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THE PORPHYRY COPPER SYSTEM AND THE PRECIOUS METAL-GOLD POTENTIAL

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ABSTRACT

It has been established that porphyry copper/copper-gold deposits have formed from 1 Ma to 2 Ga ago. Generally, they are related to the Mesozoic-Cenozoic interval with few reported occurrences from the Palaeozoic or Precambrian. A reason cited is the erosion of these deposits which are often related to convergent plate margins and orogenic belts.

Observations of the alteration and mineralisation within and around porphyry copper/copper-gold systems have been included in numerous idealised models. These alteration and mineralisation patterns are dependent on the phases of intrusion, the tectonic setting and rock type, depth of emplacement and relationship to coeval volcanics, physiochemical conditions operative within and surrounding the intrusive and many other mechanical and geochemical conditions.

Island arc and cratonic arc/margin deposits are generally considered to be richer in gold than their molybdenum-rich, intra-cratonic counterparts. Metal zonation may occur around these copper/copper-gold deposits, e.g. copper in the core moving out to silver, lead, zinc and gold. This zonation is not always present and gold may occur in the core, intermediate or distal zones.

Examples of gold-rich porphyry deposits from British Columbia, Chile and the SW Pacific Island regions suggest gold is closely associated with the potassic-rich zones. Generally these gold-rich zones have greater than 2% magnetite and a high oxygen fugacity is considered to be an important control for gold deposition. High Cl^- contents within the magma are necessary for gold mobility within the host intrusive centres. Beyond this zone HS_2^- becomes an important transporting ligand.

Exploration for porphyry copper-gold deposits includes an integrated geological, geophysical and geochemical approach. Petrographic work through to Landsat imagery may be used to determine the chemical conditions of the system, ore association, favourable structural zones and alteration patterns, in order to focus exploration activities.

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1. INTRODUCTION

The potential for bulk, low-grade mining of copper from porphyry copper systems was essentially only recognised with the discovery of Bingham Canyon during the 1860's (Guilbert, 1992). Since then, much effort has been expended in attempting to understand the porphyry system and the associated mineralisation and alteration features. The classic model as proposed by Lowell and Guilbert (1970), (Figure 1), for alteration and mineralisation about the porphyry stock, has been used as a basis for further research and exploration of porphyry copper deposits (PCDs). This research and exploration has been undertaken by persons such as Titley (1966, 1975, 1978, 1982, 1992), Sillitoe (1972, 1975, 1979, 1983, 1989), Gustafson and Hunt (1971), Beane (1982) and Jones (1992), to name but a few. Their work and others, combined with the geological information from the mining operations of PCDs throughout the world (Plan 1 - Appendix 2), has helped in improving our knowledge and understanding of the geochemistry and ore deposition-alteration mechanisms of these systems.

Today, gold-enriched bulk-mineable porphyry copper deposits are important exploration targets and are, according to Jones (1992), among the largest revenue generators in the mining industry. Only in the past 80 years or so has the exploration community recognised that gold deposits can be found in the porphyry system. The possible cause of gold enrichment in some porphyry systems has been addressed by Titley (1978), Sillitoe (1979), Kesler (1973), Keith (1984), Cox and Singer (1988), Leveille et al. (1988) and Jones (1992).

Gold-rich or associated porphyry copper-gold deposits occur in various tectonic settings associated with various rock types. Fingerprinting the characteristics of these deposits is not straightforward and answers are being sought by many academics and explorationists. Due to the numerous variables (e.g. tectonic setting, composition of the intrusive, country rock composition, depth of emplacement, fluid interaction, temperature and composition of the mineralising fluid and structural pathways) which may control the ore forming process related to porphyry systems, it can only be remarked that gold-rich porphyry copper systems are less well understood than their copper or copper-molybdenum counterparts. There appears at present to be no definite set of variables or characteristics which can be assigned

to fingerprint barren porphyry intrusives from mineralised ones, and gold-rich copper porphyries from copper-rich porphyries.

It is therefore the objective of this dissertation to gather all relevant information on porphyry systems and highlight the models and characteristics proposed for porphyry copper deposits. This will be discussed in Part A and will serve as an introduction to the gold-rich porphyry systems to be discussed in Part B. The ideas proposed and discussed in these two sections will then be integrated and guidelines developed for the initiation of a porphyry copper-gold exploration programme.

PART A

2. A REVIEW OF THE PORPHYRY MODELS AND CHARACTERISTICS

2.1 General

Models showing alteration and mineralisation features of porphyry metal systems have been developed by numerous authors, e.g. Lowell and Guilbert (1970), Gustafson and Hunt (1975) and Sillitoe (1973) (Figures 1, 2 and 3). These models allow generalised predictions to be made concerning the properties of the porphyry system.

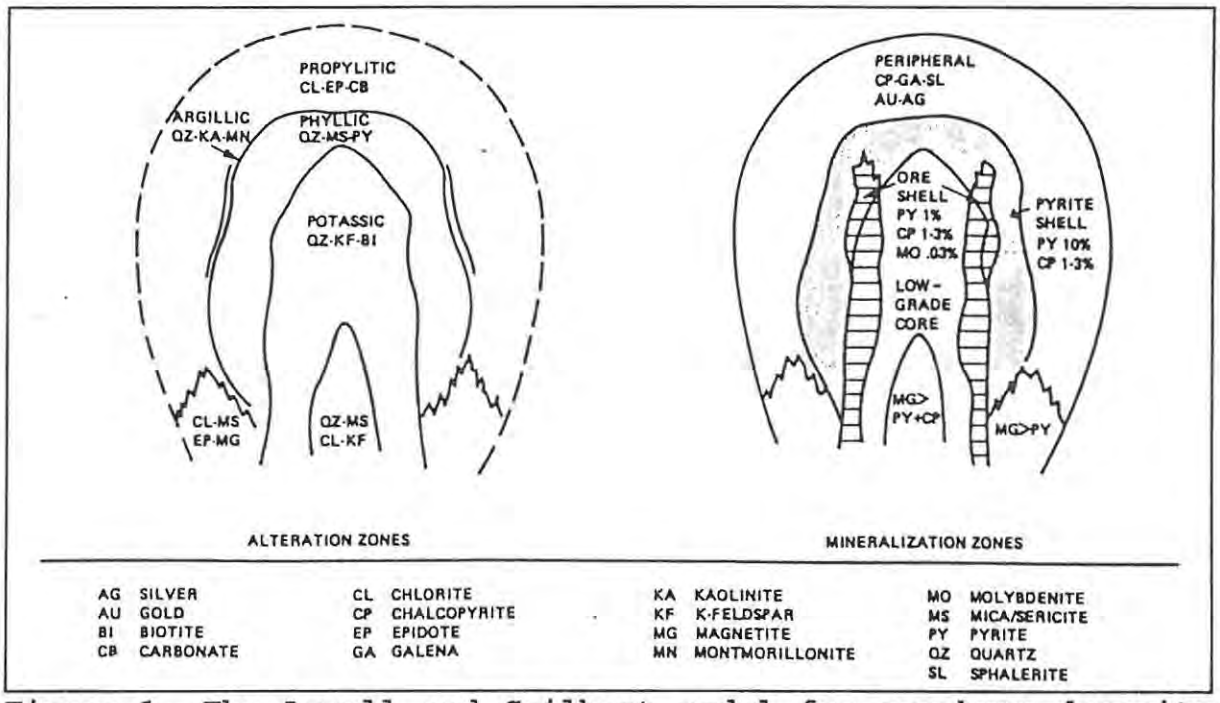


Figure 1. The Lowell and Guilbert model for porphyry deposits indicating the alteration and mineralisation zones (after Lowell and Guilbert, 1970).

They are however unable to predict the properties of mineralisation and the precious metal potential of the system. The sites and controls of base metal and precious metal concentrations, as depicted in mineralisation and alteration models, e.g. Lowell and Guilbert (1970) - Figure 1, are commonly site specific. The observed alteration assemblages (and metal associations) may occur with many variations as a result of multiple igneous intrusions and the telescoping of alteration and mineralising events.

Table I. Characteristics of typical Cordilleran porphyry copper deposits of the three major deposit types (after McMillan et al., 1991).

	Classic (Stock-related)	Volcanic	Plutonic
Setting	Associated with post-orogenic stocks intruding unrelated host rocks; co-magmatic volcanic piles rarely preserved. Cordilleran deposits are of Late Mesozoic to Tertiary age.	In basic to intermediate volcanic piles intruded by comagmatic calcalkalic or alkalic (dioritic or shoshonitic suite) plutons; magmatism produces consanguineous and intimately associated intrusive/extrusive assemblages. Cordilleran deposits are of Mesozoic age.	In large calcalkalic plutons emplaced in or near comagmatic volcanic rocks; plutons typically have mafic borders and are moderately to strongly differentiated. Cordilleran deposits are of Mesozoic age.
Plutons	Multiple phases emplaced as successive, small (0.5 to 2 km²), cylindrical porphyritic intrusions; numerous pre, intra, and post-mineral porphyry dikes; emplaced at shallow depth.	Calcalkalic — very small to small sheets, dikes and plugs (0.2 to 10 km²), with much textural variation; subvolcanic emplacement. Alkalic — high level sheets, dikes and plugs associated with underlying differentiated mesozonal pluton or small batholith.	Batholithic rocks (>100 km²) immobilized at relatively deep levels (2 to 4 km). Phaneritic coarse grained to porphyritic rocks with local swarms of pre to post-ore porphyritic dikes.
Structural Control of Intrusions	Passive, structure need not be significant; many stocks localized by intersections of regional faults.	Calcalkalic — emplacement in volcanic vents, fault zones, radial fractures. Alkalic — intrusive centres localized by regional structures. High level intrusive rocks invade volcanic vents and fault zones.	Diapiric emplacement; magmatic pulses and differentiation cause sharp to gradational internal phase boundaries.
Breccias	Abundant and characteristic; post-ore argillic diatremes are common. Other types present include collapse breccias, intrusive breccias, and carapace or stoping breccias. Early breccias can be mineralized.	Calkalkalic — common and diverse; include primary pyroclastic tephra, alteration pseudobreccias, vent agglomerate, shatter and igneous breccias. Mineralized breccias are characteristic; some contain magnetite or tourmaline. Alkalic — intrusive and volcanic breccias common and generally mineralized, as in calcalkalic types.	Common in association with late-stage porphyry dike swarms. Breccias pre, intra, and late-stage.
Alteration	Potassic, phyllic and propylitic universally developed as annular shells around intrusions; argillic of varying importance. Early developed biotite (EDB) can be part of an isochemical hornfels and has often been misidentified as part of the potassic zone.	Calcalkalic — propylitic is widespread; potassic is more restricted but can be intense; alteration centred on zones of high permeability. Similar to classic type deposits with small core zones of potassic and local phyllic and/or argillic shells. Alkalic — local intense to pneumatolytic potassic alteration; early hydrothermal biotite overprinted by propylitic, then by sodic and/or potassic (albite-K-feldspar) and rarely scapolite alteration.	Phyllic, propy-argillic, and propylitic types are best developed; local potassic alteration. Fracture controlled to pervasive, commonly as alteration envelopes on multistage fractures and veins. Centered on orebodies but patterns of zoning complicated by overprinting.
Orebodies	In margins and adjacent to porphyry intrusion(s) as annular ore shells, or as domal cappings; pronounced lateral zoning. Pyrite is found throughout; the weakly mineralized core is surrounded by zones dominated by molybdenite, then chalcopyrite, and finally, a pyrite halo.	Calkalkalic — generally Cu-Mo deposits intimately associated with breccias and intensely altered rocks; orebodies lensoid and irregular, with some preferential bedding control. Most ores contain chalcopyrite with rare bornite or molybdenite as "dry" fracture fillings. Alkalic — generally Cu-Au deposits in intrusive breccias or in highly fractured country rock; some replace porous country rock. Locally magnetite-apatite of magmatic origin present as vein or breccia infillings; zoning is from chalcopyrite, with or without magnetite, and bornite outward to a pyrite halo.	Large and diffuse vein stockworks; some breccia control, some faults mineralized; sulphides relatively sparse. Zoning is evident with iron content increasing outward from bornite, to chalcopyrite, to pyrite-rich zones; Mo distribution is variable. Some deposits have low-grade quartz-rich core zones.

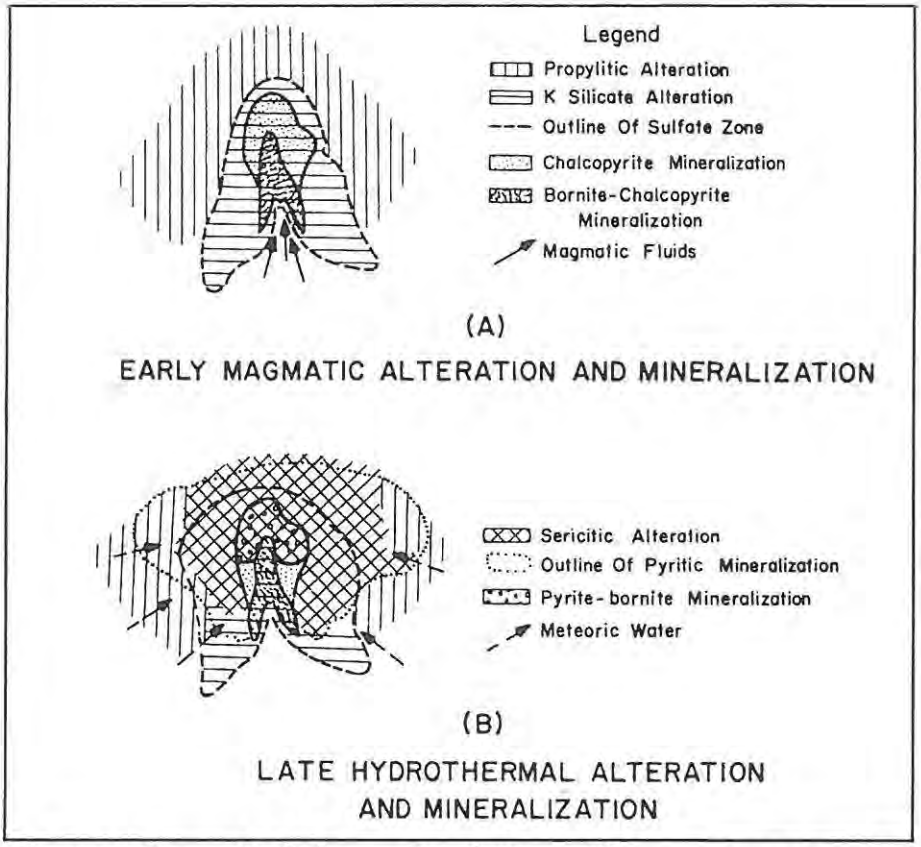


Figure 2. Model showing the stages of alteration and mineralisation about the porphyry system (modified after Gustafson and Hunt, 1975).

The classes or models of porphyry deposits, as outlined by McMillan et al. (1991) for the Cordilleran porphyry deposits, may prove to be more favourable when considering the tectonic setting, pluton composition and size, regional structural controls and the alteration of the various porphyry deposits. These three classes include the "classic", "volcanic" and "plutonic" types (Table I).

The classic deposit types are related to multiple subvolcanic plutons (Figure 4). Dykes and breccias are common and the host rocks may be volcanic or sedimentary. These deposits may be used to describe the Tertiary porphyry deposits in the southwestern United States. Andean-type stage alteration and early developed biotite is characteristic, and the change in colour of the biotite from green in the aureole to brown in the ore zone may be used as an exploration guide (Carson and Jambor, 1974). The main ore zone consists of chalcopyrite and bornite in quartz-filled fractures enclosed in a pyritic halo.

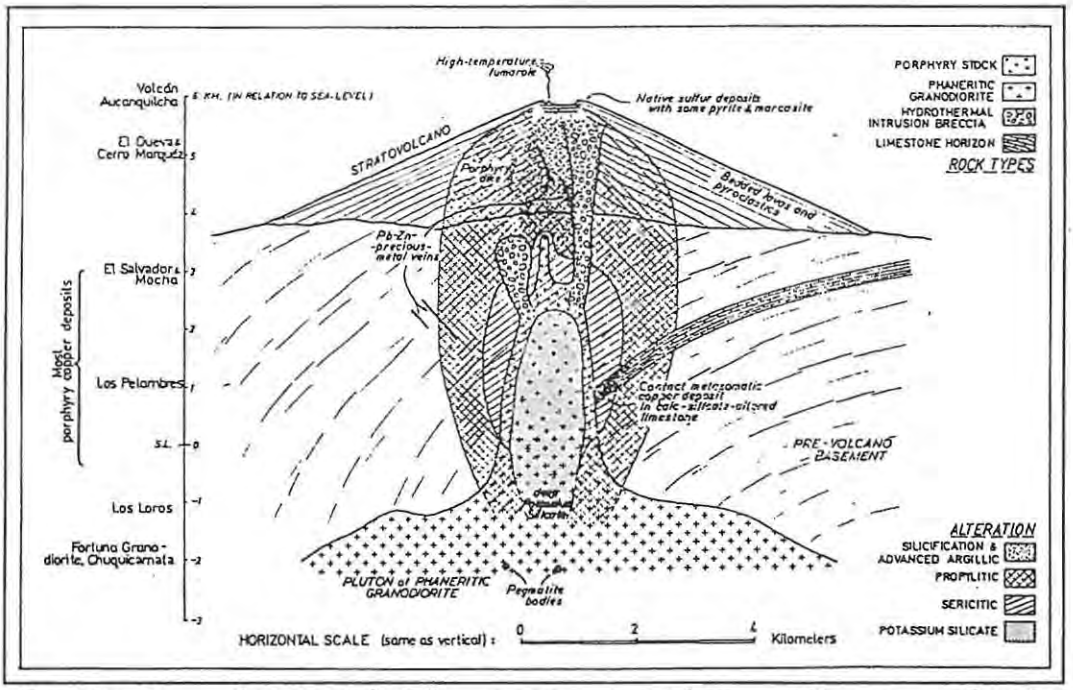


Figure 3. Generalised cross-section of a simple porphyry copper deposit showing its position between plutonic and volcanic environments (after Sillitoe, 1973).

Alteration zoning includes a potassic core with secondary biotite, through a flanking phyllic zone consisting of quartz-sericite-carbonate and pyrite, to a propylitic fringe with chlorite, carbonate and epidote.

Volcanic deposit types are formed in the root zones of ancient calc-alkalic and alkalic volcanoes as stocks, plugs, sills and dyke swarms (Figure 5). The host rocks being largely volcanic, breccias and dykes. Early developed biotite is typical, and the propylitic alteration extends well beyond the pyrite zone out into the country rock.

The plutonic deposit types form at relatively deep levels within plutons of batholith dimensions (Figure 6). The plutons are generally zoned - mafic to felsic, e.g. quartz diorite to quartz monzonite or granite. Mineralisation is very close in age to the plutonism and is associated with the younger phases. Alteration is similar to that of the classic type (but the pyrite halo is weaker). These deposits are generally Cu-Mo sulphide deposits with a low gold content (0.1g/t or less).

Generally gold-rich porphyry deposits are associated with the classic- and volcanic-types

of continental margins or island arcs.

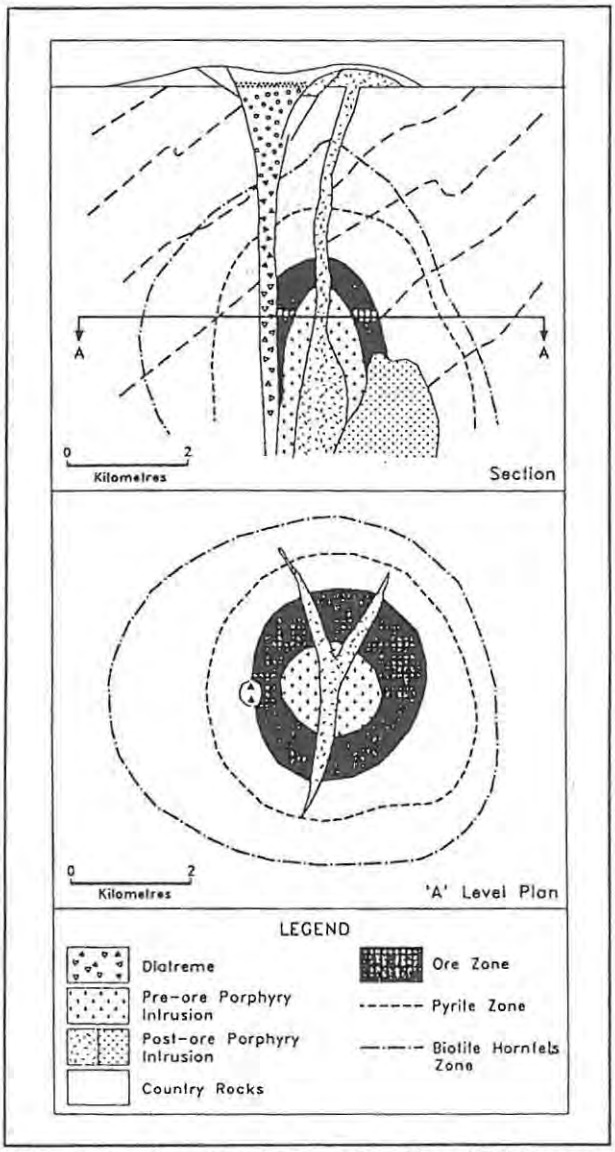


Figure 4. Model of Cordilleran classic-type porphyry copper deposits (after Sutherland Brown, 1976).

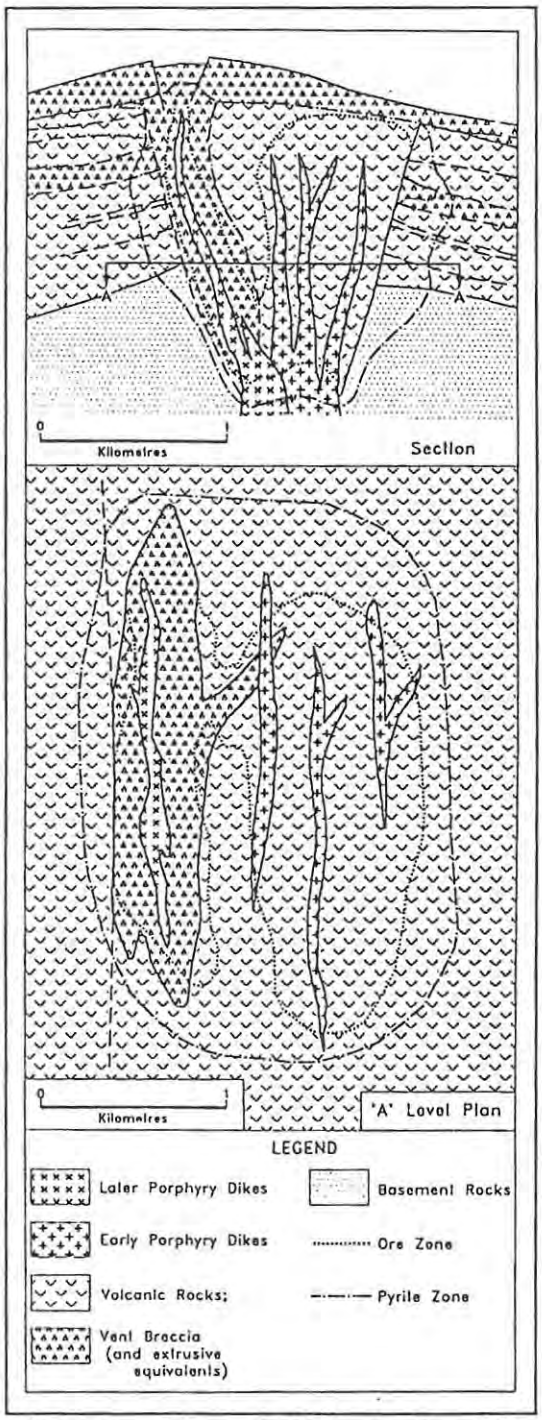


Figure 5. Model of the Cordilleran volcanic-type porphyry copper deposit after Sutherland Brown, 1976).

According to Sutherland Brown (1976), geological mapping and reconstruction indicates a maximum depth of 4km and a typical depth of 2km for porphyry deposits. Porphyry

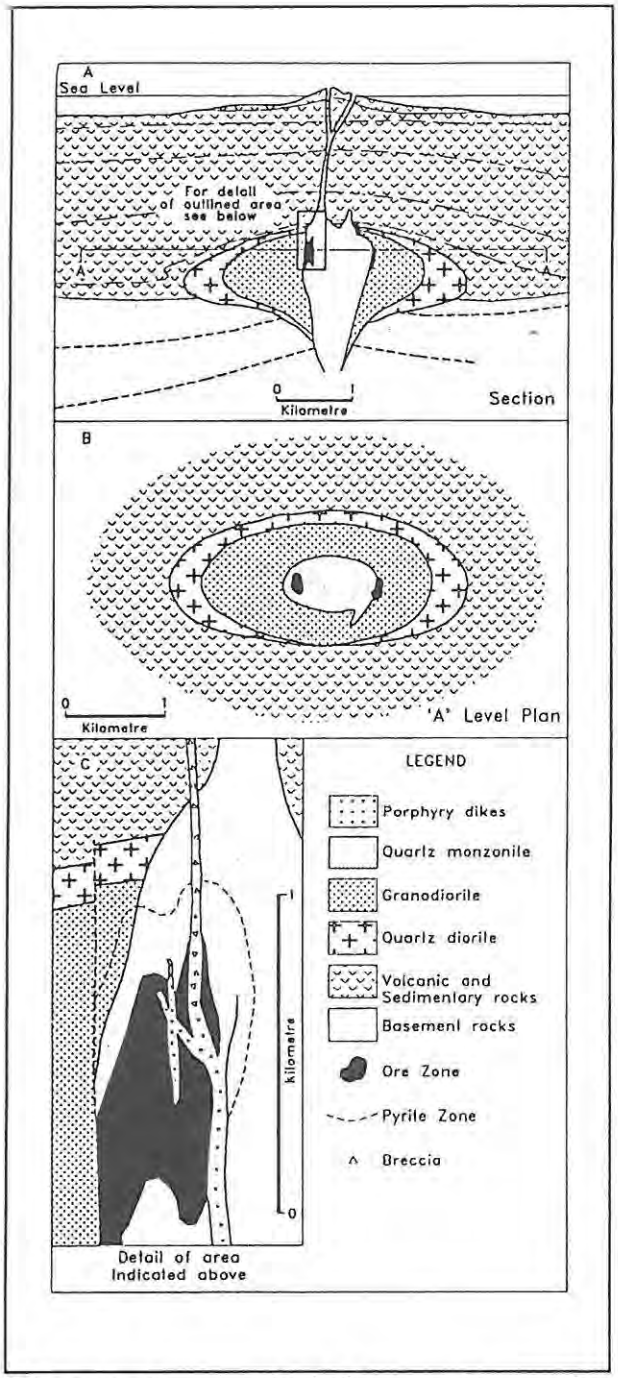


Figure 6. Model of the Cordilleran plutonic-type porphyry copper deposit (after Sutherland Brown, 1976).

intrusions are emplaced as crystal-liquid mixtures that release fluids as the magma crystallises and the confining pressure decreases during magma ascent. The rapid rise of magmas results in sudden cooling and the release of volatiles due to the change from lithostatic to hydrostatic pressure. This may lead to the formation of large hydrothermal systems with large alteration halos, hydrothermal brecciation and intense fracturing in and around intrusions. If the intrusions were saturated or oversaturated with water, the above processes would be promoted. Alteration, brecciation and fracturing would also be enhanced by the incorporation of wallrock fluids, resulting from deep groundwater circulation and metamorphic dewatering.

With respect to porphyry copper deposits, they are formed initially as closed systems which later become open with the large scale introduction of both magmatic and hydrothermal solutions along structural breaks in the rock. These breaks are formed both by regional forces and localised magmatic forces. The regional forces may be important in controlling the location and shape of igneous intrusions, and are evident in orthogonal veins and fault sets. Breccias, random crackling and radial-concentric veins are evidence for the action of magmatic forces. According to Gustafson (1978), the balance between these forces changes from time to time and from place to place within a deposit, particularly as successive intrusions are emplaced. The shifting of intrusive centres, telescoping of igneous events and

the location of fracture permeability during the evolution of hydrothermal activity are important factors controlling whether resultant mineralisation-alteration zoning is concentric, e.g. San Manuel - Kalamazoo, Arizona, or asymmetric as at Panguna, Cabang, Kiri (N Sulawesi) and Koloula.

As a result of porphyry copper(/gold) mineralisation being disseminated over large volumes of rock, it is amenable to large-scale bulk mining methods. On a microscopic scale it is usually possible to see that most of what appears to be disseminated mineralisation is actually fracture controlled. Breccias are characteristic features, often intrusive into host rocks and have a clastic, igneous or mineralised matrix.

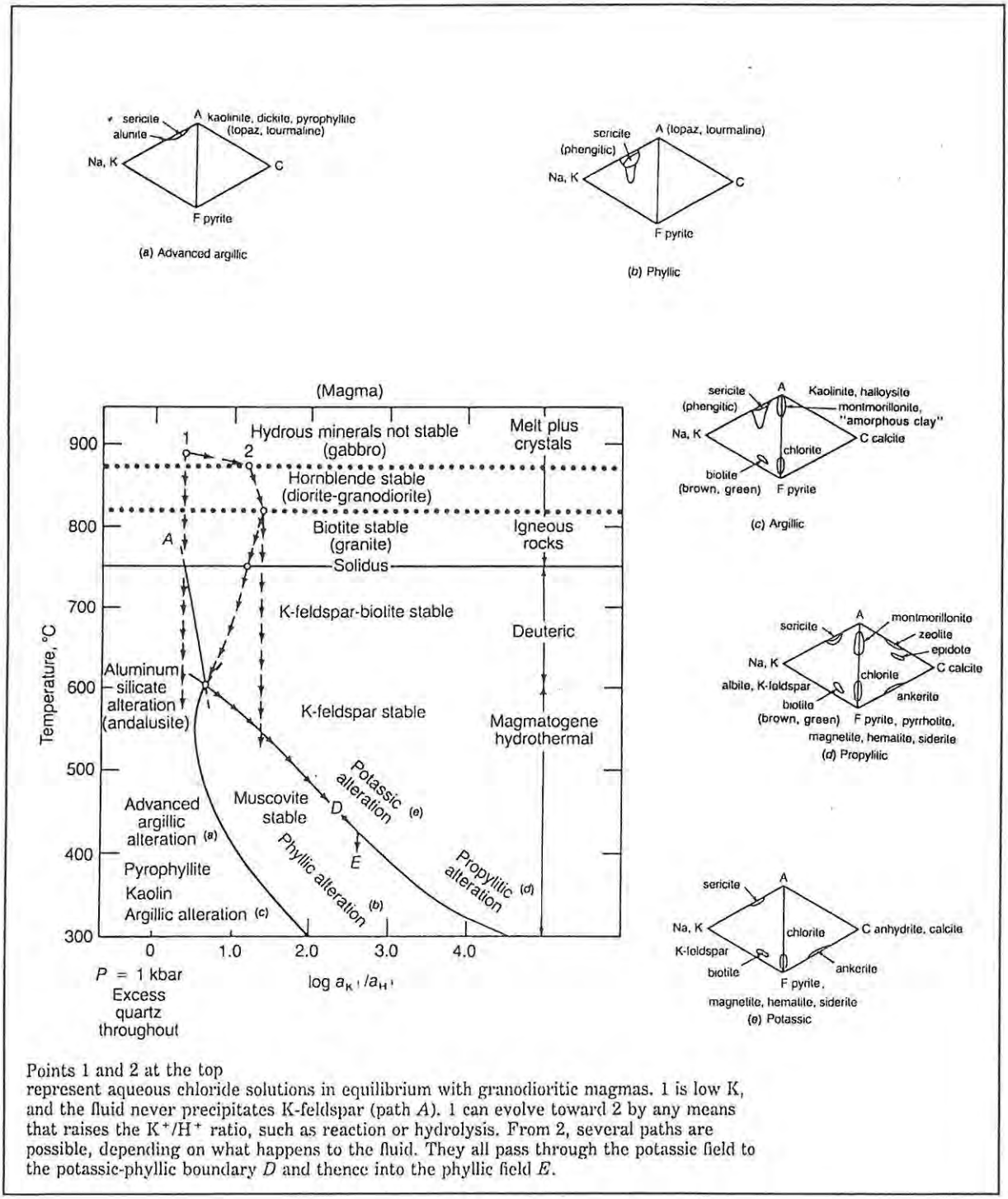
2.2 Alteration and Mineralisation within Porphyry Systems

Alteration and mineralisation result from the complex interplay of mechanical, magmatic and hydrothermal processes in and around the porphyry body. The physical and chemical conditions of ore, alteration and mineral deposition change through the geologic history of the system. The degree of conversion of original rock to alteration assemblages, ranges from local and partial replacement of selected minerals to the complete conversion of all original minerals (Titley, 1982).

The nature of the host rocks controls the alteration minerals produced under changing thermochemical conditions. This, together with the mechanical and compositional characteristics of the rock, influences the evolutionary style of alteration and mineralisation. Furthermore, the weathering conditions affect the nature and expression of alteration and mineralisation within the weathered zone. A discussion of leached cappings and their use in predicting copper grades in porphyry copper exploration is outlined in section 2.3.

Hydrothermal alteration associated with porphyry systems is essentially a base leaching process related to hydrolysis. This is controlled by the metal ion to hydrogen ion ratio in the altering solution. Factors which influence this leaching process include; pressure, temperature, water to rock ratio and fluid and country rock composition. If, as reported by McMillan et al. (1991), the ionic ratio of potassium and sodium to hydrogen is low, then minerals such as feldspars, micas and other K-, Na- and Ca-alumino silicate minerals will

be unstable and begin to alter (Figure 7).



Points 1 and 2 at the top represent aqueous chloride solutions in equilibrium with granodioritic magmas. 1 is low K, and the fluid never precipitates K-feldspar (path *A*). 1 can evolve toward 2 by any means that raises the K^+/H^+ ratio, such as reaction or hydrolysis. From 2, several paths are possible, depending on what happens to the fluid. They all pass through the potassic field to the potassic-phyllic boundary *D* and thence into the phyllic field *E*.

Figure 7. Diagram showing variations in m_{KCl}/m_{HCl} of magmatic chloride solutions and the major types of wall rock alteration expressed on AKF and ACF diagrams (modified after Burnham and Ohmoto, 1980, Meyer and Hemley, 1967 and Guilbert and Park, 1986).

