AGSO Journal of Australian Geology & Geophysics, 17(4), 97–104

Australian and western Pacific porphyry Cu–Au deposits

David R. Cooke[1], Paul S. Heithersay[2], Rohan Wolfe[1] & Alex Losada Calderon[3]

[1] Centre for Ore Deposit Research, University of Tasmania, GPO Box 252-79, Hobart, TAS 7001, Australia. [2] North Limited, GPO Box 1903R, Melbourne, VIC 3001, Australia. [3] MIM Exploration, PO Box 1121, West Perth, WA 6872, Australia

EXPLORATION MODEL

Examples

Goonumbla, Cadia (Australia); Panguna, Wafi, Ok Tedi (PNG); Grasberg, Batu Hijau (Indonesia); Far South East, Didipio, Dizon, Philex (Philippines).

Target

- Size: 10–1000 Mt (av. 50–100 Mt).
- Grade: 0.5–1.4% Cu; 0–1.8 g/t Au; 0–0.1% Mo.
- Major metals: Cu, Au.
- Associated metals: Mo, Ag, Pb, Zn.

Mining and treatment

- Large-tonnage low-grade disseminated deposits that are commonly mined by open pit techniques.
- Block caving (e.g. E26N, Goonumbla, New South Wales).
- Sulphide grain size: typically 0.1–2 mm.
- Pyrite ± arsenopyrite may be present in some ore, and can affect recovery; high As penalty in shallow epithermal ore.

Regional geological criteria

- Presence of known porphyry mineralisation in region indicates favourable setting and the right level of erosion.
- Host rocks generally unmetamorphosed.
- Cu–Au porphyries generally associated with island-arc tectonic setting.
- Cu–Mo porphyries associated with continental margins or cratonic settings.
- Mineralisation associated with oxidised I-type (magnetite series) subvolcanic intrusions.
- Host stratigraphy generally characterised by volcanic rocks and associated volcaniclastics (may be cogenetic with the intrusive suite).
- Maar volcanism related to post-mineral diatreme formation, deeper erosion level may expose diatreme breccia pipe that contains clasts of porphyry mineralisation.
- Minor clastic sediments ± limestones may be present.
- Some deposits localised at fault intersections (arc-parallel and arc-oblique structures at Grasberg, Batu Hijau, etc.).
- Spatial association with epithermal, skarn and Carlin-type mineralisation.

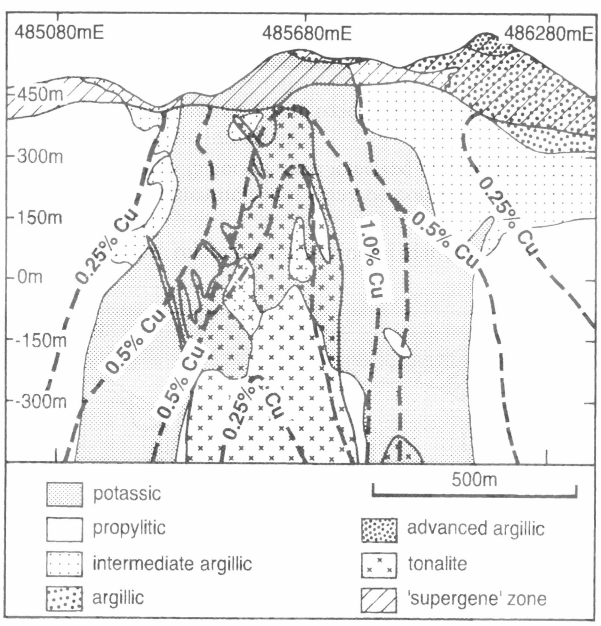

Figure 1. Cross-section through the Batu Hijau porphyry Cu–Au deposit, Indonesia, showing hypogene and supergene alteration zones, Cu contours and the host intrusions (after Irianto & Clark 1995).

Local geological criteria

- Mineralisation forms during emplacement of cogenetic porphyritic intrusions.
- Porphyritic quartz diorite to monzonite stocks; larger biotite-altered parent intrusion at depth (e.g. Goonumbla) may provide a bigger geophysical target.
- Depth of emplacement: ~1–2 km (can be deeper).
- Stocks are elongate, needle-like apophyses that extend up from coarse-grained phaneritic intrusions.
- Mostly subaerial volcanic setting.
- Identifying breccias related to mineralisation can be crucial.
- Age of ore: Palaeozoic (Australian), Mesozoic–Cainozoic (western Pacific).

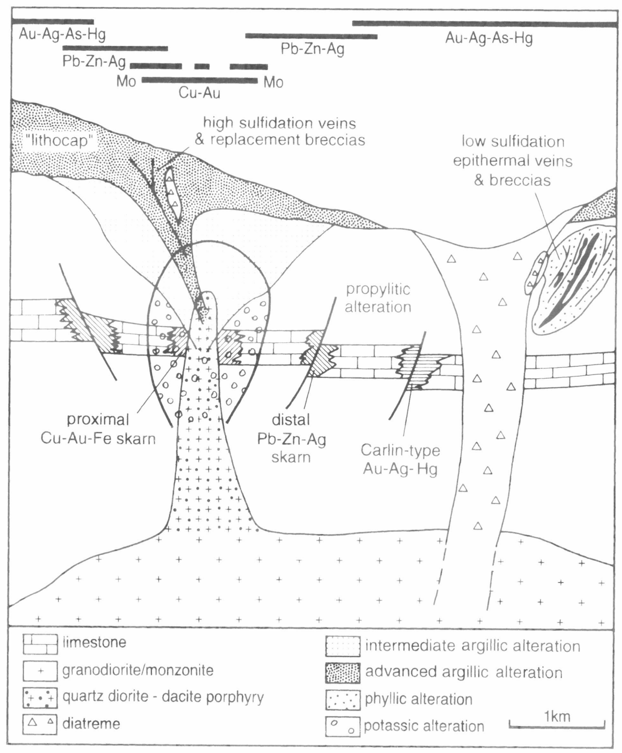

Figure 2. Schematic ore deposit model for western Pacific porphyry Cu–Au deposits, showing the association with diatremes, epithermal and carbonate-hosted Au–base-metal mineralisation (after Sillitoe 1989).

Mineralisation features

- Stockwork and disseminated Cu–Au(–Mo) mineralisation generally associated with K-silicate alteration.
- Metallogenic associations: Cu-only; Cu–Au; Cu–Mo; Cu–Au(–Mo); Mo-only and Au-only varieties of porphyry deposits are recognised worldwide; Cu–Au common in western Pacific and New South Wales.

