background within the confines of the main gold-copper anomaly, although they are highly anomalous at higher elevations between Cerro Casale and Cerro Catedral. The molybdenum anomaly is slightly offset southwestward with respect to the gold and copper. The copper response is relatively subdued compared with many gold-rich porphyry deposits because of the relatively low hypogene copper content (0.29%). The maximum talus-fines gold value is 10.4 ppm. Note that talus-fines geochemistry effectively pinpoints the deposit in this high-altitude (4,050–4,430 m asl), arid environment.

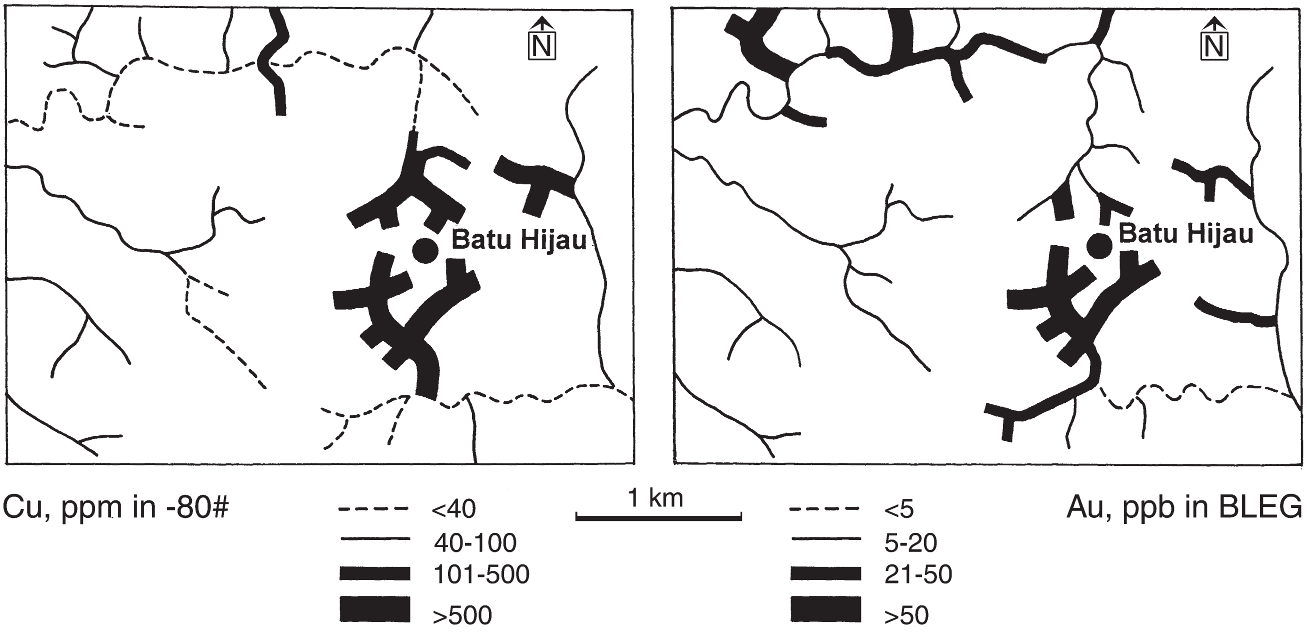

FIG 12. BLEG gold and –80# stream-sediment copper anomalies obtained during follow-up sampling of creeks draining the Batu Hijau gold-rich porphyry deposit, Sumbawa Island, Indonesia (taken from Meldrum et al., 1994). BLEG values decay from 196 ppb near the deposit to 7 ppb about 10 km downstream, whereas –80# silts range from 2.9 percent near the deposit (exceptionally high because of copper oxide mineralization outcropping in the drainage) to 110 ppm about 10 km downstream (Maula and Levet, 1996). Note that both drainage geochemical methods clearly define the deposit in this deeply incised, tropical rain forest environment.

stocks, and its influence on the mineralization processs. Detailed study of intrusion-veinlet relations may help to solve this problem.

4. The temperature, salinity, and composition of fluid responsible for early Ca-Na silicate alteration and its variants. Is the fluid always magmatic, as favored above, or can it sometimes be externally derived (e.g., Dilles et al., 1995)?

5. The fluid(s) responsible for overprinted intermediate argillic and sericitic alteration. Fluid inclusion and light stable isotope studies, like those carried out at Far Southeast-Lepanto by Hedenquist et al. (1998), will be required. If a late-stage, low-temperature, low-salinity magmatic fluid rather than influx of meteoric water is the cause of the overprinting (Hedenquist et al., 1998), such fluid should be present in veinlets that cut A type quartz veinlets (containing high-salinity brine) in underlying K silicate alteration. The late magmatic fluid cannot have ascended from the underlying parent chamber without leaving telltale signs.

6. The causes of advanced argillic alteration to form lithocaps in porphyry systems. What are the relative roles of ionization of all acidic components during fluid ascent and cooling, and of absorption of acidic volatiles, including HCl and SO_2, in meteoric water?

7. The origin of the fluid responsible for high sulfidation gold and copper mineralization in the lithocap environment. Do the metals in this fluid exit the porphyry stock in magmatic brine or volatiles? How much metal is remobilized from the underlying porphyry environment?

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REFERENCES

Allibone, A.H., Windh, J., Etheridge, M.A., Burton, D., Anderson, G., Edwards, P.W., Miller, A., Graves, C., Fanning, C.M., and Wysoczanski, R., 1998, Timing relationships and structural controls on the location of Au-Cu mineralization at the Boddington gold mine, Western Australia: Economic Geology, v. 93, p. 245–270.

Anderson, J.A., 1982, Characteristics of leached capping and techniques of appraisal, *in* Titley, S,R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 275–295.

Arancibia, O.N., and Clark, A.H., 1996, Early magnetite-amphibole-plagioclase alteration-mineralization in the Island Copper porphyry copper-gold-molybdenum deposit, British Columbia: Economic Geology, v. 91, p. 402–438.

Arribas, A., Jr., Hedenquist, J.W., Itaya, T., Okada, T., Concepcion, R.A., and Garcia, J.S., Jr., 1995, Contemporaneous formation of adjacent porphyry and epithermal Cu-Au deposits over 300 ka in northern Luzon, Philippines: Geology, v. 23, p. 337–340.