Furthermore, boiling and magmatic vapour saturation can also lead to acid solutions being formed, resulting in argillic alteration. Fluid inclusion data from these porphyry systems indicate that the solutions are sulphur and chlorine rich.

In an idealised model such as that proposed by Lowell and Guilbert (1970), alteration is portrayed as a series of shells around the porphyry intrusion (Figure 1). From the core of the intrusion outwards, the following alteration patterns were recognised :

- Barren core - quartz, muscovite, chlorite and K-feldspar.
- Potassic zone - quartz, K-feldspar, biotite, muscovite, anhydrite.
- Phyllic zone - quartz, muscovite and pyrite.
- Argillic zone - quartz, kaolinite and chlorite.
- Propylitic zone - chlorite, epidote, carbonate, albite and adularia.

In reality, hydrothermal systems should be seen as being dynamic, and as they cool the system may collapse downward resulting in younger alteration overprinting and destroying older alteration, e.g. early potassic and propylitic alteration overprinted by phyllic and later argillic alteration. An example of this is at Silver Bell in Arizona and Escondida in Chile, where quartz and sericite (phyllic alteration) has pervasively overprinted the potassic zone (pers. observ.).

Alteration associated with two main petrochemical classes of porphyry deposits may have different alteration patterns. The calc-alkaline deposits have alteration patterns like those described from the southwestern United States. Alteration associated with alkalic deposits also have a central potassic zone, or albitic plagioclase envelope. These alteration zones may be overlapping, and according to McMillan (1992) alteration is patchier and no phyllic zone is developed (Figure 8). According to Lowell (1989), the alkalic deposits tend to have gold enrichment in the potassic core zones and are related to high level intrusions.

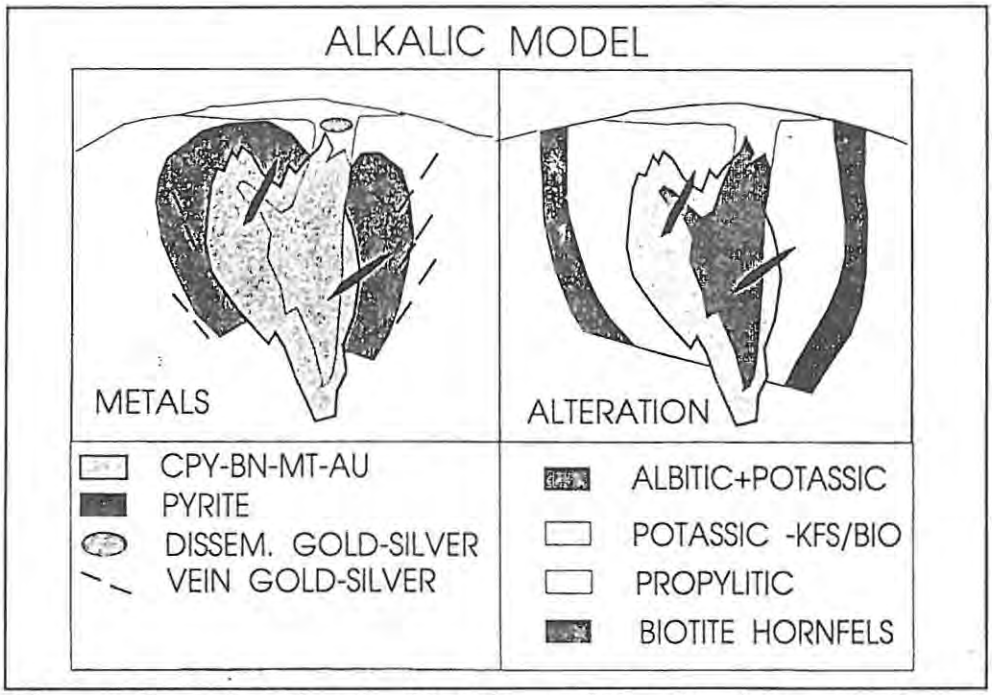


Figure 8. Idealised alkalic model showing metal and alteration zonation (after McMillan, 1992).

In the porphyry system, potassic and flanking propylitic alteration form early (Figure 9). In the potassic zone, minerals are unstable, and quartz, biotite, intermediate plagioclase and K-feldspar are typical alteration phases, while anhydrite and hornblende occur locally. The alteration process in the propylitic zone occurs under weak hydrolysis. Quartz and potassic feldspar are stable, but plagioclase, generally of intermediate composition, alters to a mixture of albite, epidote, carbonate and montmorillonite. The mafic minerals are replaced by epidote and chlorite, or less commonly by actinolite and tremolite. Argillic and phyllic alteration precede the earlier two phases, and represent increasing intensity of hydrolysis. Quartz, kaolinite, chlorite and lesser mixed-layer clays form within the argillic zone. With intense hydrolysis, advanced argillic alteration may overprint the other phases and the mineral assemblage will include quartz, pyrophyllite, kaolinite, dickite and sometimes andalusite.

Typical metal zonation within the porphyry system is indicated in Figure 1. Here, a copper ore shell is flanked by a pyrite shell, a low pyrite shell and a peripheral lead-zinc, gold zone. Today it is recognised that porphyry deposits in the world may display some of the following metal zonation characteristics as indicated by Jones (1992). Jones (1992) recognises the following possible metal zones as determined from the Bingham district:

Barren core - molybdenum - bornite and gold - chalcopyrite - pyrite with gold in shear zones - lead, zinc and silver - gold/silver veins - disseminated to replacement epithermal gold in distal areas (Figure 10).

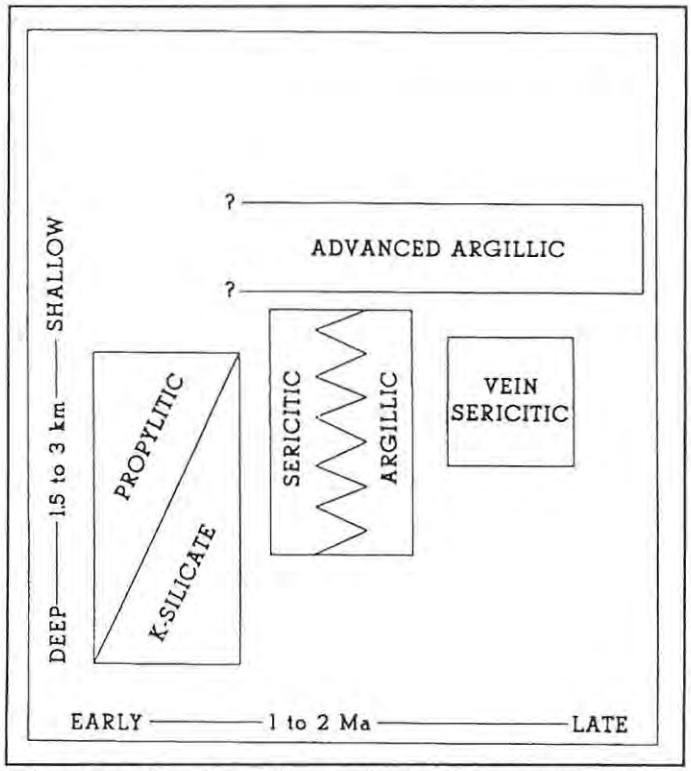


Figure 9. Depth and time model for alteration related to porphyry copper-gold deposits (after McMillan, 1991).

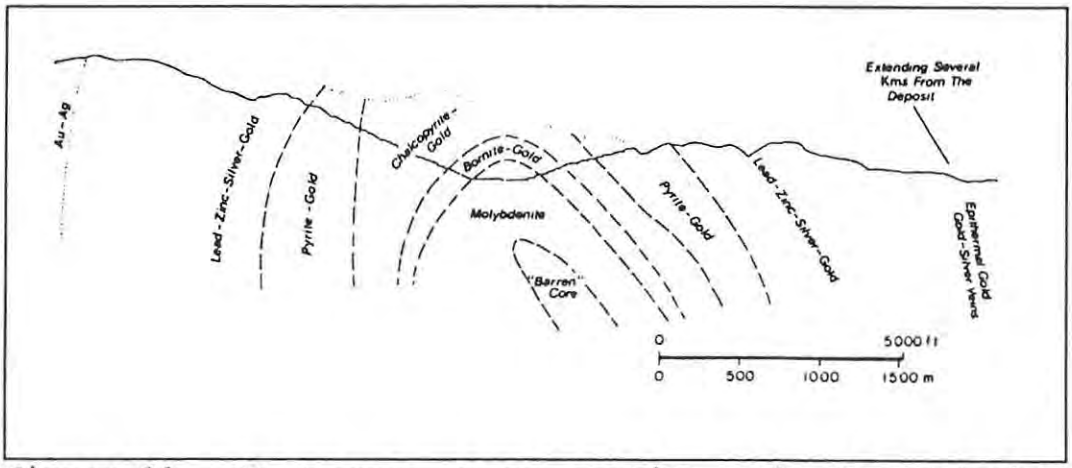


Figure 10. East-west cross-section of the Bingham district, Utah, showing generalised metal zones (from Jones, 1992).

2.3 Leached Cappings

Oxidation and leaching of sulphide-rich deposits, such as porphyry copper-gold deposits, results in the formation of limonite minerals which are portrayed on surface in various forms (Plates 1 and 2). The oxidation and solution of sulphide minerals results in cellular pseudomorphs forming as a result of the precipitation of ferric oxide hydrates (Blanchard, 1968).

The characteristics of the original sulphide minerals are portrayed in the cellular structure and texture of the limonite products. For example, the limonite formed and the structures preserved after the leaching of chalcopyrite will differ from that developed after leaching of pyrite or bornite (Figures 11, 12 and 13).

Plate 1. Leached capping from the Morenci porphyry copper mine, SW United States.

Plate 2. Leached capping from the El Hueso porphyry copper-gold district, Chile.

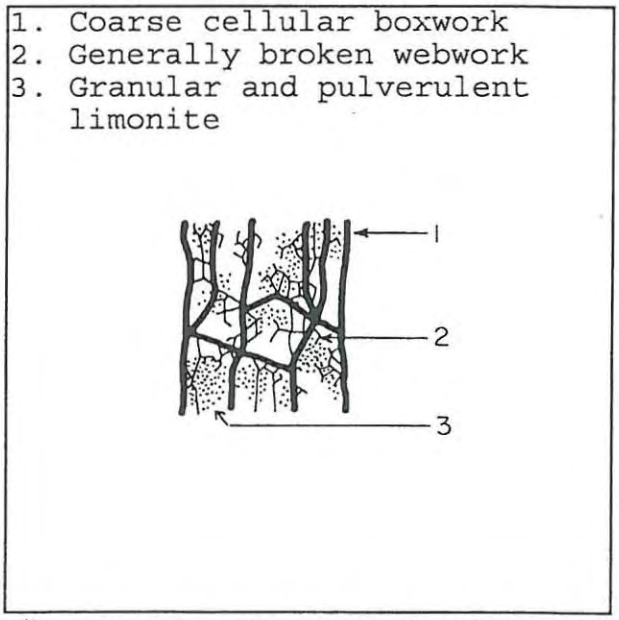


Figure 11. Characteristic cell pattern of limonite after chalcopyrite (after Blanchard, 1968).

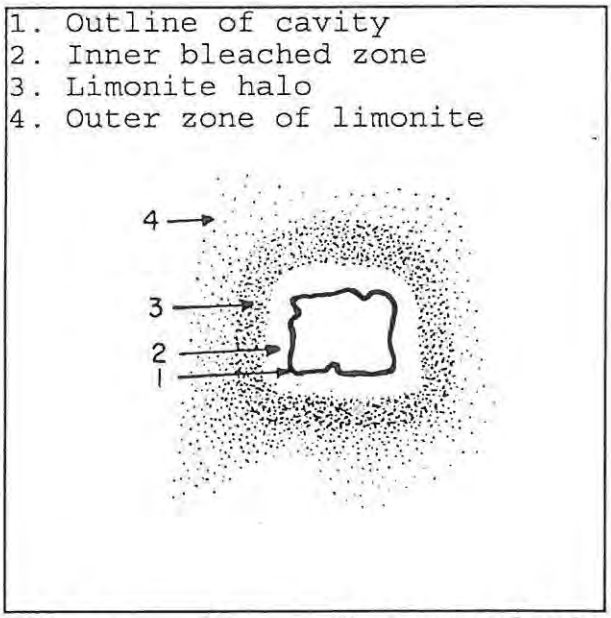


Figure 12. Characteristic oxidation products of pyrite (after Blanchard, 1968).

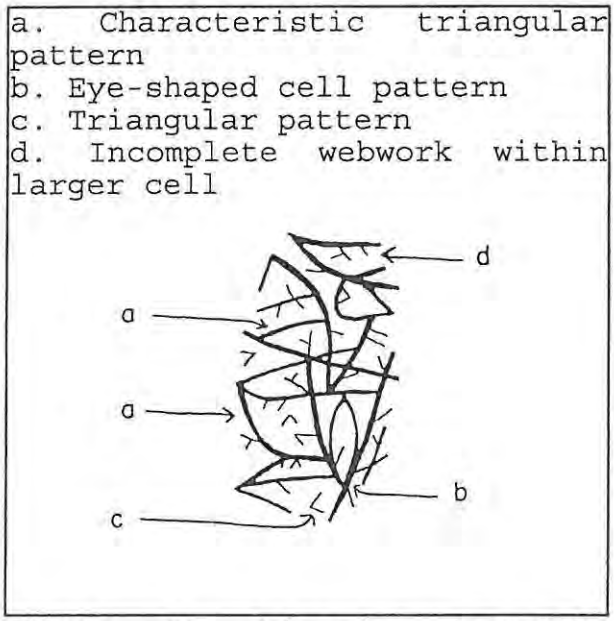


Figure 13. Limonite boxworks derived from bornite (after Blanchard, 1968).

The degree of leaching is controlled largely by the sulphide content of the deposit and the degree of oxidation and acid production. The presence of pyrite in such deposits is for example, an important source of sulphur and iron, and may cause high acidity in the oxidising solutions which are promoted in tropical and semi-arid climates, e.g.

$$4FeS_2 + 7H_20 + 14\ ½O_2 \rightarrow 2H.FeO_2 + 6H_2SO_4 + 2FeSO_4$$

The pH conditions and the expected copper potential can be determined from the percentage of hematite : goethite in the leached capping and the copper minerals which are camouflaged in the co-precipitating limonite (Anderson, 1982). For example:

a) A high goethite content indicates weak acid leaching, no secondary enrichment of copper, and antlerite [$Cu_3(OH)_4SO_4$], brochantite [$Cu_4(OH_6)SO_4$] and cuprite (Cu_2O) may be evident in the capping.

b) A high hematite and/or jarosite content indicates strong acid leaching, possible secondary enrichment of copper at depth, and minerals such as pitch limonite [$H(Fe,Cu)O_2$], neotocite [$(Cu,Fe,Mn)SiO_2$] and more rarely turquoise ($CuO.3Al_2O_3.2P_2O_5.9H_2O$) may be evident in the capping.

Neotocite cappings have been documented to have formed over deposits with chalcopyrite ratios ranging from 9.0 to 0.5 (Anderson, 1982). This is important to identify when doing porphyry copper exploration.

Minerals commonly found in leached cappings are attached in Appendix 1.

2.4 Age Distribution of Porphyry Ore Deposits

From radioactive charting, it has been established that PCDs have possibly formed from 1 Ma ago to 2 Ga ago, e.g. Haib in Namibia, and are probably forming at present (Hunt, 1991). According to erosion and exposure factors, Meyer (1985) has concluded that the richest and largest PCDs, and probably the majority, formed during the Phanerozoic e.g:-

DEPOSIT	Age (Ma)
Ray	70 - 60
Dos Pobres	60 - 69
Morenci	67
Bingham	37 - 38
Ok Tedi	1 - 2
Panguna	3 - 4
Grasberg	3.1

(see Table III - Appendix 1 for ages of some principal copper-gold deposits).

As outlined above, these PCDs were emplaced at intervals throughout the Mesozoic and Cenozoic, with a large number of deposits being of late Cretaceous-Palaeogene age.

According to Sillitoe (1972), the following factors control the space-time distribution of porphyry ore deposits :

- The level of exposure - largely dependent on the erosion rate.
- The time and location of magma generation, and the quantity of metals incorporated in magmas on a subduction zone.

With the exception of a few PCDs, e.g. in Uzbekistan and Kazakhstan, Eastern Australia and Finland, PCDs are not characteristically reported from older orogenic belts. This apparent absence has been tentatively attributed to the effects of Mesozoic-Cenozoic erosion, which has removed the upper parts of batholiths, the loci for PCDs. However, PCDs may be encountered in pre-Mesozoic origins where the erosion has been less severe.

If erosion does play a major part in PCDs being preserved, then PCDs in the SW Pacific Belt, with a tropical climate and high erosion rate, may be expected to yield a predominance of younger ages.

The distribution of ages may be explained by the lateral and secular pattern of magma generation, and the availability of metals on subduction zones. Data presently available suggests the periods of porphyry copper (PC) formation in Chile were separated by quiescent intervals with durations of about 15-25Ma (Sillitoe 1972). There are also

similarly reported pulse-like igneous intrusions in W North America, with pulses lasting approximately 10-15Ma, and separated by 30Ma intervals. Therefore, the changes in relative motion of plates every 10-20Ma in the NE Pacific, as deduced by Francheteau, Sclater and Menard (1970), might be significant in controlling the emplacement and ages of PCDs.

Furthermore the position of oceanic ridges, rifts, seamounts and other upwelled zones in relation to subduction zones may also be responsible for the "metal budget" and the location of porphyry districts. However, if the locus of magma generation on a subduction zone does not migrate systematically with time, then no clear pattern of PC ages is to be expected e.g. random ages in British Columbia (BC).

According to Sillitoe (1972), theories invoking the extraction of copper from the continental crust or upper mantle fail to account for the concentration of most of these PCDs within a limited time period.

2.5 The Tectonic and Structural Setting of Porphyry Deposits

Porphyry deposits are found in the following three tectonic settings:

- Island Arc
- Continental arc/margin
- Continental setting/craton.

The tectonic setting of major ore deposit types has been described by numerous authors, viz. Sawkins (1984) and Mitchell and Garson (1981). From this and other work the roles of magma-type and ore deposition styles in the many lithotectonic terranes have been established. However, as a result of exploration and discoveries in the past it has been highlighted that porphyry copper deposits are much more diverse than was previously thought. This applies to the wide range of host rocks related to different tectonic settings e.g calcic-diorite rocks at Panguna, calcic-alkalic granodiorite rocks mostly in the western United States, alkali shoshonitic rocks, e.g. OK Tedi and even Ne-normative alkalic syenite rocks in Stikine, British Columbia.

From this it has been suggested that calcic-diorite rocks seem to be characteristic of island arc magma systems developed on oceanic crust. Calc-alkalic and alkalic-calcic granodiorite to quartz monzonite associations are developed in continental margin settings. The association and variation of metals, viz. gold - copper - molybdenum within various settings and host rocks generally appears to be true. This may have important genetic implications regarding the source and evolution of porphyry systems and the focusing of exploration activities.

It has been suggested by Keith (1978) and Westra and Keith (1981), that the geographic distribution of variations in Cu-Mo-Zn-Pb-Au in the North American PCDs may be related to the changes in the angle of plate subduction and to distance from the trench to the arc orogen hearth of magmatic activity. Recent discoveries in Argentina, east of the porphyry Cu-Mo deposits of Chile, tend to corroborate those findings.

Generally PCDs are related to Mesozoic-Cenozoic orogenic belts, and active lithospheric plate-boundaries. Many are in island arc rocks in the circum-Pacific orogenic belts, and the central portion of the Alpide orogenic belt (Figure 14).

In these orogenic belts, copper deposits are related to high level calc-alkalic or alkalic porphyry intrusions of intermediate composition.

The western Americas belt, continental margin, and accreted island arc terranes, containing most of the world's porphyry deposits (Sillitoe, 1972), extends from western Argentina and central and northern Chile, through Peru, Ecuador, Panama, Mexico, the western USA to British Columbia, the Yukon and Alaska (Plan 1 - Appendix 2).

Marked concentrations of PCDs occur in Sonora, Arizona, New Mexico and in British Columbia. PCDs in the Dominican Republic and Puerto Rico are considered to be an offshoot of the western Americas belt. Other belts hosting PCDs include the Taiwan, Philippines, Borneo, West Irian, Papua New Guinea, and the Solomon Islands region (SW Pacific Belt) and in the South Barat district of Romania, Yugoslavia, central Bulgaria, Armenia, Iran and West Pakistan (Alpide Belt). PCDs outside of these post-Palaeozoic orogenic belts are those in Uzbekistan and Kazakhstan and the Eastern Australian porphyry

copper province (Plan 1-Appendix 2).

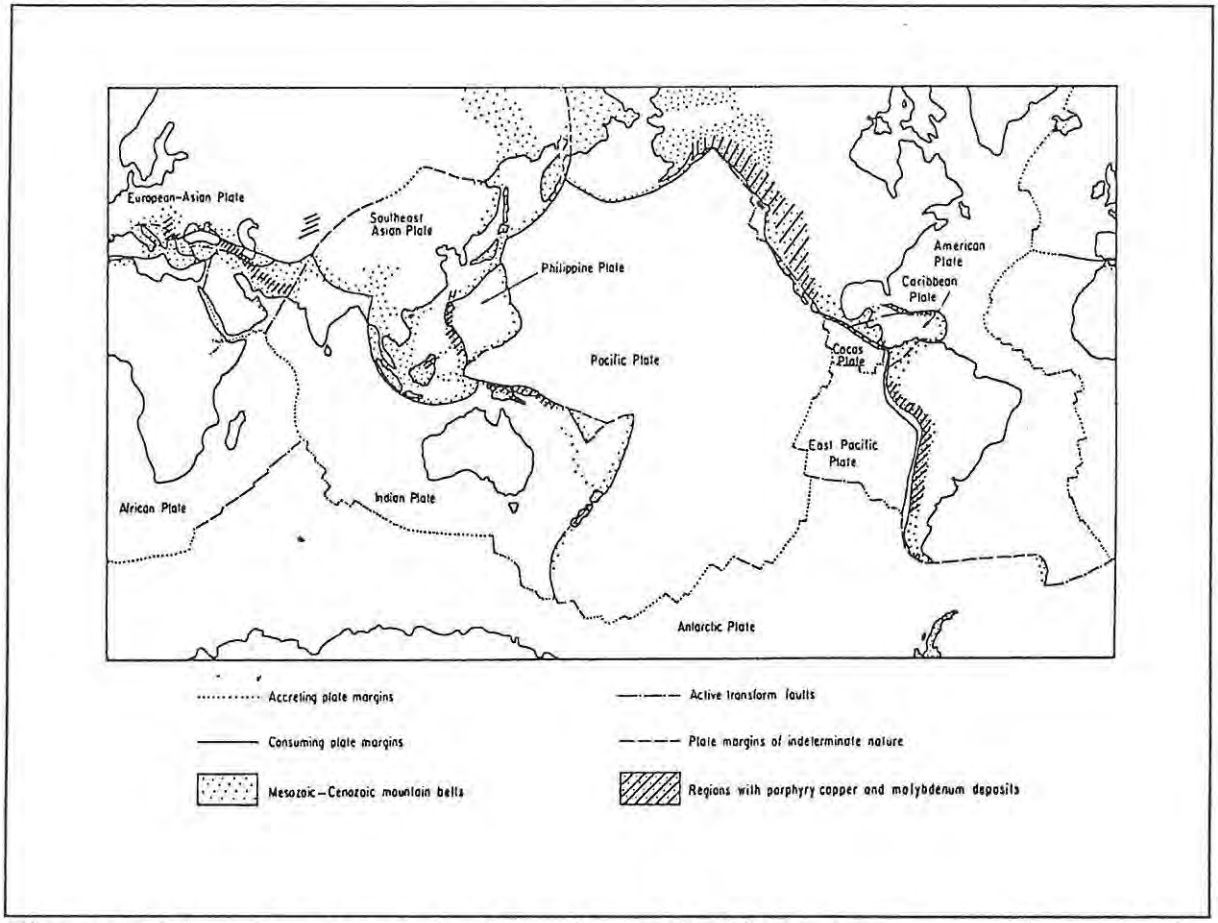


Figure 14. Porphyry belts in relation to consuming plate boundaries (after Sillitoe, 1972).

The time intervals during which the formation of porphyry deposits took place are shown to be broadly coincident with periods of lithospheric plate convergence, and porphyry deposits may still be forming above currently active subduction zones.

Gustafson (1979) suggests that a wide range of orogenic calc-alkaline magmas generated from a range of source areas and diverse mechanisms (not necessarily active subduction) are capable of forming porphyry copper deposits. He proposes that the history of volatile evolution during the rise of magmas through the crust is the critical factor, and only melts that avoid separation of the CO_2-rich fluid phase may reach shallow crustal levels with enough sulphur and metals to produce significant concentrations in cupola areas.

A few authors who have written on the regional setting of porphyry copper deposits include : Titley (1972, 1975, 1982), Sillitoe (1972), Kesler (1973), Hollister (1974), Lowell (1974), Kesler et al. (1975), Titley and Beane (1981). According to Hunt (1991), most of these more recent authors have emphasised the apparent association of PCDs on a world wide scale, with calc-alkaline and alkaline magmas and andesitic volcanism, especially at convergent tectonic plate boundaries. Lowell (1974) questioned the relevance of plate tectonic mechanisms for the generation of certain SW United States porphyry copper deposits. He emphasised their apparent correlation in size with times of continental emergence.

Identification of structural controls guiding the emplacement of ore rich porphyries has not been successfully accomplished. Even the 1 Ma old OK Tedi deposit has not provided answers to the structural control. However, the cluster of 35-40 Ma old PCDs in Northern Chile which extend along a mappable and specific fault zone, the West Fissure, are possibly the only exceptions which provide information on the structural control.

2.6 A Discussion of the Differences in Composition of Porphyry Deposits of Continental Settings vs Island Arcs

The differences in composition of PCDs in continental arc/margin setting and those in an island arc setting remain a matter of speculation. These differences have been suggested by Kesler (1973) to possibly be related to differences between the respective igneous progenitors.

Molybdenum enriched PCDs in continental settings, may reflect the greater complexity of continental rocks across which intrusions have penetrated or, as proposed by Hollister (1977), an intrusion across thickened sialic crust. Deposits of island arcs may reflect a closer relationship with parent basalts with less crustal contamination than deposits in continental settings. Relatively higher gold contents may be related to the high gold content of certain igneous rocks/basalts (Krauskopf, 1967). Keays and Scott (1976), also suggest that under certain conditions, such rocks might be the source of some epigenetic gold mineralisation.

Titley (1978) however, proposed that factors other than the geologic-geotectonic setting must be responsible for the variation in the metal contents of deposits in the arc vs continental settings. For example, OK Tedi and Ertsberg are copper deposits high in gold, but interpreted as lying above the N edge of the Australian continental block. The Yanderra deposit however is enriched in molybdenum, and lies within rocks of the mobile belt of New Guinea, presumably above rocks of oceanic affiliation rather than continental rocks.

Titley (1978) also suggested some relationship between Au:Mo ratios and the age of porphyry copper deposits. Relatively lower Au to Mo ratios are the phenomenon of some older deposits which are not regionally restricted, nor are they relatable to specific wall rocks.

Compositional variations therefore seem not to be controlled solely by wall rocks or by any particular group of unique geological parameters related to the process of ore deposition. According to Titley (1978), there may be a crude correlation with age or with depth of erosion. Differences in composition with age may relate to primary vertical zoning and depths of erosion. Vertical zoning of metals has been reported from a few porphyry copper systems. Molybdenite overlaps copper but extends below it at Bingham (James, 1971 and Babcock, et al., 1992). Gold diminishes perceptibly with depth in some deposits of the Philippines (Titley 1978). These observations have been suggested by Titley (1978) to possibly be related to primary hydrothermal processes as well as to post-ore history and possibly to primary properties of the parent to porphyry melts.

The most common type of intrusive rock associated with porphyry copper deposits in the continental areas of SW U.S.A., N Mexico and W South America, are granodiorites and quartz monzonites (Stringham 1966, Hollister 1973, and Creasey, 1966). Deposits described from island arc areas such as the Philippines, New Guinea, Solomon Islands and Puerto Rico, by authors such as Wolfe (1973), Titley (1973) and Cox et al. (1973), have drawn attention to the dominance of quartz diorite related ore deposits.

Although most of the mineralised arc intrusions are quartz diorites, the potassic intrusions of quartz monzonites and syenites have lower-K than their craton counterparts. Island arc intrusions also appear to be depleted in lead and rubidium and the $^{87}Sr/^{86}Sr$ ratios are 0,705

or less, which is lower than those for cratonic settings (Figure 15). Copper, and possibly zinc, are enriched in the island arc intrusions.

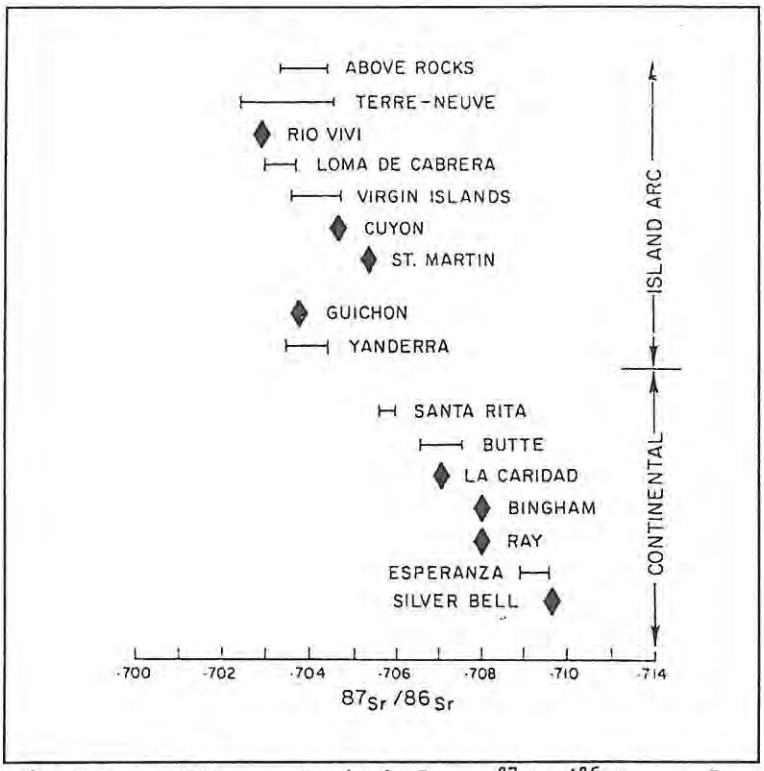


Figure 15. Initial $^{87}Sr/^{86}Sr$ for intrusive rocks associated with porphyry copper mineralisation in island arc and craton environments (after Kesler, Jones and Walker 1975).

Generally, geochemical data indicate that island arc PC related intrusions are compositionally more primitive than their craton counterparts.

Not withstanding the occurrence of significant Mo values in some island arc porphyries, e.g. Yanderra and Yau Yau, Titley (1978), and Sillitoe (1979), suggest it is generally true that deposits generated in island arcs tend to be richer in gold and poorer in molybdenum than those in continental margin orogenes. This generalisation does not however suggest that geotectonic setting is the critical factor controlling Au:Cu and Mo:Cu ratios in PCDs.

Local factors related to the evolution of porphyry systems, e.g. oxygen fugacity, water content, composition of the magmatic fluids and depth of emplacement, may account better for the evolution of the gold-rich nature of certain PCDs. These factors possibly controlling gold-enrichment will be discussed in Part B on porphyry copper-gold deposits. From

Sillitoe's (1979) paper, it is asked why a higher than normal fO_2/fS_2 in the magmatic environment is proposed to be more suitable for gold concentration ?

Moreover, why should gold-rich porphyry deposits and hence fO_2/fS_2 appear to be more prevalent in island arc environments than those at continental margins ? It is suggested that this may be due to conditions;

- prevailing in the underlying subducting plate,
- affecting magma composition during their ascent,
- influencing the in-situ differentiation and crystallisation of magma bodies and the separation of a hydrothermal fluid phase.

If the second alternative is accepted, then Sillitoe (1979) suggests island arc magmas would have a greater chance of having a higher oxygen fugacity than those emplaced at continental margins. However this does not account for the few hundred fold difference in gold content between closely spaced, possibly co-magmatic stocks at Saindak, Pakistan. This may therefore support Tillings et al.'s (1973) conclusion, for gold deposits in general, that geochemical conditions of gold transport and deposition are the major factors controlling the concentration of gold.

In the following chapters the porphyry copper-gold system will be discussed in more detail with respect to many of the characteristics introduced in the above section.

PART B

3. GOLD-RICH PORPHYRY COPPER DEPOSITS.

3.1 General

According to Sillitoe (1988), a spectrum of gold and/or silver deposits may be generated as part of the porphyry copper and molybdenum systems. Gold in porphyry copper deposits may be viewed, according to Hunt (1991), in terms of its timing in the system. Apparently gold is both early and late, and related to magmatic and/or circulating meteoric waters. Early gold mineralisation is closely associated with the potassic alteration zone and bornite. Late mineralisation, derived from circulating hydrothermal and meteoric waters, is associated with pyrite and either sericitic, advanced argillic or skarn- destructive argillic alteration. Furthermore, the spectrum of porphyry deposit types may be characterised by the types of magmatism, palaeotectonic environments and some general geochemical associations as illustrated for example in Table II.

From Table II the gold-copper porphyry deposits are seen to be closely related to island-arc volcano-plutonic suites, composed of basalt-andesite volcanic and gabbro-diorite-quartz-diorite associations (Zvezdov et al., 1993). These deposits are also associated with the diorite model proposed by Hollister (1975).

Precious metal deposits, which may occur within, around or above porphyry copper deposits, are often amenable to bulk mining, and the economic incentive in looking for these deposits is attractive. For example, Grasberg is expected to produce 1 billion tonnes of copper and 48t of gold annually by the year 1996 (Mining Record, Oct. 20, 1993). Precious metal deposits associated with the original porphyry (copper) system, have accounted for important sources of gold in the circum-Pacific region, e.g. 26 major deposits containing greater than 7000 tonnes of gold (Sillitoe, 1990).

Table II. Porphyry deposit types (modified after Zvezdov, et al., 1993).