- Main ore minerals: chalcopyrite, bornite, native gold (electrum), molybdenite.
- Gangue minerals: quartz, orthoclase, anhydrite, magnetite, biotite ± sericite ± pyrite.
- Zonation within deposit: low pyrite, Cu-rich core, outer pyrite-rich halo; some deposits have Cu–Au-rich cores surrounded by intermediate Mo-rich annulus and outer pyrite halo.
- District scale zonation: Cu–Au–Mo (core) → Ag–Pb–Zn → Au–As–Hg–Sb–Te (peripheral).
- Sulphides also zoned: chalcopyrite, bornite in core, widespread disseminated outer pyrite halo.
- Magnetic minerals: abundant magnetite associated with biotite alteration.
- Anhydrite present as a vein mineral and in most alteration assemblages in the western Pacific deposits.

Alteration

- Classic and diagnostic hydrothermal alteration assemblages.
- Strong lithological controls on local alteration assemblages.
- Alteration halos can extend hundreds of metres from stock.
- Supergene enrichment zone may be present (depends on local climate, topography and hydrology).
- Several hypogene alteration types may be present; overprinting relationships are characteristic:
  - *K-silicate*—biotite, magnetite, orthoclase, quartz, anhydrite, chalcopyrite, actinolite;
  - *Propylitic*—chlorite, epidote, calcite, pyrite, albite;
  - *Intermediate argillic (SCC)*—sericite, chlorite, kaolinite or illite, pyrite, calcite;
  - *Phyllic*—sericite, quartz, pyrite;
  - *Advanced argillic*—alunite, kaolinite, pyrophyllite, quartz, dickite, gibbsite, pyrite, enargite, covellite;
  - *Calc-silicate*—garnet, pyroxene, epidote, wollastonite.

Deposit geochemical criteria

- Deposits associated with calc-alkaline to shoshonitic volcanic sequences.
- Alteration and mineralisation halos are diagnostic, so geochemical vectors to ore can be devised.
- $\delta^{34}S$ values: magmatic; sulphides may evolve to more negative values in oxidised systems.
- $\delta^{18}O$ and δD values: magmatic in K-silicate zone; commonly meteoric in phyllic zone; possibly magmatic in fault-zone sericitic and advanced argillic alteration zones.
- Metal ratios variable; highest Au/Cu ratios may occur in core of Au-rich porphyry system.
- Elevated Cu and S in propylitic zone may be vector to ore.

Surficial geochemical criteria

- Anomalous Cu, Au, Mo, Ag, Zn, Pb, As, Sb, Hg, Te, Sn, S.
- Drainage geochemistry (stream sediment, pan concentration and BLEG) and float samples most effective in young terrains (e.g. discovery of Batu Hijau).
- Soil sampling useful at the prospect scale.
- Bedrock sampling by RAB or aircore drilling in suitable areas (e.g. Goonumbla).
- $\delta^{18}O$ depletion in phyllic alteration zone.
- Alluvial gold fineness potentially useful exploration tool.
- Hand-held spectrometers can be used to identify high-temperature clays in the lithocap environment.

District-scale zonation

- Peripheral styles of hydrothermal mineralisation can be associated with porphyry centres.
- High-sulphidisation epithermal Au–Cu–As systems may form above or immediately adjacent to the porphyry system (e.g. Lepanto/Far South East), and may be part of a wide-spread lithocap that covers the buried porphyry deposit.
- Skarns form adjacent to the porphyritic stock if impure limestones are present (e.g. Thanksgiving)
- Low sulphidisation epithermal Au–Ag veins and breccias are generally offset laterally by several kilometres, but can be 'telescoped' onto porphyry systems (e.g. Lihir, Acupan).
- Sediment-hosted Au deposits (Carlin-style) may form distally (up to 8 km away) in calcareous sediments (e.g. Bau, Mesel?).

Geophysical criteria

- Low-level aeromagnetics commonly used in regional and district-scale exploration in Australia.
- Annular or bullseye magnetic highs could be associated with biotite–magnetite alteration zones.
- Magnetic lows (common) associated with widespread phyllic and/or intermediate argillic alteration.
- Deposits can occur on the flanks of granitoid batholiths, i.e. adjacent to large gravity lows.
- Airborne and ground radiometric data can help delineate K-silicate alteration in Australia.
- IP response variable, but can be useful in some cases (especially in areas of high erosion), given the widespread and disseminated nature of the sulphides; generally not a direct vector to ore.
- Landsat TM, SLAR and aerial photography can be used to identify eroded calderas and regional-scale structures.

Fluid chemistry and source

- Initial high-T (>500°C), hypersaline (>30 eq. wt% NaCl) brines and low-density vapour derived from crystallising stock.
- Lower T (200°–350°C), moderate salinity (<10 eq. wt% NaCl) meteoric fluids (phyllic alteration?).
- High T (>300°C) magmatic volatiles associated with late-stage advanced argillic alteration.
- Oxidation state: high ($H_2S \approx SO_4^{2-}$).
- Precipitation mechanism: combination of cooling and water–rock interaction causes Cu–Au (+Mo) deposition.

Comments on genesis

- Hydrous oxidised magnetite series magmas intrude to shallow depths in convergent plate margin settings.
- Aqueous phase begins to separate and migrates up through the frothy magma, ponding beneath a crystalline carapace.
- Hydrostatic pressure eventually exceeds lithostatic, resulting in carapace failure, stockwork formation and deposition of high-T Cu–Au–Mo mineralisation.
- Repeated carapace crystallisation and failure cycles form complex cross-cutting vein network.
- Eventual collapse of the thermal anomaly and ingress of meteoric water results in internediate argillic and/or phyllic alteration.
- Late-stage regional faults tap magmatic volatiles from deep within the porphyritic stock, resulting in fault-related deep-level sericitic and high-level advanced argillic alteration, possibly associated with a lithocap telescoped onto the top of the K-silicate zone.

Introduction

Much of our current understanding of the characteristics of porphyry deposits comes from studies in the 1970s of the Laramide porphyry Cu systems (southwest USA). In recent years, it has been recognised that Tertiary and Quaternary gold-rich porphyry Cu deposits in the western Pacific and South East Asia have their own characteristics, which result from the distinctive tectonic setting and host rock lithologies found in island arcs (Sillitoe & Gappe 1984). These are typified by the Philippine systems such as Santo Tomas II, Dizon, and Far South East, but also include deposits such as Grasberg and Batu Hijau (Indonesia), and Ok Tedi, the Frieda River deposits, and Panguna (Papua New Guinea). Porphyry Cu–Mo (e.g. southwest Negros, Philippines) and porphyry Mo deposits (e.g. Pollilo, Philippines) are also present, but are less significant economically than the Cu–Au deposits, whose importance is exemplified by Grasberg, Irian Jaya (>1000 Mt @ 1.25% Cu, 1.55 g/t Au; I. Kavalieris Indonesia, personal communication 1996) and Batu Hijau, Sumbawa (1060 Mt @ 0.5% Cu, 0.37 g/t Au; Maula & Levet 1996).