Babcock, R.C., Jr., Ballantyne, G.H., and Phillips, C.H., 1995, Summary of the geology of the Bingham district, Utah: Arizona Geological Society Digest, no. 20, p. 316–335.

Ballantyne, G., Maugham, C.J., and Smith, T., 1995, The Bingham copper-gold-molybenum deposit, Utah: Why Bingham is a "super–giant," *in* Clark, A.H., ed., Giant ore deposits—II, Giant ore deposits workshop, 2nd, Kingston, Ontario, 1995, Proceedings: Kingston, QminEx Associates and Queen's University, p. 300–315.

Bamford, R.W., 1972, The Mount Fubilan (Ok Tedi) porphyry copper deposit, Territory of Papua and New Guinea: Economic Geology, v. 67, p. 1019–1033.

Barr, D.A., Fox, P.E., Northcote, K.E., and Preto, V.A., 1976, The alkaline suite porphyry deposits—a summary: Canadian Institute of Mining and Metallurgy Special Volume 15, p. 359–367.

Bodnar, R.J, 1995, Fluid-inclusion evidence for a magmatic source for metals in porphyry copper deposits: Mineralogical Association of Canada Short Course Volume 23, p. 139–152.

Bouley, B.A., St. George, P., and Wetherbee, P.K., 1995, Geology and discovery at Pebble Copper, a copper-gold porphyry system in southwest Alaska: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 422–435.

Boutwell, J.M., 1905, Economic geology of the Bingham mining district, Utah: U.S. Geological Survey Professional Paper 38, 413 p.

Bowman, J.R., Parry, W.T., Kropp, W.P., and Kruer, S.A., 1987, Chemical and isotopic evolution of hydrothermal solutions at Bingham, Utah: Economic Geology, v. 82, p. 395–428.

Brimhall, G.H, Jr., 1980, Deep hypogene oxidation of porphyry copper potassium-silicate protore at Butte, Montana; A theoretical evaluation of the copper remobilization hypothesis: Economic Geology, v. 75, p. 384–409.

Browne, P.R.L., 1978, Hydrothermal alteration in active geothermal fields: Annual Review of Earth and Planetary Sciences, v. 6, p. 220–250.

Burnham, C.W., 1967, Hydrotherml fluids at the magmatic stage, in Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, p. 34–76.

——1979, Magmas and hydrothermal fluids, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits, 2nd edition: New York, John Wiley and Sons, p. 71–136.

Caira, N.M., Findlay, A., DeLong, C., and Rebagliati, C.M., 1995, Fish Lake porphyry copper-gold deposit, central British Columbia: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 327–342.

Candela, P.A., 1989, Felsic magmas, volatiles, and metallogenesis: Reviews in Economic Geology, v. 4, p. 223–233.

——1991, Physics of aqueous phase exsolution in plutonic environments: American Mineralogist, v. 76, p. 1081–1091.

——1992, Controls on ore metal ratios in granite-related ore systems: An experimental and computational approach: Royal Society of Edinburgh Transactions: Earth Sciences, v. 83, p. 317–326.

Candela, P.A., and Blevin, P.L., 1995, Physical and chemical magmatic controls on the size of magmatic-hydrothermal ore deposits, *in* Clark, A.H., ed., Giant ore deposits—II, Giant ore deposits workshop, 2nd, Kingston, Ontario, 1995, Proceedings: Kingston, QminEx Associates and Queen's University, p. 2–37.

Carlile, J.C., and Kirkegaard, A.G., 1985, Porphyry copper-gold deposits of the Tombulilato district, North Sulawesi, Indonesia: An extension of the Philippine porphyry copper-gold province, *in* Asian Mining '85: London, Institution of Mining and Metallurgy, p. 351–363.

Carmichael, I.S.E., 1991, The redox states of basic and silicic magmas: A reflection of their source regions?: Contributions to Mineralogy and Petrology, v. 106, p. 129–141.

Carr, J.M., and Reed, A.J., 1976, Afton: A supergene copper deposit: Canadian Institute of Mining and Metallurgy Special Volume 15, p. 376–387.

Cathles, L.M., 1981, Fluid flow and genesis of hydrothermal ore deposits: Economic Geology 75th Anniversary Volume, p. 424–457.

Christopher, P.A., and Carter, N.C., 1976, Metallogeny and metallogenic epochs for porphyry mineral deposits: Canadian Institute of Mining and Metallurgy Special Volume 15, p. 376–387.

Clark, A.H., and Arancibia, O.N., 1995, Occurrence, paragenesis and implications of magnetite-rich alteration-mineralization in calc-alkaline porphyry copper deposits, *in* Clark, A.H., ed., Giant ore deposits—II, Giant ore deposits workshop, 2nd, Kingston, Ontario, 1995, Proceedings: Kingston, QminEx Associates and Queen's University, p. 511–581.

Clark, G.H., 1990, Panguna copper-gold deposit: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1807–1816.

Claveria, R.J.R., Cuison, A.G., and Andam, B.V., 1999, The Victoria gold deposit in the Mankayan mineral district, Luzon, Philippines, *in* Pacrim

'99 Congress, Bali, Indonesia, 1999, Proceedings: Melbourne, Australasian Institute of Mining and Metallurgy, p. 73–80.

Cline, J.S., 1995, Genesis of porphyry copper depoits: The behavior of water, chloride, and copper in crystallizing melts: Arizona Geological Society Digest, no. 20, p. 69–82.

Cline, J.S., and Bodnar, R.J., 1991, Can economic porphyry copper mineralization be generated by a "typical" calc-alkaline melt?: Journal of Geophysical Research, v. 96 (B5), p. 8113–8126.

Clode, C., Proffett, J., Mitchell, P., and Munajat, I., 1999, Relationships of intrusion, wallrock alteration and mineralisation in the Batu Hijau copper-gold porphyry deposit, *in* Pacrim '99 Congress, Bali, Indonesia, 1999, Proceedings: Melbourne, Australasian Institute of Mining and Metallurgy, p. 485–498.