Essentially porphyry copper and gold-copper porphyry	Gold-bearing porphyry molybdenym-copper	Gold-containing porphyry copper-molybdenum	Porphyry molybdenum
Main ore-forming minerals			
Pyrite, chalcopyrite, magnetite, hematite, bornite (pyrrhotite)	Pyrite, chalcopyrite, molybdenite (bornite, magnetite, galena, sphalerite)	Pyrite, chalcopyrite, molybdenite, bornite (sphalerite, galena)	Pyrite, molybdenite, chalcopyrite, (scheelite, cassiterite)
Geochemical peculiarities of ore			
Cu/Mo ratio in primary ore			
200:1–250:1 and greater	30:1–200:1	15:1–40:1	1:1–20:1
Cu/Au ratio			
8500:1–75,000:1	10,000:1–200,000:1	75,000:1 and greater	more than 200,000:1
RE content in molybdenite (g/t)			
600–1500 (up to 1800)	200–1000 (up to 1600)	from 50–200 up to 800–1000	50–550
Associated mineralization			
Pb–Zn	Pb–Zn–Ag	Pb–Zn–Ag	Sn–W
Composition of hydrothermal alterations and their zoning[1]			
S–B–P, S–A–P, B–P	K+B–S–A–P, B–S–A–P, S–A–P	K–B–S–A–P, K+B–S–A–P	K–S–A–P, K+B–S–A–P
Ore-bearing intrusion associations			
Gabbro-diorite-quartz-diorite (plagiogranitic), sodic	Gabbro-diorite-granodiorite, potassic-sodic	Diorite-granodiorite-monzonite, sodic-potassic	Diorite-granodiorite-granite, potassic
K_2O/Na_2O ratio			
0.1–0.4	0.5–0.8	0.9–1.2	1.2
Granitoid series			
I	I	I–S	S
Index values: $S/I = Al_2O_3/(Na_2O+K_2O+CaO)$			
0.6–0.9	0.7–1.0	0.8–1.1	0.9–1.3
Geochemical characteristics (content in g/t)			
Rb: 100	no data	200	200–800
Sr: 500–100	no data	400–1200	125
Nb: 5	no data	20	25–200
After Titley and Beane, 1981			
$^{87}Sr/^{86}Sr$: 0.705	0.703–0.707	0.706–0.710	no data
Geotectonic position			
Late synclinal basaltic volcano-plutonic belts	Orogenic andesite volcano-plutonic belts		
	On basic substratum	On sialic-basic substratum	On sialic substratum
Deposit models			
"Diorite" (after Hollister, 1975)	"Granodiorite"	"Monzonite" (after Lowell and Guilbert, 1970)	"Granite"
Deposits			
Salavatskoye (RF), Panguna (Papua-New Guinea)	Kounrad (Kazakhstan), Erdentuin-Obo (Mongolia)	Peschanka (RF), Bingham (USA)	Sorskoye (RF), Climax (USA)

[1]From the centre towards the periphery: K—potash feldspathization, B—biotitization, S—Sericitization and silicification (phyllic alteration), A—argillization, P—propylitization.

The gold-rich porphyry category was arbitrarily defined by Sillitoe (1979) to include deposits containing ≥ 0,4ppm gold. Deposits with much lower average gold grades may however contain very large tonnages of gold, e.g. 779 metric tonnes of gold at the Bingham porphyry copper deposit (excluding the peripheral contact-metasomatic mineralisation) in which the average gold grade of the K-silicate altered porphyry (now mined out) was only 0,3 ppm gold (Sillitoe, 1988). Many porphyry systems, especially the "failed", pyritic ones which carry low copper and molybdenum values, have according to Sillitoe (1988), never been explored for gold and silver.

According to Sillitoe (1990), gold-rich porphyry copper deposits possess all the essential geological features of their gold-poor counterparts. Gold may be present in zones of veinlet stockworks and/or disseminated within or contiguous to porphyry stocks. These stocks can constitute the foci of more extensive hydrothermal systems, within which gold of high and low sulphidation epithermal veins, skarns and replacements in carbonate and non-carbonate rocks may occur. In this report porphyry copper-gold deposits will include copper-gold mineralisation directly related to porphyry intrusives, and the following will be addressed:

- Certain tectonic settings have a greater abundance of any particular porphyry ore type.
- Porphyry copper-gold deposits may be related to depth of emplacement and associated vertical zonation of ore metals.
- Weathering and erosion control the preservation age.
- The fO_2/fS_2 ratios within a porphyry system and the presence or absence of magnetite may determine the gold potential.
- Porphyry copper-gold deposits are generally smaller in size than their copper-molybdenum counterparts.
- Weathering and erosion and the exposure of alteration types give an indication of the porphyry being mineralised.
- Alteration types may help in distinguishing between favourable gold-copper porphyry systems and barren porphyry deposits.
- The mineral composition of the intrusive porphyry may indicate the potential gold-copper bearers.
- Regional structures and structural lineaments may favour the concentration of known porphyry copper-gold-molybdenum deposits.
- The degree of fracturing and veining may indicate the more favourable sites for ore deposition.
- No single characteristic can be used as the basis for exploration for these copper-gold porphyry systems. The use of weighted criteria of the various characteristics may be the only possible method of implementing a successful exploration programme.

Further questions which remain to be answered and which will be addressed in this report include:

- Were porphyry copper deposits without gold-bearing halos characterised by metal budgets which were too low, or were physiochemical conditions unsuitable for gold deposition beyond the porphyry stock ?
- Do porphyry deposits with gold-rich centres lack auriferous halos (not always the case) because of the absence of reactive and/or permeable host rocks ?

3.2 Characteristics

From Table II and Table III (Appendix 1) and papers by Sillitoe (1979, 1990), Cuddy and Kesler (1982), Cox and Singer (1986, 1988), Schroeter et al. (1989), Titley (1992) and others, the following will be discussed:

- Age
- Tectonic Setting
- Structural Controls and Porphyry Emplacement
- Rock Types
- Wall Rocks
- Magnetite Content
- Deposit Size and Tonnage
- Alteration
- Metal Zonation

3.2.1 Age

The ages of porphyry Cu-Au deposits range from the Palaeozoic through to the late Pliocene - early Pleistocene (Table III and Figure 16). In general, there does appear to be a greater abundance of porphyry copper deposits and gold-rich porphyry deposits associated with younger Tertiary intrusives (Table III and Figure 16). This could be related to the greater preservation potential of these younger systems compared to the older deposits. Rapid uplift and erosion associated with subduction and continental margin areas would also result in the shallow emplaced porphyries being eroded away, or result in only the lower

portions being preserved.

Within some porphyry copper districts, gold-rich deposits tend to have a different age (Lowell, 1989). An example cited is where gold-poor deposits in the SW United States are of Laramide age, while the gold-rich deposits tend to be upper Tertiary in age. Similarly the Cretaceous age - Andacollo porphyry gold related vein deposit in Chile tends to be high in gold, while the mid-Tertiary systems tend to be gold-poor (Sillitoe, 1982). However there are many exceptions and the controlling factor does not appear to be age.

What significance one may assign to age, and the potential gold-rich deposits, may be somewhat indirect. For if gold- rich systems are associated with the shallow emplacement of porphyry intrusives and there is a genetic association to rock type, then age is important. Older, shallow emplaced bodies may have been eroded away and the younger, shallower emplaced bodies which are gold-rich, preserved.

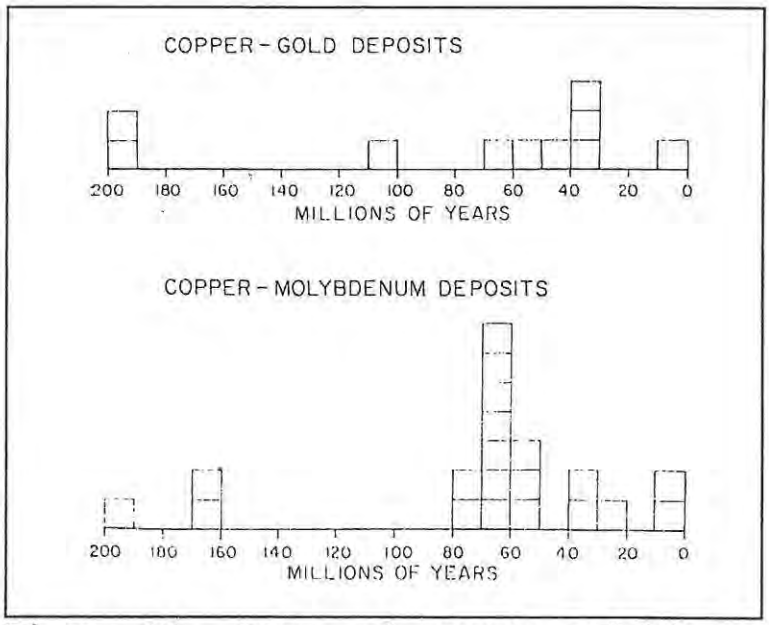


Figure 16. Ages of copper-molybdenum and copper-gold deposits (Kesler, 1973).

3.2.2 Tectonic Setting

Outlined in Table III are some characteristics of the more principal gold-rich porphyry copper deposits.

The majority of the intrusion related gold-rich porphyry copper deposits tabulated in Table III were generated at Phanerozoic convergent plate boundaries above zones of active subduction. In general these have formed in a primitive island arc or mature continental arc/margin setting. Over the years two schools of thought have been proposed for the variation of Cu-Mo-Au deposits in these environments. The one school of thought (Hollister, 1978, Titley and Beane, 1981) proposes that Cu/Mo ratios decrease with increasing thickness of the sialic crust and distance from the Benioff Zone. High Mo and high silica would indicate a thick sialic crust. By contrast the high gold or high Cu/Mo ratios, e.g. SW Pacific Island porphyry deposits, would indicate a thin and more mafic crust. In this instance the mafic rocks such as the oceanic crust and dioritic plutons would be the source of the metals, viz. Cu and Au ± Mo.

The second school of thought, proposed by Sillitoe (1986), disagrees with the fact that Cu/Mo or Au ratios have any relationship to crustal thickness. He believes the only control of metal sources is the subducting oceanic crust (including the subducting sediments, upper mantle wedge and possibly the zone of underplating by rising mafic melts beneath the crust). In support of this argument he cites the Andes as an example where there is a marked distribution of porphyry deposits in a N-S trend in parallelism with the Peru-Chile trench. These deposits lie over thickened sialic crust and do not have high Mo contents.

However, what is apparent, is that the continental margin deposits are generally the Cu-Mo-Au deposits, while the island arc deposits are the porphyry gold or porphyry copper-gold deposits (Figure 17).

As mentioned earlier, porphyry deposits occur along active or ancient subduction zones. The source of mineralisation, as determined from fluid inclusion, isotope and trace element studies by workers such as Rona (1978), appears to be related to primary magmatic sources. There is, as outlined by Sillitoe (1988) and Titley (1982), a close genetic association between porphyry deposits and volcanogenic orebodies.

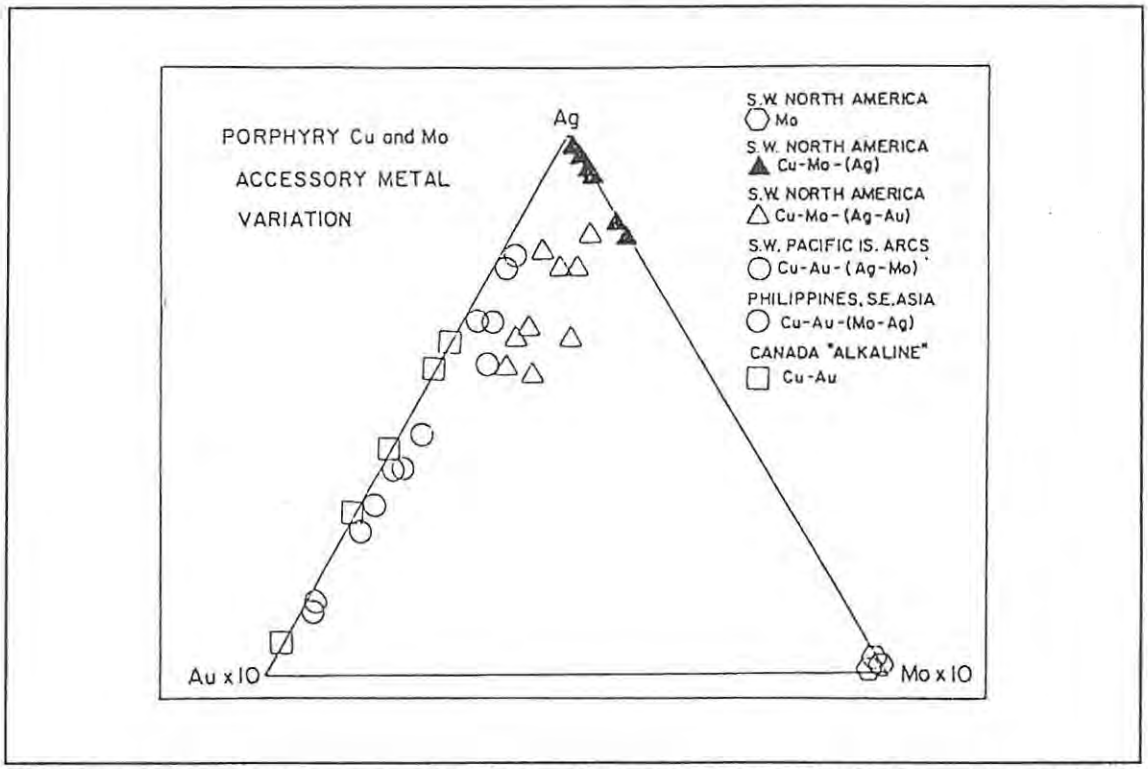


Figure 17. Ternary variation diagram plotting Ag, Au and Mo for regionally distinct porphyry systems (after Titley, 1990).

All porphyritic plutons need not be mineralised, and mineralised plutons may also be overlain by barren andesites. Regions which may seem to be in ideal geologic settings can be quite unproductive, e.g. New Zealand (Sillitoe, 1980). This, Sillitoe (1980) concluded, can be accounted for partly in terms of the type of volcanism involved but there may also be many unexplained reasons.

Dated deposits suggest that mineralisation was an event and not a continuous or repetitive process (Heys, 1987). Metal provinces have been associated with a metallogenic epoch of ± 5-20 Ma duration. Within this timespan, mineralisation tends to have occurred only once at any locality and migrates systematically through the province (usually elongate). This was noted by Sillitoe (1974) to be the case in the Andes.

However, besides a global association of porphyry copper deposits with, e.g. subduction zones or colliding plate margins, there also appears to be regional association of porphyry deposits with certain faults, shears and other structural lineaments within these tectonic

areas. This association has not been fully evaluated, but in the next section attention is drawn to the possible significance of such structures in further copper-gold porphyry localisation.

Within any tectonic environment, e.g. intra-continental, continental margin or island arc setting, the emplacement of intrusive porphyry bodies is strongly controlled by the regional stress regime operative during that period.

3.2.3 Structural Controls and Porphyry Emplacement

If one considers that gold-rich porphyry copper deposits are more closely related to island arc and continental arc settings (section 3.2.2), then the following must be considered as controls for the emplacement of porphyry intrusions:

- The angle of the subducting plate.
- Rate of subduction.
- Collisional angle of the subducting plate and the overriding plate.
- Fracture patterns due to the compressive or extensional regimes operative during subduction.
- Geothermal gradients.

There are two models of subduction which have been proposed by Uyeda (1982). These two models are essentially related to the angle of the subducting plate. The Chilean-type, or less steeply dipping plate, causes a compressional stress regime in the arc and back-arc regions. The Marianna-type, with a steeply dipping subducting plate, causes a tensional regime in the arc and back-arc regions (Figure 18).

It is this change in the angle of the subducting slab which is thought to be a control on porphyry emplacement. This is illustrated by the mineralised porphyry deposits in Chile whereby the principal copper and gold deposits occur in two discrete linear magmatic arcs. These two arcs are of late Palaeocene to early Eocene (59-52 Ma) and late Eocene to early Oligocene (42-31 Ma) in age. During this time it is thought that the central Andes was underlain by a shallower Chilean-type subduction zone (Mpodozis and Ramos, 1989).

Migration of the magmatic arc eastward is also suggested to be related to subduction zone flattening (Maksaev and Zentilli, 1988).

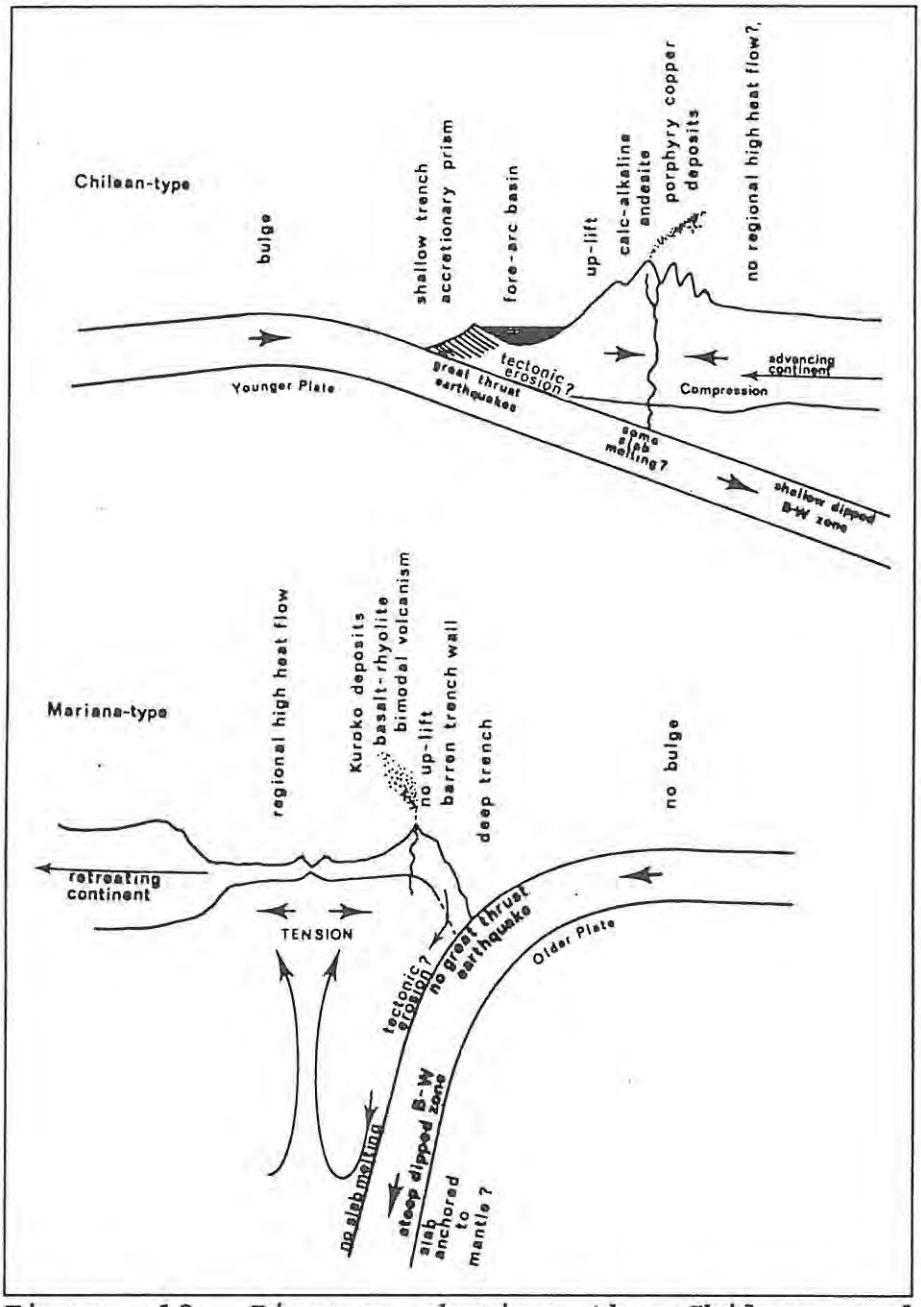


Figure 18. Diagram showing the Chilean and Marianna-type subduction (after Uyeda, 1982).

Porphyry deposits have had evolutionary histories associated with plate interactions. These may be related to interactions involving continental and oceanic plates. Although the relationship of these porphyry copper deposits to plate tectonics is still largely unresolved, the episodic nature of events related to sea-floor spreading has been recognised (Le Pichon, 1968).

Porphyry copper evolution in the SW Pacific Island regions appear to coincide (at least some of the time) with, initial increase in rates of convergence of the Australian and Pacific plates. Examples include:

- Change in direction and rate of spreading at ca 25 Ma,
- the increase in the rate of spreading at some time between 20 Ma and 10 Ma and
- the near doubling of spreading rates in the eastern Central Pacific at ca 10 Ma.

It has been suggested by Le Pichon (1968) that low rates of convergence produce compressional features at surface, while high rates of convergence produce tensional features on surface.

Karig (1974) has also shown that intrusives in the Philippine Sea are closely related to volcanic activity. This he suggests corresponds to times of rapid subduction. This rapid convergence is also tentatively suggested by Titley (1975) to have resulted in uplift with extension, and producing deep penetrating channels along which magmas can travel to reach surface.

Uplift of the northern side of the Papuan Basin occurred in the mid-Pliocene and this time corresponds broadly to the time of mineralisation at Kainantu (Cu-Au), Yanderra (Cu-Au) and to times of some intrusions at Mount Fubilan and to the Ertsberg intrusion (Cu-Au) (Figure 19). Evolution of the copper-gold systems in these regions appear to be episodic rather than continuous and this may be true for other areas in the circum-Pacific.

It is suggested by Titley (1975) that if convergence rates can be established, during the interval of about 19 to 15 Ma and at about 8 to 5 Ma, the case for rapid convergence, as a triggering mechanism for volcanism and attendant intrusion and porphyry copper-(gold) formation, would be strengthened.

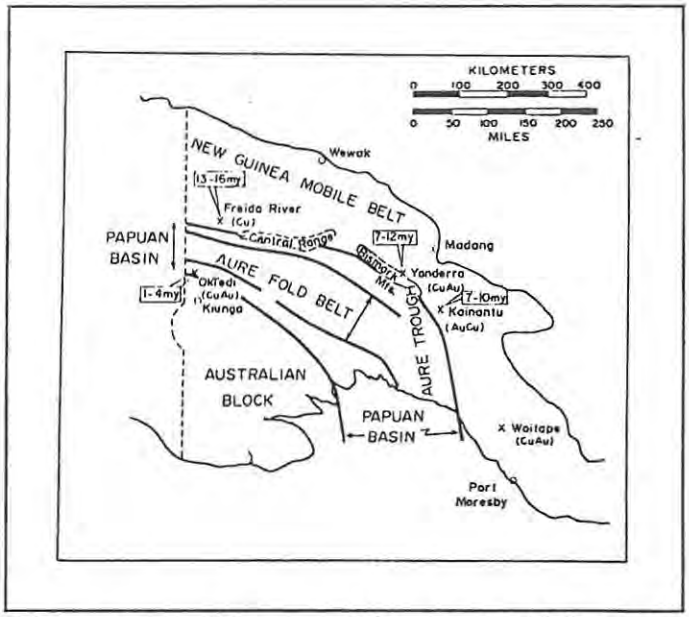


Figure 19. Miocene-Pliocene palaeogeography of a part of New Guinea with superimposed porphyry copper-(gold) deposits (after Titley, 1975).

The rise and emplacement or extrusion of magma into or onto the continental crust is controlled by extensional tectonics, structural weaknesses and the temperature of the rising magma. Within a zone of regional compression (e.g. an oceanic plate colliding and subducting beneath a continental plate), extensional tectonics can operate. This extension is related to the doming of the overlying crust due to thinning by high heat flow and/or the pull of the trailing edge of the continent downward by the subducting plate.

With the extension, high heat flow, rifting and magmatic activity operative on surface above the subducting plate; the ideas of Cartwright (1992) are examined in order to understand where, how and what controls magma emplacement. Although Cartwrights (1992) ideas are related to continental rifts, the principles of possible porphyry/magma emplacement may be similar. Continental rifts commonly consist of segments linked by a complex pattern of intense fracturing along trends which are generally transverse or oblique to the main rift bounding structures. These transverse zones are often the foci for high heat flow anomalies and magmatic activity. They are also sites of hydrocarbon and metalliferous ore accumulations (Cartwright, 1992).

From the review of various rifts by Cartwright (1992), e.g. the North Sea, Rhine, Rio Grande, Lake Tanganyika, Horn and Oslo, there appears to be a control on magmatic activity by basement lineaments and transverse rift structures. It was also observed that magmatic centres are preferentially located along the traces of the basement lineament, often a great distance away from the rifts. This is thought to suggest that transverse zones developed in direct response to deep seated dislocations along lineaments.

As an example, the Rio Grande Rift (Figure 20) can be seen to be broken into segments by NE trending transverse shear zones (Chapin et al., 1978). These shear zones continue into the rift flanks as major crustal discontinuities. The rift related magmatism occurs some distance from the rift which may suggest that the transverse shear zones extend to far greater depths than the rift border faults (Figure 21). It is suggested by Cartwright (1992) that these transverse structures occur as narrow vertical shear zones in the mantle and pass upwards into more diffuse zones of discontinuous faulting in the brittle upper crust creating a lithospheric flower structure (Figure 21).

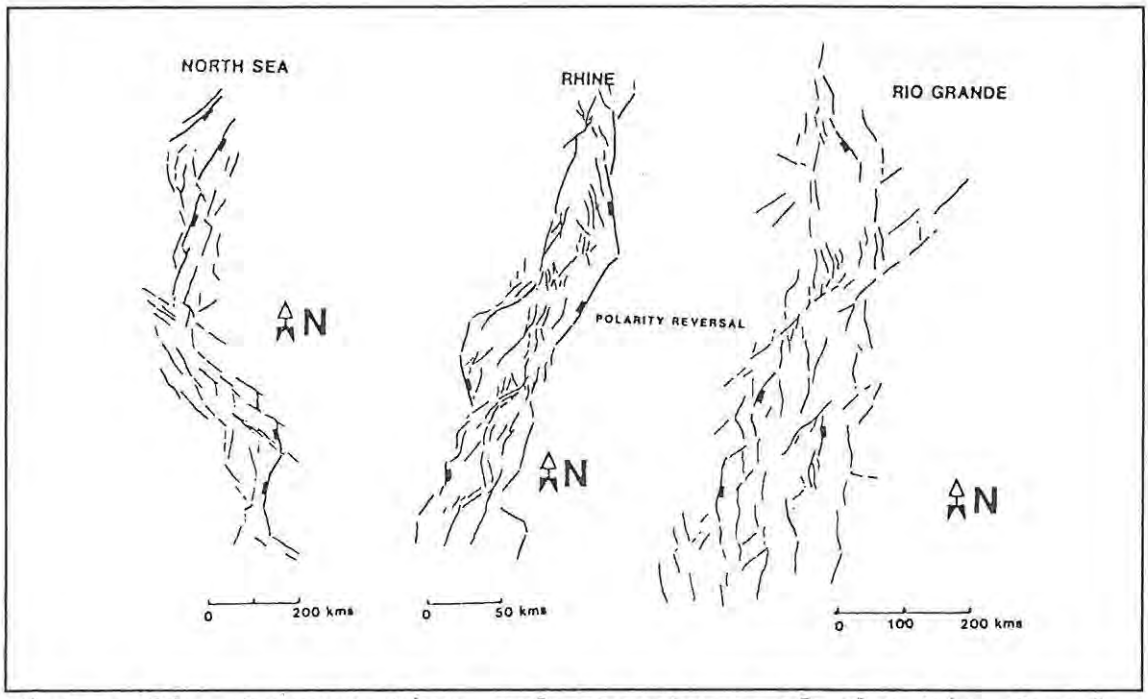


Figure 20. Segmentation and structure of the Rio Grande, Rhine and North Sea Rifts (after Cartwright, 1992).

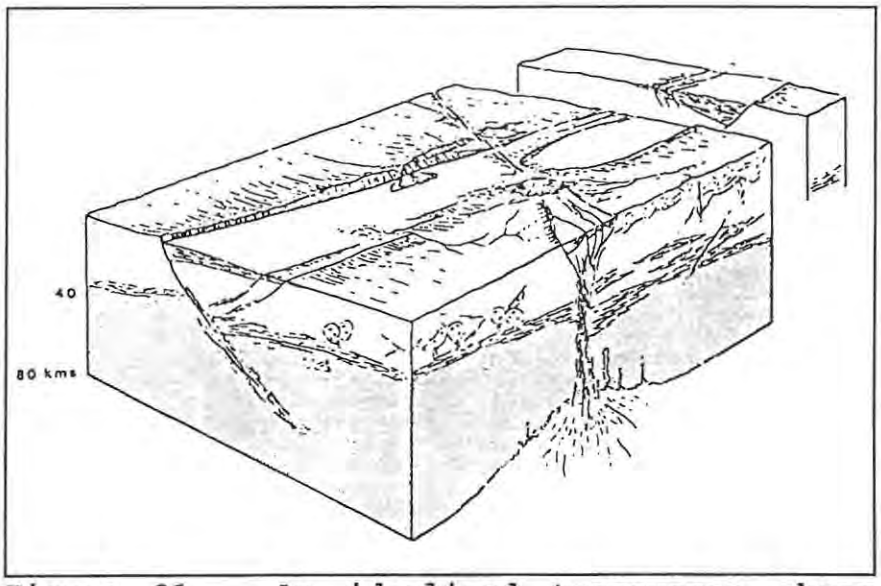


Figure 21. An idealised transverse shear zone (after Cartwright, 1992).

The arguments presented above may be circumstantial but, from the regional tectonics of Chile and the location of porphyry deposits along and offset from the West Fissure by NW trending structures, this idea requires further investigation.

From Figure 22 it can be seen that the principal gold and copper deposits in Chile are related to metallogenic belts of different ages which formed during the migration of the magmatic arc eastward with time (Sillitoe,1992). The large Oligocene porphyry copper deposits were, according to Mpodozis and Ramos (1989), emplaced along a zone of crustal weakness trending north-south.

This zone of crustal weakness is thought to be characterised by strike slip faults such as the West Fissure. Although there are numerous porphyry deposits associated with or in close proximity to the West Fissure, other transverse structures may have a greater control on their structural location. Both NW and NE trending fractures and faults are observed on the mine scale, e.g. Chuquicamata (pers. observ.) and on a regional scale, e.g. NW alignment of the El Salvador, Potrerillos and La Coipa porphyry copper and/or gold deposits (Figure 22).

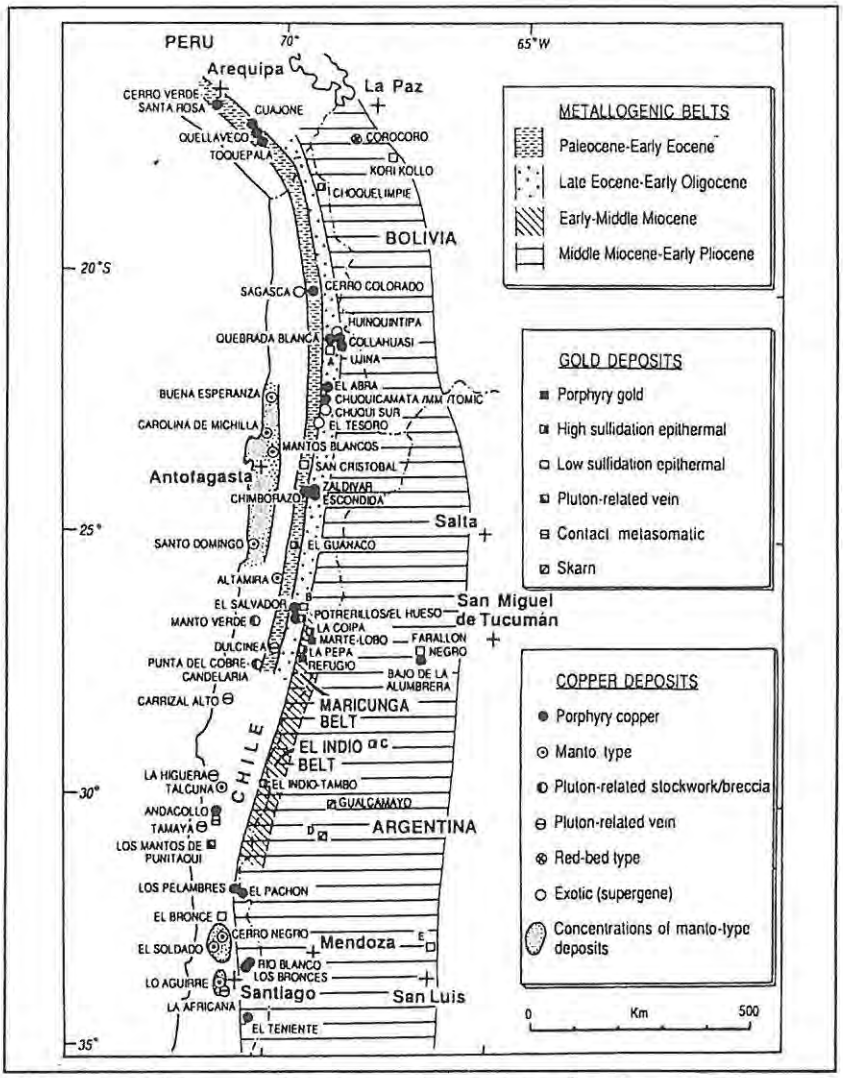


Figure 22. Types of principal gold and copper deposits in the central Andes. Deposits containing >10t Au or >100000t Cu are named (after Sillitoe, 1992).

Although this association of faulting, and possible controls on porphyry emplacement and mineralisation is likened to Cartwrights (1992) extensional rift model, another possibly more relevant compressional model, is discussed.

This apparent structural control, as suggested above for the porphyry copper deposits in Chile, could also be related to dilational jogs developed between strike-slip fault systems (Figure 23). This may be compared to the southern San Andreas fault system where the loci for major magmatic-hydrothermal systems are major dilational jogs developed throughout the seismogenic region.

