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MAJOR REGIONAL FACTORS FAVOURING LARGE SIZE, HIGH HYPOGENE GRADE, ELEVATED GOLD CONTENT AND SUPERGENE OXIDATION AND ENRICHMENT OF PORPHYRY COPPER DEPOSITS

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Abstract - Porphyry copper deposits occur in volcano-plutonic arcs worldwide; however, superior orebodies, whether due to large size and high hypogene grade, elevated gold content or well-developed supergene oxidation and/or enrichment, are confined to restricted arc segments. Regional factors are believed to be the fundamental controls on the location of these superior porphyry copper deposits. Large, high grade hypogene deposits develop in arcs built on continental crust that undergoes compressive tectonism and high rates of uplift and exhumation during intrusion and mineralization. Gold-rich deposits are generated in arc segments or individual districts where highly oxidised magma is emplaced. Oxidation and enrichment are optimised where uplift of deposits takes place under semi-arid climatic conditions, with several million years being required for the development of mature supergene profiles.

Introduction

Economic reality dictates that three types of porphyry copper deposit are the principal focus of current exploration activity: (1) those that are large and characterised by high hypogene copper grades, (2) those in which copper is accompanied by appreciable gold contents and (3) those that underwent extensive supergene oxidation and/or cumulative chalcocite enrichment.

Such superior porphyry copper deposits, like their smaller and less well endowed brethren, were generated and subsequently exposed in volcano-plutonic arcs along convergent plate boundaries characterised by subduction (Sillitoe, 1972). However, there is evidence, reviewed here, to suggest that the formation of superior deposits is regulated by metallogenic, factors that only affected restricted arc segments.

Large, high-grade hypogene deposits

In the context of current low copper prices, large, high-grade hypogene porphyry copper deposits may be defined as ones containing >1000 million tonnes averaging ≥1 % Cu. Very few deposits comprise this elite category, which has representatives in only the late Miocene-Pliocene (10-4 Ma) belt of central Chile and the Plio-Pleistocene (3.5-1 Ma) belt in the Central Range of New Guinea (Figs. 1 and 2; Table 1). However, deposits containing large tonnages of hypogene copper, but at somewhat lower grades, also occur in the late Eocene-early Oligocene (43-31 Ma) belt of northern Chile, the Palaeocene-early Eocene (5952 Ma) belt of southern Peru (Fig. 1), the Laramide (74-52 Ma) province and Eocene (43-31 Ma) belt of southwestern North America and the Neogene Central Volcanic belt of Iran (Table 1).

Table 1. Sizes, grades and ages of superior porphyry copper deposits

Deposit	Category[1]	Size, Mt	Cu %	Au, g/t	Age, Ma
El Teniente	LHGH	2855	1.31		5-4
Rio Blanco - Los Bronces	LHGH	2885	0.99		6-4
Grasberg	LHGH-GR	1730 (3146	1.13 0.88	1.22 0.78)	3.3-3.1
Rosario (Collahuasi)	LHGH	1200	0.87		33
Cuajone	LHGH-(SOE)	1600	0.74		52
Cananea	LHGH-(SOE)	1950	0.70		58
Bingham	LHGH-(GR)	2995	0.73	0.31	39
Sar Cheshmeh	LHGH-(SOE)	1100	0.90		~12
Minas Conga	GR	237	0.32	0.93	~20
Bajo de La Alumbrera	GR	551	0.52	0.67	7
La Verde (Refugio)	GR	216		0.88	23
Cerro Casale	GR	791 (+56 oxide	0.29	0.71 0.84)	12
Far Southeast	GR	356	0.73	1.24	1.5-1.2
La Escondida	SOE	1760	1.59	0.24	35-31
Chuquicamata	SOE	2229 enriched 506 oxide	1.41 1.56		34-31

[1] LHGH = large high-grade hypogene deposit; GR = gold-rich deposit; SOE = supergene oxidized and/or enriched deposit; (SOE) = supergene profile present but excluded from tonnage-grade estimate; (GR) = moderately gold rich deposit.

The high hypogene grades at El Teniente, Grasberg and Bingham are integral parts of extensive volumes of K-silicate-altered rock, whereas elsewhere they are due to superposition of alteration-mineralization types. For example, K-silicate alteration is overprinted by large volumes of sericitized tourmaline breccia at Río Blanco-Los Bronces (Skewes and Stern, 1995) and by structurally localised sericitic alteration accompanied by high-sulphidation sulphide assemblages (e.g., pyrite-enargite-covellite-digenite-bornite) at Chuquicamata (Freraut et al., 1997) and Rosario in the Collahuasi district (Dick et al., 1994).