Gold-rich porphyry Cu deposits are not restricted to the southwest Pacific (e.g. Bingham Canyon, Utah; Mt Milligan, British Columbia). Some of the oldest known porphyry Cu–Au deposits occur in the Ordovician volcano-sedimentary sequences of New South Wales (e.g. Goonumbla, Cadia, Copper Hill, Cargo, Lake Cowal). Other porphyry-related deposits in Australia include the Devonian porphyry Cu–Au–Mo deposits at Yeoval, New South Wales, and the Permo-Carboniferous Cu–Mo porphyry-related Au deposits of northern Queensland (e.g. Kidston, Mount Leyshon).

The Ordovician Cu–Au porphyry deposits of New South Wales and the western Pacific porphyry provinces, while having a number of similarities, also have several distinctive characteristics. Continuing exploration success relies on understanding the variations in geological, geochemical and geophysical characteristics of porphyry deposits in both provinces. This paper, therefore, reviews the characteristics of Australian and western Pacific porphyry deposits, highlighting features that may be important for exploration programs.

Tectonic setting

Most of the world's porphyry deposits are restricted to Mesozoic–Cainozoic orogenic belts and active convergent plate boundaries (Sillitoe 1972). The deposits are associated with intrusions that range in composition from calc-alkaline, to high-K calc-alkaline to alkaline. Porphyry Cu–Mo deposits of the eastern Pacific have formed mainly in continental margin and cratonic (thick continental crust) settings, with the latter generally containing the higher Mo and Ag contents (Titley 1990). In contrast, many Au-rich porphyry Cu deposits occur in island arc settings around the southwestern Pacific rim (particularly in Papua New Guinea and the Philippines). While exceptions do exist (e.g. porphyry Mo mineralisation at Polillo, Philippines; Knittel & Burton 1985), it appears that Mo-enriched porphyry deposits are *generally* associated with magmas that have passed through (and interacted with) a significant volume of continental crust. Many porphyry Cu–Au deposits, in contrast, have formed in island arc settings, in association with I-type/magnetite series intrusions that have primitive strontium isotopic ratios. These magmas have suffered little or no crustal contamination compared to their eastern Pacific porphyry Cu–Mo counterparts (Sillitoe 1987).

There is an obvious global association of porphyry deposits with subduction-related environments. However, it is debatable whether active subduction is necessary for the development of porphyry-related magmas or whether post-subduction partial melting of metasomatised mantle is the key to metal enrichment. Porphyry Cu–Au deposits in any given district or cluster of deposits can have different Cu/Au ratios (e.g. Goonumbla, New South Wales), indicating that local geological factors also strongly influence the final metal contents of specific systems.

In the Philippines, porphyry Cu–Au mineralisation occurs mostly in subaerial volcanic arc settings. Cordon and possibly Didipio may have formed in a back-arc setting in northern Luzon. The porphyry deposits of mainland Papua New Guinea and Irian Jaya have formed in a collisional environment (e.g. Ok Tedi, Grasberg). In Australia, the Ordovician porphyry deposits of New South Wales occur in two volcano-sedimentary belts that are at least partly marine in character (the Junee–Narromine and Molong volcanic belts), and the tectonic setting (subduction vs post-subduction) is still debated (Wyborn 1994, Glenn et al 1997). Most of the western Pacific deposits are Tertiary to Quaternary in age, whereas the eastern Australian deposits range from Ordovician to Permo-Carboniferous.

The magma that forms a porphyry deposit must be undersaturated with respect to reduced sulphur. If a magma becomes sulphur-saturated early in its history, an immiscible sulphide liquid may form that scavenges chalcophile elements (e.g., Cu, Au) from the silicate magma, resulting in these metals being retained in the source regime, instead of being transferred to the upper crust. Metasomatised lithospheric mantle, rather than oceanic crust, appears to be the most likely source for Au-enriched, S-undersaturated magmas (Wyborn 1994).

Solomon (1990) noted that many porphyry Cu–Au deposits were formed in island arcs after a period of reversal of arc polarity (e.g., Philippines, Papua New Guinea). 'Arc reversal' may therefore be a controlling factor in the formation of at least some porphyry Cu–Au deposits. The cessation of subduction during collisional events could result in partial melting of the down-going slab. This might cause the mantle wedge to be hybridised and oxidised, resulting in the generation of Au-bearing I-type melts (McGinnis & Cameron 1994), such as those associated with the porphyries of the Irian–Papuan fold-thrust belt (Grasberg, Ok Tedi).

Terrane evolution and metallogeny

Although the database of information is too limited to allow definite conclusions to be drawn, the metallogenic evolution of the Lachlan fold belt appears to be reflected in the metal content of the porphyry deposits. Ordovician porphyry mineralisation is exclusively Cu–Au in character, and occurs in belts of shoshonitic to calc-alkaline volcanics. Originally, these may have been oceanic island arcs, accreted onto the eastern Australian continental margin after the Ordovician. By the Devonian, eastern Australia had evolved to a continental arc setting (Cas 1983), which appears to be reflected in the change in metal tenor of the porphyry systems. Cu–Au–Mo porphyries formed at Yeoval (New South Wales) in the Devonian, and sub-economic Cu–Mo porphyry mineralisation formed as a precursor to the Permo-Carboniferous breccia-hosted Au deposits of northern Queensland (Kidston, Mount Leyshon).

The inferred temporal evolution of eastern Australian porphyry metallogenesis appears to be similar to that known for the Mesozoic and Cainozoic porphyry deposits of British Columbia. Many of the Canadian porphyry Cu–Au deposits formed in island arc settings before accreting onto the western margin of the North America continent at 185 Ma. In the post-accretion setting, a more varied assemblage of porphyry deposits formed, including porphyry Cu, Mo, Au, Cu–Mo and Cu–Au–Mo deposits (McMillan et al. 1995). The more varied metal tenor in post-accretion settings appears to relate to the variability in basement components, with oceanic crust, metasomatised lithospheric mantle and continental crust all present. Accretion and amalgamation of exotic terranes may be important for developing porphyry deposits of varied metal tenor in a given province. In the case of the Philippines, the variable metal content, from Cu–Au (e.g., Central Cordillera) to Cu–Mo (e.g., SW Negros) to Mo (Polillo), may also relate to variable basement components, as the Philippines are an example of amalgamated exotic terranes in an island arc setting (Mitchell et al. 1986).