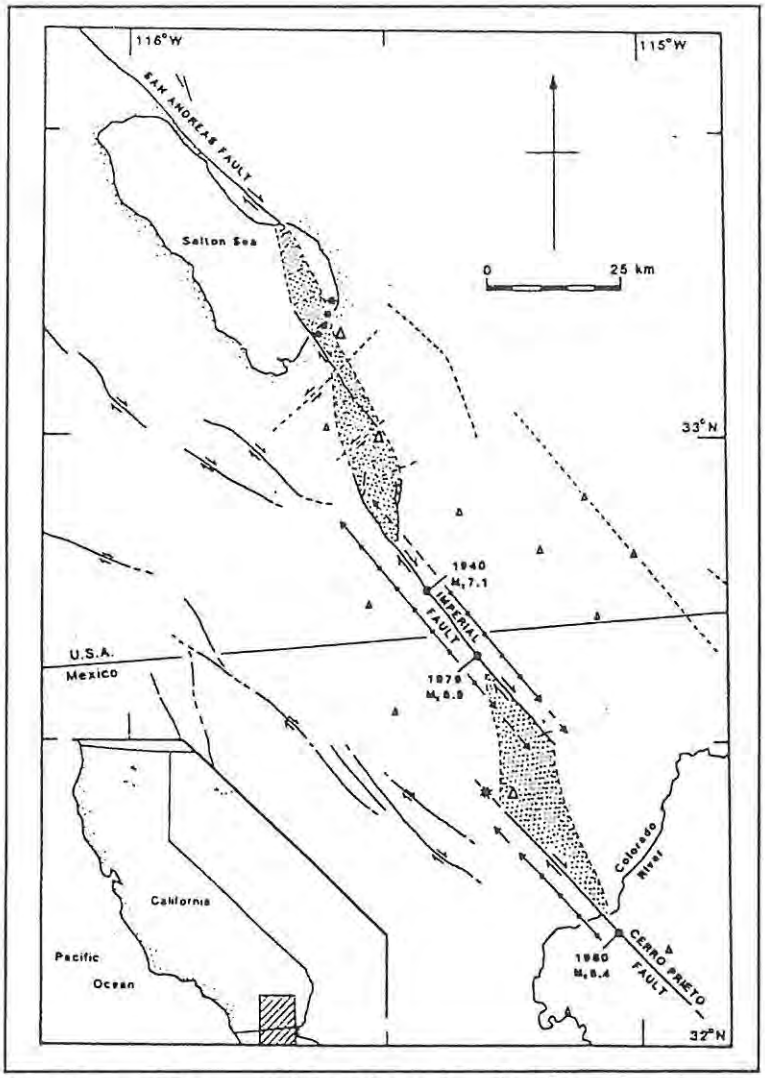


Figure 23. Dilational fault jogs in the southern San Andreas fault system (modified after Sibson, 1987).

Another area where porphyry-type mineralisation, alteration and brecciation (porphyry emplacement), is thought to be controlled by structures, is Eastern Queensland, Australia.

In this area (Figure 24), like Chile, the majority of the porphyry deposits (early Cretaceous porphyries) are seen to be related to a longitudinal belt which in this case trends northwest. However, along this NW trending belt there are transverse belts and linear zones orientated east-northeast in Southern Queensland to east-west in Northern Queensland. These transverse structures appear to have had some influence on mineralisation in the longitudinal belts, as some of the important Cu-Mo deposits, e.g. Coalstoun (70) and Moonmera (51 - Figure 24) are situated at their intersections (Horton, 1978).

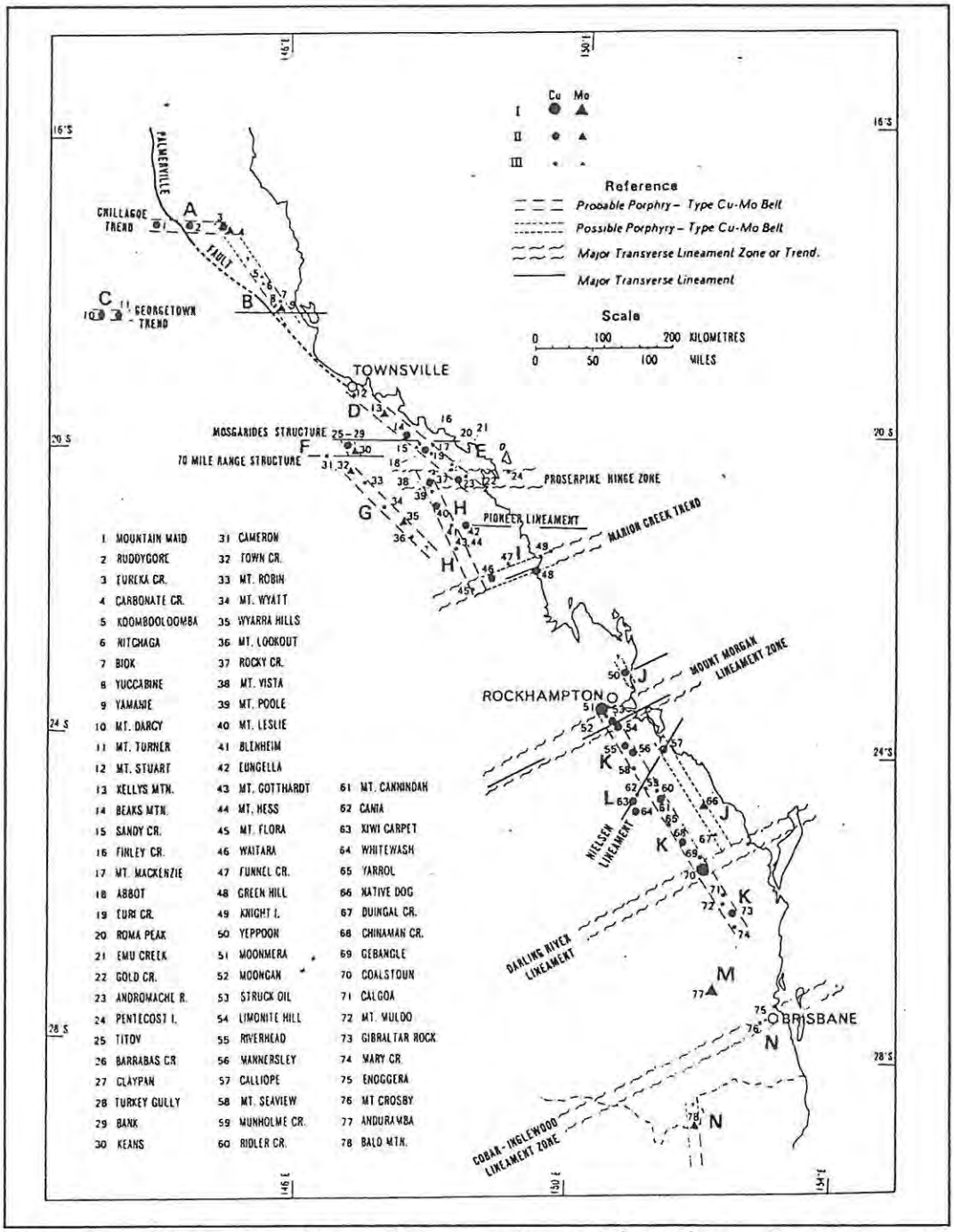


Figure 24. Porphyry-type mineralisation belts and associated transverse elements in eastern Queensland (modified after Horton, 1978).

Further controls of structural features on mineralised porphyry emplacement is in northern Sonora, Mexico. Evidence from remote sensing, geophysics and geochemistry indicates that NE trending lineament zones may have controlled the emplacement of the known porphyry copper deposits (Figure 25).

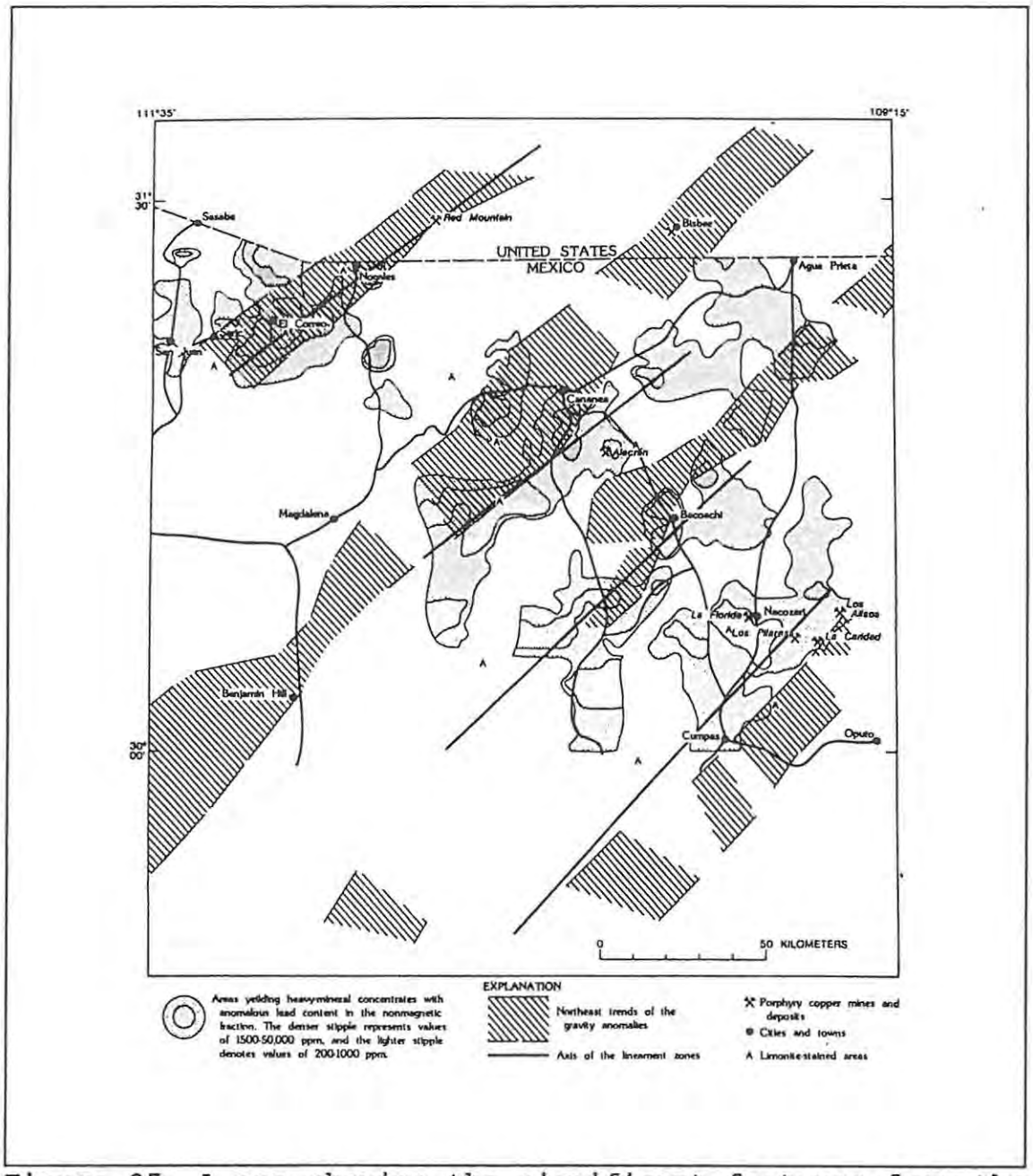


Figure 25. A map showing the significant features from the remote sensing, geophysical and geochemical studies in Mexico (after Turner et al., 1982).

The structural controls described above may control the emplacement of porphyry intrusives but other factors such as the rock type and the physiochemical conditions operative within the magma determine the potential for the formation of porphyry copper-gold-molybdenum orebodies.

3.2.4 Rock Types

The various types of porphyry copper mineralisation may be related in part to different rock types. It is generally recognised that Cu-Au-Mo porphyry deposits are associated with granodiorite, quartz monzonite, quartz diorite granitoids and that the Sn-W-U and rare metals occur in more felsic varieties. Although the petrological distinction has been related to a number of genetic classification systems (Chappel and White, 1974 and Burnham and Ohmoto, 1980), none is totally successful. If for example, the descriptions of rock types believed to be genetically related to porphyry deposits, as taken from the literature and converted into standard rock terminology (Streckeisen, 1973) (Figure 26), are compared, then the following associations are apparent from the study by Cox and Singer (1988).

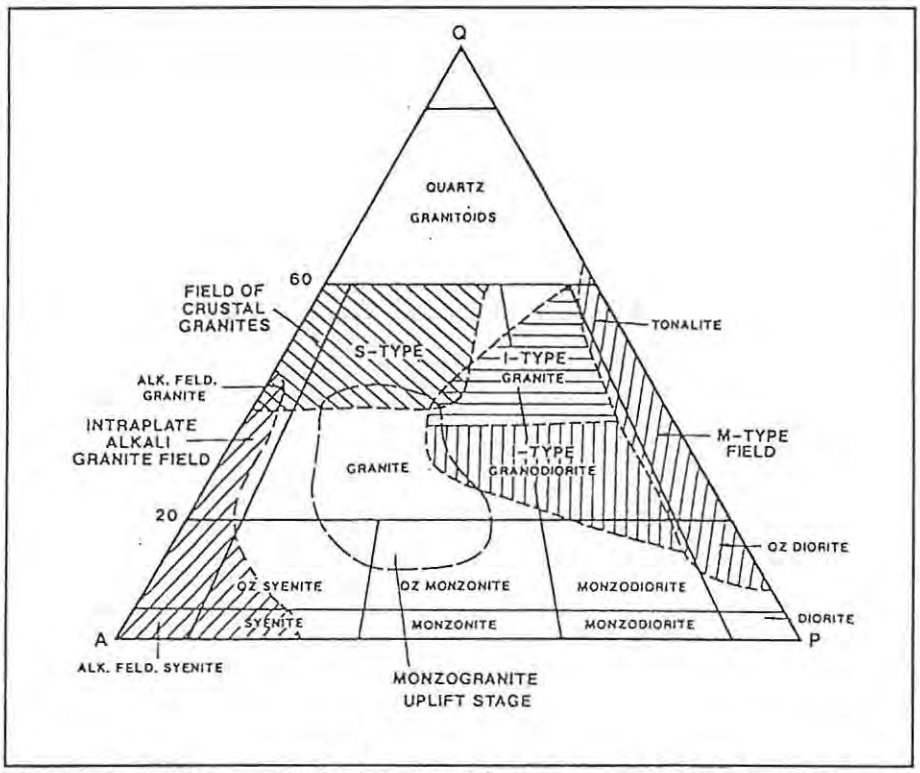


Figure 26. Granite fields plotted on a Streckeisen diagram (after Streckeisen, 1973).

Types	Tonalite/or Q. Diorite	Syenite/or Monzonite	Granodiorite/or Monzogranite	?
Au-rich	8	6	6	
Au-Mo rich	4		13	2
Mo-rich	3		12	1

(Q = Quartz, ? = Uncertain) (after Cox and Singer, 1988).

From the above data we may agree with Sillitoe (1979) that associated rock type is not a good describer of porphyry copper-gold deposits. However, it may be suggested that porphyry copper-gold systems may possibly show a close association with rocks rich in mafic minerals compared to the more Mo-rich systems associated with monzogranites and granodiorites having a low mafic mineral content. Partial melting of hornblende-bearing mafic rocks of igneous origin, e.g. oceanic basalts of subducting plates or hornblende gabbro's in the lower continental crust, may yield I-type calc-alkaline magmas with the required chemical composition to be progenitors of hornblende-bearing copper-gold porphyries (M.Sc course notes).

When the abundances of common ore metals in igneous rocks are compared (Table IV) the following is apparent:

- Generally high copper, molybdenum and gold occurs in mafic rocks.
- Gold abundances are the same, molybdenum abundances are 0.2 ppm and copper abundances 6X lower in granitic rocks.
- Gold is 50% higher, molybdenum is 83% lower and copper 83% lower in ultramafic rocks.

Furthermore, part of the problem in recognising productive granitoids (Cu-Au-rich, Cu-Au-Mo-rich etc.) is the multiplicity of possible sources of any element in any particular sample. In surface samples the situation is further complicated by the effects of weathering .

Table IV. Abundances of common ore metals in igneous rocks in parts per million (from Guilbert and Park, 1986).
100ppm = 0.01 %

Element	Ultramafic Rocks	Mafic Rocks	Intermediate Rocks	Granitic Rocks	Syenites
Li	0.5	16	22	40	28
Be	0.2	1	2	5	1
Ti	300	12,000	6000	1600	3500
V	40	225	95	42	30
Cr	1800	180	36	15	2
Mn	1600	1750	800	500	850
Co	175	47	14	3	1
Ni	2000	145	35	7	4
Cu	15	90	33	15	5
Zn	40	120	66	50	130
As	0.8	2	2.2	1.5	1.4
Se	0.05	0.05	0.05	0.05	0.05
Zr	37	120	200	185	500
Nb	10	20	20	20	35
Mo	0.25	1.45	1.0	1.2	0.6
Ag	0.06	0.1	0.06	0.04	0.0*X*
Cd	0.1	0.2	0.1	0.12	0.13
Sn	0.5	1.5	1.5	3	*X*
Sb	0.1	0.6	0.2	0.2	0.*X*
Ce	0.*X*	20	80	96	160
Ta	0.5	0.8	2.5	4	2
W	0.5	0.8	1.2	1.9	1.3
Au	0.006	0.004	0.004	0.004	0.00*X*
Hg	0.02	0.09	0.08	0.08	0.0*X*
Tl	0.04	0.2	0.6	1.8	1.4
Pb	0.6	7	15	20	12
Bi	0.001	0.007	0.01	0.01	—
Th	0.005	3.5	7.8	17.5	13
U	0.002	0.75	2.4	3.3	3.0
S	200	300	250	350	300

It may also be suggested that "specialisation" (association of ore metal with granitoid type) only provides an indication of the potential for mineralisation, provided tectonic and other geological conditions are appropriate.

Important porphyry copper precious metal deposits are also associated with alkaline rocks which include alkali gabbros and syenites (silica saturated and undersaturated plutons) (Figure 27). They are characterised by high sulphur abundances, and the Cu-sulphides are disseminated in veins and blebs in the matrix. Carbonate, K-metasomatic, redox, and phyllic alteration occur as the major alteration types.

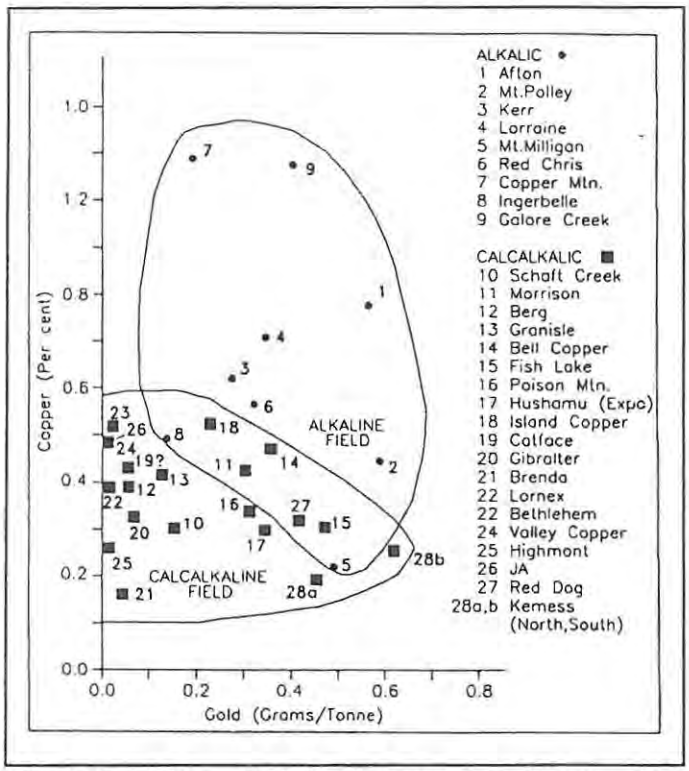


Figure 27. Gold-copper values for some porphyry deposits in British Columbia (after Schroeter et al., 1989).

These porphyry copper precious metal deposits may grade upward into epithermal gold deposits which may be preserved or eroded away. In the epithermal deposits gold may be transported as thiosulphide-Au, whereas in the porphyry system it may be transported as a telluro-Au-complex (Mutschler, et al., 1985) or a chloro-complex.

Alkali source rocks with a high exploration potential may be classified as:

- Alkaline : ($Na_2O + K_2O$ (wt%) > 0.3718 SiO_2 (wt%) -14,5)
- Members of the alkalic basalt or,
- felsic syenite ($Na_2O + K_2O$ > 10 wt% and MgO < 2 wt%) assemblages.
- Showing local anomalies in some of the following: Au > 10ppb, Ag, As, Bi, Ce, Cu, F, Hg, La, Mo, Nb, Pb, S, Sb, Te, Tl, U and V.
- High Ba and Sr in Ba:Sr:Rb ratios.
- Showing one or more of the following alteration assemblages;
  - K-metasomatism (K_2O) > Na_2O)
  - redox Fe_2O_3 > 1,5 FeO or carbonatic CO_2 > 0,5wt%.

Many porphyry-style gold ± copper deposits worldwide are associated with, or are hosted by potassic igneous rocks and shoshonites (Muller and Groves, 1993). They are characterised by high halogens such as Cl and F, high large ion lithophile elements (LILE) (K, Ba, Rb, Sr) and low High Field Strength Trace Elements (HFSE) (Zr, Nb, Y, and REE).

Mineralisation associated with potassic igneous rocks are generally restricted to three tectonic settings, viz. late oceanic arcs, continental arcs and post-collisional arcs (Figure 28).

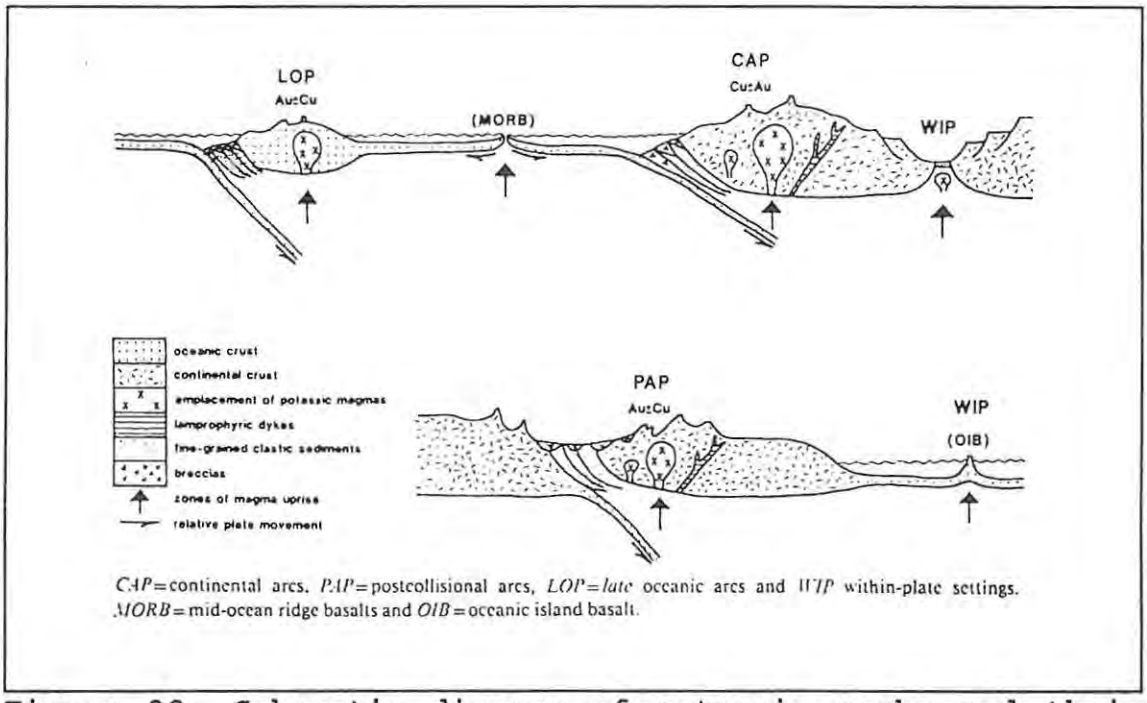


Figure 28. Schematic diagram of potassic rocks and their tectonic setting (after Muller and Garson, 1993).

- Late oceanic arcs - Potassic volcanic rocks form the youngest eruptions after volcanics of tholeiitic and calc-alkaline series (Muller and Groves, 1993).
  - Lihir Island - Papua New Guinea deposits.

- Continental arcs - Characterised by zones of oblique plate convergence and the subduction of oceanic crust beneath continental crust.
  Generally characterised by flat subduction angles and broad Benioff zones (Muller and

Groves, 1993).

- Porphyry copper deposits in Chile.

- Post-collisional arcs - Areas where the process of subduction has ceased and the continental plates have collided.
  - Miocene Porgera gold deposit in PNG.

"Shoshonites" sensu-stricto show high K_2O/Na_2O ratios (> 0.5), high $Na_2O + K_2O$ (> 5wt %), high LILE enrichments viz. (K, Ba, Rb, Sr), high but variable Al_2O_3 (zero to 9wt %) and generally low TiO_2 (Joplin, 1968, Morrison, 1980). These rocks are commonly formed during the late stage of arc evolution erupted after low K-tholeiites and calc-alkaline rock series.

Most Cretaceous to Cenozoic epithermal and porphyry-type copper-gold deposits in the Chilean Andes are hosted by high K - calc-alkaline igneous rocks (Gropper et al., 1991 and Reyes, 1991). There also appears to be a direct genetic link between potassic magmatism and mineralisation in the continental-arc (Muller and Groves, 1993).

High Cl concentrations (> 0.04 wt %) in mica phenocrysts are present in all mineralised potassic volcanic rocks. Cl-rich hydrothermal fluids were probably exsolved during magma crystallisation and were responsible for gold and/or base metal transport. Therefore, it may be no coincidence that many gold deposits tend to be associated with the more volatile rich, potassic and calc-alkaline magmas (Spooner, 1993). Muller et al. (1993), also indicates that the Goonumbla porphyry Cu-Au deposit is interpreted to have been generated in a late oceanic-arc setting and the micas are enriched in both Cl and F (Figure 29).

The halogen contents of mica phenocrysts from high-K igneous rocks may therefore be used with caution as a measure of Au-Cu mineralisation potential in continental post-collisional and late oceanic arcs.

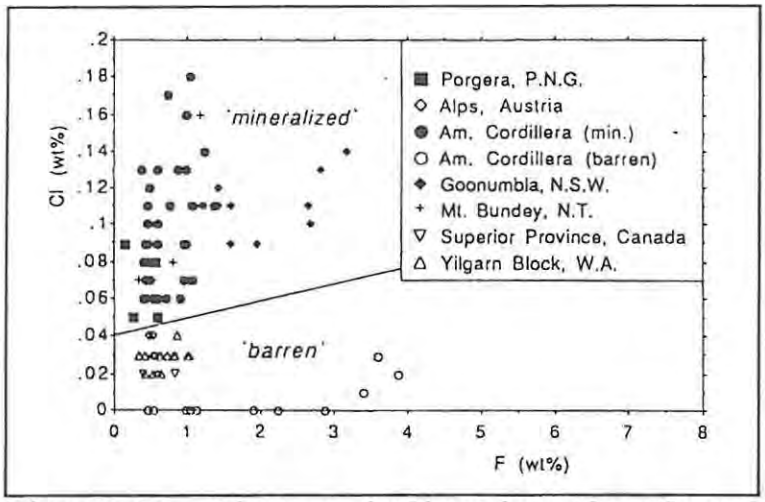


Figure 29. Diagram indicating the Cl and F content of mineralised and unmineralised potassic volcanic rocks (after Muller and Groves, 1993).

Caution must be taken when looking at high-K rocks from within plate settings as they have high halogen contents, although no genetic relationship to Cu-Au has yet been established (Muller and Groves, 1993).

Mineralised (Cu-Au) high-K rocks from late oceanic arcs may be typified by both anomalous high Cl and F but this awaits confirmation from a larger database.

Porphyry intrusions of the SW Pacific Islands differ from the porphyry copper related deposits in the SW United States in that they are more dioritic (Figure 30). Generally porphyritic calc-alkaline intrusions in the SW Pacific occur within andesitic and dacitic volcanic piles.

3.2.5 Wall Rocks

Porphyry copper-gold deposits are found associated with a variety of wall rocks. For example, andesitic wall rocks are found at the Lepanto Far Southeast deposit in the Philippines, Marte in Chile and Bajo de la Alumbrera in Argentina. While sedimentary wall rocks are the host to the Bell Copper deposit in British Columbia, the Porgera deposit in Papua New Guinea and the Grasberg deposit in Indonesia.

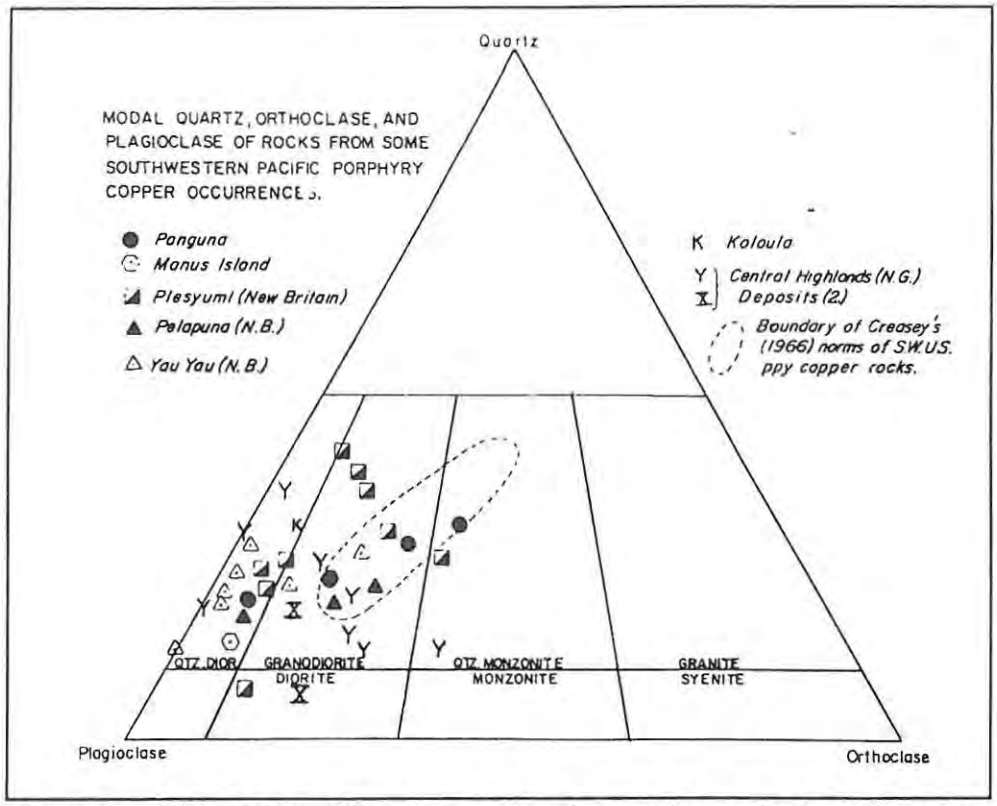


Figure 30. AFM diagram showing the plot of some porphyry copper-related rocks (after Titley, 1975).

The wall rocks do not control the gold content of the deposit but their composition or structural characteristic may control ore deposition beyond the porphyry stock. The release of high temperature, acid rich, highly saline, gold-rich fluids from the emplaced magma body into carbonate rocks will be more suited for a peripheral gold deposit than if the host rocks were a non-reactive quartzite. Chemical reactions between the ore solutions and the wall rocks are therefore important in localising the ore-rich fluids beyond the porphyry intrusive.

3.2.6 Magnetite Content

According to Saegart and Lewis (1977) and Sillitoe (1979), most porphyry copper-gold orebodies contain more than 1% magnetite in veinlets. Magmatic hydrothermal magnetite is associated with the potassic zone where it forms a stable assemblage with chalcopyrite, biotite, anhydrite, K-Feldspar, chlorite or actinolite.

In the study by Cox and Singer (1988) in which the porphyry copper deposits outlined in

Table V were examined, the following was determined. Magnetite was positively correlated with the gold grades in these deposits and a triangular plot of the magnetite content versus gold, molybdenum and copper is illustrated in Figure 31.

Table V. Types of porphyry copper deposits (Cox and Singer, 1988).

Porphyry copper-gold	Porphyry copper-gold-molybdenum	Porphyry copper-molybdenum
Afton, British Columbia	Ajo, Arizona	Berg, British Columbia
Basay, Philippines	Andacolla, Chile	Bethlehem, British Columbia
Bell, British Columbia	Bingham, Utah	Brenda, British Columbia
Caribou Bell, British Columbia	Brenmac-Sultan, Washington	Gambier Island, British Columbia
Copper Mountain, British Columbia	Cash, Yukon Territory	Gibraltar, British Columbia
Dos Pobres, Arizona	Casino, Yukon Territory	Highmont, British Columbia
Fish Lake, British Columbia	Cerro Colorado, Panama	Huckleberry, British Columbia
Frieda River, Papua New Guinea	Copper Flat, New Mexico	Inspiration, Arizona
Galore Creek, British Columbia	Dexing, China	Lornex, British Columbia
Ingerbelle, British Columbia	Granisle, British Columbia	Morenci, Arizona
Mamut, Malaysia	Island Copper, British Columbia	Ray, Arizona
Marcopper, Philippines	Kalamazoo, Arizona	Sierrita-Esperanza, Arizona
Ok Tedi, Papua New Guinea	Morrison, British Columbia	Tyrone, New Mexico
Panguna, Papua New Guinea	Poison Mountain, British Columbia	Twin Buttes, Arizona
Red Chris, British Columbia	Ruth, Nevada	Valley Copper, British Columbia
Rio Vjvi, Puerto Rico	Shaft Creek, British Columbia	
Saindak South, Pakistan	Sipalay, Philippines	
Star Mountain, Papua New Guinea	Yandera, Papua New Guinea	
Tanama, Puerto Rico	Santa Rita, Arizona	
Taysan, Philippines		

There are however exceptions; for example, at the Bethlehem deposit in B.C secondary magnetite appears as clusters with the K-feldspar in the potassic alteration zone without any gold mineralisation. At Mineral Park in Arizona a late magnetite-chalcopyrite-chlorite vein system cuts early quartz-K-feldspar-biotite-molybdenite veins with the molybdenum orebody containing essentially no gold (Cox and Singer, 1988).

Further illustrations of the correlation of gold and magnetite are highlighted in Figure 32 and Table VI.