Corbett, G.J., and Leach, T.M., 1998, Southwest Pacific rim gold-copper systems: Structure, alteration, and mineralization: Society of Economic Geologists Special Publication 6, 237 p.

Cox, D.P., 1985, Geology of the Tanamá and Helecho porphyry copper deposits and vicinity, Puerto Rico: U.S. Geological Survey Professional Paper 1327, 59 p.

Cox, D.P., and Singer, D.A., 1988, Distribution of gold in porphyry copper deposits: U.S. Geological Survey Open-File Report 88-46, 22 p.

Creasey, S.C., 1966, Hydrothermal alteration, *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 51–74.

Cuddy, A.S., and Kesler, S.E., 1982, Gold in the Granisle and Bell Copper porphyry copper deposits, British Columbia, *in* Levinson, A.A., ed., Precious metals in the northern Cordillera: Rexdale, Ontario, Association of Exploration Geochemists, p. 139–155.

Danti, K.J., Brimhall, G.H, and Donovan, J.D., 1988, Gold distribution at the Ok Tedi porphyry copper deposit, Papua New Guinea: An electron microprobe investigation [abs.]: Geological Society of America Abstracts with Programs, v. 20, p. A92.

Dewey, J.F., and Bird, J.M., 1970, Mountain belts and the New Global Tectonics: Journal of Geophysical Research, v. 75, p. 2625–2647.

Dilles, J.H., and Einaudi, M.T., 1992, Wall-rock alteration and hydrothermal flow paths about the Ann-Mason porphyry copper deposit, Nevada—a 6-km vertical reconstruction: Economic Geology, v. 87, p. 1963–2001.

Dilles, J.H., and Proffett, J.M., 1995, Metallogenesis of the Yerington batholith, Nevada: Arizona Geological Society Digest, no. 20, p. 306–315.

Dilles, J.H., Farmer, G.L., and Field, C.W., 1995, Sodium-calcium alteration by non-magmatic saline fluids in porphyry copper deposits: Results from Yerington, Nevada: Mineralogical Association of Canada Short Course Volume 23, p. 309–338.

Economou-Eliopoulos, M., and Eliopoulos, D.G., 2000, Palladium, platinum and gold concentration in porphyry copper systems of Greece and their genetic significance: Ore Geology Reviews, v. 16, p. 59–70.

Emmons, W.H., 1917, The enrichment of ore deposits: U.S. Geological Survey Bulletin 625, 530 p.

——1927, Relations of disseminated copper ores in porphyry to igneous intrusions: American Institute of Mining and Metallurgical Engineers Transactions, v. 75, p. 797–809.

Enns, S.G., Thompson, J.F.H., Stanley, C.R., and Lang, J.R., 1995, The Galore Creek porphyry copper-gold deposits, northwestern British Columbia: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 630–644.

Florendo, F.F., 1994, Tertiary arc rifting in northern Luzon, Philippines: Tectonics, v. 13, p. 623–640.

Fournier, R.O., 1999, Hydrothermal processes related to movement of fluid from plastic into brittle rock in the magmatic-epithermal environment: Economic Geology, v. 94, p. 1193–1211.

Fraser, R.J., 1993, The Lac Troilus gold-copper deposit, northwestern Quebec: A possible Archean porphyry system: Economic Geology, v. 88, p. 1685–1699.

Fraser, T.M., Stanley, C.R., Nikic, Z.T., Pesalj, R., and Gorc, D., 1995, The Mount Polley alkalic porphyry copper-gold deposit, south-central British Columbia: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 609–622.

Gammons, C.H., and Williams-Jones, A.E., 1997, Chemical mobility of gold in the porphyry-epithermal environment: Economic Geology, v. 92, p. 45–59.

Garrett, S., 1996, The geology and mineralisation of the Dinkidi porphyry related Au-Cu deposit, *in* Porphyry related copper and gold deposits of the Asia Pacific region, Cairns, 1996, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 6.1–6.15.

Gibson, S.A., Thompson, R.N., Leonardos, O.H., Dickin, A.P., and Mitchell, J.G., 1995, The late Cretaceous impact of the Trindale mantle plume: Evidence from large-volume, mafic, potassic magmatism in SE Brazil: Journal of Petrology, v. 36, p. 189–229.

Giggenbach, W.F., 1984, Mass transfer in hydrothermal alteration systems—a conceptual approach: Geochimica et Cosmochimica Acta, v. 48, p. 2693–2711.

——1997, The origin and evolution of fluids in magmatic-hydrothermal systems, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits, 3rd edition: New York, John Wiley and Sons, p. 737–796.

Gilluly, J., 1946, The Ajo mining district: U.S. Geological Survey Professional Paper 209, 112 p.

Guilbert, J.M., 2000, El yacimiento de cobre y oro de Bajo de la Alumbrera, Argentina: Historía, exploración y desarrollo de modelos geológicos, *in* Primer volumen de monografías de yacimientos minerales Peruanos. Historia, exploración y geología: Lima, Instituto de Ingenieros de Minas del Perú, p. 155–175.

Gustafson, L.B., 1978, Some major factors of porphyry copper genesis: Economic Geology, v. 73, p. 600–607.

Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: Economic Geology, v. 70, p. 857–912.

Gustafson, L.B., and Quiroga G., J., 1995, Patterns of mineralization and alteration below the porphyry copper orebody at El Salvador, Chile: Economic Geology, v. 90, p. 2–16.

Hattori, K., 1993, High-sulfur magma, a product of fluid discharge from underlying mafic magma: Evidence from Mount Pinatubo, Philippines: Geology, v. 21, p. 1083–1086.

Hayashi, K., and Ohmoto, H., 1991, Solubility of gold in NaCl and H_2S bearing aqueous solutions at 250–350°C: Geochimica et Cosmochimica Acta, v. 55, p. 2111–2126.

Hedenquist, J.W, and Richards, J.P., 1998, The influence of geochemical techniques on the development of genetic models for porphyry copper deposits: Reviews in Economic Geology, v. 10, p. 235–256.

Hedenquist, J.W., Arribas, A., Jr., and Reynolds, T.J., 1998, Evolution of an intrusion-centered hydrothermal system: Far Southeast-Lepanto porphyry and epithermal Cu-Au deposits, Philippines: Economic Geology, v. 93, p. 373–404.