The late Cenozoic tectonic settings of central Chile and New Guinea are markedly different, although both are underlain by continental crust. Central Chile lies at a Cordilleran margin that did not undergo post-Palaeozoic collision, whereas the Central Range of New Guinea is a fold-and-thrust belt generated since the Middle Miocene by collision between the northern passive margin of the Australian craton and the Melanesian island arc to the north (Fig. 2). Notwithstanding this tectonic contrast, both regions underwent horizontal compressive deformation and crustal thickening and, as a direct consequence, high rates of isostatic uplift and erosion at the time of porphyry copper emplacement, in marked contrast to the extension that prevailed in most volcano-plutonic arcs (Hamilton, 1995).

$^{40}Ar/^{39}Ar$ mineral dating and whole-rock chemical analyses of Miocene intrusive rocks near El Teniente show rapid Neogene crustal thickening, uplift and exhumation that culminated at 8-5 Ma, the time of porphyry copper mineralization (Kurtz et al., 1997). The erosion rate immediately prior to porphyry copper formation at El Teniente is calculated as 3 km/m.y. (Kurtz et al., 1997). Crustal shortening by thrusting and associated compressive deformation caused the thickening and coincided with eastward arc migration that may be attributed to slab flattening (Skewes and Stern, 1995). Slab flattening is thought by some investigators (e.g., Skewes and Stern, 1995) to have been induced by subduction of the buoyant Juan Fernández aseismic ridge.

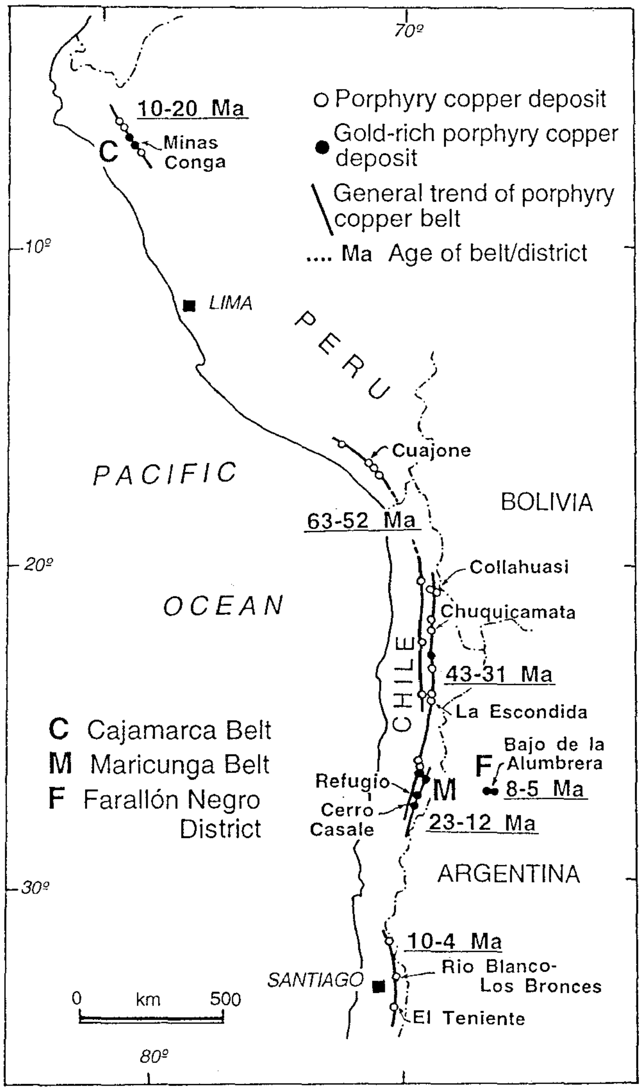

Figure 1 Principal porphyry copper belts and districts of the central Andes. Selected molybdenum- and gold-rich deposits, listed in Table 1 and discussed in the text, are named. Ages of belts and districts updated from Sillitoe (1988).

Collision-induced crustal stacking in the Central Range orogenic belt of New Guinea gave rise to dramatic uplift and denudation since the middle Miocene (~8 Ma: Crowhurst et al., 1996). At about 3 Ma, the time the Grasberg porphyry copper-gold deposit was formed near the crest of the range, kilometre-scale folding had already ceased, but uplift and unroofing are shown using apatite fission-track thermochronology to have continued at an average rate as high as 0.7 km/m.y. (Weiland and Cloos, 1996).

Compressive tectonism leading to thickening of continental crust was also active during intrusion and mineralization at other large, high-grade porphyry copper deposits. Formation of the late Eocene-early Oligocene porphyry copper belt of northern Chile accompanied dextral transpression along the Domeyko fault system (Mpodozis and Ramos, 1990), and was followed immediately by arc extinction and eastward migration of the locus of magmatism. In contrast to the pre-eminent late Miocene-Pliocene and late Eocene-early Oligocene belts, the other economically less important porphyry belts in Chile, including the Palaeocene copper-molybdenum belt and the Miocene gold-copper and gold-only deposits of the Maricunga belt (Fig. 1), were generated during extensional events as mirrored by the associated magma chemistry (La/Yb <18, cf., 15-35 for compressive belts; Mpodozis et al., 1995).