Geological characteristics

In the past three decades, a large body of literature has been published on many aspects of disseminated and vein mineralisation associated with emplacement of subvolcanic intrusive stocks. The 'porphyry' class of deposits encompasses a broad and varied spectrum, all of which are related to one or more subvolcanic porphyritic stocks. Stock emplacement occurs immediately before and/or during the onset of fracture-controlled mineralisation.

The basic empirical model for porphyry Cu deposits, defined by Emmons (1927), Lowell & Guilbert (1970) and Sillitoe (1973), continues to be used in district evaluation. This model is constantly being refined, with the timing and nature of magmatism (e.g. single vs multiple intrusions; significance and extent of barren post-mineral intrusions), host rock controls (e.g. the effects of metasomatism are subdued in most sedimentary lithologies; skarns only form in impure limestones; etc.), depth of erosion and exposure, importance and origin of breccias, potential for peripheral Au deposits, and the presence, extent and possible telescoping of lithocaps now also recognised as important features to be considered in any evaluation of a porphyry district.

Sillitoe & Gappe (1984) provided a comprehensive summary of many aspects of the Philippines porphyry Cu–Au systems that was drawn from a large and, most importantly, consistent database compiled for 48 deposits. The Philippines deposits share many characteristics with those in other island arc settings (e.g. Indonesia, Papua New Guinea, Solomon Islands, Fiji) and have been proposed as the type area for island arc porphyry deposits (Sillitoe & Gappe 1984). Some of the characteristic geological features of Philippines deposits noted by Sillitoe & Gappe (1984) are summarised below, along with comments on other western Pacific and Australian deposits.

Porphyritic stocks

Andesitic volcanism and porphyritic diorite to quartz diorite intrusions characterise most of the Philippines and Indonesian porphyry deposits that occur in typical 'arc' settings (e.g. Philex, Batu Hijau). Hornblende is the characteristic primary mafic mineral in these intrusions. In back-arc and collisional settings of the western Pacific, more evolved magmas (monzonites and monzodiorites) are related to Cu–Au mineralisation (e.g. Didipio, Grasberg). Shoshonitic volcanism and monzonite to monzodiorite intrusions are also diagnostic of the Ordovician Cu–Au porphyry deposits of New South Wales. Clinopyroxene and/or biotite are common primary mafic minerals in both the western Pacific and eastern Australian porphyry-related monzonites. Porphyry deposits that are enriched in molybdenum tend to be associated with more felsic (quartz monzonite to syenite) stocks in both the Philippines (e.g. Polillo) and Australia (e.g. Yeoval). The Permo-Carboniferous porphyry-related gold deposits of northern Queensland (e.g. Kidston, Mount Leyshon, Red Dome) are associated with rhyolitic to trachyitic subvolcanic complexes, and are genetically related to subeconomic porphyry Cu–Mo mineralisation (Morrison 1988).

Compared to their eastern Pacific counterparts, the mineralised stocks in the western Pacific and Australian provinces are small (mostly <0.5 km^2 in area). They are, however, either known or inferred to have a significant depth, with the known vertical extent of the porphyritic stocks at Grasberg extending over more than 1500 m (Kavalieris 1994). Many stocks are cylindrical and tend to widen with depth, although mushroom-style geometry is also known (e.g. Atlas). The uppermost portions of the stocks are probably emplaced at 1–2 km below the palaeosurface, and Cu–Au mineralisation may extend 1.5 km vertically (Grasberg), and up to several hundred metres outwards from the stock into the wall rocks.

Deposit clusters

In the western Pacific and Australian porphyry provinces, some deposits occur in clusters. They are common in the Philippines (e.g. Atlas, Cebu; southwestern Negros) and Australia (e.g. E22, E26N, E27 and E48 at Goonumbla; Cadia Hill, Cadia East, Cadia Quarry and Ridgeway at Cadia). There are many cases where two or more deposits are situated within 3 km of each other and are probably derived from the same deep-seated phaneritic intrusion. The outer propylitic alteration halos of these deposit 'pairs' generally overlap.

Isolated deposits also occur in both the western Pacific (e.g. Panguna, Batu Hijau) and Australian porphyry provinces (e.g. Kidston, Mount Leyshon). Porphyry deposits in both provinces can be associated with the emplacement of one stock (e.g. Ok Tedi, Wafi) or multiple phases of mineralised intrusions (e.g. Grasberg, Batu Hijau, E26N).

Relationship to phaneritic intrusions

Of the known porphyry deposits and prospects in the Philippines, approximately three-quarters have been emplaced within 4 km of the margin of a large equigranular pluton (Sillitoe & Gappe 1984). While there is a close spatial relationship between batholiths and porphyry stocks, it is less common for porphyry deposits to have been emplaced within plutonic host rocks (e.g. Marian, Philippines). In many cases (e.g. Northern Luzon), there is a significant time break (>10 Ma) between early batholith emplacement and late porphyry intrusion, and the spatial superposition of the intrusive suites is related to the erosion that occurred during this time interval. It may be that crystalline plutonic rocks and batholiths provide effective barriers to later high-level intrusions, which are, therefore, emplaced around the weaker (usually fractured) margins of the phaneritic intrusions.

In Australia, the Permo-Carboniferous Kidston breccia pipe and Mount Leyshon diatreme (Queensland) have formed partly within and on the margin of older, unrelated Palaeozoic granitoids (Baker & Andrew 1991, Morrison et al. 1987). Although there is no obvious spatial association between the Ordovician porphyries of New South Wales and older batholiths, the quartz monzonite porphyries at Goonumbla are interpreted to be apophyses from the side of a larger comagmatic intrusion (the E31 stock; Heithersay & Walshe 1995). The only Australian porphyry deposits contained in a larger (but coeval) pluton are the uneconomic Devonian Cu–Au–Mo deposits in the Yeoval Monzodiorite, New South Wales (Yeoval—37 Mt @ 0.23% Cu, 0.007% Mo; plus minor prospects at Goodrich, Porphyry King, Cyclops, etc.; Paterson et al. 1983, Cooke 1985). The small Yeoval deposits share some similarities with the intrusion-hosted Highland Valley porphyry deposits of British Columbia, where mineralisation occurs in and is genetically related to a zoned multiphase phaneritic intrusion (Casselman et al. 1995).