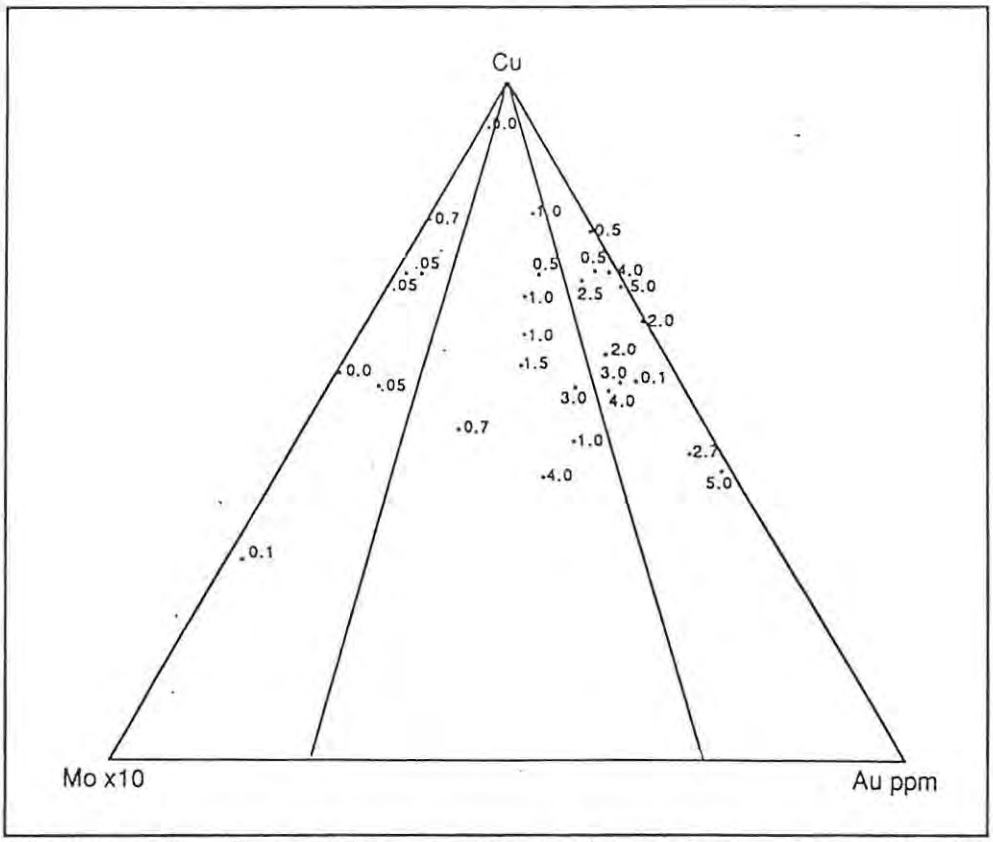


Figure 31. Magnetite content in volume percent in potassic alteration zones in porphyry copper deposits (after Cox and Singer, 1988).

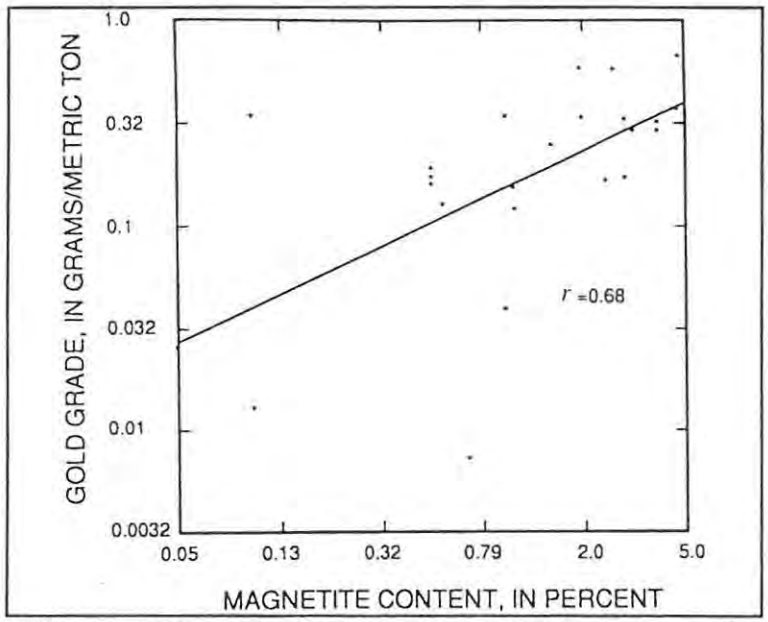


Figure 32. Magnetite content vs gold grade for 26 porphyry copper deposits. Correlation is 0.68 and significant at the 1% level (after Cox and Singer, 1988).

Table VI. Median grades, tonnages and depths of some porphyry-type copper deposits (after Cox and Singer, 1988).

	Porphyry copper-gold type	Porphyry copper-gold-molybdenum type	Porphyry copper molybdenum type
Number of deposits	20	19	16
Metric tons $\times 10^6$	160	390	500
Copper (percent)	.55	.48	.41
Molybdenum (percent)	.003	.015	.016
Gold (g/t)	.38	.15	.012
Silver (g/t)	1.69	1.63	1.22
Magnetite content (percent)	2.6	1.0	.05
Depth (km)	1.0	.9	3.6

The evidence for high magnetite-to-pyrite ratios in porphyry copper-gold systems indicates the high fO_2/fS_2 which Sillitoe (1982) postulates is responsible for the trapping of gold in the copper-rich part of the system. A possible mechanism suggested by Cox and Singer (1988) for maintaining the high fO_2/fS_2 during early gold deposition is the dissolution of H_2O to H_2 and O_2. This reaction would be favoured by the high temperatures and low pressures associated with the emplacement of tonalitic and other mafic intrusions at high levels in the crust. The high fO_2/fS_2 conditions would be attained by the escape of the smaller hydrogen molecules. The high fO_2/fS_2 in turn would favour the formation of magnetite, and gold would be restricted.

In deposits with a low magnetite-pyrite ratio in the potassic alteration zone, sufficient sulphide ions may have been present to cause gold to remain mobile as gold thiocomplex ions during falling temperatures (Henley, 1973). Under such chemical conditions gold may migrate outward to form peripheral gold vein-type deposits (see section 3.2.9).

As a result of the fO_2 having a potential influence on mineralisation, it would be important to note the observation made by Mason and Mcdonald (1978) on ferromagnesian phenocrysts from productive porphyries. Amphiboles from productive porphyries tend to be enriched in Mg towards their rims. This Mason and Mcdonald (1978) interpreted as indicating increasing oxygen fugacity within the crystallising melt. The fingerprinting of

these amphiboles together with the magnetite content of the intrusive may be a useful tool in the exploration for porphyry copper-gold deposits.

3.2.7 Deposit Size and Tonnage

Porphyry copper-gold deposits with gold grades greater than or equal to 0.44ppm, range in size from approximately 5 million tonnes, e.g. Marian (Philippines) to 900 million tonnes at Panguna. Grades and tonnages of some SW Pacific Island and Chilean deposits are shown in Figures 33, 34 and 35. Sillitoe (1979) noted that there was no relation between deposit tonnage and gold grade, however from more recent work by Cox and Singer (1988) (Table VI) there appears to be a greater number of small deposits on the gold side compared to larger deposits on the molybdenum side. Median tonnages for the porphyry copper-gold type are 160 x 10^6 metric tonnes compared to 500 x 10^6 metric tonnes for the porphyry copper-molybdenum type. This difference in tonnage is possibly related to the volcanic and plutonic association of the deposit types (Cox and Singer, 1988).

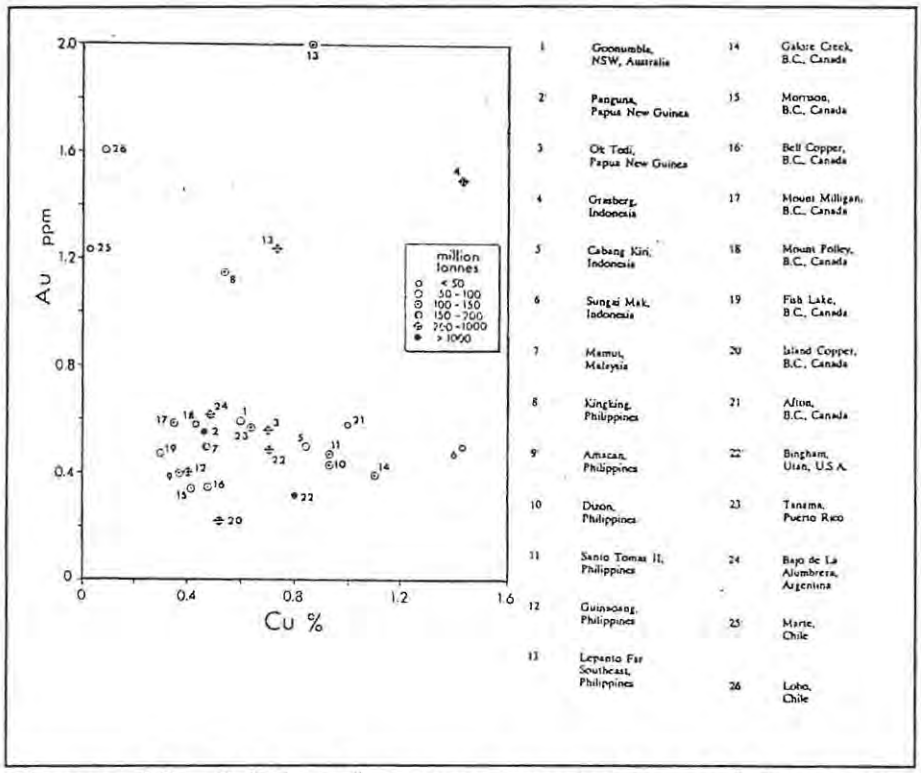


Figure 33. Gold and copper contents and tonnages of some circum-Pacific porphyry Cu-Au deposits (after Sillitoe, 1990).

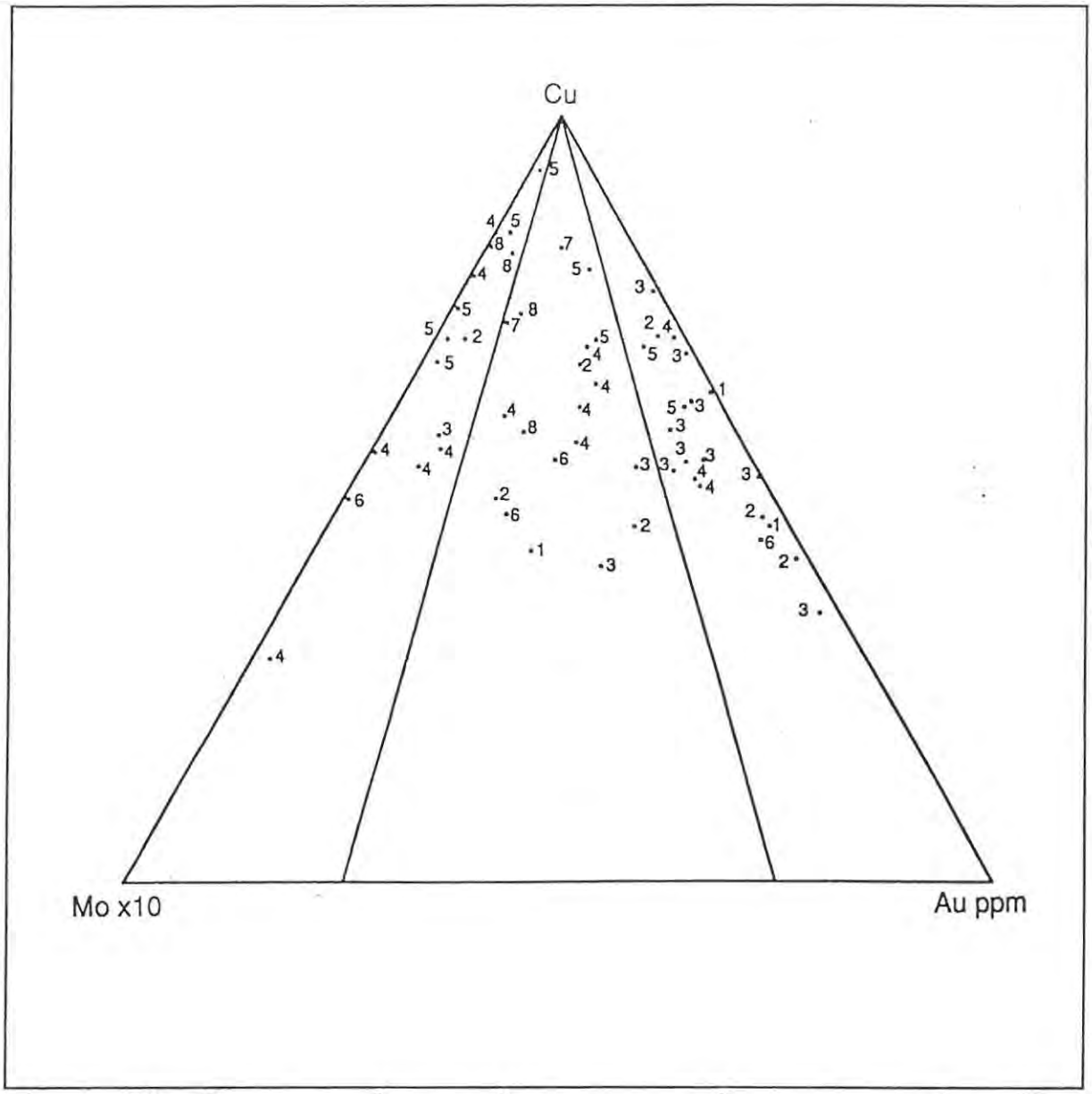
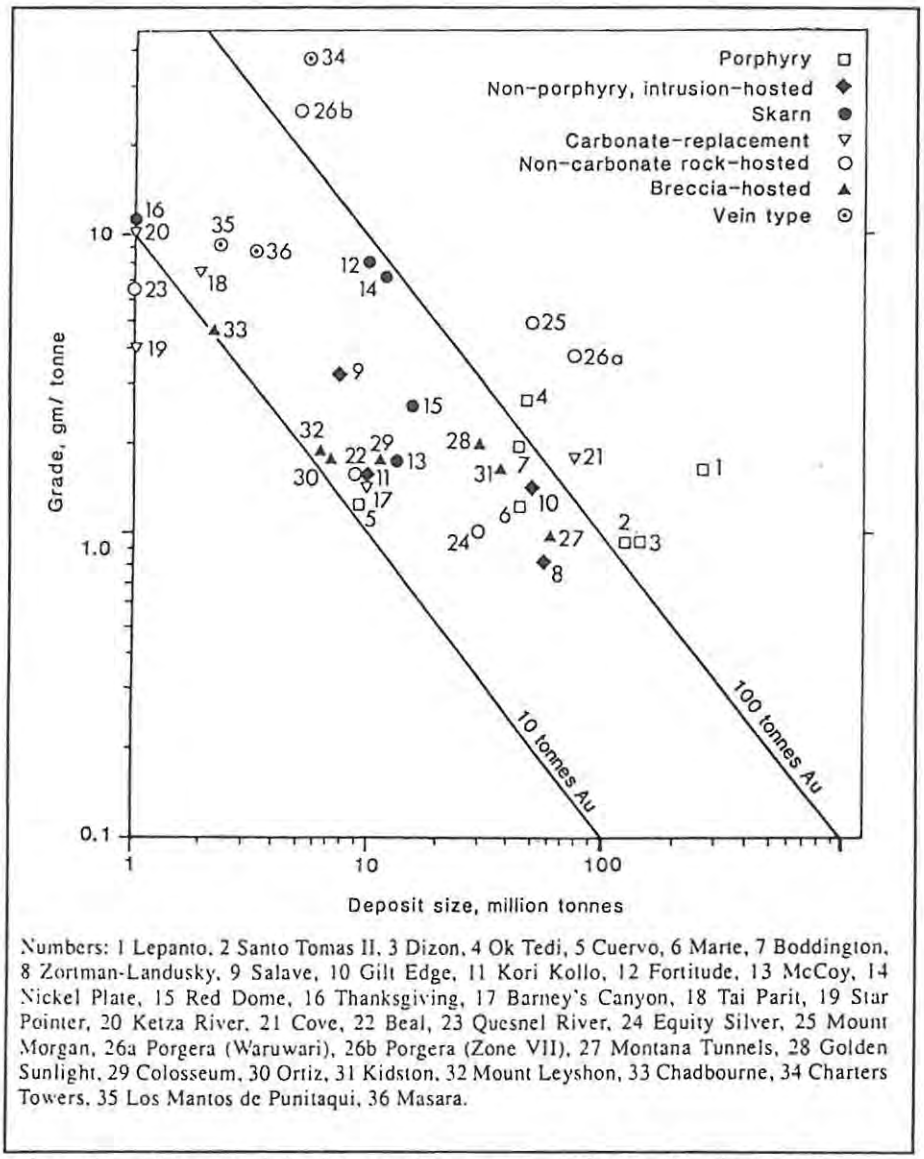


Figure 34. Tonnages classes for some porphyry copper deposits, defined in millions of metric tonnes (Cox and Singer, 1988).

1 = 0 to 50
2 = 51 to 100
3 = 101 to 200
4 = 201 to 400
5 = 401 to 800
6 = 801 to 1600
7 = 1601 to 3200
8 = 3201 to 6400

Average copper and gold grades are shown in Figures 35, 36 and 37 with the average tonnage shown in Figure 38.



Numbers: 1 Lepanto, 2 Santo Tomas II, 3 Dizon, 4 Ok Tedi, 5 Cuervo, 6 Marte, 7 Boddington, 8 Zortman-Landusky, 9 Salave, 10 Gilt Edge, 11 Kori Kollo, 12 Fortitude, 13 McCoy, 14 Nickel Plate, 15 Red Dome, 16 Thanksgiving, 17 Barney's Canyon, 18 Tai Parit, 19 Star Pointer, 20 Ketza River, 21 Cove, 22 Beal, 23 Quesnel River, 24 Equity Silver, 25 Mount Morgan, 26a Porgera (Waruwari), 26b Porgera (Zone VII), 27 Montana Tunnels, 28 Golden Sunlight, 29 Colosseum, 30 Ortiz, 31 Kidston, 32 Mount Leyshon, 33 Chadbourne, 34 Charters Towers, 35 Los Mantos de Punitaqui, 36 Masara.

Figure 35. Gold deposits associated with the various deposit types (after Sillitoe, 1990).

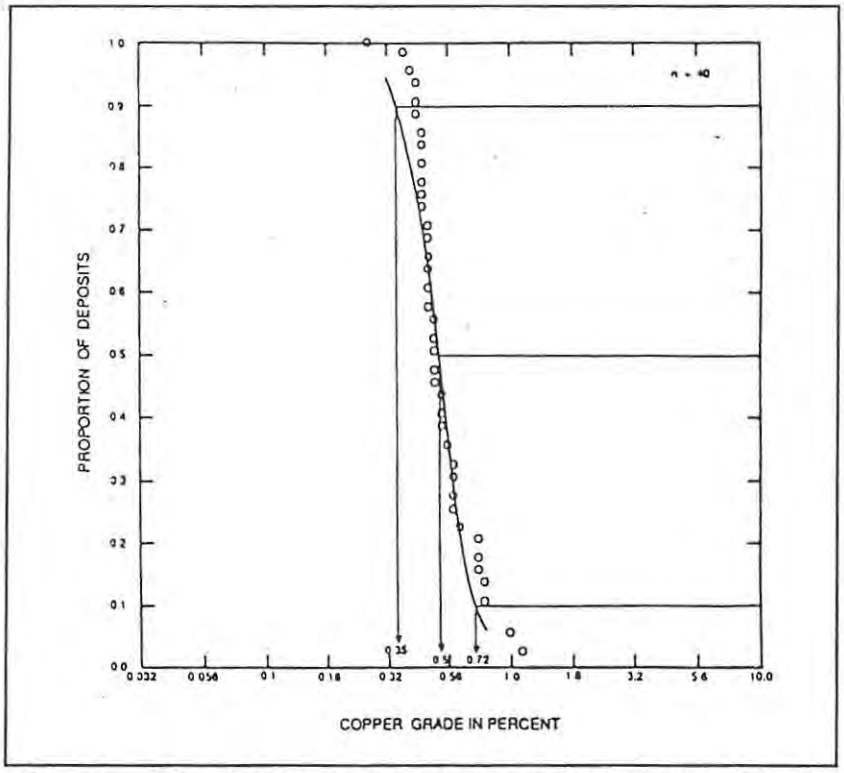


Figure 36. Copper grades of porphyry Cu-Au deposits (after Cox and Singer, 1986).

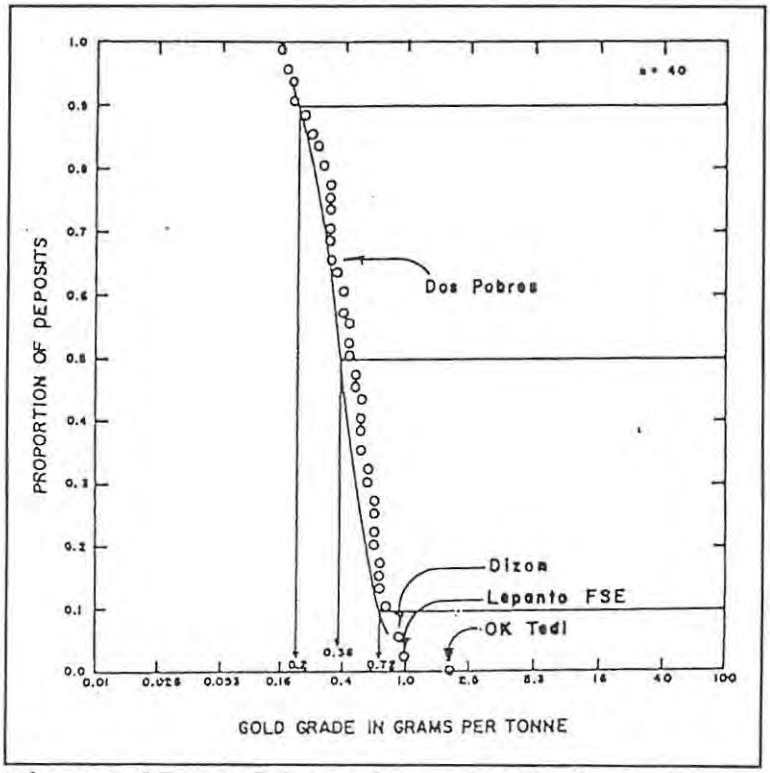


Figure 37. Gold grades of porphyry Cu-Au deposits (after Cox and Singer, 1986).

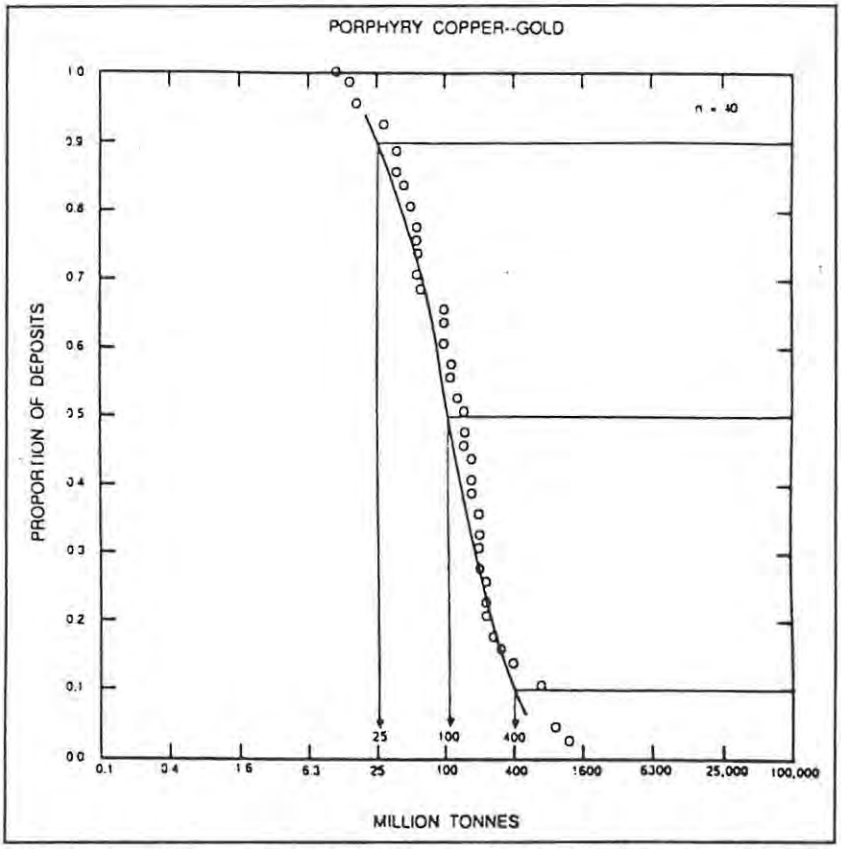


Figure 38. Tonnages of porphyry Cu-Au deposits (after Cox and Singer, 1986).

3.2.8 Alteration

The types of alteration which may be observed over copper-gold-rich porphyry deposits are related to the rock type, movement of magmatic and hydrothermal fluids through the system (favoured by extensive fracturing), the chemical conditions of the fluids and the sulphide content of the intrusive.

Alteration associated with porphyry systems are outlined in Figure 39.

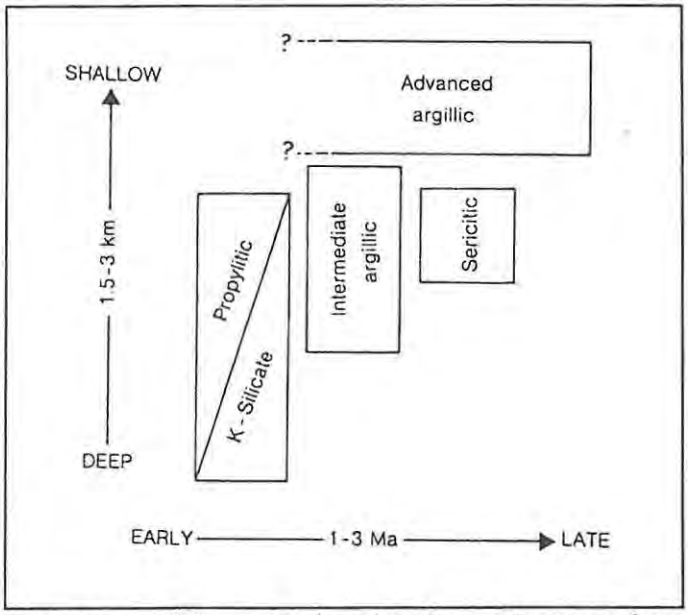


Figure 39. Principal alteration types in gold-rich porphyry copper deposits (after Sillitoe, 1990).

- Potassic - (core zone) - Secondary K-feldspar, quartz biotite ± plagioclase, ± pyrite ± anhydrite.
  - High Temperature.
- Propylitic - (outer zone) - Chlorite, epidote, albite, calcite and pyrite.
  - High temperature.
- Phyllic - (intermediate zone) - Quartz sericite and pyrite.
  - Low Temperature.
- Argillic - (intermediate zone) - Kaolinite, quartz, chlorite.
- Advanced Argillic - Quartz-alunite plus kaolinite, quartz-alunite-native sulphur, quartz-diaspore [AlO(OH)], quartz-alunite-sericite.

The alteration types of porphyry Cu-Au deposits in the SW Pacific Islands, Chile and British Columbia are compared to determine whether there are any differences related to:

Rock type : Quartz diorites - Monzonites (SW Pacific, Chile).
Alkalic-rich rocks - Shoshonites (SW Pacific and British Columbia.

Tectonic Setting : Continental Arc - Chile
Island Arc - SW Pacific
Accreted Island Arcs - British Columbia.

3.2.8.1 K - Silicate Alteration

Potassic alteration is the most important alteration type associated with porphyry Cu-Au mineralisation (Sillitoe, 1990). The alteration is characterised by the presence of biotite together with K-feldspar and/or amphibole and often well developed quartz veining. K-feldspar is more abundant in high-K calc-alkaline and alkaline intrusions, whereas amphibole (hornblende and/or actinolite) is more common in diorites to quartz diorites due to the greater availability of calcium (Sillitoe, 1990). Within the SW Pacific Island deposits it is reported that potassium feldspar is less abundant than biotite within potassically altered diorites and quartz diorites (Saegart and Lewis, 1977). Albitisation rather than potassic feldspar may occur in more alkalic porphyry deposits, e.g. Afton and Ajax in British Columbia (McMillan, 1991).

Anhydrite is also commonly widespread in the potassic zone, as is hydrothermal magnetite, which may amount to 5-10% by volume of some deposits (Sillitoe 1979, 1980, and Cox and Singer 1988).

Abundant quartz veinlets (stockwork) contain hypogene sulphides and iron oxides viz. chalcopyrite, pyrite and bornite (% cp + bn = 0.5 - 3) (Sillitoe 1990). The iron oxides commonly present include magnetite and hematite, Hematite may occur in the specular form or as martite after magnetite (Vila and Sillitoe, 1991).

3.2.8.2 Propylitic Alteration

This alteration type is characteristic of both calc-alkaline and alkalic porphyry deposits in the continental and island arc environments. It occurs peripherally to K-silicate and/or argillic alteration, and includes chlorite, epidote, calcite and pyrite.

3.2.8.3 Phyllic Alteration

The more potassic-alkalic deposits do not generally contain a phyllic zone as was evident in the porphyry copper-gold deposits in British Columbia (McMillan, 1991). Quartz-sericite alteration is more restricted in the Au-rich porphyry deposits of Chile and the Philippines compared to Cu-Mo-rich porphyry deposits of Chile and/or the Western Hemisphere deposits (Saegart and Lewis, 1977 and Sillitoe, 1990).

3.2.8.4 Argillic Alteration

Argillic alteration is often unrecognised as an overprint to K-silicate assemblages particularly in the upper parts of stocks (Sillitoe, 1990).

The alteration assemblage which includes quartz-chlorite-sericite-illite-smectite and calcite is often a widespread overprint in the ore zones of calc-alkaline porphyry copper-gold deposits in the SW Pacific Islands and the Maricunga belt in Chile (Vila and Sillitoe, 1991).

3.2.8.5 Advanced Argillic Alteration

Sillitoe, (1990) suggests that the advanced argillic alteration is thought to be more widespread in the upper volcanic hosted parts of porphyry gold-rich systems. It's preservation potential in such gold-rich porphyry systems is therefore determined largely by erosion rates and age of the system. Calc-alkaline deposits in Chile and the SW Pacific Islands, e.g. Marte and Dizon, have advanced argillic alteration caps (Sillitoe, 1990, Vila et al., 1991 and Malihan, 1987).

The alteration minerals include chalcedonic quartz, alunite, pyrophyllite and diaspore. Small amounts of rutile and tourmaline have also been reported in some of the deposits, e.g. Marte.

3.2.9 Metal Zonation

In gold-rich porphyry systems gold may commonly occur throughout the system. However, according to Jones (1992), it generally shows a preference for deposition and enrichment in either the central, intermediate or distal gold zones. Examples of these are highlighted below.

3.2.9.1 The Central Copper-Gold Zone

Many gold-bearing porphyry copper deposits have a high correlation between hypogene copper and gold grades. Gold has been reported by Sillitoe (1979) and Cox and Singer (1988), to be associated with bornite in a potassic assemblage dominated by secondary biotite and magnetite. Porphyry deposits with a central Cu-Au zone include Panguna (Figure 40), OK Tedi in Papua New Guinea, Bell and Granisle in British Columbia.

3.2.9.2 Intermediate Gold Zone

This intermediate gold zone occurs between the central copper zone and the lead-zinc zone of some porphyry deposits. This has been documented and reported by many workers such as Sillitoe (1988), Sillitoe and Bonham (1990), and Lowell (1988). Deposits with economically important intermediate gold mineralisation include the Copper Canyon district in Nevada (Figure 41), San Manuel-Kalamazoo in Arizona, Tanama and Helecho in Puerto Rico, Robinson district in Nevada and Mt Milligan in British Columbia (Jones, 1992).

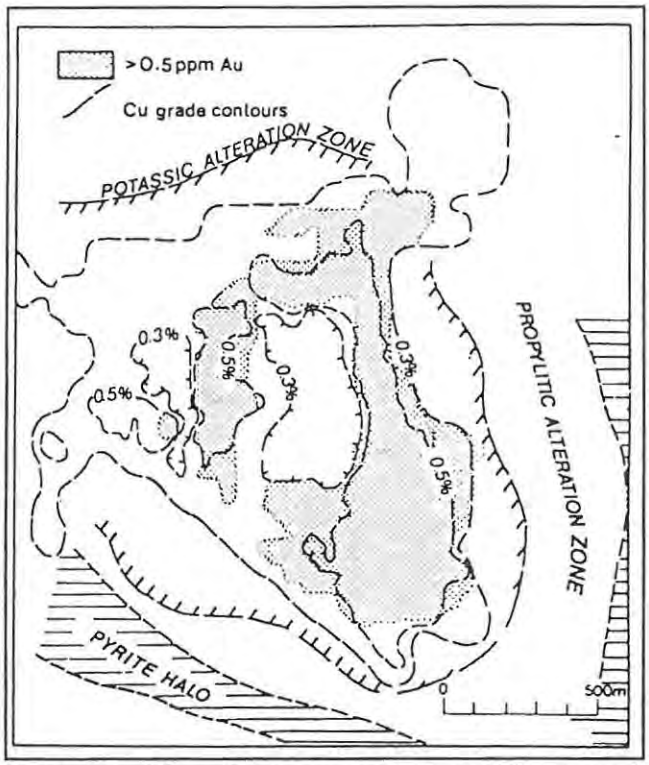


Figure 40. Copper-gold zoning and alteration at the Panguna deposit, Papua New Guinea (after Jones, 1992).

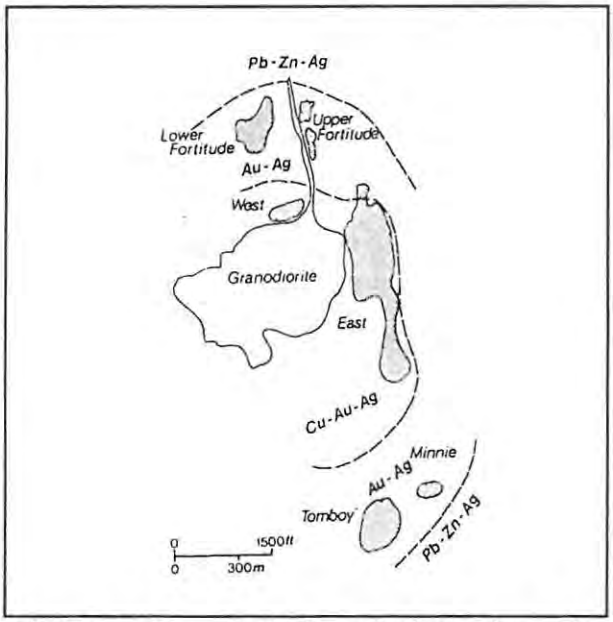


Figure 41. Metal zoning in the Copper Canyon district, Nevada, porphyry system (after Jones,1992).