Heinrich, C.A., Günther, D., Audétat, D., Ulrich, T., and Frischnecht, R., 1999, Metal fractionation between magmatic brine and vapor, determined by microanalysis of fluid inclusions: Geology, v. 27, p. 755–758.

Heithersay, P.S., and Walshe, J.L., 1995, Endeavour 26 North: A porphyry copper-gold deposit in the Late Ordovician, shoshonitic Goonumbla volcanic complex, New South Wales, Australia: Economic Geology, v. 90, p. 1506–1532.

Heithersay, P.S., O'Neill, W.J., van der Helder, P., Moore, C.R., and Harbon, P.G., 1990, Goonumbla porphyry copper district—Endeavour 26 North, Endeavour 22 and Endeavour 27 copper-gold deposits: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1385–1398.

Heithersay, P.S., Jones, G., and Love, M., 1996, The Goonumbla Lake Cowal porphyry copper gold belt, *in* Porphyry related copper and gold deposits of the Asia Pacific region, Cairns, 1996, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 15.1–15.10.

Hemley, J.J., 1959, Some mineralogical equilibria in the system K_2O-Al_2O_3-SiO_2-H_2O: Amerian Journal of Science, v. 257, p. 241–270.

Hemley, J.J., and Hunt, J.P, 1992, Hydrothermal ore-forming processes in the light of studies in rock-buffered systems: II. Some general geologic applications: Economic Geology, v. 87, p. 23–43.

Hemley, J.J., and Jones, W.R., 1964, Chemical aspects of hydrothermal alteration with emphasis on hydrogen metasomatism: Economic Geology, v. 59, p. 538–569.

Henley, R.W., and McNabb, A., 1978, Magmatic vapor plumes and groundwater interaction in porphyry copper emplacement: Economic Geology, v. 73, p. 1–20.

Herrington, R.J., Jankovic, S., and Kozelj, D., 1998, The Bor and Majdanpek copper-gold deposits in the context of the Bor metallogenic zone (Serbia, Yugoslavia), *in* Porter, T.M., ed., Porphyry and hydrothermal copper and gold deposits. A global perspective, Perth, 1998, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 169–178.

Hitzman, M.W., Oreskes, N., and Einaudi, M.T., 1992, Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits: Precambrian Research, v. 58, p. 241–287.

Holland, H.D., 1972, Granites, solutions, and base metal deposits: Economic Geology, v. 67, p. 281–301.

Hollister, V.F., 1975, An appraisal of the nature and source of porphyry copper deposits: Minerals Science and Engineering, v. 7, p. 225–233.

Hunt, J.P., 1991, Porphyry copper deposits: Economic Geology Monograph 8, p. 192–206.

Ishihara, S., 1981, The granitoid series and mineralization: Economic Geology 75th Anniversary Volume, p. 458–484.

James, J, and Thompson, J.F.H., 1997, Geology, alteration and mineralization of the Cerro Corona porphyry Cu-Au deposit, Cajamarca Province, Peru [abs]: Geological Association of Canada–Mineralogical Association of Canada Program with Abstracts, v. 22, p. A–73.

Jerome, S.E., 1966, Some features pertinent in exploration of porphyry copper deposits, *in* Titley, S.R., and Hicks, C.L., eds., Geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 75–85.

Jones, B.K., 1992, Application of metal zoning to gold exploration in porphyry copper systems: Journal of Geochemical Exploration, v. 43, p. 127–155.

Kay, S.M., Mpodozis, C., Tittler, A., and Cornejo, P., 1994, Tertiary magmatic evolution of the Maricunga mineral belt in Chile: International Geology Review, v. 36, p. 1079–1112.

Keith, J.D., Whitney, J.A., Cannan, T.M., Hook, C., and Hattori, K., 1995, The role of magmatic sulphides and mafic alkaline magmatism in the formation of giant porphyry and vein systems: Examples from the Bingham amd Tintic mining districts, Utah, *in* Clark, A.H., ed., Giant ore deposits—II, Giant ore deposits workshop, 2nd, Kingston, Ontario, 1995, Proceedings: Kingston, QminEx Associates and Queen's University, p. 316–339.

Kesler, S.E., 1973, Copper, molybdenum, and gold abundances in porphyry copper deposits: Economic Geology, v. 68, p. 106–112.

Kirkham, R.V., 1971, Intermineral intrusions and their bearing on the origin of porphyry copper and molybdenum deposits: Economic Geology, v. 66, p. 1244–1249.

Kirkham, R.V., and Sinclair, W.D., 1996, Porphyry copper, gold, molybdenum, tungsten, tin, silver, *in* Eckstrand, O.R., Sinclair, W.D., and Thorpe, R.I., eds., Geology of Canadian mineral deposit types: Geological Survey of Canada, Geology of Canada, no. 8, p. 421–446.

Kosaka, H., and Wakita, K., 1978, Some geologic features of the Mamut porphyry copper deposit, Sabah, Malaysia: Economic Geology, v. 73, p. 618–627.

Lang, J.R., Lueck, B., Mortensen, J.K., Russell, J.K., Stanley, C.R., and Thompson, J.F.H., 1995a, Triassic-Jurassic silica-undersaturated and silica-saturated alkalic intrusions in the Cordillera of British Columbia: Implications for arc magmatism: Geology, v. 23, p. 451–454.

Lang, J.R., Stanley, C.R., and Thompson, J.F.H., 1995b, Porphyry copper-gold deposits related to alkalic igneous rocks in the Triassic-Jurassic arc terranes of British Columbia: Arizona Geological Society Digest, no. 20, p. 219–236.

Lang, J.R., Stanley, C.R., Thompson, J.F.K., and Dunne, K.P.E., 1995c, Na-K-Ca magmatic-hydrothermal alteration in alkalic porphyry Cu-Au deposits, British Columbia: Mineralogical Association of Canada Short Course Volume 23, p. 339–366.

Langton, J.M., and Williams, S.A., 1982, Structural, petrological, and mineralogical controls for the Dos Pobres orebody: Lone Star mining district, Graham County, Arizona, *in* Titley, S.R., ed., Advances in geology of the porphyry copper deposits, southwestern North America: Tucson, University of Arizona Press, p. 335–352.