Porphyry Cu–Au deposits in both provinces can contain weakly mineralised to barren intra- or post-mineral intrusions (e.g. Goonumbla, Batu Hijau, Grasberg). They are (in most cases) petrographically and geochemically similar to the mineralised stocks, and it can be difficult to distinguish between mineralised, weakly mineralised, and barren intrusions in the field. Post-mineral intrusions in the western Pacific include weakly altered to unaltered andesite porphyry dykes, post-mineral diatremes and/or dacite domes, all of which may have destroyed and/or diluted significant quantities of mineralisation when they were emplaced. Diatremes are not present in the Ordovician porphyry deposits of New South Wales, suggesting that local hydrology (and climate?) did not favour the explosive interaction of magma and groundwater. Permo-Carboniferous diatreme volcanism occurred at Mount Leyshon (Morrison 1988).

Porphyry copper deposits in the Philippines have mostly formed above either early Mesozoic greenschist facies metavolcanic and metasedimentary sequences or Mesozoic/Cainozoic ophiolites (Sillitoe & Gappe 1984). Cratonic basement occurs beneath Grasberg and Ok Tedi in Irian Jaya and Papua New Guinea, respectively. The nature of the basement for eastern Australian porphyry deposits is controversial; both oceanic and sialic basements have been proposed (Heithersay 1994). Porphyry deposits in the western Pacific and Australian provinces have generally been emplaced in sequences of volcanic and/or volcaniclastic rocks, although the largest known deposit (Grasberg) is hosted by a thick platform-carbonate sequence (MacDonald & Arnold 1994).

In both the Australian and western Pacific provinces, some porphyry deposits are inferred to have a close association with basement structures and/or fault intersections, although the structural controls generally remain enigmatic. The Goonumbla porphyries are aligned along the N–S-trending Endeavour Linear (Heithersay et al. 1990), although relationships to larger regional-scale faults remain uncertain. The intersection of arc-parallel and arc-normal structures appears to have been favourable for localising porphyry mineralisation in Papua New Guinea (Corbett & Leach 1995). Strike-slip faulting has been recognised as an important factor in the emplacement and localisation of some porphyry deposits (e.g. Chuquicamata, Chile; Lindsay et al. 1995). There is an obvious spatial association between many of the porphyry deposits of the Philippines and the major left-lateral strike-slip Philippine Fault. In northern Luzon, a zone of transpressional uplift in a restraining bend of the Philippine Fault appears to have favoured the superposition of porphyry and low sulphidation epithermal mineralisation (Cooke & Berry 1996). This type of structural setting generally appears to be favourable for shallow-crustal Cu–Au porphyry emplacement.

Hydrothermal alteration and related mineralisation

The most distinctive feature of porphyry deposits is the widespread and varied hydrothermal alteration assemblages localised in and around the porphyritic stock. These are intimately associated with disseminated sulphide mineralisation and stockwork veining. Individual alteration assemblages have a broadly similar paragenesis from deposit to deposit, giving rise to several of the 'classic' alteration zones documented by Lowell & Guilbert (1970). While it is unlikely that any two systems would produce exactly the same alteration mineral assemblages, owing to varying lithology and fluid composition, several of the 'type' alteration assemblages are always recognisable. The assemblages common to most porphyry systems are K-silicate (or potassic), quartz–sericite (or phyllic) and propylitic. The alteration type that is most variable in its extent and distribution is the 'argillic' assemblage. Workers have identified several varieties of hypogene argillic alteration assemblages, including phyllic–argillic, intermediate argillic and advanced argillic types. Sillitoe & Gappe (1984) have documented numerous examples of intermediate argillic or sericite–clay–chlorite (SCC) alteration from the Philippines. Similar intermediate argillic assemblages are present in other porphyry deposits (e.g. chlorite–sericite alteration at Panguna—Ford 1978; El Salvador—Gustafson & Hunt 1975), but their origin has not been discussed in any detail.

Many of the features of hydrothermal alteration and mineralisation assemblages in western Pacific and Australian porphyries are similar to those of their eastern Pacific counterparts. There are also some noticeable differences. Tourmaline is uncommon in western Pacific and Australian deposits, whereas some in North and South America contain abundant tourmaline. In many North American porphyry Cu deposits, anhydrite occurs only in the K-silicate zone (Titley 1982). In contrast, anhydrite may be present in all alteration assemblages of the western Pacific porphyry deposits, and can reach more than 5 per cent by volume in ore zones (e.g. Sillitoe & Gappe 1984, Kavalieris 1994).

The six most commonly recognised hypogene alteration assemblages in western Pacific and Australian porphyry deposits are K-silicate, propylitic, phyllic, advanced argillic, calc-silicate and intermediate argillic (SCC) alteration assemblages (e.g. Sillitoe & Gappe 1984). The first five have been well documented in the literature (e.g. Meyer & Hemley 1967, Lowell & Guilbert 1970). The intermediate assemblage has not been widely reported from the classic porphyry Cu districts of the United States and South America, although it is present. A seventh variety, sodic–calcic alteration, is uncommon in the western Pacific deposits, but occurs in several Australian systems. The following sections provide brief summaries of the characteristics of the seven main alteration types, based partly on the observations of Sillitoe & Gappe (1984) from the Philippine deposits. Supergene enrichment blankets are also briefly discussed.

K-silicate alteration is the earliest-formed alteration assemblage in most porphyry deposits, and is closely associated with Cu–Au mineralisation in the western Pacific and Australian Ordovician examples. Biotite is the diagnostic hydrothermal mineral, together with K-feldspar, magnetite, quartz and anhydrite. Some K-silicate assemblages also contain actinolite, chlorite, albite and/or (rarely) epidote. There is a component of lithological control on the mineralogy of K-silicate assemblages, with secondary biotite and magnetite more commonly developed in mafic rocks, and secondary K-feldspar in felsic units. Sulphides (chalcopyrite, bornite, pyrite, molybdenite) are present in veinlets and as disseminations in the K-silicate zone. Gold commonly occurs as exsolution blebs in chalcopyrite and/or bornite. Molybdenum-rich annuli surround Cu–Au cores at some deposits. Generally, Au and magnetite appear to be enriched in the more mafic stocks, whereas Mo tends to be enriched in the felsic intrusions. The association of anhydrite and magnetite with the early potassic assemblage is an indirect indication of the oxidised nature of the parent magmas. Both the extensive development of magnetite in biotite-altered zones and a positive magnetite–Au correlation have important implications for geophysical exploration.

Propylitic alteration is weakly developed in all other alteration 'zones' in the porphyry environment, but appears to be most closely associated with K-silicate alteration. It also occurs as an outer alteration halo, extending for several hundred metres up to several kilometres away from the main mineralised centre. Propylitic alteration of barren late- and post-mineral intrusions has been noted from a number of deposits, suggesting that this alteration assemblage has a protracted or episodic history of formation. The mineralogy of the propylitic alteration assemblage depends strongly on lithology, but is generally characterised by chlorite, calcite, albite, minor pyrite and epidote.