The Laramide orogeny in southwestern North America was coincident with emplacement of numerous porphyry copper deposits, including the pre-eminent Cananea deposit in northern Mexico, and involved thrusting, crustal thickening to 50 km (Coney and Harms, 1984), metamorphism, localised crustal melting and uplift (Burchfiel et al., 1992). The contractile deformation is generally ascribed to low-angle subduction induced by an increase of convergence rate and, possibly, the subduction of an aseismic ridge (Henderson and Gordon, 1984). Transpressive tectonism affected southern Peru during emplacement of the major porphyry copper deposits, which concluded activity of the Palaeocene-early Eocene arc at ~52 Ma, possibly in response to slab flattening (Sandeman et al., 1995). Thus the Palaeocene-early Eocene arc comprised a compressive segment in southern Peru and an extensional segment in northern Chile (Fig. 1). Compression and uplift during the formation of the Sar Cheshmeh porphyry copper deposit in Iran was a result of collision between the Eurasian and Arabian continents to form the Zagros suture (Sengör and Kidd, 1979).

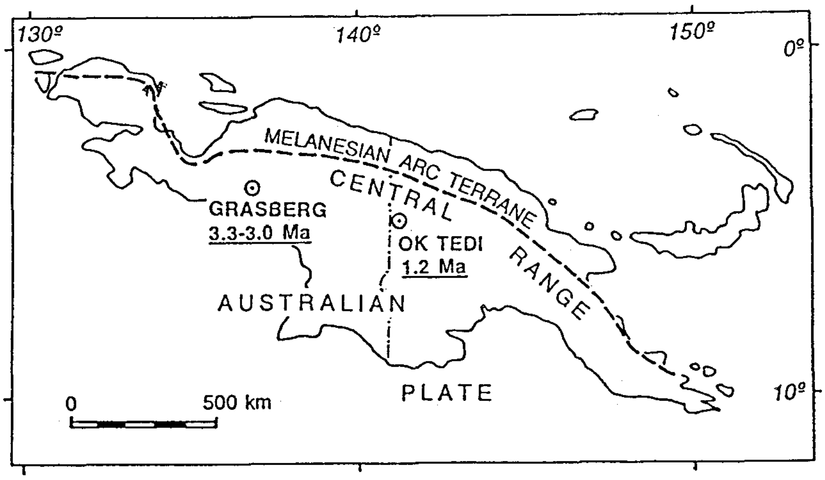

Figure 2 Principal gold-rich porphyry copper deposits and their ages in the Central Range fold-and-thrust belt of New Guinea (Irian Jaya, Indonesia in the west; Papua New Guinea in the east). Northward subduction beneath the Melanesian island arc ended as a result of collision with the Australian plate. The site of collision (east-west dashed line) is marked by an ophiolitic suture. Continued post-collisional convergence gave rise to folding, thrusting and uplift in the Central Range.

Emplacement of hydrous calc-alkaline or alkaline magma into the upper crust during compressive (including transpressive) deformation and rapid tectonic uplift and unroofing are thought to favour the development of large, high-grade porphyry copper deposits for a combination of reasons:

First, compression impedes magma ascent in the upper crust and consequent eruption and tends to generate shallow magma chambers that are larger than those beneath extensional arcs (Clemens and Mawer, 1992; Fig. 3). Indeed, in contrast to many porphyry copper systems, some of these large deposits - including those in the late Eocene-early Oligocene belt of northern Chile (Mpodozis and Ramos, 1990) - may have lacked appreciable volumes of coeval volcanic products.

Second, large shallow magma chambers should fractionate efficiently, thereby promoting volatile saturation and the release of far larger volumes of metal-bearing fluid than their smaller counterparts. Although the fluid liberated from magma chambers as small as 50 km^3 is calculated to be sufficient to form porphyry copper deposits (Cline and Bodnar, 1991), it