Leach, T.M., 1999, Evolution of selected porphyry copper-gold systems in the southwest Pacific region and its relevance to exploration: Pacrim '99 Congress, Bali, Indonesia, 1999, Melbourne, Australasian Institute of Mining and Metallurgy, Proceedings, p. 211–225.

Learned, R.E., and Boisson, R., 1973, Gold—a useful pathfinder element in the search for porphyry copper deposits in Puerto Rico, *in* Jones, M.J., ed., Geochemical exploration 1972: London, Institution of Mining and Metallurgy, p. 93–103.

Leggo, M.D., 1977, Contrasting geochemical expressions of copper mineralization at Namosi, Fiji: Journal of Geochemical Exploration, v. 8, p. 431–456.

Lindgren, W., 1905, The copper deposits of the Clifton-Morenci district, Arizona: U.S. Geological Survey Professional Paper 43, 375 p.

Llosa T., F., Georgel P., J.M., and Veliz M., J., 2000, Los pórfidos Au-Cu de Minas Conga, *in* Primer volumen de monografías de yacimientos minerales Peruanos. Historia, exploración y geología: Lima, Instituto de Ingenieros de Minas del Perú, p. 177–195.

López, D.L, and Williams, S.N., 1993, Catastrophic volcanic collapse: Relation to hydrothermal processes: Science, v. 260, p. 1794–1796.

Loucks, R.R., and Mavrogenes, J.A., 1999, Gold solubility in supercritical hydrothermal brines measured in synthetic fluid inclusions: Science, v. 284, p. 2159–2163.

Lowder, G.G., and Dow, J.A.S., 1978, Geology and exploration of porphyry copper deposits in North Sulawesi, Indonesia: Economic Geology, v. 73, p. 628–644.

Lowenstern, J.B., 1993, Evidence for a copper-bearing fluid in magma erupted in the Valley of Ten Thousand Smokes, Alaska: Contributions to Mineralogy and Petrology, v. 114, p. 409–421.

——1994, Dissolved volatile concentrations in ore-forming magma: Geology, v. 22, p. 893–896.

Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, p. 373–408.

MacDonald, G.D., and Arnold, L.C., 1994, Geological and geochemical zoning of the Grasberg igneous complex, Irian Jaya, Indonesia: Journal of Geochemical Exploration, v. 50, p. 143–178.

Maranzana, F., 1972, Application of talus sampling to geochemical exploration in arid areas: Los Pelambres hydrothermal alteration area, Chile: Institution of Mining and Metallurgy Transactions, sec. B, v. 81, p. B26–B33.

Maula, S., and Levet, B., 1996, Porphyry copper gold signatures and the discovery of the Batu Hijau deposit, Sumbawa, Indonesia, *in* Porphyry related copper and gold deposits of the Asia Pacific region, Cairns, 1996, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 8.1–8.13.

McInnes, B.I.A., and Cameron, E.M., 1994, Carbonated, alkaline hybridizing melts from a sub-arc environment: Mantle wedge samples from the Tabar-Lihir-Tanga-Feni arc, Papua New Guinea: Earth and Planetary Science Letters, v. 122, p. 125–141.

McInnes, B.I.A., McBride, J.S., Evans, N.J., Lambert, D.D., and Andrew, A.S., 1999, Osmium isotope constraints on ore metal recycling in subduction zones: Science, v. 286, p. 512–516.

Meinert, L.D., 2000, Gold in skarns related to epizonal intrusions: Reviews in Economic Geology, v. 13, p. 347–375.

Meldrum, S.J., Aquino, R.S., Gonzales, R.I., Burke, R.J., Suyadi, A., Irianto, B., and Clarke, D.S., 1994, The Batu Hijau porphyry copper-gold deposit, Sumbawa Island, Indonesia: Journal of Geochemical Exploration, v. 50, p. 203–220.

Meyer, C., and Hemley, J.J., 1967, Wall rock alteration, *in* Barnes, H.L., ed., Geochemistry of hydrothermal ore deposits: New York, Holt, Rinehart and Winston, p. 166–235.

Moyle, A.J., Doyle, B.J., Hoogvliet, H., and Ware, A.R., 1990, Ladolam gold deposit, Lihir Island: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1793–1805.

Müller, D., and Forrestal, P., 1998, The shoshonite porphyry Cu-Au association at Bajo de la Alumbrera, Catamarca province, Argentina: Mineralogy and Peterology, v. 64, p. 47–64.

Newcrest Mining Staff, 1998, Cadia gold-copper deposit: Australasian Institute of Mining and Metallurgy, Monograph 22, p. 641–646.

Noll, P.D., Jr., Newsom, H.E., Leeman, W.P., and Ryan, J.G., 1996, The role of hydrothermal fluids in the production of subduction zone magmas: Evidence from siderophile and chalcophile trace elements and boron: Geochimica et Cosmochimica Acta, v. 60, p. 587–611.

Norton, D.L., and Knight, J.E., 1977, Transport phenomena in hydrothermal systems: Cooling plutons: American Journal of Science, v. 277, p. 937–981.

Parry, W.T., Wilson, P.N., Jasumback, M.D., and Heizler, M.T., 1997, Clay mineralogy and Ar^{40}/Ar^{39} dating of phyllic and argillic alteration at Bingham Canyon, Utah: Society of Economic Geologists Guidebook Series, v. 29, p. 171–188.

Perkins, C., Walshe, J.L., and Morrison, G., 1995, Metallogenic episodes of the Tasman fold belt system, eastern Australia: Economic Geology, v. 90, p. 1443–1466.

Petford, N., and Atherton, M.P., 1994, Cretaceous-Tertiary volcanism and syn-subduction crustal extension in northern central Peru: Geological Society [London] Special Publication 81, p. 233–248.

Phillips, C.H., Smith, T.W., and Harrison, E.D., 1997, Alteration, metal zoning, and ore controls in the Bingham Canyon porphyry copper deposit, Utah: Society of Economic Geologists Guidebook Series, v. 29, p. 133–145.