Intermediate argillic (SCC) alteration is not recognised in the Australian porphyry deposits, but is common in the western Pacific examples. Intermediate argillic alteration generally makes the original host rock pale green, and results in the partial to complete replacement of plagioclase by a pale green aggregate of sericite ± clays (kaolinite or illite) and the formation of chlorite pseudomorphs after mafic minerals. Calcite is a common accessory phase and epidote is rare. In the Philippines, Au and Cu mineralisation associated with K-silicate alteration do not appear to have been remobilised by the intermediate argillic alteration event, although Trudu & Bloom (1988) noted that additional Au deposition occurred during the formation of intermediate argillic alteration at Tirad. In the Philippines, clay minerals in the intermediate argillic assemblages are most likely a later overprint, as the limited available fluid-inclusion data (Cooke et al. 1993, Trudu & Bloom 1988) suggest that high-temperature (>300°C) magmatic–hydrothermal fluids are involved in the formation of this alteration assemblage. More detailed stable isotope and fluid-inclusion research is required into the origin of this alteration assemblage.

Sericite–quartz–pyrite (phyllic) alteration is typically poorly developed in many western Pacific and Australian porphyry systems. In most deposits, well-defined 'zones' of phyllic alteration are absent. This is a major contrast between the southwestern United States and Chilean porphyries, where phyllic alteration zones related to the ingress of meteoric water are widespread (e.g. Taylor 1974). Mineralogically and texturally, the phyllic alteration assemblage in the western Pacific and Australian deposits is identical to phyllic assemblages described from North and South American porphyry Cu deposits. Sericite, quartz and pyrite are the characteristic alteration minerals. Sericite alteration has generally overprinted earlier formed K-silicate and (in the western Pacific deposits) intermediate argillic assemblages. In some deposits (e.g. Batu Hijau, E26N, E48), sericite vein selvedges occur deep within the potassic 'core' of the deposit. Oxygen and deuterium isotope analyses have shown that sericite at E48 is most likely magmatic–hydrothermal in origin (Wolfe et al. 1996), in contrast to the meteoric origin documented for phyllic alteration assemblages of the eastern Pacific (Taylor 1974).

Advanced argillic alteration occurs in the upper levels of a number of western Pacific porphyry Cu deposits, and a silicified lithocap may occur as a blanket over the entire district. In some cases, high-sulphidation epithermal Cu–Au–As mineralisation occurs in the advanced argillic zone (e.g. Lepanto). Where present, advanced argillic alteration has invariably overprinted all other alteration styles and is interpreted as the last alteration assemblage to form. The alteration mineralogy is complex, with alunite, kaolinite, quartz, pyrophyllite and pyrite generally being the most abundant alteration minerals. Important Cu–Au mineralisation can occur in association with this assemblage, and enargite, luzonite and hypogene covellite are diagnostic hypogene ore minerals. The acid fluids responsible for advanced argillic alteration can cause extreme leaching of the host rocks (especially in the vicinity of structural conduits), resulting in a residual texture known as vuggy silica. All minerals apart from quartz are leached from the rock, leaving a porous, residual siliceous rock that can act as a favourable depositional site for later sulphide–sulphosalt–Au mineralisation. Depending on erosion rates, advanced argillic alteration and the lithocap environment may be telescoped down into the K-silicate alteration zone, resulting in the spatial superposition of high-sulphidation epithermal Au mineralisation onto the porphyry Cu–Au system.

Calc-silicate (skarn) alteration can form in porphyry systems if impure limestone occurs near the porphyritic stock. Characteristic minerals include garnet, diopside and epidote—many other minerals, including chlorite, pyrite, chalcopyrite and magnetite, may be present. Examples include Browns Creek (New South Wales), Red Dome (Queensland), Ertsberg (Indonesia) and Thanksgiving (Philippines).

Sodic–calcic alteration is an uncommon alteration assemblage in porphyry systems. It is well documented from the Yerrington district, Nevada, where it consists of Na-feldspar + epidote + quartz ± actinolite ± sphene ± rutile ± chlorite and is interpreted to be a prograde assemblage related to ingress and heating of groundwater (Dilles & Einaudi 1992). Sodic–calcic assemblages occur in some of the Australian deposits (e.g. chlorite–epidote–calcite–sphene–albite–sericite alteration at Cadia Hill and Yeoval; Newcrest 1996, Cooke 1985), but they appear to be more closely related to ore deposition than at Yerrington. Secondary albite in the Australian porphyry deposits can be a strong pink colour, which leads to its common misidentification as K-feldspar.

Supergene enrichment is poorly developed or absent in many western Pacific porphyry deposits, in contrast to the Andean and North American systems. This is probably due to the rapid uplift and erosion that can take place in subequatorial island arc settings. Partial oxidation of sulphides commonly occurs at depths of less than 100 m (typically 30–60 m), and is thickest below ridge crests. Ok Tedi in Papua New Guinea has the richest and best-developed supergene blanket in the western Pacific, with a resource of 18 Mt @ 2 g/t Au and 0.05 % Cu (Rogerson & McKee 1990).

District-scale zonation

Zoned mineral districts are associated with some porphyry Cu–Au centres (e.g. Baguio and Mankayan districts, Philippines), increasing the prospectivity of this class of deposits. High-sulphidation epithermal Au–Cu–As systems may form above or immediately adjacent to the porphyry system (e.g. Lepanto/Far South East). If impure limestone is present in the stratigraphy, skarns may form adjacent to the porphyritic stock (e.g. Ertsberg, Thanksgiving). Low-sulphidation epithermal Au–Ag veins and breccias can be associated with porphyry deposits, but are generally offset laterally by several kilometres (Sillitoe 1989). Some low-sulphidation epithermal deposits have been 'telescoped' onto porphyry systems (e.g. Acupan; Cooke & Bloom 1990; Lihir; Sillitoe 1994). Sediment-hosted Au deposits (Carlin-style) may form in calcareous sediments distal to the porphyritic intrusion (e.g. Bau; Sillitoe & Bonham 1990)

Exploration criteria

Explore near known systems

From a regional perspective, areas of known porphyry mineralisation are the most prospective for further discoveries. The local environment is known to be favourable for the development of porphyry systems, and the level of erosion is appropriate for exposure of the deposit at or near the surface.

Volcanic and regional structures

Landsat TM, SLAR, and aerial photography can be used to identify eroded calderas and investigate regional structures that may have influenced magmatism. Understanding the regional structural trends is also important for targeting likely sites for peripheral epithermal veins.