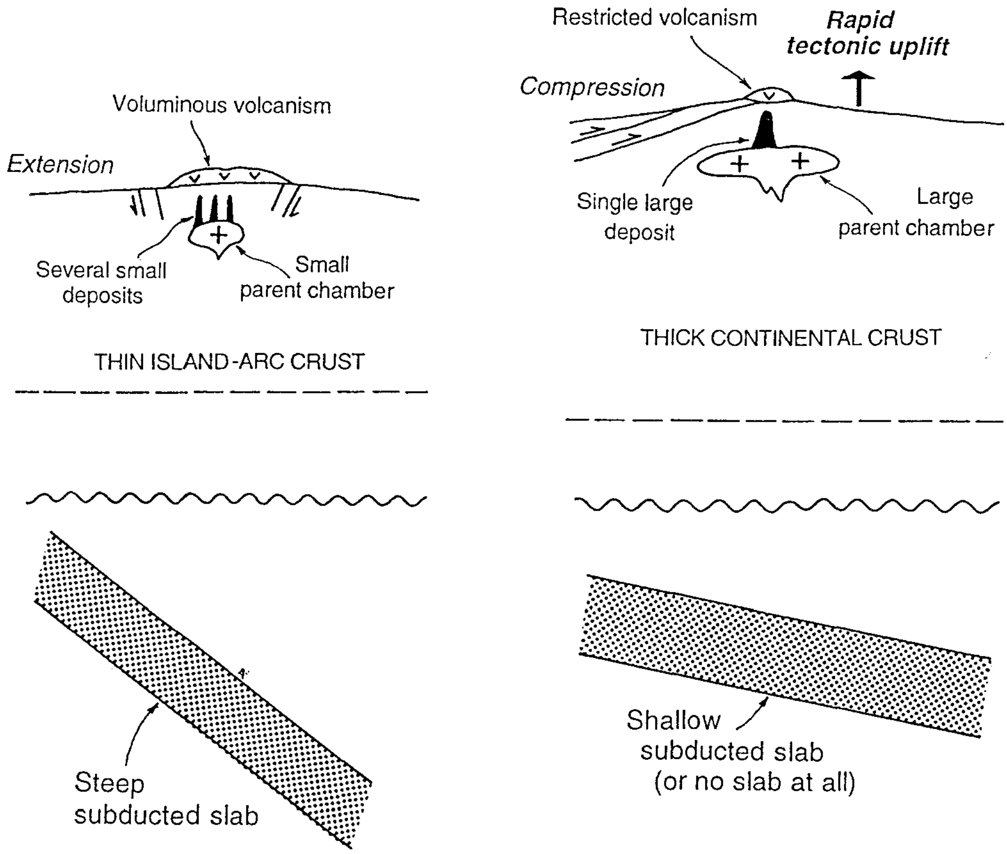

Figure 3 Schematized contrasts between the tectonic settings believed to favour the formation of small versus large porphyry copper deposits. Extensional arcs above steeply dipping subducted slabs tend to be built on relatively thin, low-elevation crust hosting small magma chambers that undergo fairly limited fractionation because of active throughput and voluminous eruption of magma. The magma chambers may be topped by clusters of relatively small, low-grade porphyry copper deposits. In contrast, compressive arcs above shallowly dipping slabs are typified by crustal thickening, isostatic uplift, restricted volcanism and large fractionated magma chambers, the last ideally overlain by single large, high-grade porphyry copper deposits.

is obvious that the larger the fluid volume, the larger could be the resulting deposit. Isotopic (Sr, Nd) evidence from central Chile suggests that these parental magma chambers may be produced by multiple magma pulses, each with the capability of supplying metal-bearing fluid (Skewes and Stern, 1995).

Third, compression minimises the number of steep, extensional faults and, hence, potentially the number of cylindrical subvolcanic porphyry stocks that develop on the roofs of parent magma chambers. As a result, large percentages of the available magmatic fluid are focused through a single stock to form a large porphyry copper deposit rather than through several stocks to give a cluster of correspondingly smaller deposits (Fig. 3). Many of the large, high-grade porphyry copper deposits, such as Chuquicamata (including the Radomiro Tomic extension), Río Blanco-Los Bronces, El Teniente, Cuajone, Cananea, Bingham and Sar Cheshmeh, are apparently isolated deposits that lack satellites; however, Grasberg and Collahuasi are notable exceptions. Although the horizontal dimensions of the subvolcanic stocks do not seem to control the size and grade of porphyry copper deposits, as a comparison of the Chuquicamata (3.5 x 1-1.5 km) and El Teniente (0.6 x 0.2 km) porphyries reveals, there is a suggestion that relatively impermeable wallrocks, especially massive limestone, favour the development of high grades because of fluid retention within the stocks (e. g., Grasberg; Sillitoe, 1997).

Fourth, abrupt reductions of confining pressure caused by catastrophic unroofing during rapid tectonically induced uplift (up to 12 km/m.y.; Burbank et al., 1996) may complement fluid overpressuring (Burnham, 1979) in the efficient extraction and upward transport of magmatic fluid from parent chambers. Cessation of magma replenishment and consequent rapid magma chamber cooling as a result of arc extinction, with or without arc migration, would further promote effective fluid exsolution.