3.2.9.3 Distal Gold Zone

The close proximity of certain gold deposits with porphyry stocks possibly suggests some genetic relationship exists. Examples include sediment hosted gold mineralisation at Bau in Sarawak and Carlin type gold mineralisation in the Yauricocha district in Peru and Barneys Canyon near Bingham mine (Figure 42).

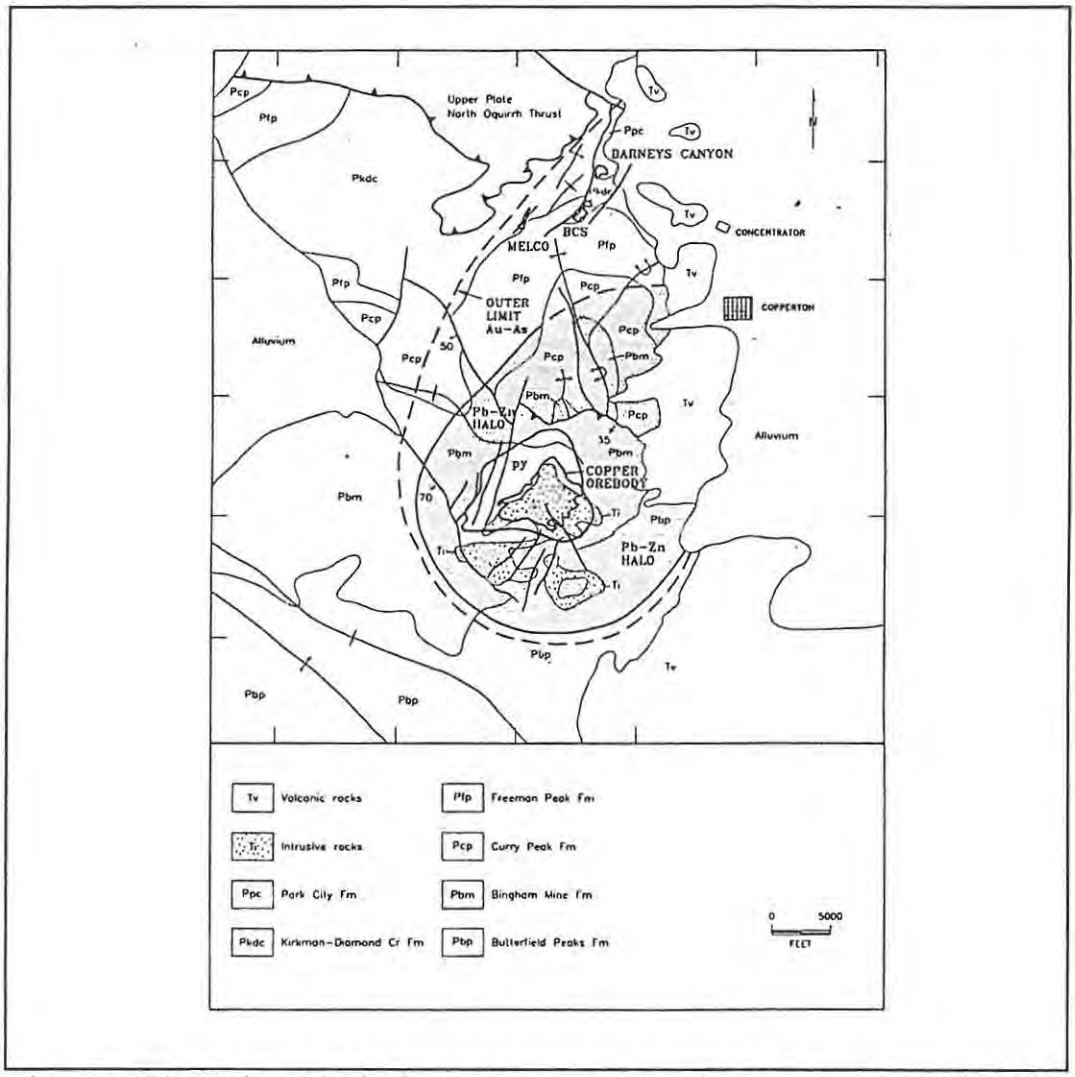


Figure 42. Simplified geology and metal zonation in the Bingham district (after Babcock et al., 1992).

3.2.9.4 Systems with Multiple Gold Zones

Certain districts display gold enrichment in all of the above three zones. This is characteristic of the large porphyry copper deposits with extreme gold enrichment. Examples include Bingham Canyon in Utah and Lepanto in the Philippines (Figures 42 and

43).

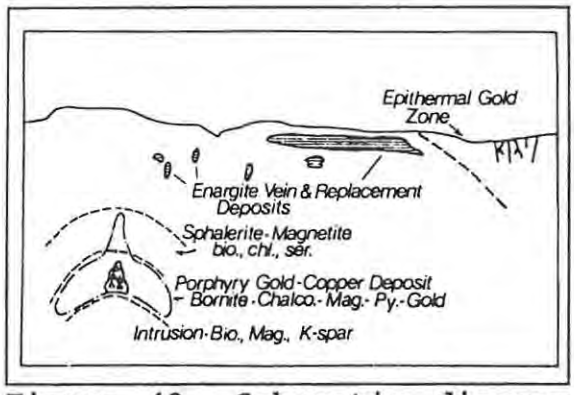


Figure 43. Schematic diagram showing the location of gold enriched deposits at Lepanto (after Jones, 1992).

From the above recorded distribution of gold, it is clear that gold has the potential to precipitate in economic concentrations both within and at various distances away from the progenitor intrusions.

Traditional hydrothermal zoning (Fe-Ni-Sn-Cu-Zn-Pb-Ag-Au-Sb-Hg), Barnes (1975), does not explain the above zoning. It only predicts the distal precipitation of gold along with Sb, Hg and $\pm$ As. Hemley et al. (1987) showed that hydrothermal zoning is dependent mainly on temperature-concentration relationships and suggested that zoning reversals are due to the differences in the relative concentration of metals.

4. PHYSIOCHEMICAL CONSTRAINTS ON PORPHYRY COPPER-GOLD MINERALISATION

4.1 General

According to Burnham (1981) six major physiochemical constraints of the parent magma are recognised for efficient mineralisation within the porphyry system. These include:

1) H_2O content
2) Temperature
3) Metal content
4) Chlorine content
5) Sulphur content
6) Oxidation state.

Generally it is suggested by Burnham (1981) that copper-gold porphyries are related to calc-alkalic hornblende-biotite quartz diorites and granodiorites typical of island arcs, i.e. I-type granite systems. Alkalic biotite, quartz monzonites and syenites tend to be more typical of most molybdenum and continental copper-molybdenum porphyries. Furthermore markedly peraluminous, generally biotite-bearing, granitoids are typical of the tin-tungsten porphyries.

Porphyry copper-gold magmas possess characteristics of the igneous or chemically unfractionated source rocks from which they were derived. Partial melting of hornblende-bearing mafic rocks of igneous origin, either amphibolitised oceanic basalts in a subduction zone or hornblende gabbros in the lower continental crust, yield I-type calc-alkaline magmas with the requisite chemical composition to be direct progenitors of copper-gold porphyries. The moderate low water content and the high temperatures of magmas derived from more mafic source rocks, enables them to reach high levels within the crust and possibly into the epizonal environment where gold-rich deposits tend to be found, e.g. Marte in Chile.

Hornblende-bearing mafic rocks yield melts capable of ascending to the surface that contain approximately 2,7 wt% H_2O (Burnham and Ohmoto, 1980). These melts have initial temperatures of 1000°C to 1050°C and are granodioritic in composition. Biotite-bearing

granodioritic and tonalitic source rocks yield initial alkalic melts in the lower continental crust at temperatures of 800° - 850°C with 3,3 wt% H_2O. These melts are also capable of ascending to depths of 2 to 3km without becoming crystalline. Alkali melts derived from muscovite-bearing source rocks are incapable of reaching epizonal depth of porphyry magma emplacement due to their 8,4 wt% H_2O content and moderate temperatures of 700° - 750°C.

4.2 H_2O Content of Magmas

The H_2O content of magmas must be such that the mechanical energy released during crystallisation and exsolution of aqueous fluids (second boiling) is sufficient to produce extensive fracturing at depths of 2-8 km. Magmas with less than 2 wt% H_2O are incapable of extensive fracturing and the formation of hornblende or biotite as a phenocryst phase.

4.3 Temperatures

Temperatures of porphyry magmas are inversely related to the H_2O contents. Temperature must be high enough to carry the magmas in a largely liquid state to depths of 4km or less. Therefore temperatures in the source regions of these magmas must be 800°C or higher (Burnham, 1979).

4.4 Metal and Chlorine Contents

The minimum metal content of the source rocks necessary to yield economic mineralisation is difficult to quantify as it is dependant on numerous factors, e.g. structural sites, transporting ligands etc. (Burnham, 1981).

The higher the chlorine content of the fluid, the greater its capacity to transport both metals (mainly Fe) and reduced sulphur (H_2S). Fluids with chlorine contents less than 1.8%, i.e. slightly less than seawater, and equivalent to 0,05 wt% in the magma, are relatively ineffective in transporting large quantities of metals (chiefly Fe) and sulphur necessary to produce a pyrite-rich porphyry copper-type mineralisation.

Burnham (1981) reports that a 100 million ton orebody averaging 0,5% copper could be obtained from only one cubic kilometre of magma that contains 200ppm Cu.

To be effective copper-gold bearers, porphyry magmas should contain at least 0,05 wt% Cl^-.

In fluids of average total chlorine content released from the H_2O saturated carapace of porphyry plutons, at temperatures above the stability field of hornblende and biotite, 60 mole% of the Cl is associated with Na and K. A further 27% is associated with metals (chiefly Fe), 4% with Ca in $CaCl_2$ and 9% with H in HCl. With exsolution of a chloride-rich brine from a magmatic-hydrothermal fluid, HCl is the only chloride complex to be concentrated in the H_2O-rich (steam) phase together with H_2S and SO_2. Chlorides are concentrated in the brine (up to 77 wt% NaCl) and the metal oxide and sulphide solubilities are also exponentially dependent on the chloride concentration, which results in the high-temperature brine phase being very effective in redissolving already precipitated sulphides and oxides.

These brines are then capable of transporting metals and sulphur to lower temperature regions of the fracture system where reaction with the acid volatile-enriched aqueous fluids results in the precipitation of sulphides, oxides and sulphates over relatively narrow temperature ranges (Burnham, 1981).

The precipitation of oxides such as cassiterite and magnetite is accompanied by the release of HCl to the hydrothermal fluids. Examples are indicated below :

1) 1 mole of chalcopyrite or pyrite deposited, results in 4 moles of HCl being released.
2) 1 mole of cassiterite deposited, results in 2 moles of HCl being released.
3) The deposition of 1 mole of magnetite (Fe_3O_4), releases ± 8 moles of HCl.

This release of HCl is regarded as the principal source of acid for phyllic alteration.

4.5 The Sulphur Content and Oxidation State

Generally S-type porphyry magmas are sulphur-rich and contain in excess of 0,2 wt% S. However, many I-type magmas are constrained to contain perhaps only 1/10 of this amount sulphur (Burnham, 1981).

Fluids exsolved from low fO_2 S-type magmas, result in all the sulphur forming H_2S which inhibits dissolution of already precipitated sulphides. It also limits the transport of metals such as iron, copper and gold, by chloride-rich magmatic hydrothermal fluids. Fluid derived from high fO_2 I-type magmas, result in the lowering of already low H_2S fugacities by oxidation of H_2S to SO_2. This SO_2 is insoluble in the melt phase (Burnham, 1979) and may form oxidised aqueous complexes. Already precipitated sulphides are redissolved, and the transport of metals and sulphur out of the H_2O saturated carapace is greatly enhanced in the porphyry system.

The immiscible separation of chloride-rich brines from I-type magmatic fluids during its escape into the fracture system, results in the SO_2 and H_2S in the original magmatic aqueous phase to be partitioned into the H_2O-rich "steam" phase. Cooling of the sulphur-rich fluid and the formation of H_2S from SO_2 occurs at temperatures between 500°C and 350°C (Burnham and Ohmoto, 1980). This is essentially the same temperature interval over which the acid-rich volatile phase rehomogenises with the chloride-rich brine phase.

It is this hydrolysis and rehomogenisation process which is regarded as the major, if not dominant, factor controlling the localisation of ores (copper-gold) in the porphyry copper system.

The reduced magmas associated with gold-rich porphyry deposits (Leveille et al., 1988), evolve fluids with lower oxygen and sulphur fugacities resulting in chalcopyrite-magnetite-bornite assemblages rather than the chalcopyrite-pyrite assemblages of gold-poor porphyry deposits (Figure 44).

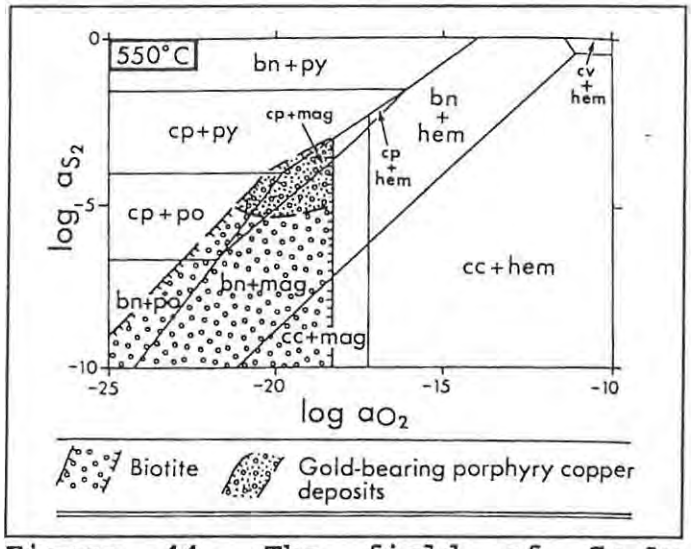


Figure 44. The field of Cu-Au deposition in K-silicate alteration zones of gold-rich porphyry copper deposits as a function of fO_2/fS_2 (after Sillitoe, 1990).

5. TRANSPORT OF GOLD

5.1 General

According to Large et al. (1989) gold is transported in hydrothermal solutions either as thio-complexes [$Au(HS)_2$, $Au_2(HS)_2^-S^{-2}$] or chloro-complexes ($AuCl_2^-$). Other complexing agents may include sulphide-, telluro-, carbonyl- or carbonate gold complexes. The $AuCl_2^-$ complex is the most important complex involved in initial gold transport in porphyry copper systems.

The importance of the thio- and chloro- complexes in a hydrothermal fluid is controlled by temperature, pH, salinity and the H_2S activity.

Gold transported as $AuCl_2^-$ is favoured by:

1) High temperature fluids (>300°C),
2) with low pH (<4.5),
3) low H_2S concentration ($<10^{-2.5}$m),
4) high salinity (> seawater) and
5) moderate to high fO_2 (pyrite or magnetite ± hematite stable).

Gold transported as $Au(HS)_2^-$ is favoured by:

1) Lower temperature fluids (150-300°C),
2) with moderate to alkaline pH (>4,5),
3) high H_2S concentration ($>10^{-2.5}$m),
4) low salinity (< seawater) and
5) moderate fO_2 (pyrite field only).

The switchover from $AuCl_2^-$ transport to $Au(HS)_2^-$ occurs at about 290°C given pH=4, $H_2S=10^{-3}$, 1m NaCl, $SO_4^{-2}/H_2S=10^{-1}$ (Figure 45). The variation in temperature, pH, concentration of H_2S and salinity, controls this switchover position.

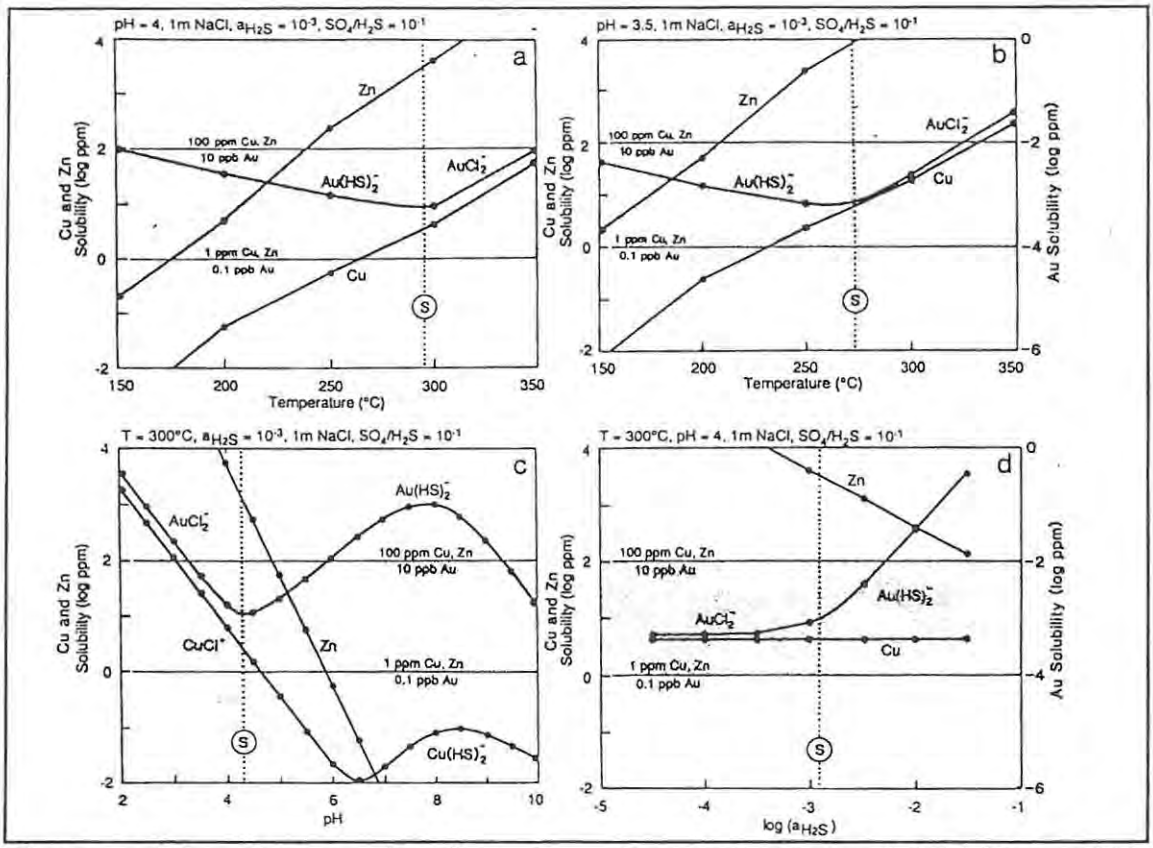


Figure 45. Plots showing Au, Cu and Zn solubility with temperature (a,b), pH(c) and log a_{H2S}(d). The switchover line from $Au(HS)_2^-$ to $AuCl_2^-$ predominance is shown (S) (after Large et al.,1989).

From Figure 45 it can be seen that for high temperatures and low pH, where $AuCl_2^-$ predominates, gold and copper show very similar solubility characteristics (Cu/Au ratios ± 10000:1 at saturation). Gold and copper can therefore be transported and deposited together at temperatures above 270°C to 300°C with dropping temperature or increasing pH.

At lower temperatures (150-270°C) $Au(HS)_2^-$ predominates and Zn and Au are transported and deposited together at low temperatures and moderate to neutral pH.

The sulphur carrying capacity of a given aqueous chloride solution is directly dependent on the oxygen fugacity in the system. Fluids derived from generally more oxidised "I-type" or magnetite series magmas are more effective gold and base metal sulphide mineralises than fluids derived from the more reduced "S-type" or ilmenite series magmas (Burnham and Ohmoto, 1980).

5.2 Effect of Salinity on Gold Transport

With increasing salinity, the $Au(HS)_2^-$ solubility decreases and the $AuCl_2^-$ solubility increases to about 4 wt% NaCl where it starts to flatten out (Figure 46).

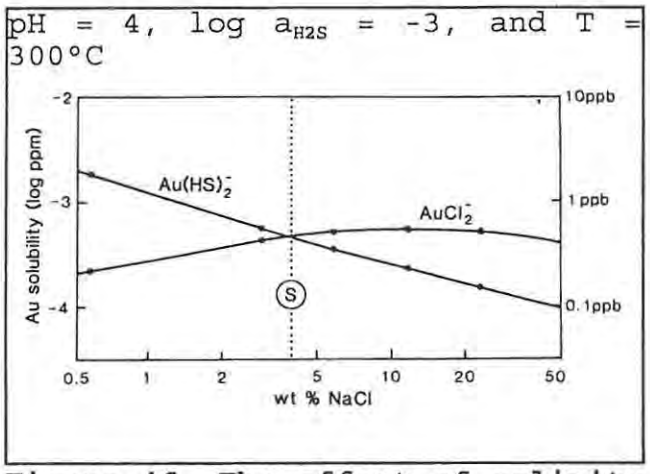


Figure 46. The effect of salinity on solubility of $Au(HS)_2^-$ and $AuCl_2^-$ complex (after Large et al., 1989).

In East China, salinities of ore-bearing solutions from porphyry copper-gold systems are between 15 and 55 wt% NaCl. Temperatures of 250° - 450°C are recorded for the transport of these metals as a chloride complex (Ren et al., 1990).

5.3 Temperature-fO_2 Control on Gold Transport

From Figure 47 it can be seen that $AuCl_2^-$ is soluble at high temperatures and high fO_2 and is independent of iron sulphide or oxides present. However $Au(HS)_2^-$ is more stable at lower temperatures. It forms a solubility window within the pyrite field. The solubility of $Au(HS)_2^-$ decreases rapidly adjacent to the pyrite-hematite boundary. With the reaction taking place as follows: $4Au(HS)_2^- + 2H_2O + 15O_2 \leftrightarrow 4Au^0 + 8SO_4^{-2} + 12H^+$

Under these conditions gold deposition is favoured by:

1) increasing fO_2,
2) decreasing temperature, and
3) increasing pH (Large et al., 1989).

(Possible cause - mixing of hydrothermal fluid with seawater).

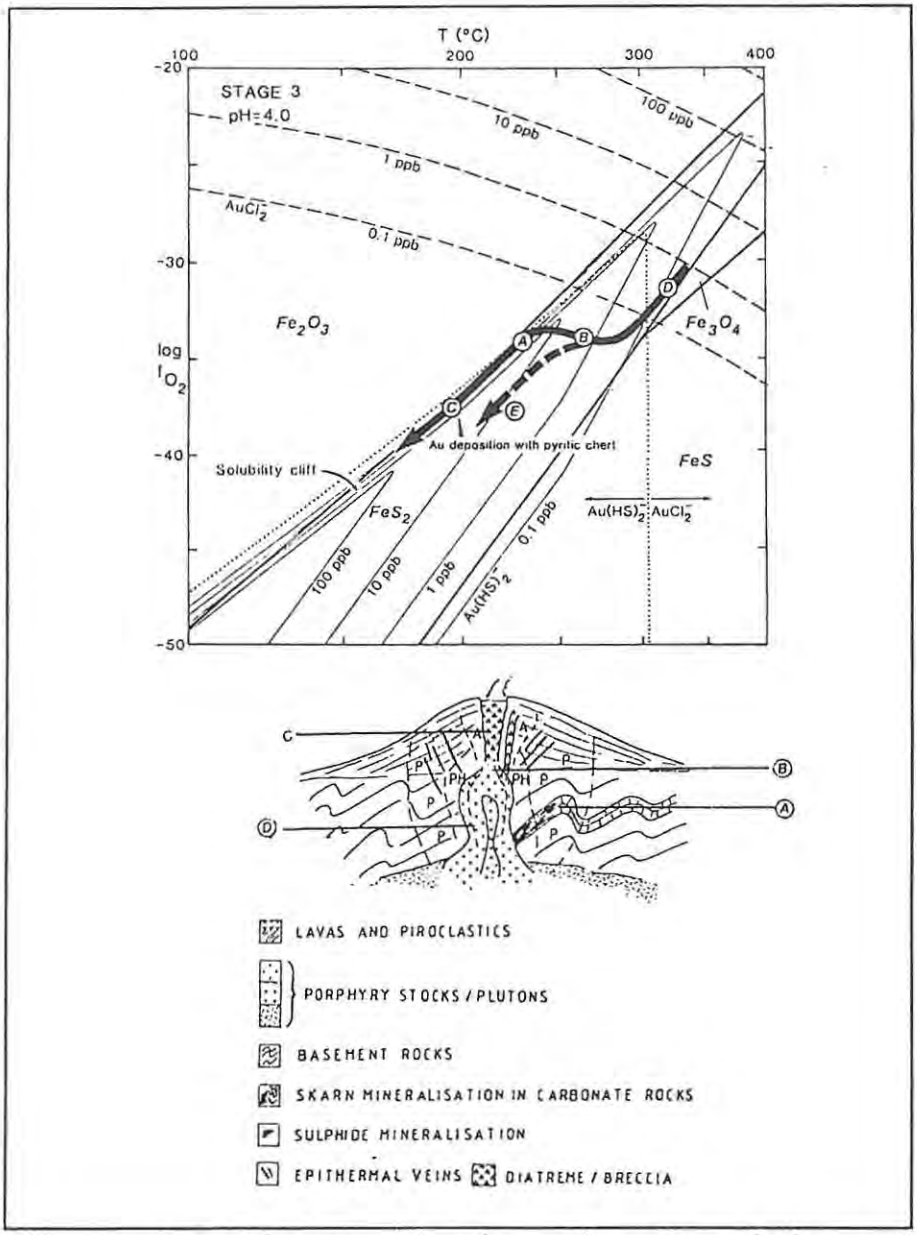


Figure 47. Diagram showing the deposition of gold in a porphyry system (modified after Large et al., 1989 and Pirajno, 1992).

From the geologic thermodynamic model proposed by Large et al. (1989) for gold concentrations in massive sulphide deposits, the following scenario could possibly apply to the porphyry system. This scenario is as follows:

If gold, copper, lead and zinc are carried in the same porphyry system, the following deposition trends may be expected to occur. Gold and copper may be expected to be deposited in the central portions of the porphyry system with decreasing temperature and/or increasing pH. For gold deposition it is assumed that gold is being transported as a hot, ≥

290 - 300°C, $AuCl_2^-$ complex, point (D) . With further cooling, ≤ 290°C, gold is transported as a $Au(HS)_2^-$ complex and deposited in more distal zones. Gold deposition may be controlled by oxidation resulting in the loss of H_2S, e.g.

$$H_2S + 2O_2 \rightarrow 2H^+ + SO_4^{-2}$$ and an increase in the SO_4^{-2}/H_2S ratio.

This would correspond to the movement of $Au(HS)_2^-$ from point (B), Figure 47, to point (C) where there is a steady temperature and fO_2 decline. If however the H_2S content is high, and as a result the SO_4^{-2}/H_2S ratio is low, the ore fluid may be buffered and will follow the BE path with little or no gold enrichment in the peripheral zones to the porphyry system.

Further work on the FeS content of sphalerite, in massive sulphide deposits has shown that gold-rich zinc ores are associated with low FeS (< 5 mole %) contents in sphalerite. Furthermore gold-rich copper ores are associated with pyrite ± magnetite ± sericite ± kaolinite and high FeS contents(> 5 mole %) in sphalerite.

The above could possibly be applied to porphyry copper-gold exploration provided that zinc is derived from the same system. The location of peripheral gold zones to copper porphyry systems, using the FeS contents of sphalerite, may together with fO_2, temperature and amphibole geochemistry, provide a vector for exploration.

The gold-copper association in the central part of the porphyry system reflects gold transport as a $AuCl_2^-$ complex from high temperature (> 300°C), low pH (< 4,5), moderate to high fO_2 and high salinity fluids. Whereas the gold-zinc association in the peripheral zones reflects gold transport as a $Au(HS)_2^-$ complex from lower temperature (200° - 250°C), moderate pH (4,5 - 6) and moderate fO_2 fluids.

6. GOLD-SULPHIDE ASSOCIATION - METALLURGICAL IMPLICATIONS

An important factor in assessing the economic viability of a copper-gold porphyry deposit is the mineral association of gold within the system. From the work done by Cuddy and Kesler (1982) on the Granisle and Bell porphyry copper-gold deposit in British Columbia, the following may be highlighted:

- Gold shows a close association with bornite in deposits containing this mineral and with undisturbed potassic alteration zones.
- Gold shows a random association with pyrite and chalcopyrite in the absence of bornite (usually in deposits with sericitic overprints).
- At temperatures of 600°C both bornite and chalcopyrite exhibit extensive solid-solution of Cu, Fe and S (Craig and Scott, 1974), and probably of gold.
- If bornite or chalcopyrite were deposited from a gold-bearing hydrothermal solution at 600°C, it would carry gold in solid solution.
- With cooling the gold would exsolve, but at 400°C chalcopyrite does not exhibit extensive solid solution and would probably not carry gold in solid solution. Therefore with the deposition of a 400°C chalcopyrite-pyrite ore such as at Bell, gold in solution will not go into chalcopyrite but instead it will deposit randomly on both sulphide minerals.
- Bornite-bearing ore formed at higher temperatures, i.e. about 600°C, would cause any gold to concentrate in the bornite and to exsolve during cooling.
- From the magmatic A veins in the centre of Granisle, gold was found to show a positive correlation with bornite, a negative correlation with magnetite and no correlation with chalcopyrite.
- In veins collected from the outer edge of the potassic zone (absence of bornite but the presence of pyrite) at Granisle, gold shows a positive correlation with chalcopyrite. However from an optical examination of the mill products at Bell, Owens (1974) found three grains of electrum, (10 to 55 micron diameter) two enclosed in chalcopyrite and one grain attached to pyrite. Thus, although gold occurs with chalcopyrite, a smaller but probably important amount may be associated with pyrite.

From the above gold-sulphide associations the following may be concluded :

- Gold recoveries would be expected to be greater from bornite-bearing ores compared to chalcopyrite-pyrite ores. The reason for this being that gold forming middling grains with pyrite report to the tailings, while gold-bornite middling grains report to the copper concentrate.
- Recovery of gold from the tailings would be difficult unless the material went directly to a cyanide circuit.
- If the gold was not adequately liberated from the pyrite, or the cyanide consumption was too high, it would be necessary to prepare a pyrite concentrate and roast it before cyanide treatment. This may then prove to be too costly.

7. EXPLORATION

7.1 General

According to Sillitoe (1988) the following may be considered as favourable signs for precious metals in the porphyry system.

- High contents of hydrothermal magnetite commonly occurring with K-silicate assemblages.

- Hydrothermal breccias, within and above porphyry copper-molybdenum deposits, may localise gold mineralisation. Gold mineralisation is most likely to occur within the most permeable parts of the breccia, e.g. sheeted contact zones.

- Regional and district fault zones may control precious metal mineralisation around, above and/or superimposed on porphyry copper deposits.

- Reactive wall rocks (carbonate bearing) may enhance the precious metal prospectivity of porphyry systems.

- Positions where carbonates are transformed to jasperoid or gossan after massive sulphides (rather than magnetite or andradite garnet) may be considered favourable targets (Sillitoe, 1988).

- Non-carbonate wall rocks with a high permeability, such as volcanic breccias, amygdaloidal flows and conglomerates, may also localise distal precious metal deposits.

- Porphyry copper systems with well developed peripheral alteration zones (propylitic and sericitic zones) and pyritic halos, may be more likely to host distal vein and metasomatic precious metal deposits.

- Bodies of chalcedonic silica (including jasperoid) in zones of advanced argillic alteration above porphyry copper deposits with prominent hydrothermal brecciation offer excellent precious metal targets.

Although all porphyry copper orebodies contain some gold, Lowell (1989) reports that there seems to be a fairly sharp break in the gold content at about 0,1g/t gold for gold-rich porphyry copper deposits.

Mineralised porphyry deposits may have formed at specific times, e.g. in the SW Pacific, emplacement of copper associated magmas occurred during the Miocene and predominantly in the Pliocene period. There may also be a specific range in time during which copper bodies in given regions may have formed, e.g. at Ray a 10 million year pre-mineralisation intrusion history has been documented. Similar pulse-like histories are suggested by the radiometric age data from deposits in the Sierrita and Patagonia Mountains of Arizona (Titley, 1970).

Exploration for gold-rich porphyry copper systems requires an understanding of the general characteristics of the deposits (described in this report) and subjectively prioritising these variables. Other criteria used for general porphyry copper exploration such as geophysics, alteration studies, relict sulphide studies, mapping of vein intensities and geochemical surveys, forms the basis for exploration once a region has been targeted.

7.2 Tectonic Setting and Rock Type

It would appear as though the gold-rich porphyry copper systems outlined in Table III and Table V and elsewhere in the literature are more prevalent in island arc and continental arc/(margin) settings. The intra-continental deposits tend to be more molybdenum-rich. The tectonic setting is possibly the most important variable in the "exploration equation". Within the island arc and continental arc(/margin) setting, the magma types associated with these gold-rich porphyry copper deposits include :

- Low-K calc-alkaline diorites to quartz diorites.
- High-K calc-alkaline granodiorites to quartz monzonites.

- Potassic alkaline diorites through to syenites and shoshonites (Figure 48).

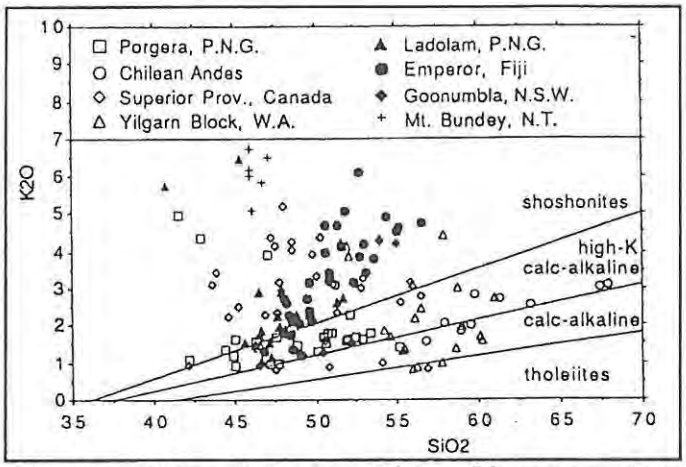


Figure 48. K_2O vs SiO_2 diagram for some gold-rich deposits (after Muller and Groves, 1993).

These are part of the I-type magnetite series of Ishihara (1981), and in general the $^{87}Sr/^{86}Sr$ ratios are between 0.702 and 0.707. The exceptions being the high K-shoshonitic rocks which may have high $^{87}Sr/^{86}Sr$ ratios, e.g. Bajo de la Alumbrera which may be taken as evidence for crustal contamination (Figure 49).