Airborne geophysical signatures

Low-level aeromagnetic data can be used to help delineate regional geology and detect magnetic lows related to magnetite-destructive alteration (phyllic, intermediate argillic, etc.) or (in rare cases) bullseye and annular magnetic highs related to the magnetite-bearing, biotite-altered core zone. Radiometric data may also prove useful in delineating K-silicate alteration. The spatial association of granitic batholiths and porphyritic stocks means that many porphyry Cu–Au deposits occur adjacent to large gravity lows. IP anomalies may be associated with porphyry-style mineralisation, although they do not necessarily provide a direct vector to ore (Thompson 1993). IP has not been successful in areas that contain conductive overburden (e.g. Goonumbla).

Geochemical signatures

The most effective method for detecting porphyry Cu–Au systems in young terrains is drainage geochemistry (stream sediment, pan concentration and BLEG) combined with float mapping (e.g. Batu Hijau; Maula & Levet 1996). Allen et al. (1995) used the trace element chemistry of alluvial Au (particularly Pt, Pd, Cu and Ag) to rank potential porphyry sources in Irian Jaya. In Tertiary and Quaternary porphyry provinces of the western and eastern Pacific, identifying porphyry centres beneath zones of widespread silicification and advanced argillic alteration assemblages remains one of the great exploration challenges. Discriminating hypogene lithocaps from supergene leached caps may be possible, using alunite chemistry, which can be identified by XRD, PIMA or FTIR. Hand-held spectrometers have excellent potential for identifying high-temperature clay phases (e.g. dickite, some smectites, pyrophyllite) and alunite in the lithocap environment. Soil sampling is still a common and effective tool in porphyry exploration, although in suitable areas (e.g. Goonumbla), bedrock sampling by RAB or aircore drilling may prove more effective, because it avoids the enrichment/depletion effects of soil profiles and the dilution or masking effects of transported material. In the Palaeozoic porphyry provinces of

Australia, volcanic geochemistry can help target porphyry systems on the regional scale, as mineralisation is generally associated with belts of calc-alkaline to shoshonitic volcanics. Alteration and mineralisation vectors can be designed, based on the classic zonation patterns developed around porphyritic stocks. For example, Cu and S values are most enriched in the cores of porphyry deposits, owing to chalcopyrite/bornite addition, whereas Ca and Mg are lower, because of the breakdown of plagioclase and hornblende.

Stable isotope geochemistry

Light oxygen and deuterium isotopes are characteristic of meteoric fluids associated with phyllic altered zones, whereas magmatic $\delta^{18}O_{(H2O)}$ and $\delta D_{(H2O)}$ values are associated with the K-silicate zone. Sulphur isotopes generally range between -5 and +5‰, although lighter $\delta^{34}S$ values may occur in the core of more oxidised systems (e.g. E26N; Heithersay & Walshe 1995) and may provide a vector to ore.

Breccias

Understanding the significance and origins of breccias is a critical but often overlooked step in the evaluation of porphyry Cu districts. Thus, high-quality geological mapping remains an essential component of exploration programs both at the district and prospect scales, owing to the complex overprinting and timing relationships.

Acknowledgments

Thanks to June Pongratz and Debbie Harding for help with the layout and for preparing the figures. The thoughtful reviews of John Thompson and Imants Kavalieris were greatly appreciated.

References

Allen, J.M., Artmont, G.J. & Palmer, K., 1995. Application of alluvial gold mineralogy to exploration of the Central Ranges, Irian Jaya, Indonesia. In: Mauk, J.L. & St George, J.D. (editors), PACRIM Congress 1995—Exploring the Pacific. Australasian Institute of Mining and Metallurgy, Melbourne, 9/95, 7–12.

Baker, E.M. & Andrew, A., 1991. Geologic, fluid inclusion and stable isotope studies of the gold-bearing breccia pipe at Kidston, Queensland, Australia. Economic Geology, 86, 810–830.

Cas, R.A.F., 1983. Palaeogeographic and tectonic development of the Lachlan Fold Belt, South Eastern Australia. Geological Society of Australia, Special Publication 10, 104.

Casselman, M.J., McMillan, W.J. & Newman, K.M., 1995. Highland Valley porphyry copper deposits near Kamloops, British Columbia: a review and update with emphasis on the Valley deposit. In: Schroeter, T.G. (editor), Porphyry deposits of the Northwestern Cordillera of North America. CIM Special Publication 46, 161–191.

Cooke, D.R., 1985. The geology and geochemistry of the Naringla Monzodiorite, and the mineralisation and alteration of the associated porphyry copper deposits, Yeoval, NSW. B.Sc. Hons thesis, La Trobe University, Melbourne, 105 pp. (unpublished).

Cooke, D.R. & Berry, R.F., 1996. Porphyry-epithermal relationships in the Baguio district, Philippines—telescoping of low sulfidation mineralisation by transpressional uplift and erosion. Geological Society of Australia, Abstracts, 28 (7), A-155.

Cooke, D.R. & Bloom, M.S., 1990. Epithermal and subjacent porphyry mineralization, Acupan, Baguio District, Philippines: a fluid-inclusion and paragenetic study. In: Hedenquist, J.W., White, N.C. & Siddeley, G. (editors), Epithermal gold mineralisation of the Circum-Pacific: geology, geochemistry, origin and exploration, I. Journal of Geochemical Exploration, 35, 297–340.

Cooke, D.R., Bloom, M.S. & Cartwright, I.C., 1993. The Acupan South porphyry copper–gold prospect, Baguio District Philippines: relationship to epithermal mineralisation. Geological Society of Australia, Abstracts, 34, 16–17.

Corbett, G. & Leach, T.M., 1995. Southwest Pacific Rim gold–copper systems: structure, alteration and mineralisation. Short course notes, Orange, New South Wales, 162 pp. (unpublished).

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

Emmons, W.H., 1927. Relations of the disseminated copper ores in porphyry to igneous intrusives. American Institute of Mining and Metallurgical Engineers, Transactions, 75, 797–815.

Ford, J.H., 1978, A chemical study of alteration at the Panguna porphyry copper deposit, Bougainville, Papua New Guinea. Economic Geology, 73, 703–720.

Glenn, R.A., Walshe, J.L., Barron, L.M. & Watkins, J.J., 1997. New model for copper–gold deposits in Ordovician volcanics. NSW Mining and Exploration Quarterly, 56, 4–6.

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

Heithersay, P.S., 1994. The central west New South Wales Cu–Au province. CODES Key Centre, Master of Economic Geology, short course notes. University of Tasmania, 1.1–1.26 (unpublished).