Plank, T., and Langmuir, C.H., 1993, Tracing trace elements from sediment input to volcanic output at subduction zones: Nature, v. 362, p. 739–743.

Pollard, P.J., 1999, Unmixing of H_2O-CO_2-salt fluids: consequences for alteration in Fe-oxide-Cu-Au systems: Townsville, Australia, James Cook University, Economic Geology Research Unit Contribution 58, p. 30–35.

Potter, D., 1996, What makes the Grasberg anomalous, implications for future exploration, *in* Porphyry related copper and gold deposits of the Asia Pacific region, Cairns, 1996, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 10.1–10.13.

Presnell, R.D, 1997, Structural controls on the plutonism and metallogeny in the Wasatch and Oquirrh Mountains, Utah: Society of Economic Geologists Guidebook Series, v. 29, p. 1–9.

Rebagliati, C.M., Bowen, B.K., Copeland, D.J., and Niosi, D.W.A., 1995, Kemess South and Kemess North porphyry gold-copper deposits, northern British Columbia: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 377–396.

Richards, J.P., 1995, Alkalic-type epithermal gold deposits—a review: Mineralogical Association of Canada Short Course Volume 23, p. 367–400.

Roedder, E., 1971, Fluid inclusion studies on the porphyry-type ore deposits at Bingham, Utah, Butte, Montana, and Climax, Colorado: Economic Geology, v. 66, p. 98–120.

Rowins, S.M., 2000, Reduced porphyry copper-gold deposits: A new variation on an old theme: Geology, v. 28, p. 491–494.

Rush, P.M., and Seegers, H.J., 1990, Ok Tedi copper-gold deposits: Australasian Institute of Mining and Metallurgy Monograph 14, p. 1747–1754.

Sales, R.H., 1954, Genetic relations between granites, porphyries, and associated copper deposits: Mining Engineering, v. 6, p. 497–505.

Sapiie, B., and Cloos, M., 1995, Strike-slip faulting and related veining in the Grasberg porphyry Cu-Au ore system, Gunung Bijih (Ertsberg) mining district, Irian Jaya, Indonesia (west New Guinea) [abs]: Geological Society of America Abstracts with Program, v. 27, p. A–377.

Schwartz, G.M., 1947, Hydrothermal alteration in the “porphyry copper” deposits: Economic Geology, v. 42, p. 319–352.

Serafica, V.S., and Baluda, R.P., 1977, Geology of the Philex Sto. Tomas II ore body: Symposium on Mineral Resources Development, 5th, Baguio City, Philippines, 1977, Section 1, Paper 3.

Seward, T.M., 1991, The hydrothermal geochemistry of gold, *in* Foster, R.P., ed., Gold metallogeny and exploration: Glasgow, Blackie, p. 37–62.

Seward, T.M., and Barnes, H.L., 1997, Metal transport by hydrothermal ore fluids, *in* Barnes, H.L., Geochemistry of hydrothermal ore deposits, 3rd edition: New York, John Wiley and Sons, p. 435–486.

Shayakubov, T., Islamov, F., Golovanov, I., Kashirsky, S., Kremenetsky, A., and Minzer, E., 1999, Almalyk and Saukbulak ore fields, *in* Shayakubov, T., Islamov, F., Kremenetsky, A., and Seltmann, R., eds., Au, Ag, and Cu deposits of Uzbekistan, Excursion Guidebook, Excursion B6 of the Joint SGA-IAGOD Symposium, London/Tashkent, 1999: Potsdam Germany, International Geological Correlation Project Publication 11, p. 75–90.

Sheets, R.W., Nesbitt, B.E., and Muehlenbachs, K., 1996, Meteoric water component in magmatic fluids from porphyry copper mineralization, Babine Lake area, British Columbia: Geology, v. 24, p. 1091–1094.

Sheppard, S.M.F., Nielsen, R.L., and Taylor, H.P., Jr., 1971, Hydrogen and oxygen isotope ratios in minerals from porphyry copper deposits: Economic Geology, v. 66, p. 515–542.

Shinohara, H., and Hedenquist, J.W., 1997, Constraints on magma degassing beneath the Far Southeast porphyry Cu-Au deposit, Philippines: Journal of Petrology, v. 38, p. 1741–1752.

Silberman, M.L., 1985, Geochronology of hydrothermal alteration and mineralization: Tertiary hydrothermal precious-metal deposits in the Great Basin: U.S. Geological Survey Bulletin 1646, p. 55–70.

Sillitoe, R.H., 1970, South American porphyry copper deposits and the New Global Tectonics [abs]: Congreso Latinoamericano de Geología, 1st, Lima, Peru, Resumenes, p. 254–256.

——1972, A plate tectonic model for the origin of porphyry copper deposits: Economic Geology, v. 67, p. 184–197.

——1973, The tops and bottoms of porphyry copper deposits: Economic Geology, v. 68, p. 799–815.

——1975, Lead-silver, manganese, and native sulfur mineralization within a stratovolcano, El Queva, northwest Argentina: Economic Geology, v. 70, p. 1190–1201.

——1979, Some thoughts on gold-rich porphyry copper deposits: Mineralium Deposita, v. 14, p. 161–174.

——1983, Enargite-bearing massive sulfide deposits high in porphyry copper systems: Economic Geology, v. 78, p. 348–352.

——1985, Ore-related breccias in volcanoplutonic arcs: Economic Geology, v. 80, p. 1467–1514.

——1989, Gold deposits in western Pacific island arcs: The magmatic connection: Economic Geology Monograph 6, p. 274–291.

——1991, Intrusion-related gold deposits, *in* Foster, R.P., ed., Metallogeny and exploration of gold: Glasgow, Blackie, p. 165–209.

——1992, Gold and copper metallogeny of the central Andes—past, present, and future exploration objectives: Economic Geology, v. 87, p. 2205–2216.

——1993, Gold-rich porphyry copper deposits: Geological model and exploration implications: Geological Association of Canada Special Paper 40, p. 465–478.

——1994, Erosion and collapse of volcanoes: Causes of telescoping in intrusion-centered ore deposits: Geology, v. 22, p. 945–948.