It is interesting to note that in both central Chile and the Central Range of New Guinea, the two premier belts for exceptionally large deposits, magma ascent into the upper crust took place without the oft-cited assistance of major high-angle regional faults or lineaments, although district-scale dilational fault segments clearly existed. Therefore, although the Domeyko transpressive fault zone may have facilitated magma ascent (cf., Hutton, 1997) and exerted a powerful influence on the styles of some porphyry copper deposits in the late Eocene-early Oligocene belt of northern Chile (Mpodozis and Ramos, 1990), it is not considered as a fundamental requirement for their exceptionally large sizes.

A notable feature of many large porphyry copper deposits is their youthfulness, always Cenozoic in age and, in the case of the largest and highest grade deposits, ≤5 Ma (Table 1). If compressive deformation and uplift are fundamental features of the arc segments in which they formed, then continued uplift at the same high rates would result in rapid erosional removal. For example, if the Grasberg area had been unroofed at the same rate (1.7 km/m.y.) as that estimated for the range front, some 20 km farther south, where rainfall is four-times higher (11 m/yr; Weiland and Cloos, 1996), the deposit already would have been lost to erosion.

The hypothesis presented here has two obvious corollaries: First, the compressive pulses that favour the generation of large, high-grade deposits must be short-lived at any given place in order to avoid protracted high-rate uplift and deposit destruction. Second, porphyry copper deposits in pre-Cenozoic and, especially, pre-Mesozoic orogenic belts are likely to be small and low-grade because their preservation implies a relatively extensional arc setting (Thompson and Mortensen, 1997). Indeed they are, as exemplified by the overall small size and low tenor of porphyry copper systems in the Tasman and Appalachian orogens (Horton, 1978; Hollister et al., 1974).

Gold-rich deposits

Although Kesler's (1973) proposal that porphyry copper deposits in island arcs are gold-rich and those at continental margins are molybdenum-rich may still retain some statistical validity, numerous exceptions to this rule imply that the control of by-product metal content is not simply a matter of crustal composition and thickness. Indeed, as noted previously, the world's premier gold-rich porphyry copper deposit, Grasberg, is at the thickened leading edge of the Australian continental plate. Furthermore, gold-rich and gold-poor porphyry copper deposits occur in close proximity to one another, as in northern Peru, northern Chile (Fig. 1) and elsewhere.

Although gold-rich porphyry copper deposits tend to be scattered widely along convergent plate boundaries, the most important deposits economically are present in the Central Range of New Guinea, the Luzon Central Cordillera of the Philippines and the central Andes (Table 1). In the first two regions, most porphyry copper deposits and prospects are gold-rich, whereas in the central Andes the most important deposits are molybdenum-rich and gold-poor. The relatively small, gold-rich deposits in the central Andes tend to be confined to discrete mineral belts or districts, most notably the Cajamarca belt of northern Peru, the Maricunga belt of northern Chile and the Farallón Negro district of northwestern Argentina (Fig. 1).

One of the striking features of most of these gold-rich porphyry copper deposits, when compared to those that are gold-poor, is an abundance of hydrothermal magnetite, which provides evidence for involvement of oxidized magmatic fluid (Sillitoe, 1979). Oxidized fluid argues strongly for derivation from oxidized magma (Fig. 4). The host porphyries may be calc-alkaline or alkaline and range in composition from diorite and quartz diorite through granodiorite, quartz monzonite and monzonite to syenite (Sillitoe, 1979), although less-fractionated examples are more common (Fig. 4). Precipitation of magmatic sulphide grains and their scavenging effect on gold are inhibited in oxidized magmas, thus maximising gold availability at the hydrothermal stage (Cygan and Candela, 1995). The highly oxidized state of magmas parental to gold-rich porphyry copper deposits is likely to have been imposed at source (Carmichael, 1991), and seems likely to have been conditioned by contributions from subducted slabs (cf., Thompson, 1995).