Figure 49. Initial $^{87}Sr/^{86}Sr$ ratios for rocks associated with porphyry Cu systems (after Sillitoe, 1987).

Sillitoe (1987) suggests that Cu-Au deposits may be generated in volcano-plutonic arcs underlain by thin island arc crust (30km thick) or thick (up to 70km) cratonic crust.

7.3 Age

The ages of porphyry copper-gold deposits are generally quite variable, however the preservation potential of such deposits is higher in Tertiary age porphyry bodies.

7.4 Multiple Intrusive Events

Intrusive events appear to be associated with certain time periods and mineralisation, viz. copper and gold are associated with certain epochs, e.g. 10-20 Ma in the SW Pacific Islands and 42-31 Ma in Chile. During these epochs certain areas, due to the structural controls and/or the angle of subduction and the melting of the subducting plate, may be characterised by the telescoping of porphyry intrusives. It is this telescoping of intrusives which is thought by Sillitoe (1990) to be typical of many mineralised porphyries, e.g. Grasberg and Marte. Identification of multiple intrusive porphyry bodies may empirically be more favourable for mineralisation, provided that the other criteria such as tectonic setting, rock type and other chemical constraints (magnetite content and chlorine content) are satisfied. No conclusive evidence is however available, but multiple intrusive events should be considered as being of significance when doing exploration.

7.5 Magnetite Content

The percentage magnetite, associated with the potassic alteration zone, can be an indication of the Cu-Au potential. As indicated in section 3.2.6, this is related to the oxygen fugacity within the system, and the crystallisation of magnetite causes gold to be precipitated out. Sillitoe (1979), Saegart and Lewis (1977) and Cox and Singer (1988) indicate that most porphyry copper-gold orebodies contain more than 1% magnetite. This appears to be especially true of porphyry copper-gold deposits in British Columbia associated with alkalic rocks, and deposits in the SW Pacific Islands associated with calc-alkaline and shoshonitic rocks. Furthermore, from the mine visit to El Salvador (porphyry copper deposit) in Chile, it was noticed that abundant magnetite was associated with the potassically altered "K-porphyry" in the Inca decline area. Gold grades from this primary ore zone were reported to be ± 0.6g/t, compared to 0.02-0.03g/t in other areas of the mine. Although there are

exceptions to this gold-magnetite association, the magnetite content must be considered in the exploration model.

7.6 Country Rocks

As a result of porphyry copper-gold deposits being associated with continental and island arc environments, there is usually an association with volcanics. This association with coeval volcanics may also suggest that these deposits are associated with the more high level intrusive porphyries. Intrusion of Cu-Au-rich porphyries into carbonate rocks may also lead to important Au-skarn deposits, e.g. OK Tedi. It is therefore suggested that the type of wall rocks, e.g. carbonates, may be important in localising mineralisation about the porphyry stock, and the coeval volcanics may suggest more favourable high level intrusives for Cu-Au mineralisation. Association of porphyry intrusives with coeval volcanics and carbonate host rocks (or other favourable reactive lithologies), may be assigned a higher exploration rating than porphyries with no coeval volcanics and/or sandstones as the wall rocks.

7.7 Chlorine/Fluorine Ratios

From studies done by Muller and Groves (1993) on gold-copper deposits associated with potassic igneous rocks, (e.g. shoshonites) in continental arc and late oceanic arc environments, the following is proposed.

Porphyry style Au ± Cu mineralisation associated with high-K igneous rocks are generally characterised by high contents of Cl and F (halogens), high LILE (K, Rb, Sr and Ba), low TiO_2 and low High Field Strength Trace elements (Zr, Nb, Y, REE).

The high Cl concentration (> 0.04 wt% Cl) in mica phenocrysts from mineralised intrusives may, according to Muller and Groves (1993), support a genetic relationship between magmatism and the mineralising fluids (highly saline, high temperature and low pH fluids for gold transport as a chloro-complex). Furthermore, Spooner (1993) suggests that gold deposits tend to be associated with the more volatile-rich potassic and calc-

alkaline magmas.

The use of Cl and F as an exploration tool for porphyry Cu-Au deposits may be significant and warrants further investigation. Caution must however be taken when analysing rocks from within plate settings which have inherently high halogen contents (Muller and Groves, 1993).

7.8 Amphibole Chemistry

Another possible exploration tool is the chemistry of amphiboles in the intrusive. Studies of amphibole grains in mineralised and unmineralised intrusives in Papua New Guinea by Mason and Mc Donald (1978), suggest the following :

- Mineralised porphyries display Mg-enrichment toward the rims of amphiboles (e.g. magnesio-hornblende to actinolite).

- Unmineralised porphyries contain amphiboles which display Fe-enrichment toward their rims.

It is suggested by Czamanske and Wones, (1973) and Helz, (1973) that the high oxygen fugacity (fO_2) caused Mg-enrichment in amphiboles of mineralised suites. This is therefore important and could be used as another tool in exploration programmes.

7.9 Vein Intensity

Measuring the fracture density during exploration mapping (N° of cumulative lengths of veins in the sample area divided by the sample area) can, according to Titley (1992 pers. comm.), be used as an aid in targeting sites of potential mineralisation. The area with the higher fracture density should be the potentially more favourable area for mineralisation (provided other criteria such as metal content, rock type, alteration features and other factors are favourable).

7.10 Alteration

The identification and mapping of the alteration types and intensities is important in locating the ore zone generally associated with potassic alteration and magnetite. In alkalic deposits, such as those in British Columbia, the phyllic, argillic and advanced argillic alteration zones are poorly developed. In more calc-alkaline deposits, e.g. in the SW Pacific Islands and in Chile, argillic and advanced argillic alteration zones are common and may be located using Landsat imagery. Furthermore, potassium radiometric highs, reflecting hydrothermal alteration related to copper-gold mineralisation, may be used to locate target zones.

Alteration mapping, superimposed on a vein intensity plan, geochemical plan and relict sulphide plan can be extremely useful in targeting the ore zone.

Alteration types recognised in the SW Pacific are generally the same types which occur in the SW USA deposits. The difference, however, is that alteration in the W Hemisphere deposits is interpreted as being zoned and less commonly considered in the context of paragenesis (Titley, 1978). However, the SW Pacific alteration types tend to be less discreetly zoned and are best described by the process of telescoping of intrusions and alteration types.

Further departures of the alteration mineralogy is related to the rock types. In the more dioritic rocks, orthoclase veining is commonly attended by epidote, which is the possible result of potassic alteration of more basic rock, or of sodium metasomatism. Carbonate alteration is also more widespread in the SW Pacific than for deposits in the W Hemisphere. Calcite alteration in the propylitic zone seems to be closely associated in time with at least some significant copper occurrences. This carbonate alteration appears to be a manifestation of "intense" types of alteration in SW USA.

7.11 The Effect of Climate on the Characteristics of the Leached Capping and the Mobility of Copper and Gold

In this section a brief overview of porphyry Cu-Au deposits in arid and humid tropical conditions is given, with respect to supergene leaching processes, leached cappings and copper and gold within the system.

Copper-gold deposits formed in humid, high rainfall areas may be expected to be deeply weathered with significant oxidation, leaching and resultant enrichment. Strong weathering may lead to the formation of reddish saprolites and iron oxides which may include hematite, goethite and jarosite.

In a very humid, high rainfall, environment the groundwaters can be expected to have a higher pH due to the diluting action of the abundant rain (e.g. La Huaca in northern Peru - 1-2m p.a., Snoep and Zeegers, 1979 and Yanderra in Papua New Guinea, Sillitoe, 1975).

In a humid environment, with a high water table, deep oxidation is prevented, rapid leaching is curtailed and copper is expected to have a lower mobility and bind either as an oxide or in combination with iron-oxides. The development of a secondary enriched blanket is less likely in this environment compared to, e.g. semi-arid areas, where deep oxidation and leaching, (because of the low water table), allows periodic recharge water to remove capillary solutions from the oxide zone, leading to enrichment (Anderson, 1982). Secondary copper enrichment is further prevented if the pyrite ratio is low, (limits acid production), which for gold-rich deposits in the circum-Pacific is reported by Sillitoe (1990), to be as follows; py/cp + bn = 0.5-3.

Gold in this humid, wet environment is also relatively immobile, and will not be concentrated in the "enriched blanket" but will more than likely be scavenged by the iron oxides in the leached capping (Figure 50).

Copper-gold porphyry deposits formed in an arid environment, e.g. the Maricunga Belt in Chile, may be characterised by an extensively oxidised and leached horizon overlain by

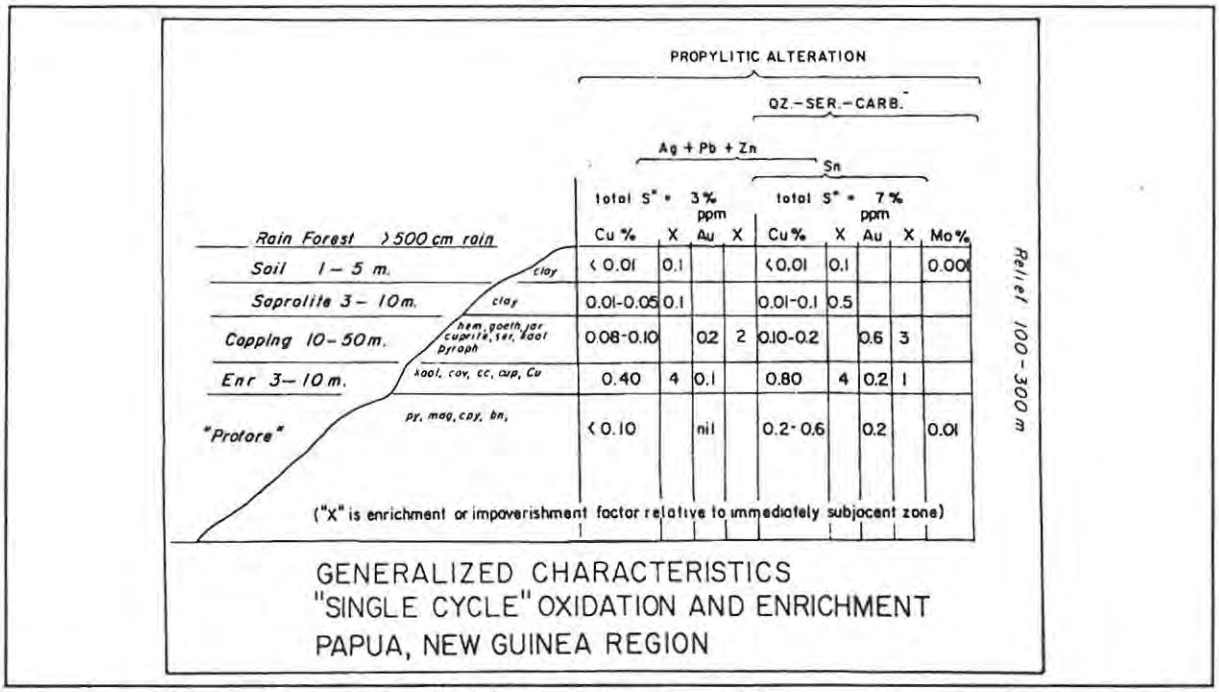


Figure 50. Characteristics of leaching and enrichment of metals in rain forest environments (after Sillitoe, 1975).

a capping of hematite, goethite and jarosite. Below the leached horizon a well developed secondary enriched copper blanket may form. This environment is favourable for the formation of acid waters after pyrite dissolution and high Eh conditions extending to greater depths. Copper is leached out and is highly mobile under these acid conditions. It precipitates out and may form a secondary enriched chalcocite blanket at/or close to the water table (change in redox status). Gold however is relatively immobile under acid conditions and is generally not enriched in the secondary copper blanket. Gold concentrations in the leached capping will closely reflect the potential of the protore below as a gold orebody.

It is therefore important to consider the environment of formation of these deposits and bear in mind that gold-copper anomalies will not necessarily coincide in arid environments. The formation of acid solutions favours the transport of copper, but not gold, out of the system or some distance from the protore.

7.12 Geochemical Surveys

Regional stream sediment geochemical sampling of major drainages is initially required. Where possible, field panning of stream sediments (e.g. 30 litres at 30 to 100 cm depths - Nuchanong et al., 1991) may prove useful as an indication of the coarseness and content of gold in the stream. Generally, samples are sieved to produce minus 63 micron and/or minus 80 micron fraction (e.g. Nuchanong et al., 1991, Lowder and Dow, 1978). However, the ideal sampling size must be determined during an initial orientation survey. In more arid environments, gold may be in the coarser fraction. The samples collected should be analysed for Fe, K, Pb, Zn, Cu, Mo, Au, As, Ag and Mn.

Follow up on reconnaissance surveys should include soil sampling. The soil sampling programme should include an orientation survey whereby the most favourable soil horizon is chosen for sampling. In the more humid and tropical environments, e.g. Thailand, Indonesia and Northern Peru (Nuchanong et al., 1991, Lowder and Dow, 1978 and Snoep and Zeegers, 1979), the samples are taken from the B-horizon close to bedrock and/or in the saprolites. The sample size may vary between 300-500g.

In the more arid environments, e.g. Southern Peru and Chile, two types of samples may be taken. This includes residual soil samples over the intrusive body and/or rock chip samples. Caution must be taken not to take samples from transported soil horizons or younger aeolian deposits.

Multi-element zoning patterns may be evident in indicating areas favourable for drilling. Copper-gold porphyry deposits may have a high-K anomaly associated with the potassic alteration zone, a gold anomaly which outlines the centre of the mineralised zone and/or a copper anomaly. In the arid environments, the copper and gold anomaly need not overlap the central mineralised zone due to the high mobility of copper in the oxidised acid leached upper portion of the profiles.

Another form of geochemical prospecting which is being considered for gold-copper mineralisation is the use of tourmalines (Koval et al., 1991). According to Koval et al.

(1991), the high abundances of Au, Ag and As in tourmalines are effective signs of gold mineralisation. Application of this method to porphyry copper-gold exploration is not yet proven and requires confirmation of its usefulness from a larger database.

7.13 Geophysics

Airborne electromagnetic surveys, aeromagnetic surveys, ground magnetic surveys, induced polarisation surveys and radiometric surveys are used in porphyry copper-gold-molybdenum exploration.

Airborne electromagnetic surveys are used mainly for structure mapping and identifying zones of low and high resistivity over porphyry intrusives. Identification of structural lineaments, lineament intersections, lineament trends and possible fault jog zones can be used in targeting further geological mapping and ground geophysical surveys. Aeromagnetic surveys are also used to identify copper-gold porphyry intrusives with associated magnetite. These have been used successfully in British Columbia and the SW Pacific Islands (McMillan, 1992 and Zonge, 1992).

Radiometric surveys for regional alteration mapping and identifying energy in lithologies can be used. Identifying potassically altered zones can be made, provided the vegetation cover is not very dense.

The use of IP surveys for identification of sulphide-rich intrusive bodies is useful, provided that highly conductive clays do not overlie such intrusives.

All the above geophysical methods may be used to various degrees in an exploration area. These methods are only tools which may confirm regional geological mapping of rock types, alteration zones and sulphide mineralogy.

7.14 Aerial Photography

Making extensive use of aerial photography in the initial exploration phase is relatively inexpensive and can be very useful. Structural lineaments and intersections can be identified which may control porphyry emplacement. Weathering and alteration phenomena may be identified for further follow-up work.

7.15 Remote Sensing

Structural controls on porphyry emplacement are important, and remote sensing is a very effective method for exploring and evaluating such controls. Images that highlight lineaments and other structural features include colour-enhanced bands, colour composites, principal components, edge enhancements and images that enhance hydrothermally altered areas, (Spatz, 1992). The selection depends on what the explorationist believes would best reveal important structures. According to Spatz (1992), the Multi-Spectral Scanner (MSS) instrument with a ground resolution of 80m has proven to be very effective in regional structural analysis. Furthermore, Landsat TM offers a 30m resolution and with the near infra-red bands, alteration analysis and the possible application to structural controls may prove useful.

Structural lineaments may further be highlighted using edge enhancements (Spatz, 1992). This process utilises either non-directional filters or directional filters which highlight linear features in preferred directions.

When using Landsat TM imagery, bands 5/7 highlight hydrothermal alteration minerals and should be used in the colour composites for alteration mapping. MSS data does not have bands which can highlight these alteration minerals (Figure 51).

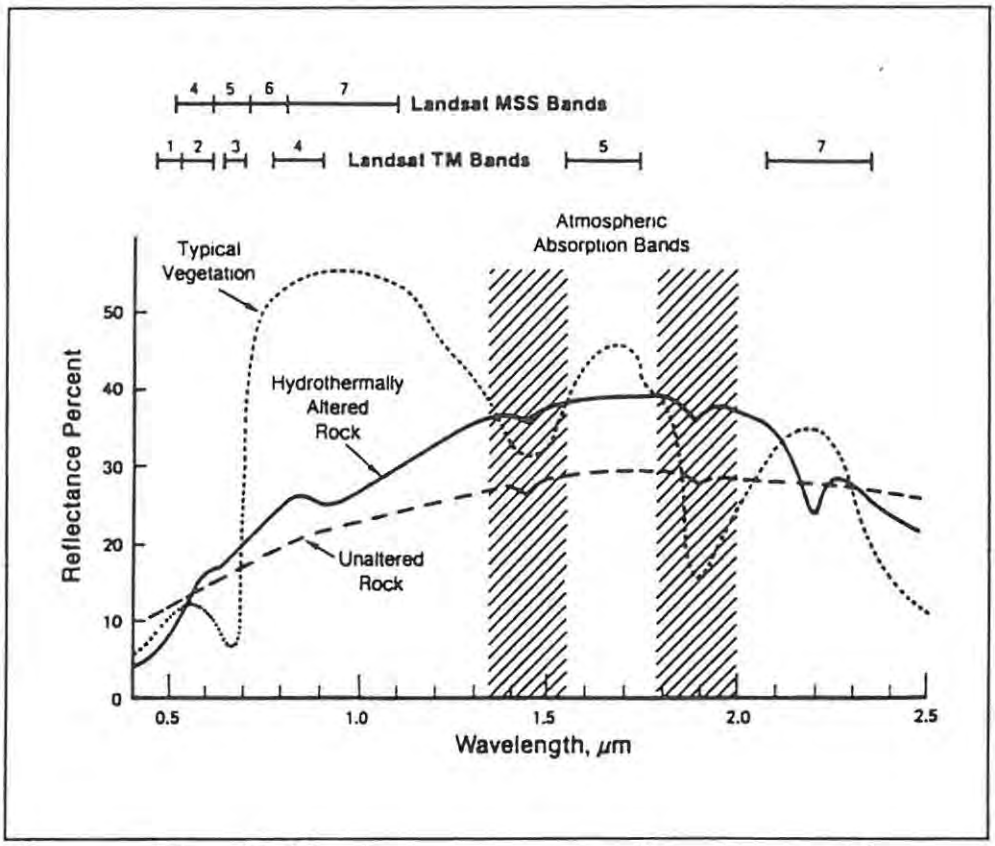


Figure 51. Reflectance curves for vegetation on altered rocks and hydrothermally altered rocks, with the MSS and TM bands superimposed (after Sabins, 1987).

Other bands which can enhance oxides, vegetation and rock types are indicated in Table VII.

Remote sensing data can be used very effectively in regional porphyry copper-gold exploration, provided that the user understands what his requirements are. Therefore the image acquired should be such that the colour bands used will best highlight rock/soil cover, alteration or vegetation.

Table VII. Guide to Landsat TM imagery for mineral exploration (after Zonge, 1992).

(R – Red, G – Green, B – Blue)

Band 2	Highlights surficial disturbances, prospects, roads, and excavations (bright) and desert varnish (dark).
Band 3	Iron oxides are bright and vegetation darker than rock and soil
Band 4	Vegetation is extremely bright
Band 5	Best contrast among dark and light colored rocks, and other surface covers. Best single band for structural analysis and highlighting light tonal anomalies.
Band 7	Low values for most alteration minerals and vegetation. Bright values for "evolved" alkalic and per-alkaline rocks.
Bands 3-5-7	Color composite emphasizes contrast among lithologies in semi-arid terrain.
Bands 5-4-2	Color composite provides excellent contrast among all cover types including vegetation.
Bands 3-2-1	Color composite in RGB provides normal color image similar to a photograph.
Bands 3/1	Enhances iron oxides and contrasts rock/soil (bright) with vegetation (dark).
Bands 4/3	Enhances vegetation (bright)
Bands 5/4	Enhances rock/soil (bright) over vegetation (dark).
Bands 5/7	Hydrothermal alteration minerals are bright, "evolved" alkalic rocks are dark.
Bands 3/1, 5/7, 5/4	Color composite in RGB iron oxides are reddish, secondary hydrothermal minerals are greenish, rock/soil are blue and vegetation is subdued.
Bands 3/1, 5/7, 4/3	Color composites in RGB, iron oxides are reddish, secondary hydrothermal minerals are greenish, vegetation is blue.

PRINCIPLE COMPONENT IMAGES

Band 1	Best overall band for scene contrast. Similar to a TM Band 5 image
Band 2	Best contrast among lithologies. Vegetation subdued in semi-arid terrain.
Band 3	Highlights vegetation (bright) in semi-arid terrain. Similar to a TM 4/3 ratio.
Band 5	May highlight hydrothermal products (bright).
Bands 2-4-5	Color composite emphasizes rock, soils and hydrothermal alteration at the expense of vegetation.

8. CONCLUSION

Bulk mineable porphyry copper-gold deposits are related to subduction generated plutonism and volcanism at consuming plate margins. These deposits are more prevalent in island arc and continental arc settings than intra-continental settings. The predominant host rocks include diorites, quartz diorites, granodiorites and the more alkalic (e.g. shoshonites) rock types compared to monzonites and/or S-type granites.

The alteration and mineralisation models, as outlined by Lowell and Guilbert (1970), Gustafson and Hunt (1975), Sillitoe (1973) and Hollister (1975), allow generalised predictions to be made concerning the properties of the porphyry system. However from observations made it would appear that the metal and alteration assemblages may occur with many variations. The variation in metal and alteration assemblages is a combination of factors, viz. metal content, type of intrusion, physiochemical conditions operative within the magma during emplacement and multiple igneous intrusions resulting in the telescoping of alteration and mineralising events.

Alteration associated with the various classes of porphyries (alkalic vs calc-alkalic) vary from potassic near the intrusion, through to phyllic (not seen in the alkalic intrusions) - argillic and propylitic in the peripheral areas. These alteration halos vary in size and shape with deposits and may often be the only clue to hidden mineralisation.

Porphyry copper-gold deposits appear to be more shallowly emplaced than their molybdenum-rich counterparts, and may be associated with the volcanic model (Table I). These intrusions, due to their tectonic setting, are often associated with multiple intrusive events and coeval volcanics. The deposits are generally of late Tertiary age, but their preservation potential is related to the depth of emplacement and rates of erosion.

Mineralisation within these gold-rich deposits is closely associated with potassic alteration and high magnetite content, e.g. $\geq 2\%$. The high magnetite content being related to high oxygen fugacities. The high oxygen fugacities, together with the other physiochemical factors, such as the complexing agent, viz. chlorine, pH and temperature, control copper-gold transport and deposition.

Petrological determinations of magnesium enrichment towards the rims of amphiboles and Cl/F contents of mica phenocrysts may prove to be significant in assessing the mineralisation potential of these systems.

Mineralisation may also be found surrounding these porphyry intrusions. Unlike the expected metal zonation of copper in the centre moving out to lead-zinc-silver-gold veins in distal areas, gold may be deposited in the core, intermediate or distal zones. The control of this is related to the magma type, temperature of the fluids, pressure, depth of intrusion, host rocks, "metal budget" of the intrusion and a favourable complexing agent, e.g. HS_2^- for transporting gold beyond the stock.

Generally these porphyry copper-gold deposits may be expected to have a median tonnage of 100 million tonnes, with grades of 0.5% Cu and 0.38 g/t Au. Exceptions to this include Grasberg, which has reserves in excess of 1 billion tonnes averaging 1.4% Cu and 1.8 g/t Au.

Exploration for these deposits involves a multidisciplinary approach whereby numerous geophysical, geochemical and geological techniques are used. Structural lineaments and intersections favouring porphyry emplacement may be located using aerial photographs and remote sensing data, viz. edge enhancements. Aeromagnetic surveys may prove useful in confirming the presence of an intrusive body at the selected sites. Furthermore, thematic mapper colour composites, in particular components of bands 5 and 7, can be used to identify areas of alteration. These areas identified from the desk study must then be checked, the alteration types mapped and a geochemical survey conducted to target areas for further drilling. Identification of the potassic alteration zones and copper and gold anomalies will aid in the target selection. Caution must be paid to the environment of formation of the porphyry of interest. In arid environments copper and gold anomalies need not necessarily coincide, and secondary copper enrichment may not overlie the main porphyry body.

Porphyry copper-gold deposits are confined essentially to the circum-Pacific. The identification of target areas is dependant on an understanding of the concepts introduced in this dissertation and the successful implementation of exploration programmes.

9. REFERENCES

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, Univ. Arizona Press, 275-295.

Babcock, R.C. (Jr), Black, J.E. and Ballantyne, G.H. (1992). Summary of the Geology of the Bingham District, Utah. Porphyry Copper Short Course (1992). Northwest Mining Association, Short Course, Tucson-Arizona and Spokane-Washington, Nov. 28-Dec. 1, 1992.

Barnes, H.L. (1975). Zoning of ore deposits. Types and causes. Trans. Roy. Soc. Edin., 69, 295-311.

Balfour Holdings Incor. and Doppler & Assoc. (1993). Porphyry occurrences of the Western Hemisphere. Vol. 1 : The United States and Canada, 435pp.

Beane, R.E. (1982). Hydrothermal alteration in silicate rocks. In Titley, S.R. (Ed.), Advances in geology of the porphyry copper deposits, southwestern North America, Tucson, Univ. Arizona Press, 117-137.

Blanchard, R. (1968). Interpretation of leached outcrops. Nevada Bur. Mines Bull., 66, 196p.

Bureau of Mines and Geosciences. (1986). Geology and mineral resources of the Philippines, Vol 2, Mineral Resources. 445pp.

Burnham, C.W. (1979). Magmas and hydrothermal fluids. In : Barnes, H.L. (Ed.), Geochemistry of Hydrothermal Ore Deposits, 2nd Edition, New York, John Wiley and Sons, 71-136.

..... (1981). Physiochemical constraints on porphyry mineralization. In : Dickinson, W.R. and Payne, W.D. (Eds.), Relations of Tectonics to Ore Deposits in the

Southern Cordillera. Arizona. Geol. Soc. Digest, XIV, 71-77.

.....and Ohmoto, H. (1980). Late-stage processes of felsic magmatism. In : Ishihara, S. and Takenouchi, S., (Eds.), Granitic Magmatism and Related Mineralization. Mining Geol. (Japan), Spec. Issue, 8, 1-11.

Carson, D.J.T. and Jambor, J.L. (1974). Mineralogy, zonal relationships and economic significance of hydrothermal alteration of porphyry copper deposits, Babine Lake Area, British Columbia. CIMM. Bull., 76, 110-133.

Cartwright, J.A. (1992). Fundamental crustal lineaments and transverse structural zones in continental rifts. In : Mason, R. (Ed.), Basement Tectonics, 7, 209-217.

Chapin, C.E., Chamberlin, R.H., Osburn, G.R., White, D.W. and Sandford, A.R. (1978). Exploration framework of the Socorro geothermal area, New Mexico. New Mexico Geol. Soc. Spec. Publ., No. 7, 114-129.

Chappell, B.W. and White, A.J.R. (1974). Two contrasting granite types. Pacific Geol., 8, 173-174.

Cox, D.P. and Singer, S.A. (Eds.). (1986). Mineral Deposit Models. USGS Bull., 1693, 378pp.

..... and Singer D.A. (1988). Distribution of gold in porphyry copper deposits. U.S. Geol. Surv. Open File Rept., 88-46, 23pp.

....., Larson, R.R. and Tripp, R.B. (1973). Hydrothermal alteration in Puerto Rican porphyry copper deposits. Econ. Geol., 68, 1329-1334.

Craig, J.R. and Scott S.D. (1974). Sulfide phase equilibria. In: Ribbe, P.H. (Ed.), Sulfide Mineralogy, Vol 1, Mineral Soc. Amer. Short Course Notes, CS 1-110.

Creasey, S.C. (1966). Hydrothermal alteration. In Titley, S.R. and Hicks, S.L. (Eds.), The geology of the porphyry copper deposits, southwestern North America. Tuscon, Univ. Arizona Press, 51-74.

Cuddy, A.S. and Kesler, S.E. (1982). Gold in the Granisle and Bell porphyry copper deposits, British Columbia. In : Levinson, A.A. (Ed.), Precious metals in the Northern Cordillera. Rexdale, Ontario, Assoc. Explor. Geochem., 139-157.

Czamanske, G.K. and Wones, D.R. (1973). Oxidation during magmatic differentiation, Finnmarka Complex, Oslo area, Norway. Part 2 : The mafic silicates. J. Petrol., 14, 349-380.

Francheteau, J., Sclater, J.G., and Menard, H.W. (1970). Pattern of relative motion from fracture zone and spreading rate data in the north-eastern Pacific. Nature, 226, 746-748.

Gencor Internal Report. (1993). Field notes.

Godwin, C.I. (1976). Casino. In: Sutherland Brown, A. (Ed.), Porphyry Deposits of the Canadian Cordillera. Spec. Vol. 15, 510pp.

Gropper, H., Calvo, M., Crespo, G., Bisso, C.R., Cuadra, W.A., Dunkerley, P.M. and Aguirre, E. (1991). The epithermal gold-silver deposit of Choquelimpie, Northern Chile. Econ. Geol., 86, 1206-1221.

Guilbert, J.M. (1986). Recent advances in Porphyry base metal deposit research. In: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H. and Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits. Spec. Publ. No. 4 of the Soc. for Geology Applied to Mineral Deposits. Springer - Verlag, Berlin, 592pp.

..... (1992). Porphyry Copper in the Twentieth Century. In Porphyry Copper Model - Regional Talks and Settings. Northwest Mining Association, Short Course. Tucson-Arizona and Spokane-Washington, Nov. 28-Dec. 1, 1992.

..... and Park, C.F. (Jr). (1986). The geology of ore deposits. Freeman, New York, 985pp.

Gustafson, L.B. (1978). Some major factors of porphyry copper genesis. Econ. Geol., 73, 600-607.

..... (1979). Porphyry copper deposits and calc-alkaline volcanism. In McElhinny, M.W. (Ed.), The earth: Its origin, structure and evolution. London, Academic Press, 427-469.

..... and Hunt, J.P. (1971). Evolution of mineralisation at El Salvador, Chile, (abs.). Econ. Geol., 66, 1266-1267.

..... and Hunt, J.P. (1975). The porphyry copper deposit at El Salvador, Chile. Econ. Geol., 70, 857-912.

Helz, R.T. (1973). Phase relations of basalts in their melting range at P H_2O = 5kb as a function of oxygen fugacity. Part 1 : Mafic phases. J. Petrol., 14, 249-302.

Hemley, J.J., Cygan, G.C.M, Woo, C.L. and d'Angelo, W.M. (1987). Exploration studies on metal sulfide solubilities in buffered systems. Implications to zoning in ore deposits. Geol. Soc. Amer. Abstr. Programs 19, 699.

Henley, R.W. (1973). Solubility of gold in hydrothermal chloride solutions. Chem. Geol., 11, 73-87.

Heys, G.R. (1987). Porphyry copper deposits : A plate tectonics based distribution and occurrence model. In : Pacific Rim Congress 87, AIMM, 169-172.

Hollister, V.F. (1973). Regional characteristics of porphyry copper deposits of South America. AIME Preprint, 73, 1-2.

..... (1974). Regional characteristics of porphyry copper deposits in South America. Am. Inst. Mining Metall. Petroleum Engineers Trans., 256, 45-63.

..... (1975). An appraisal of the nature and source of porphyry copper deposits. Min. Sci. Eng., 7, 225-233.

..... (1977). Metallogenic provinces of the cordilleran of western North and South America - Discussion. Mineralium Deposita, 12, 239-240.

..... (1978). Geology of the porphyry copper deposits of the western hemisphere. Am. Ins. Min. Metall. Petr. Eng. 219pp.

Horton, D.J. (1978). Porphyry-type copper-molybdenum mineralization belts in Queensland, Australia. Econ. Geol., 73, 904-921.

Howell, W.J.S., Fardon, R.S.H., Carter, R.J. and Bumstead, E.D. (1978). History of the Ok Tedi porphyry copper prospect, Papua New Guinea, II. The years 1975 to 1978. Econ. Geol. 73, 802-809.

Hunt, J.P. (1991). Porphyry copper deposits. Econ. Geol., Monograph 8, 192-206.

Ishihara, S. (1981). The granitoid series and mineralization. In : Skinner, B.J. (Ed.), Econ. Geol. 75th Anniv. Vol. Econ. Geol Publ. Company, El Paso, Texas, 458-484.

James, A.H. (1971). Hypothetical diagrams of several porphyry copper deposits. Econ. Geol., 66, 43-47.

Jones, B.K. (1992). Application of metal zoning to gold exploration in porphyry copper systems. J. of Geochemical Exploration, 43, 127-155.

Joplin, G.A. (1968). The shoshonite - a review. J. Geol. Soc. Australia 15, 275-294.

Karig, D.E. (1974). Implications for the origin of the Philippine Sea from DSDP Leg 31

and S.I.O. Cruise Tusaday (abs.). Eos, 55, No. 4, 298.

Keays, R.R. and Scott, R.B. (1976). Precious metals in ocean ridge basalts: Implications for basalts as source rocks for gold mineralisation. Econ. Geol., 71, 705-720.

Keith, S.B. (1978). Palaeosubduction geometrics inferred from Cretaceous and Tertiary magmatic patterns in southwestern North America. Geology, 6, 516-521.

..... (1984). Magma series and mineral deposits. Magma Chem-Explor. Inc., Phoenix, AZ, 60pp.

Kesler, S.E. (1973). Copper, molybdenum and gold abundances in porphyry copper deposits. Econ. Geol., 68, No 1, 106-112.

..... , Jones, L.M. and Walker, R.L. (1975). Intrusive rocks associated with porphyry copper mineralization in island arc areas. Econ. Geol., 70, 515-526.

Kosaka, H. and Wakita, K. (1978). Some geologic features of the Mamut porphyry copper deposit, Sabah, Malaysia. Econ. Geol., 73, 618-627.