——1995a, Exploration of porphyry copper lithocaps: Pacific Rim Congress 1995, Auckland, New Zealand, 1995, Melbourne, Australasian Institute of Mining and Metallurgy, Proceedings, p. 527–532.

——1995b, Exploration and discovery of base- and precious-metal deposits in the circum-Pacific region during the last 25 years: Resource Geology Special Issue 19, 119 p.

——1997, Characteristics and controls of the largest porphyry copper-gold and epithermal gold deposits in the circum-Pacific region: Australian Journal of Earth Sciences, v. 44, p. 373–388.

——1998, Major regional factors favouring large size, high hypogene grade, elevated gold content and supergene oxidation and enrichment of porphyry copper deposits, *in* Porter, T.M., ed., Porphyry and hydrothermal copper and gold deposits. A global perspective, Perth, 1998, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 21–34.

——1999, Styles of high-sulphidation gold, silver and copper mineralisation in porphyry and epithermal environments, *in* Pacrim ’99 Congress, Bali, Indonesia, 1999, Proceedings: Melbourne, Australasian Institute of Mining and Metallurgy, p. 29–44.

Sillitoe, R.H., and Angeles, C.A., Jr., 1985, Geological characteristics and evolution of a gold-rich porphyry copper deposit at Guinaoang, Luzon, Philippines, *in* Asian Mining, ’85: London, Institution of Mining and Metallurgy, p. 15–26.

Sillitoe, R.H., and Gappe, I.M, Jr., 1984, Philippine porphyry copper deposits: Geologic setting and characteristics: Bangkok, Thailand, United Nations ESCAP, CCOP Technical Publication 14, 89 p.

Sillitoe, R.H., and Khan, D.N., 1977, Geology of the Saindak porphyry copper deposit, Pakistan: Institution of Mining and Metallurgy Transactions, sec. B, v. 86, p. B27–B42.

Sillitoe, R.H., and McKee, E.H., 1996, Age of supergene oxidation and enrichment in the Chilean porphyry copper province: Economic Geology, v. 91, p. 164–179.

Simon, G., Kesler, S.E., Essene, E.J., and Chryssoulis, S.L., 2000, Gold in porphyry copper deposits: Experimental determination of the distribution of gold in the Cu-Fe-S system at 400° to 700°C: Economic Geology, v. 95, p. 259–270.

Sketchley, D.A., Rebagliati, C.M., and DeLong, C., 1995, Geology, alteration and zoning patterns of the Mt. Milligan copper-gold deposits: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 650–665.

Solomon, M., 1990, Subduction, arc reversal, and the origin of porphyry copper-gold deposits in island arcs: Geology, v. 18, p. 630–633.

Stoffregen, R, 1987, Genesis of acid-sulfate alteration and Au-Cu-Ag mineralization at Summitville, Colorado: Economic Geology, v. 82, p. 1575–1591.

Stolper, E., and Newman, S., 1994, The role of water in the petrogenesis of Mariana trough magmas: Earth and Planetary Science Letters, v. 121, p. 293–325.

Tarkian, M., and Stribrny, B., 1999, Platinum-group elements in porphyry copper deposits: A reconnaissance study: Mineralogy and Petrology, v. 65, p. 161–183.

Tau-Loi, D., and Andrew, R.L., 1998, Wafi copper-gold deposit: Australasian Institute of Mining and Metallurgy, Monograph 22, p. 827–831.

Taylor, H.P., Jr., 1974, The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition: Economic Geology, v. 69, p. 843–883.

Thompson, J.F.H., 1993, Application of deposit models to exploration: Geological Association of Canada Special Paper 40, p. 51–67.

——1995, Exploration and research related to porphyry deposits: Canadian Institute of Mining, Metallurgy and Petroleum Special Volume 46, p. 857–870.

Thompson, J.F.H., Sillitoe, R.H., Baker, T., Lang, J.R., and Mortensen, J.K., 1999, Intrusion-related gold deposits associated with tungsten-tin provinces: Mineralium Deposita, v. 34, p. 323–334.

Titley, S.R., 1990, Contrasting metallogenesis and regional settings of circum-Pacific Cu-Au porphyry systems: Pacific Rim Congress 90, Gold Coast, Queensland, 1990, Melbourne, Australasian Institute of Mining and Metallurgy, Proceedings, p. 127–133.

Titley, S.R., and Beane, R.E., 1981, Porphyry copper deposits. Part I. Geologic settings, petrology, and tectogenesis: Economic Geology 75th Anniversary Volume, p. 214–235.

Tobey, E., Schneider, A., Alegría, A., Olcay, L., Perantonis, G., and Quiroga, J., 1998, Skouries porphyry copper-gold deposit, Chalkidiki, Greece: Setting, mineralization and resources, *in* Porter, T.M., ed., Porphyry and hydrothermal copper and gold deposits. A global perspective, Perth, 1998, Conference Proceedings: Glenside, South Australia, Australian Mineral Foundation, p. 159–167.

Ulrich, T., Günther, D., and Heinrich, C.A., 1999, Gold concentrations of magmatic brines and the metal budget of porphyry copper deposits: Nature, v. 399, p. 676–679.

Van Nort, S.D., Atwood, G.W., Collinson, T.B., Flint, D.C., and Potter, D.R., 1991, Geology and mineralization of the Grasberg porphyry copper-gold deposit, Irian Jaya, Indonesia: Mining Engineering, v. 43, p. 300–303.

Vila, T., and Sillitoe, R.H., 1991, Gold-rich porphyry systems in the Maricunga belt, northern Chile: Economic Geology, v. 86, p. 1238–1260.

Vila, T., Sillitoe, R.H., Betzhold, J., and Viteri, E., 1991, The porphyry gold deposit at Marte, northern Chile: Economic Geology, v. 86, p. 1271–1286.

Waite, K.A., Keith, J.D., Christiansen, E.H., Whitney, J.A., Hattori, K., Tingey, J.A., and Hook, C.J., 1997, Petrogenesis of the volcanic and intrusive rocks associated with the Bingham Canyon porphyry Cu-Au-Mo deposit, Utah: Society of Economic Geologists Guidebook Series, v. 29, p. 69–90.