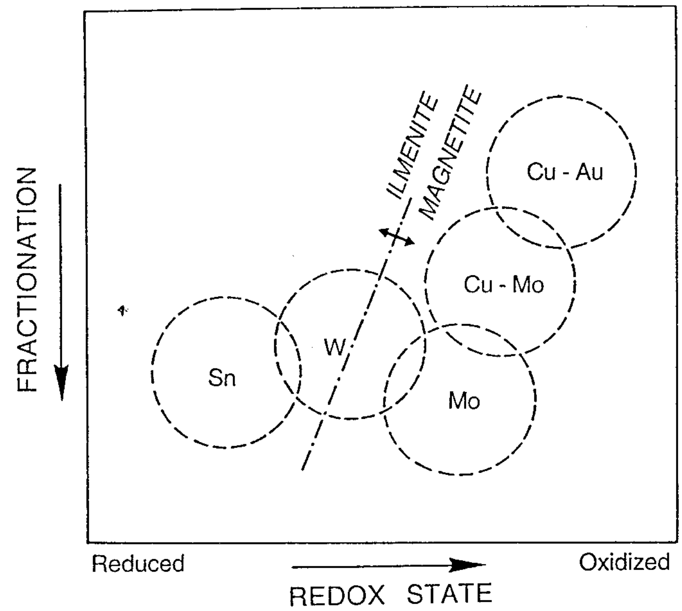

Figure 4 Schematised redox conditions and degrees of fractionation appropriate for generation of gold-rich and molybdenum-rich porphyry copper deposits. Gold enrichment is believed to be favoured by the most oxidized and least-fractionated magmas. Fields for molybdenum, tungsten and tin deposits and the approximate boundary between Ishihara's (1977) ilmenite- and magnetite-series magmas are also shown. Highly fractionated ilmenite-series magmas giving rise to lithophile-element deposits typically are generated along the cratonic sides of volcano-plutonic arcs during compressive tectonism or in collisional settings and typically possess far greater crustal contributions than the magnetite-series magmas responsible for gold- and molybdenum-rich porphyry copper deposits. Modified from Thompson et al. (1999).

It should be noted that the hydrothermal magnetite, a component of K-silicate alteration, generally does not survive overprinting by other alteration types. For example, intermediate argillic (sericite-clay-chlorite) alteration results in partial to total martitisation (hematitisation) and even partial pyritisation of magnetite, whereas sericitic alteration ensures its complete replacement by pyrite (Sillitoe, 1993). Therefore K-silicate alteration that is either pristine or affected by only a weak intermediate argillic overprint must be examined if hydrothermal magnetite is to be observed directly.

Oxidized magmas and gold-rich porphyry copper deposits were generated in both extensional (Cajamarca and Maricunga belts) and compressive arc terranes, although the deposits with the highest gold contents (Table 1) formed in the latter. The collisional setting of Grasberg in New Guinea (see above) is not dissimilar to that of deposits in the Luzon Central Cordillera (e.g., Far Southeast; Table 1), which were emplaced from ~2 Ma during the ongoing collision of the Taiwan-Luzon arc with the Eurasian margin. However, the Luzon Central Cordillera, south of Taiwan, continues to undergo eastward subduction of an aseismic ridge in the South China Sea leading to slab flattening, rapid uplift and cessation of volcanism (Yang et al., 1997), events that culminated in porphyry copper emplacement.

Another tendency, in arcs characterised by both gold-rich and molybdenum-rich porphyry copper deposits, is formation of the former before the latter. In the late Eocene-early Oligocene belt of northern Chile, for example, the relatively small gold-rich systems (Fig. 1) were formed during early development of the arc (43-36 Ma) in association with quartz diorite to granodiorite porphyries, whereas emplacement of the giant molybdenum-rich porphyry copper deposits in association with granodiorite to quartz monzonite porphyries concluded arc development (35-31 Ma). This late development of the giant porphyry copper deposits coincided with advanced stages of arc compression, immediately prior to extinction and migration of the magmatic activity. It is speculated that maximisation of the oxidized slab component and minimisation of crustal interaction in both extensional arcs and the early stages of compressive arcs may favour gold over molybdenum.

Supergene oxidized and enriched deposits

Porphyry copper belts marked by mature oxidation and enrichment profiles are restricted to northern Chile, southern Peru and southwestern North America. These three belts were generated and unroofed during intervals of uplift, induced tectonically as described above, which continued, albeit perhaps at slower rates, for some time thereafter. The periods during and following porphyry copper unroofing were characterised by semi-arid climatic regimes, as shown by the widespread development of pediplains and piedmont gravel accumulations (e.g., Mortimer, 1973). These mature supergene profiles were preserved as a result of increased aridity and, locally, burial beneath post-mineral sedimentary and/or volcanic sequences (Fig. 5). In northern Chile, radiometric dating of supergene alunite from oxidized and enriched porphyry copper deposits has shown that enrichment commenced before 32 Ma and ceased about 14 Ma because of the onset of hyper-aridity (Alpers and Brimhall, 1988; Sillitoe and McKee, 1996).

Continuous or pulsed uplift and semi-arid climatic conditions are prerequisites for development of deep, mature supergene oxidation and/or enrichment (Brimhall et al., 1985; Sillitoe, 1990). Uplift places sulphides above the redox front marked by the water table, thereby exposing them to the effects of oxidation and, in many cases, downward copper leaching (Fig. 5). Without uplift, supergene processes are stymied (Fig. 6). Semi-arid climatic conditions, which generally imply seasonal rainfall, provide adequate water to promote oxidation as well as average erosion rates that are substantially slower than the oxidation and enrichment processes; they also avoid undue dilution of the descending supergene solutions and, hence, maximise their ability to precipitate chalcocite at the enrichment horizon.