Heithersay, P.S. & Walshe, J.L., 1995. Endeavour 26 North: a porphyry copper–gold deposit in the Late Ordovician shoshonitic Goonumbla Volcanic Complex, NSW, Australia. Economic Geology, 90, 1506–1532.

Heithersay, P.S., O'Neill, W.J., van der Helder, P., Moore, C.R. & Harbon, P.G., 1990. Goonumbla porphyry copper district—Endeavour 26 North, Endeavour 22 and Endeavour 27 copper–gold deposits. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 1385–1398.

Irianto, B. & Clark, G.H., 1995. The Batu Hijau porphyry copper–gold deposit, Sumbawa Island, Indonesia. In: Mauk, J.L. & St George, J.D. (editors), PACRIM Congress 1995—Exploring the Pacific. Australasian Institute of Mining and Metallurgy, Melbourne, 9/95, 299–304.

Kavalieris, I., 1994. The Grasberg Superporphyry. CODES Key Centre, Master of Economic Geology, short course notes. University of Tasmania, 3.1–3.29 (unpublished).

Knittel, U. & Burton, C.K., 1985. Polillo island (Philippines): molybdenum mineralisation in an island arc. Economic Geology, 80, 2013–2018.

Lindsay, D.D., Zentilli, M. & De La Rivera, J.R., 1995. Evolution of an active ductile to brittle shear system controlling mineralisation at the Chuquicamata porphyry Cu deposit, Northern Chile. International Geological Review, 37, 945–958.

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

MacDonald, G.D. & Arnold, L.C., 1994. Geological and geochemical zoning of the Grasberg Igneous Complex, Irian Jaya, Indonesia. In: Van Leeuwen, T.M., Hedenquist, J.W., James, L.P. & Dow, J.A.S. (editors), Mineral deposits in Indonesia—discoveries of the past 25 years. Journal of Geochemical Exploration, 50, 143–178.

Maula, S. & 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. AMF Conference Proceedings, 8.1–8.13.

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

McMillan, W.J., Thompson, J.H.F., Hart, C.J.R. & Johnston, S.T., 1995. Regional geological and tectonic setting of porphyry deposits in British Columbia and Yukon Territory. In: Schroeter, T.G. (editor), Porphyry deposits of the Northwestern Cordillera of North America. CIM Special Publication, 46, 40–57.

Meyer, C. & Hemley, J.J., 1967. Wall rock alteration. In: Barnes, H.L. (editor), Geochemistry of hydrothermal ore deposits, 2nd edn, Wiley, 166–235.

Mitchell, A.H.G., Hernandez, F. & Dela Cruz, A.P., 1986. Cenozoic evolution of the Philippine Archipelago. Journal of Southeast Asian Earth Sciences, 1, 3–22.

Morrison, G.W., 1988. Paleozoic gold deposits of Northeast Queensland. In: Morrison, G.W. (editor), Epithermal and porphyry style gold deposits of North Queensland. James Cook University, Economic Geology Research Unit, Contribution 29, 11–22.

Morrison, G.W., Teale, G.S. & Hodkinson, I., 1987. Geology and gold mineralisation at Mount Leyshon, North Queensland. In: Pacific Rim Congress '87, Australasian Institute of Mining and Metallurgy, Conference Proceedings, 777–780.

Newcrest Mining Staff, 1996. The Cadia 'wallrock-porphyry'-style gold–copper deposit, NSW. In: Porphyry-related copper and gold deposits of the Asia–Pacific region. AMF Conference Proceedings, 16.1–16.10.

Paterson, I.B.L., Bowman, H.N. & Hobbs, J.J., 1983. Yeoval copper–gold–molybdenum district. Geological Survey of New South Wales, Records, 21(2), M55–M73.

Rogerson, R. & McKee, C., 1990. Geology, volcanism and mineral deposits of Papua New Guinea. In: Hughes, F.E. (editor), Geology of the mineral deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Monograph 14, 1689–1701.

Sillitoe, R.H., 1972. A plate tectonic model for the origin of porphyry copper deposits. Economic Geology, 67, 184–197

Sillitoe, R.H., 1973. Tops and bottoms of porphyry copper deposits. Economic Geology, 68, 799–815.

Sillitoe, R.H., 1987. Copper, gold and subduction: a trans-Pacific perspective. In: Pacific Rim Congress '87. Australasian Institute of Mining and Metallurgy, Conference Proceedings, 399–403.

Sillitoe, R.H., 1989. Gold deposits in western Pacific island arcs: the magmatic connection. Economic Geology, Monograph 6, 266–283.

Sillitoe, R.H., 1994. Erosion and collapse of volcanoes: causes of telescoping in intrusion-centred ore deposits. Geology, 22, 945–948.

Sillitoe, R.H. & Bonham, H.F., 1990. Sediment-hosted gold deposits: distal products of magmatic-hydrothermal systems. Geology, 18, 157–161.

Sillitoe, R.H. & Gappe, I.M., 1984. Philippine porphyry copper deposits: geologic setting and characteristics. CCOP Technical Publication 14, 89 pp.

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

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

Thompson, J.F.H., 1993. Application of deposit models to exploration. In: Kirkham, R.V., Sinclair, W.D., Thorpe, R.I. & Duke, J.M. (editors), Mineral deposit modelling. Geological Association of Canada, Special Paper 40, 51–67.

Titley, S.R., 1982. The style and progress of mineralization and alteration in porphyry copper systems : American Southwest. In: Titley, S.R. (editor), Advances in geology of the porphyry copper deposits: southwestern North America. University of Arizona Press, Tucson, 139–184.

Titley, S.R., 1990. Contrasting metallogenesis and regional settings of circumPacific Cu–Au porphyry systems. PACRIM '90 Proceedings (II), Australasian Institute of Mining and Metallurgy, 127–133.

Trudu, A.G. & Bloom, M.S., 1988. A genetic model for the origin of hypogene gold in porphyry copper systems: the Tirad porphyry copper–gold deposit (Guinaoang, NW Luzon, Philippines). Bicentennial Gold 88 extended abstracts. Geological Society of Australia, Abstracts, 22, 211–216.

Wolfe, R.C., Cooke, D.R., Hooper, B. & Heithersay, P.S., 1996. A magmatic origin for late stage sericite–alunite alteration at the Endeavour 48 Cu–Au porphyry deposit, Goonumbla, NSW. Geological Society of Australia, Abstracts, 40.

Wyborn, D., 1994. Mantle magmatism and large gold–copper deposits. CODES Key Centre, Master of Economic Geology, short course notes. University of Tasmania, 5.1–5.4 (unpublished).

Received 1 February 1996; accepted 1 July 1997