Walshe, J.L., Heithersay, P.S., and Morrison, G.W., 1995, Toward an understanding of the metallogeny of the Tasman fold belt system: Economic Geology, v. 90, p. 1382–1401.

Watanabe, Y., Stein, H.J., Morgan, J.W., and Markey, R.J., 1999, Re-Os geochronology brackets timing and duration of mineralization for the El Salvador porphyry Cu-Mo deposit, Chile [abs]: Geological Society of America Abstracts with Programs, v. 31, p. A–30.

Weiland, R.J., and Cloos, M., 1996, Pliocene-Pleistocene asymmetric unroofing of the Irian fold belt, Irian Jaya, Indonesia: Apatite fission-track thermochronology: Geological Society of America Bulletin, v. 108, p. 1438–1449.

Whitney, J.A., 1975, Vapor generation in a quartz monzonite magma, a synthetic model with application to porphyry ore deposits: Economic Geology, v. 70, p. 346–358.

Wood, D.G., and Holliday, J.R., 1995, Discovery of the Cadia gold/copper deposit in New South Wales—by refocussing the results of previous work, *in* New generation gold mines: Case histories of discovery: Glenside, Australian Mineral Foundation, p. 11.1–11.10.

Wood, S.A., Mountain, B.W., and Pan, W., 1992, The aqueous geochemistry of platinum, palladium and gold: recent experimental constraints and a re-evaluation of theoretical predictions: Canadian Mineralogist, v. 30, p. 955–981.

Yang, T.F., Lee, T., Chen, C-H., Cheng, S-N., Knittel, U., Punongbayan, R.S., and Rasdas, A.R., 1996, A double island arc between Taiwan and Luzon: consequence of ridge subduction: Tectonophysics, v. 258, p. 85–101.

Zvezdov, V.S., Migachev, I.F., and Girfanov, M.M., 1993, Porphyry copper deposits of the CIS and the models of their formation: Ore Geology Reviews, v. 7, p. 511–549.

Questions

1. Why are gold-rich porphyry deposits confined to arc and back-arc environments at convergent plate boundaries and absent from intraplate rift settings?

2. Why do reduced magmas fail to generate true gold-rich porphyry deposits?

3. Why do many gold-rich porphyry deposits tend to form linear arrays?

4. During field work you find in outcrop a quartz diorite porphyry cut by sparse vitreous quartz veinlets containing seal-brown limonite (goethite) and minor malachite, but your samples return an average of only 0.1 g/t Au. What would be the next step?

5. During field work you encounter soft, whitish, yellow (jarosite)-stained rock outcrops crisscrossed by vitreous quartz veinlets that appear to be essentially barren. You conclude that the veinlets are A type. What could the occurrence signify?

6. During geologic mapping and ridge-and-spur soil geochemistry you determine that a zone of weathered porphyry displays patchy remnants of recognizable biotite-K feldspar (K silicate) alteration containing vitreous quartz veinlets in which you observe malachite and specks of lustrous brown limonite displaying a conchoidal fracture (pitch limonite, a cupreous goethite). The porphyry coincides with soil values of ~2,000 ppm Cu and ~200 ppb Au. What would you expect to encounter when you drill it?

7. In drill core, you recognize chalcocite and covellite as coatings on grains of pyrite disseminated in highly altered (sericitized or kaolinized) porphyry. What could be its signifícnce?

8. A ground magnetic survey reveals that a kaolinized porphyry stock containing vitreous quartz veinlets is marked by only modest magnetic susceptibility. You notice that what appears to be magnetite in veinlets and disseminated grains gives a red streak indicative of replacement by martite (hematite). How could this have happened?

Answers

1. Melting of subduction-modifed mantle, generally during or immediately following active subduction, is required to generate the hydrous and oxidized calc-alkaline to alkaline magmas that may give rise to gold-rich porphyry deposits.

2. Magmatic sulfides form and remain stable during crystallization of reduced magma and act as an effective sink for gold and copper, thereby limiting availability of these metals at the hydrothermal stage; nevertheless, large gold deposits of nonporphyry type deficient in copper accompany some reduced intrusions.

3. They are generated within or beneath volcanic centers, which themselves form linear arrays above zones of subduction-related mantle melting. Such zones typically extend for hundreds of kilometers parallel to oceanic trenches, but are only 10 to 20 km wide. Nevertheless, gold-rich porphyry deposits generated in back-arc or postsubduction-arc settings tend not to occur in linear belts.

4. Undertake detailed traversing of the outcropping stock in search of intrusive phases containing a greater density of A type quartz veinlets in the hope that such earlier intrusions contain more gold (hopefully, >0.5 g/t).

5. The rock originally underwent K silicate alteration to emplace the quartz veinlet stockwork but has since been pervasively overprinted by another alteration assemblage to give the white color. This assemblage is likely to be either hypogene sericitic or pyrophyllite, dickite, and/or kaolinite (advanced argillic) alteration indicative of a telescoped system or supergene kaolinization developed during weathering from overprinted sericite-chlorite-calcite (intermediate argillic) alteration. Sericitic, advanced argillic, and intermediate argillic alteration may all contain pyrite-dominated sulfides which, on weathering, give rise to jarositic limonite. X-ray diffraction or PIMA analysis help to distinguish sericite, pyrophyllite, dickite, and kaolinite until you have become familiar with their distinctive appearances under a hand lens.

6. An oxidized zone containing copper and gold values no greater than double those in the soils, which is underlain by pyrite-deficient hypogene sulfides reporting approximately similar copper and gold values. Chalcocite enrichment at the top of the sulfide zone would be developed only incipiently.

7. It may be a high sulfidation sulfide assemblage developed in the roots of a lithocap during telescoping. Alternatively, the copper sulfides may be a product of supergene enrichment of preexisting pyrite. The former has the potential to possess a greater vertical extent than the latter, unless you are in a region characterized by deep (>200 m) oxidation and thick enrichment zones.

8. Martitization may have accompanied intermediate argillic overprinting of the original K silicate assemblage prior to the supergene kaolinization. Alternatively, it may be a direct supergene weathering effect of the K silicate assemblage, having formed during the kaolinization. A combination of these alternatives would also be a possibility.