Within this overall regional context, local geological factors control the relative importance of oxidation versus enrichment (e.g., Sillitoe, 1990). Abundant pyrite for acid generation is required for effective leaching and downward transport of copper to generate chalcocite enrichment (Fig. 5). Enrichment is also promoted by the presence of sericitic and advanced argillic alteration, typical of the root zones of porphyry copper lithocaps (Sillitoe, 1995), because of their low acid-neutralising capacities. In contrast, porphyry copper ore poor in pyrite and hosted by K-silicate alteration, which possesses a high neutralisation capacity, tends to oxidise in situ.

The large, high-grade porphyry copper deposits in central Chile were emplaced 5-10 m.y. after the onset of hyper-aridity and cessation of supergene activity farther north but, once exposed, were subjected to continued uplift under semi-arid climatic conditions. Supergene enrichment is still immature, as shown by the absence of hematitic leached cappings indicative of cumulative enrichment (Anderson, 1982; Fig. 5), but was economically important during early mining at El Teniente (Lindgren and Bastin, 1922). In view of the large volumes of copper-bearing water that exit the late Miocene-Pliocene deposits of central

Chile, oxidation and enrichment are believed to be ongoing (Sillitoe and McKee, 1996). The same is believed to be true in the Central Volcanic belt of Iran, where the copper grade at Sar Cheshmeh was doubled in a relatively thin zone of chalcocite enrichment (Waterman and Hamilton, 1975).

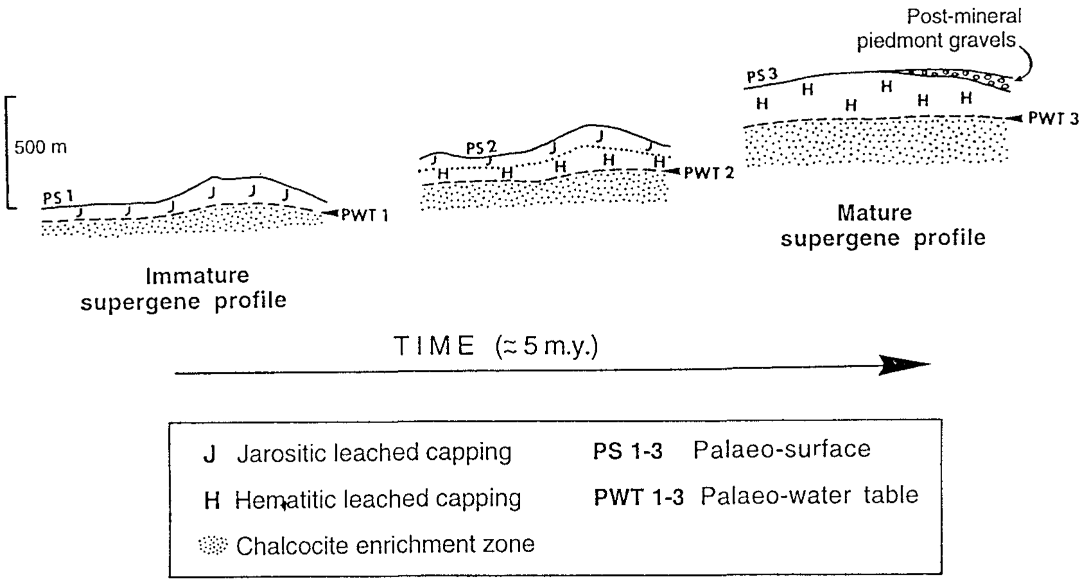

Figure 5 Schematised development of a supergene profile over a pyritic porphyry copper deposit during steady tectonic uplift, surface degradation by erosion and descent of the palaeo-water table. Oxidation of hypogene sulphides above palaeo-water table 1 leads to development of a jarositic leached capping. The copper that is leached is reprecipitated as partial chalcocite replacement of hypogene sulphides immediately beneath palaeo-water table 1 to form a zone of immature chalcocite enrichment. Once the palaeo-water table has descended to position 2, the upper part of the chalcocite enrichment zone has undergone oxidation to generate hematite-dominated leached capping underlain by appreciably higher-grade enrichment. When the palaeo-water table attains position 3, all jarositic leached capping has been eroded, all the hematitic leached capping is the oxidation product of early-stage chalcocite enrichment and the current enrichment zone is mature and high-grade. Bacteria may mediate chalcocite enrichment as well as sulphide oxidation (Sillitoe et al., 1996). Note partial preservation of the supergene profile beneath piedmont gravels.

Under conditions of high rainfall, in either temperate or tropical regions, supergene profiles are generally developed poorly because erosion rates are too high (Fig. 6). The only important exception to this rule is provided by Ok Tedi, in the Central Range of New Guinea (Fig. 2), where unroofing and development of a substantial albeit still immature enrichment zone took <0.8 m.y. (Chivas et al., 1984), thereby emphasising the relative rapidity of the oxidation and enrichment processes. Although Ok Tedi may have formed close to sea level (Chivas et al., 1984) and is subjected to very high rainfall (10 m/yr), enrichment was not outpaced by erosion, probably because of the deposit's location beneath a prominent peak that must have been subjected to appreciably lower erosion rates than its flanks and general surroundings. In contrast, and notwithstanding the existence of a similar geomorphological regime, a supergene profile is absent at nearby Grasberg, although the pyrite-poor character of the ore was undoubtedly an important suppressor of downward copper leaching.

The Tibetan Plateau, uplifted several thousand metres as a result of the India-Eurasia continental collision and characterised by a relatively semi-arid climate, would seem to be an ideal site for development of supergene oxidation and enrichment. However, porphyry copper deposits in the Yulong belt of easternmost Tibet lack appreciable supergene profiles (Tang et al., 1995), a situation that is attributed to the fact that uplift and denudation rates along the edges of the Tibetan Plateau were simply too high, at least since ~8 Ma when uplift accelerated and the summer monsoon intensified (Molnar et al., 1993).

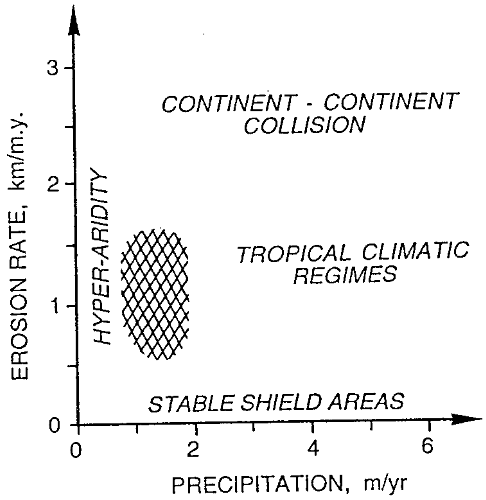

Figure 6 Optimum conditions proposed for supergene oxidation and enrichment (cross-hatched area). Supergene activity is inhibited by lack of uplift in stable shield areas as well as by hyper-arid climatic conditions. Erosion rates are faster than the oxidation and enrichment processes in arc terranes subjected to tropical climatic regimes and, in at least some continental collisional orogens, almost irrespective of climate. Where erosion outpaces supergene activity, copper is removed mechanically rather than undergoing chemical and biochemical concentration within and near the porphyry copper deposit.

Conclusions and exploration implications

Generation of large porphyry copper deposits characterised by high hypogene grades are favoured at convergent plate boundaries affected during intrusion and mineralization by compressive (including transpressive) tectonism, crustal thickening and exceptionally high uplift and unroofing rates. Such tectonic scenarios are induced by perturbation and flattening of the underthrust slab or by collision. The compressive events should be relatively short-lived to avoid erosional destruction of deposits. Exploration should target magmatic arc segments developed on continental crust that underwent thrusting and folding, possibly combined with transpressive faulting, at the time of the copper mineralization. As in the Central Range of New Guinea and the central Andes of Chile, the largest and highest-grade deposits are likely to be young (1-5 Ma) and to crop out at high elevations (3000->4000 m a.s.l.). Coeval volcanic rocks may be volumetrically minor as one consequence of the upper-crustal compression. Such sites may be characterised by young marine sedimentary rocks, such as the mid-Miocene limestone at elevations of 4000-5000 m in the vicinity of Grasberg (Weiland and Cloos, 1996).

Porphyry copper deposits containing elevated gold contents are favoured at convergent plate boundaries where the magmas parental to the deposits display high redox states. Such oxidized magmas typically are evidenced by an abundance of hydrothermal magnetite accompanying copper and gold in zones of K-silicate alteration. Gold-rich porphyry copper deposits may be scattered throughout volcano-plutonic arcs, but tend to be concentrated in isolated districts or arc segments. Preliminary evidence suggests that the largest and highest-grade deposits are favoured by compressive rather than extensional arc segments. Exploration in arc or back-arc terranes may target either calc-alkaline or alkaline (including shoshonitic) suites, although the latter may host more deposits per unit volume of igneous rock than the former (Sillitoe, 1997).

Development of mature supergene profiles which, depending on initial pyrite contents, may host zones of oxide copper and/or chalcocite enrichment are favoured during tectonic uplift under semi-arid climatic conditions. Hence the western Americas are far more prospective than western Pacific island arcs. Extreme uplift rates, as exemplified by continent-continent collisional orogens, and high rainfall regimes are both inimical to the development of mature supergene profiles. Both intensification of aridity and concealment beneath post-mineral sedimentary or volcanic cover enable fossilisation and preservation of supergene profiles. Deposits <~5 m.y. old that are subjected to optimum tectonic and climatic regimes are likely to possess only immature supergene profiles because insufficient time was available to exhume, oxidise and enrich them.

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