Koval, P.V., Zorina, L.D., Kitajer, N.A., Spiridonov, A.M. and Ariunbileg, S. (1991). The use of tourmaline in geochemical prospecting, for gold and copper mineralization. J. Geochem. Explor., 40, 349-360.

Krauskopf, K.B. (1967). Source rocks for metal bearing fluids. In Barnes, H.C., Geochemistry of hydrothermal ore deposits. New York, Holt, Rinekort and Wilson, 1-33.

Large, R.R., Huston, D.L., McGoldrick, P.J., Ruxton, P.A. and McArthur, C. (1989). Gold distribution and Genesis in Australian volcanogenic massive sulphide deposits and their significance for gold transport models. In : Keays, R.R., Ramsay, W.R.H. and Groves, D.I. (Eds.), The Geology of Gold Deposits: The Perspective in 1988. Econ. Geol. Mon. 6, 520-535.

Le Pichon, X. (1968). Sea-floor spreading and continental drift. J. Geophys. Res., 73, 3661-3697.

Leveille, R.A., Newberry, R.J. and Bull, K.F. (1988). An alkalinity-oxidation state diagram for discriminating some gold-favorable plutons. An empirical and phenomenological approach (abst). Geol. Soc. of Amer. Abstr with Programs, 20, 42.

Lowder, G.G. and Dow, J.A.S. (1978). Geology and exploration of porphyry copper deposits in North Sulawesi, Indonesia. Econ. Geol. 73, 628-644.

Lowell, J.D. (1974). Regional characteristics of porphyry copper deposits of the southwest. Econ. Geol., 69, 601-607.

..... (1988). Gold mineralisation in porphyry copper deposits. Am. Inst. Mining Metall. Petroleum Engineers Pre-print, 88-117, 1-17.

..... (1989). Gold mineralization in porphyry copper deposits discussed. Mining Eng., April 1989, 227-231.

..... and Guilbert, J.M. (1970). Lateral and vertical alteration - mineralisation zoning in porphyry ore deposits. Econ. Geol., 65, 373-408.

MacDonald, G.D. and Arnold, L.C. (1993). Intrusive and mineralization history of the Grasberg deposit, Irian Jaya, Indonesia. Soc. for Min. Met. and Explor., Inc, preprint no. 93-92, 12pp.

Maksaev, V. and Zentilli, M. (1988). Marco metalogenico de los maga-depositos de porfido cuprifero del Norte Grande de Chile. Cong. Geol. Chileno, 5th, Santiago, 1988. Actas, v 1, 181-212.

Malihan, T.D. (1987). The gold-rich Dizon porphyry copper mine in the western central Luzon Island, Philippines : Its geology and tectonic setting. Pacific Rim Congress 87, Goldcoast, Queensland, Australia. AIMM, 303-307.

Mason, D.R. and McDonald, J.A. (1978). Intrusive rocks and porphyry copper occurrences of the Papua New Guinea - Solomon Islands region - A reconnaissance study. Econ. Geol., 73, 857-877.

McMillan, W.J. (1991). Porphyry deposits in the Canadian Cordillera. In: McMillan, W.J., Hoy, T., MacIntyre, D.T., Hammock, J.L., Panteleyev, A., Ray, G.E. and Webster, I.C.L. (Eds.). Ore Deposits, Tectonics and Metallogeny in the Canadian Cordillera. British Columbia. Ministry of Energy, Mines and Petroleum Resources, 276pp.

McMillan, W.J. (1992). Alaska to Washington Regional Setting. In : Porphyry Copper Model - Regional Talks and Settings. Northwest Mining Association, Short Course, Tucson-Arizona and Spokane - Washington, Nov. 28-Dec. 1, 1992.

Meyer, C. (1985). Ore forming processes in geologic history. Econ. Geol., 75th Anniv. vol., 6-14.

Meyer, C. and Hemley, J.J. (1967). Wall rock alteration, 166-235. In: Barnes, H.L. (Eds.), Geochemistry of hydrothermal ore deposits. New York, Holt, Rhinehart and Winston, 670pp.

Mining Journal, Jun. (1993). Musto proves reserves.

Mining Magazine, Oct. (1993). Breaking new ground in Argentina, by Crawford, D., 167-179.

Mitchell, A.H.G. (1992). Andesitic arcs, epithermal gold and porphyry-type mineralization in the western Pacific and eastern Europe. Trans. Inst. Min. Metall., 101, B125-137.

..... and Garson, M.S. (1981). Mineral deposits and global tectonic settings. Academic Press, London, 405pp.

Morrison, G.W. (1980). Characteristics and tectonic setting of the shoshonitic rock association. Lithos, 13, 97-108.

Mpodozis, C. and Ramos, V. (1989). The Andes of Chile and Argentina. In : Fricksen, G.E., Cañas. Pinochet. M.T. and Reinemund, J.A. (Eds.), Geology of the Andes and its elation to Hydrocarbon and Mineral Resources. Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, 11, 59-90.

M.Sc Course Notes, (1993). Module Evt., Rhodes Univ. Geol. Dept., Grahamstown.

Muller, D. and Groves, D.I. (1993). Direct and indirect associations between potassic igneous rocks, shoshonites and gold-copper deposits. Ore Geol. Reviews, 8, 383-406.

....., Heithersay, P.S. and Groves, D.I. (1993). The shoshonite - Cu-Au association in the Goonumbla district, N.S.W., Australia. Mineral. Petrol., 48 (in press).

Mutschler, F.E., Griffen, M.E., Scott Stevens, D. and Shannon, S.S. (Jr). (1985). Precious metal deposits related to alkaline rocks in the North American Cordillera - an interpretative review. Trans. Geol. Soc. S. Afr., 88, 355-377.

Nuchanong, T, Lavin, O.P. and Nichol, I. (1991). Geochemical dispersion of gold related copper-gold mineralization in northeastern Thailand. J. Geochem. Explor., 40, 49-71.

Owens, D.R. (1974). Mineralogical examination of porphyry copper ore from the Bell Copper Deposit, Babine Lake, British Columbia. Can. Dept. Energy Mines Resources, Mines Br. Inv. Rept. IR74-24.

Pirajno, F. (1992). Porphyry systems and skarns, ch 10, 325-374. In : Hydrothermal Mineral Deposits - Principles and Fundamental Concepts for the Exploration Geologist, Springer-Verlag, Berlin.

Ren, Q., Wang, D., Yang, R. and Qiu, J. (1990). Types of auriferous hydrothermal systems related to volcanic subvolcanic activities in East China. 8th IAGOD Symposium - International conference on mineral deposit modelling. Program with Abstracts.

Ottawa, Canada, A281.

Reyes, M. (1991). The Andacollo strata-bound gold deposit, Chile, and its position in a porphyry copper-gold system. Econ. Geol., 86, 1301-1316.

Rona, P.A. (1978). Criteria for recognition of hydrothermal mineral deposits in the oceanic crust. Econ. Geol., 73(2), 135-160.

Sabins, F.F. (1987). Remote Sensing: Principles and Interpretation, 2nd edition. Freeman, 449pp.

Saegaart, W.E. and Lewis, D.E. (1977). Characteristics of Philippine porphyry copper deposits and summary of current production and reserves. Trans. Soc. Mining Eng. of AIME, 262, 199-209.

Sawkins, F.J. (1984). Metal deposits in relation to plate tectonics. Springer, Berlin, Heidelberg, New York, Tokyo, 325pp.

Schroeter, T.G., Lund, C. and Carter, G. (1989). Gold production and reserves in British Columbia. B.C. Ministry of Energy, Mines and Petroleum Resources, Open File 1989-22, 86pp.

Sibson, R.H. (1987). Earthquake rupturing as a mineralizing agent in hydrothermal systems. Geology, 15, 701-704.

Sillitoe, R.H. (1972). A plate tectonic model for the origin of porphyry copper deposits. Econ. Geol., 67, 184-197.

..... (1973). The tops and bottoms of porphyry copper deposits. Econ. Geol., 68, 799-815.

..... (1974). Tectonic segmentation of the Andes : Implications for magmatism and

metallogeny. Nature, 248, 497-499.

..... (1975). Subduction and porphyry copper deposits in southwestern North America. Econ. Geol., 70, 1474-1477.

..... (1979). Some thoughts on gold rich porphyry copper deposits. Mineral Deposita, 14, 161-174.

..... (1980). Cauldron subsidence as a possible inhibitor of porphyry copper formation. In : Ishihara, S. and Takenouchi, S. (Eds.), Mining Geol. Spec, Issue., No 8, Tokyo, 85-93.

..... (1982). Unconventional methods in porphyry deposits. Soc. of Min. Eng. of AIME, preprint no. 82-63, 13pp.

..... (1986). Space-time distribution, crustal setting and Cu/Mo ratios of central Andean porphyry copper deposits : metallogenic implication. In : Friedrick, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.). Geology and metallogeny of copper deposits. Geol. Soc. Appl. Min. Depos. Spec. Publ. 4, 235-250.

..... (1987). Copper, gold and subduction : A trans-Pacific perspective. In : Pacific Rim Congress 87, AIMM, 399-403.

..... (1988). Gold and silver deposits in porphyry systems. In : Schafer, R.W., Cooper, J.J. and Vikre, P.G. (Eds.), Bulk Mineable Precious Metal Deposits of the Western United States. Geol Soc. Nevada, Symposium Proc., Reno. 233-257.

..... (1989). Gold deposits in western Pacific Island Arcs : The magmatic connection, 266-283. In : Keays, R.R., Ramsay, W.R.H. and Groves, D.I. (Eds.), The Geology of Gold Deposits: The Perspective in 1988. Econ. Geol. Mon. 6, 667pp.

..... (1990). Gold-rich porphyry copper deposits of the circum-Pacific region - An

updated overview, In : Pacific Rim Congress 90, AIMM, 119-126.

..... (1991). Intrusion-related gold deposits, 164-209, In : Foster, R.P. (Ed.), Gold Metallogeny and Exploration, Blackie, 427pp.

..... (1992). Gold and copper metallogeny of the central Andes - Past, present and future objectives. Econ. Geol., 87, 2205-2216.

.....and Angeles (Jr), C.A. (1985). Geological characteristics and evolution of a gold-rich porphyry copper deposit at Guindoang, Luzon, Philippines. Asian Mining '85 : London Inst. Min. Metall., 15-26.

..... and Bonham, H.F. (1990). Sediment-hosted gold deposits: Distal products of magmatic - hydrothermal systems. Geol., 18, 157-161.

Snoep, J. and Zeegers, H. (1979). Multi-metal soil geochemistry : A tool for identification and exploration of porphyry copper deposits : Two examples from Peru. J. Geochem. Explor., 11, 103-130.

Spatz, D.M. (1992). Remote sensing applied to porphyry copper exploration. A practical guide for the exploration geologist. In : Porphyry Copper Model - Regional Talks and Settings. Northwest Mining Association, Short Course, Tucson-Arizona and Spokane - Washington, Nov 28-Dec 1, 1992.

Spooner, E.T.C. (1993). Magmatic sulphide/volatile interaction as a mechanism for producing chalcophile element enriched, Archean Au-quartz, epithermal Au-Ag and Au skarn hydrothermal ore fluids. Ore Geol. Reviews, 7, 359-379.

Streckeisen, A. (1973). Classification and nomenclature of plutonic rocks : Geologische, Rundschau, 63, 773-786.

Stringham, B. (1966). Igneous rock types and host rocks associated with porphyry copper deposits. In: Titley, S.R. and Hicks, C.L. (Eds.). Geology of the porphyry copper

deposits, southwestern North America. Tucson, Univ. Arizona Press, 35-40.

Sutherland Brown, A. (Ed.). (1976). Morphology and classification. In Porphyry deposits of the Canadian Cordillera. CIM. Spec. Vol. 15, 44-51.

Tilling, R.I., Gottfried, D. and Rowe, J.R. (1973). Gold abundances in igneous rocks: Bearing on gold mineralisation. Econ. Geol., 68, 168-186.

Titley, S.R. (1966). Preface. In: Titley, S.R. and Hicks, C. L. (Eds.), Geology of the porphyry copper deposits, southwestern North America, Tucson, Univ. Arizona Press, 133-142.

..... (1972). Pre-ore environment of southwestern North America porphyry copper deposits: Internat. Geol. Cong., 24th Montreal, Proc., Sec 4, 252-260.

..... (1973). Geological environment and characteristics of some, porphyry copper deposits in the southwestern Pacific. AIME Preprint 73-5-65, 25pp.

..... (1975). Geological characteristics and environment of some porphyry copper occurrences in the southwestern Pacific. Econ. Geol., 70, 499-514.

..... (1978). Copper, molybdenum and gold content of some porphyry copper systems of the southwestern and western Pacific. Econ. Geol., 73, 977-981.

..... (ed). (1982). Advances in Geology of the porphyry copper deposits, southwestern North America. Tucson, Univ. of Arizona Press, 560pp.

..... (1990). Contrasting metallogenesis and regional settings of Circumpacific Cu-Au porphyry systems, In : Pacific Rim Congress 90, AIMM, 127-132.

..... (1992). Regional settings and the porphyry copper model. In Porphyry Copper Model - Regional Talks and Settings. Northwest Mining Association, 1992, Short Course. Tucson-Arizona and Spokane-Washington, Nov. 28-Dec. 1, 1992.

.....and Beane, R.E. (1981). Porphyry copper deposits : Part 1, Geologic settings, petrology and tectonogenesis. Econ. Geol., 75th Anniversary Vol., 214-235.

Turner, R.L., Raines, G.L., Kleinkopf, M.D. and Lee-Moreno, J.L. (1982). Regional northeast-trending structural control of mineralization, Northern Sonora, Mexico. Econ. Geol., 77, 25-37.

Uyeda, S. (1982). Subduction zones : An introduction to comparative subductology. Tectonophysics, 81, 133-159.

Vila, T. and Sillitoe, R.H. (1991). Gold-rich porphyry systems in the Maricunga Belt, Northern Chile. Econ. Geol., 86, 1238-1260.

Vila, T., Sillitoe, R.H., Betzhold, J. and Viteri, E. (1991). The porphyry gold deposit at Marte, northern Chile. Econ. Geol., 86, 1271-1286.

Walker, S. (1992). Lepanto's future lies Southeast. EEMJ, Sept., 38-43.

Westra, G. and Keith, S.B. (1981). Classification and genesis of stockwork molybdenum deposits. Econ. Geol., 76, 844-873.

Wolfe, J.A. (1973). Tectonic fingerprint in Philippine porphyry deposits. AIME Preprint 73-5-37, 31pp.

Zonge, K.L. (1992). Geophysics for porphyry copper exploration. In : Porphyry Copper Model - Regional Talks and Settings. Northwest Mining Association, Short Course, Tucson-Arizona and Spokane-Washington, Nov 28-Dec 1, 1992.

Zvezdov, V.S., Migachev, I.F. and Girfanov, M.M. (1993). Porphyry copper deposits of the CIS and the models of their formation. Ore Geol. Reviews, 7, 511-549.

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APPENDIX 1

LEACHED CAPPING MINERALOGY

Pertinent notes on the mineralogy and occurrence of common capping minerals are given below. Megascopic identification of these minerals is fundamental to capping appraisal techniques. Lack of visual evidence for any of the oxide copper minerals listed below (or copper sulfide minerals) indicates that the capping contains less than 0.1% Cu.

Alunite - $(Na, K)Al_3(SO_4)_2(OH)_6$: White, streak-white commonly stained light yellow, H=4, fine crystalline to massive, conchoidal fracture, vitreous to pearly luster. Probably of hypogene origin when in porphyry copper mineral assemblages.

Antlerite - $Cu_3(OH)_4SO_4$: (orthorhombic?) Light green soft lumps and prismatic crystals but poorly crystalline. H=3, pale-green streak. Formed during the oxidation and partial leaching of copper deposits with high Cu-S ratio.

Azurite - $Cu_3(OH)_2(CO_3)_2$: Azure blue; crystalline, massive or earthy; vitreous luster. See malachite.

Brochantite - $Cu_4(OH)_6SO_4$, monoclinic: Emerald green with paler green streak, prismatic acicular crystals and drusy crusts, H=3. Formed in the oxidation and partial leaching of copper deposits with high Cu-S ratio.

Chrysocolla - $CuSiO_3 \cdot nH_2O$: Bluish green to light blue, cryptocrystalline, opal-like in texture, conchoidal fracture, white streak, H=4. Indicates partial leaching of copper. Probably forms instead of neotocite in environments with low Mn-Cu ratio or with high dissolved silica-sulfate ratio.

Cuprite - Cu_2O: Red with reddish streak and adamantine or submetallic luster, H=3.5-4. Octahedral or cubic habit. Forms in the oxidation and partial leaching of copper deposits with high Cu-S ratio. Commonly associated with chalcocite in outcrop.

Ferrimolybdite - $Fe_2(MoO_4)_3 \cdot 8H_2O$: Sulfur yellow to greenish yellow, fibrous, very soft, with greenish-yellow streak. Forms as an oxidation product of molybdenite in the presence of pyrite.

Goethite - $Fe_2O_3 \cdot H_2O$ (or $HFeO_2$): Soft, earthy, brown with dark-brown streak. Diagnostic of that portion of sulfide iron that is not leached from the outcrop. High proportions of goethite in limonite indicate that little copper has been leached. Goethite containing as much as 7% Mo is found at molybdenum deposits and commonly is reddish brown with a high luster.

Hematite - Fe_2O_3: Soft, earthy, red with red streak. The percent hematite in limonite is related to the amount and relative proportion of chalcocite in the former sulfide zone. Specular hematite is a fairly common hypogene mineral of uncertain significance.

Jarosite - $K(Fe, Al)_3(SO_4)_2(OH)_6$: Druses of small rhombohedral crystals, light yellow with light-yellow streak; vitreous luster, also occurs as very intimate mixtures with goethite and hematite. The percent jarosite in limonite is related to the degree of leaching of iron and copper from the former sulfide zone.

Lindgrenite - $Cu_3(MoO_4)_2(OH)_2$: H=4.5. Green to yellow green with pale-green streak. Tabular or platy habit. Oxidation product of copper-molybdenum sulfides. Experimental work suggests low iron environments, i.e., chalcocite-molybdenite oxidation product.

Malachite - $Cu_2(OH)_2CO_3$: Bright green; massive, incrusting, fibrous; uneven fracture. Forms instead of brochantite in cappings containing highly reactive gangue such as carbonate.

Native copper - Cu: Red, metallic, sectile. Forms in environments which have high Cu-S ratio.

Neotocite - $(Cu, Fe, Mn)SiO_3$: Black, amorphous, vitreous to drab luster, black to dark olive, waxy streak. Neotocite can be identified by the following field test: Apply 10% H_2SO_4 to the mineral, rub with wetted steel knife blade (but not stainless steel), examine knife blade for obvious coating of metallic copper. Forms in the oxidation of chalcopyrite deposits which have a chalcopyrite-pyrite ratio greater than 0.5.

Pitch limonite - $H(Fe, Cu)O_2$: Brown, amorphous, resinous luster with red internal reflection, same brown streak as goethite. Forms in the oxidation of chalcopyrite deposits with very little pyrite. Weak reaction with 10% H_2SO_4 and steel knife blade.

Tenorite - CuO: Black scales with metallic luster, H=3-4, and black streak. Occurs in alkaline environments with malachite.

Gencor Internal Report (1993).

TABLE III

SOME PRINCIPAL PORPHYRY COPPER-GOLD DEPOSITS

NAME	OK TEDI	DIZON
Location	Papua New Guinea	Philipines
Tectonic Setting	Continental Margin	Island Arc
Age (Ma)	1.2	2.7
Tonnage/Reserves	386t of Au	9.8t of Au
Igneous-Type	Potassic Calc-Alkaline	CA
Porphyry-Type	Monzonite	Quartz Diorite
Au (g/t)	0.59	0.75
Ag (ppm)	-	2.5
Cu (%)	0.65	0.43
Mo (%)	-	Minor
Coeval Volcanics	No	Yes
Alteration Associated with Ore	Hypogene + K-feldspar	Sericite-Clay-Chlorite + Martitized Magnetite
Advanced Argillic Alteration	-	Yes
Breccia/Stockwork	Quartz Stockwork	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	No	Yes
Wall Rocks	Cretaceous Siltstones and Miocene Limestones	Andesitic Volcanics
Regional Structures	-	WNW Lineaments - Mt Pinutoba
Remarks	1992 - Produced 10,50 tonnes of gold	3,0 - 4,0 Wt% total sulphides. Also associated with Cu-Au skarn.

NAME	SANTO THOMAS II	LEPANTO FAR SOUTHEAST
Location	Philippines	Philippines
Tectonic Setting	Island Arc	Island Arc
Age (Ma)	1.4	3.5 (?)
Tonnage/Reserves	204.83 x 10^6t of ore 115t of Au	356 x 10^6 of ore 441t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	Diorite and/or Quartz Diorite	Quartz Diorite
Au (g/t)	0.56	1.24
Ag (ppm)	-	-
Cu (%)	0.32	0.73
Mo (%)	-	-
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Biotite-Actinolite-Anhydrite-Magnetite	Biotite-Anhydrite-Magnetite
Advanced Argillic Alteration	No	Yes
Breccia/Stockwork	Quartz Stockwork	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Andesite Volcanics	Andesite Volcanics
Regional Structures	-	Major Lepanto fault
Remarks	-	-

NAME	AMACAN	MAMUT
Location	Philippines	Malaysia
Tectonic Setting	Island Arc	Island Arc
Age (Ma)	Miocene	± 9
Tonnage/Reserves	129 x 10^6t of ore 65t of Au	179 x 19^6t of ore 90t of Au
Igneous-Type	Calc-Alkaline	Potassic Calc-Alkaline
Porphyry-Type	Quartz Diorite	Adamellite and Granodiorite
Au (g/t)	0.50	0.5
Ag (ppm)	-	-
Cu (%)	0.42	0.476
Mo (%)	Minor	-
Coeval Volcanics	Yes	No
Alteration Associated with Ore	Biotite, Chlorite-Sericite, Epidote	Silicification and Biotite
Advanced Argillic Alteration	No	Yes
Breccia/Stockwork	Quartz Stockwork	-
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	No	No
Wall Rocks	Metasediments and Metavolcanics	Flysch sediments
Regional Structures	-	NW trending Kinabulu fault
Remarks	-	-

NAME	GRASBERG	GUINAOANG
Location	Irian Jaya	Philippines
Tectonic Setting	Continental Margin	Island Arc
Age (Ma)	3.1	3.5
Tonnage/Reserves	1 x 10^9t of ore 1800t of Au	500 x 10^6t of ore 200t of Au
Igneous-Type	Potassic Calc-Alkaline	Calc- Alkaline
Porphyry-Type	Diorite / Monzonite	Quartz Diorite
Au (g/t)	1.8	0.4
Ag (ppm)	-	-
Cu (%)	1.4	0.4
Mo (%)	-	-
Coeval Volcanics	No	Yes
Alteration Associated with Ore	Potassic	Potassic + Sericite-Clay-Chlorite Overprint
Advanced Argillic Alteration	No	Yes
Breccia/Stockwork	Quartz Stockwork	-
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes (up to 8%)	Yes
Wall Rocks	Tightly Folded Carbonates	Schists and Volcanics
Regional Structures	Intersection of Several Structures	-
Remarks	Expected production in 1996 = 1,1 billion tonnes of Cu/p.a. ± 48 tonnes of Au/p.a.	

NAME	CABANG KIRI	SUNGAI MAK
Location	Sulawesi-Indonesia	Indonesia
Tectonic Setting	Island Arc	Island Arc
Age (Ma)	16	Miocene
Tonnage/Reserves	39t of Au	20t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	Quartz Diorite	Diorite
Au (g/t)	0.65	-
Ag (ppm)	-	-
Cu (%)	0.57	-
Mo (%)	-	-
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Quartz-Diaspore-Pyrophyllite	-
Advanced Argillic Alteration	Yes	Yes
Breccia/Stockwork	Quartz Stockwork	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Miocene Volcanics	-
Regional Structures	-	-
Remarks	-	-

NAME	CASINO	CARMEN
Location	British Columbia	Philippines
Tectonic Setting	Accreted Island Arc	Island Arc
Age (Ma)	70	Early Cretaceous
Tonnage/Reserves	417 x 10^6t of ore 125t of Au	>200 x 10^6t of ore 40t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	-	Hornblende-Biotite Quartz-Diorite
Au (g/t)	0.3	0.2
Ag (ppm)	1.75 Estimate	-
Cu (%)	0.3	<0.5
Mo (%)	0.038	-
Coeval Volcanics	Yes	-
Alteration Associated with Ore	K-feldspar + Biotite + Quartz + Sericite	-
Advanced Argillic Alteration	No	-
Breccia/Stockwork	Breccia + Quartz Stockwork	-
Cu-Au with K-Silicate Alteration	Yes	-
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Quartz Monzonite	-
Regional Structures	-	-
Remarks	-	Gold Associated with Bornite Grains

NAME	GALORE CREEK	MORRISON
Location	British Columbia	British Columbia
Tectonic Setting	Accreted Island Arc	Continental Margin
Age (Ma)	198	52
Tonnage/Reserves	125 x 10^6t of ore 50t of Au	95 x 10^6t of ore 32.3t of Au
Igneous-Type	Alkaline	Calc-Alkaline
Porphyry-Type	Syenite	Quartz Diorite
Au (g/t)	0.40	0.340
Ag (ppm)	7.7	1.00
Cu (%)	1.10	0.42
Mo (%)	0.001	0.017
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	K-feldspar + Biotite	Biotite, Chlorite
Breccia/Stockwork	-	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Volcanics	Siltones, argillites and conglomerates
Regional Structures	-	-
Remarks	High level stocks and dykes. Garnet is abundant in central zone. Anhydrite + gypsum around the deposit.	Mine inactive

NAME	BELL COPPER	MOUNT MILLIGAN
Location	British Columbia	British Columbia
Tectonic Setting	Continental Margin	Accreted Island Arc
Age (Ma)	51	Jurassic
Tonnage/Reserves	23t of Au (Reserves Exhausted)	298 x 10^6t of ore 131,12t of Au
Igneous-Type	CA	A
Porphyry-Type	Quartz Diorite	Monzonite
Au (g/t)	0.3	0.44
Ag (ppm)	1.00	-
Cu (%)	0.480	0.22
Mo (%)	0.006	-
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Intense - Cu Associated with Potassic Alteration	Potassic
Advanced Argillic Alteration	-	-
Breccia/Stockwork	Quartz Stockwork	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Sedimentary-Siltstones and Argillites	Andesitic Volcanics
Regional Structures	-	-
Remarks	Mine Inactive	Mine Inactive. High level stocks and dykes.

NAME	MOUNT POLLEY	FISH LAKE
Location	British Columbia	British Columbia
Tectonic Setting	Accreted Island Arc	Continental Margin
Age (Ma)	184	77
Tonnage/Reserves	30×10^6 of ore 29t of Au	895×10^6t of ore
Igneous-Type	Alkaline	Calc-Alkaline
Porphyry-Type	Monzonite	Quartz Diorite
Au (g/t)	1.03	0.47
Ag (ppm)	-	2.30
Cu (%)	-	0.30
Mo (%)	-	0.002
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	-	K-feldspar
Breccia/Stockwork	Magnetite, Pyrite + Chalcopyrite in Breccias	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	-	Pyroclastics + Sediments
Regional structures	-	-
Remarks	Active	High level stocks and dykes - Active

NAME	ISLAND COPPER	AFTON
Location	British Columbia	British Columbia
Tectonic Setting	Accreted Island Arc	Accreted Island Arc
Age (Ma)	180	198
Tonnage/Reserves	147,4 x 10^6t of ore 32t of Au	15.5 x 10^6t of ore 9t of Au
Igneous-Type	Calc-Alkaline	Alkaline
Porphyry-Type	Rhyodacite	Diorite
Au (g/t)	0.22	0.60
Ag (ppm)	0.63	4.00
Cu (%)	0.520	1.030
Mo (%)	0.018	0.001
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Au in Biotite Alteration Zone	Potassic + Phyllic
Advanced Argillic Alteration	Yes	-
Breccia/Stockwork	Quartz Stockwork	-
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Andesitic Volcanics + Pyroclastics	Tuffs and Lava Flows
Regional structures		En-echelon Faults Trending ENE + Dip 60°-70°
Remarks	-	chalcopyrite-bornite-chalcocite are dominant ore minerals

NAME	PEBBLE	DOS POBRES
Location	British Columbia	Arizona
Tectonic Setting	Island Arc	Continental Margin
Age (Ma)	91-95	47-58
Tonnage/Reserves	454 x 10^6t of ore 160t of Au	356 x 10^6t of ore 107t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	Biotite Diorite, Quartz Monzonite, Granodiorite	Quartz Monzonite, Granodiorite
Au (g/t)	0.35	0.3
Ag (ppm)	-	2.09
Cu (%)	0.35	0.72
Mo (%)	-	-
Coeval Volcanics	-	Yes
Alteration Associated with Ore	Biotite Alteration	Biotite Alteration
Advanced Argillic Alteration	-	-
Breccia/Stockwork	Stockwork Veins + Breccia	Contact and Crackle Breccia
Cu-Au with K-Silicate Alteration	-	Yes
Abundant Magnetite/Hematite	-	-
Wall Rocks	Greywackes	-
Regional structures	-	NW fault + NE anticline
Remarks	Au + Cu are closely associated. Multiple Intrusions. No Phyllic Alteration.	Au associated with bornite.

NAME	BINGHAM	BAJO DE LA ALUMBRERA
Location	Utah	Argentina
Tectonic Setting	Continental Margin	Continental Margin
Age (Ma)	37,5 - 39,8	8
Tonnage/Reserves	1 x 10^9t of ore 440t of Au	551 x 10^6t of ore 396t of Au
Igneous-Type	Potassic Calc-Alkaline	Potassic Calc-Alkaline
Porphyry-Type	Quartz Monzonite	Dacite
Au (g/t)	0.44	0.67
Ag (ppm)	122	-
Cu (%)	0.7	0.52
Mo (%)	0.319	-
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Quartz-Sericite-Biotite Veinlets	-
Breccia/Stockwork	Quartz Stockwork	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	No	Yes
Wall Rocks	Quartzitic Limestones, Calcareous Siltstones, Dolomites	Andesitic Volcanics
Regional structures	NW + NE Folds and Thrusts	-
Remarks	Au + Bornite Association, Skarn Deposits	Still to be developed

NAME	MARTE	LOBO
Location	Chile	Chile
Tectonic Setting	Continental Margin	Continental Margin
Age (Ma)	13	13
Tonnage/Reserves	66t of Au	128t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	Diorite	Diorite
Au (g/t)	1.43	1.6
Ag (ppm)	-	-
Cu (%)	0.12	0.05
Mo (%)	0.005	0.001
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Quartz-Chlorite-Clay-Sericite	Quartz-Chlorite-Clay-Sericite
Advanced Argillic Alteration	Yes	Yes
Breccia/Stockwork	Intrusive and Hydrothermal Breccia	Quartz Stockwork
Cu-Au with K-Silicate Alteration	Yes	Yes
Abundant Magnetite/Hematite	Yes	Yes
Wall Rocks	Andesite Lavas	Andesite Lavas
Regional structures	At the intersection of NW + NNE striking structures	-
Remarks	Gypsum in orebody	-

NAME	REFUGIO	ANDACOLLO
Location	Chile	Chile
Tectonic Setting	Continental Margin	Continental Margin
Age (Ma)	23	Early Cretaceous
Tonnage/Reserves	194t of Au	33t of Au
Igneous-Type	Calc-Alkaline	Calc-Alkaline
Porphyry-Type	Diorite - Quartz Diorite	Granodiorite
Au (g/t)	0.96	2.4 (Estimate)
Ag (ppm)	-	-
Cu (%)	0.64	0.3 - 0.8
Mo (%)	-	-
Coeval Volcanics	Yes	Yes
Alteration Associated with Ore	Quartz-Biotite-Chlorite-Clay	Au with Silicification K-feldspar and Chlorite Alteration
Advanced Argillic Alteration	No	-
Breccia/Stockwork	Quartz Stockwork	-
Cu-Au with K-Silicate Alteration	-	Yes
Abundant Magnetite/Hematite	Yes	-
Wall Rocks	Andesite - Dacite lavas	Felsic Volcanics
Regional structures	-	-
Remarks	-	-

REFERENCES USED

(TABLE III)

Sillitoe (1990)

Howell et al. (1978)

Saegart and Lewis (1977)

Walker (1992)

Macdonald (1992)

Macdonald and Arnold (1993)

Sillitoe and Angeles (Jr) (1985)

Lowder and Dow (1978)

McMillan (1992)

Godwin (1976)

Carson and Jambor (1976)

Bureau of Mines and Geosciences (Philippines) (1986)

Mining Journal Jun. 4 (1993) - 320

Mining Magazine Oct. (1993) - 176-179

John Black (pers. comm.)

Kosaka and Wakita, (1978)

Balfour Holding, Inc. and Doppler & Associates, Oct. (1993).

Various Sources

APPENDIX 2

ARCTIC OCEAN

ALASKA

CANADA

Casino

Galore Creek

Morrison

Bell

Mount Polley

Fish Lake

Island Copper

Bingham

U.S.A.

ATLANTIC OCEAN

PACIFIC OCEAN

Dos Pobres

Cananea

El Arco

MEXICO

DOMINICAN REPUBLIC

JAMAICA

NICARAGUA

COSTA RICA

PANAMA

COLOMBIA

ECUADOR

Michiquillay

PERU

Quellaveco

BOLIVIA

Chuquicamata

Marte Lobo

Refugio

Andacollo

Bajo De La Alumbrera

CHILE

ARGENTINA

ATLANTIC OCEAN

PACIFIC OCEAN

LEGEND

Distribution of the Porphyry Provinces of the World

Porphyry Cu-Au Deposits / Mines

Porphyry Cu Deposits / Mines

DISTRIBUTION OF THE PORPHYR
WITH SOME MAJOR PORPHYR

PLAN

ARCTIC OCEAN

N

C.I.S.

FINLAND

POLAND

GERMANY

ROMANIA

Petelovo

YUGO-SLAVIA

BULGARIA

TURKEY

Kounrad

CHINA

IRAN

PAKISTAN

PACIFIC OCEAN

TAIWAN

Lepanto

Santo Thomas

Dizon

PHILIPPINES

Amacan

King King

Mamut

BURMA

THAILAND

MALAYSIA

SULAWESI

SUMATRA

KALIMANTAN

IRIAN JAYA

Grasberg

OK Tedi

INDONESIA

SOLOMON ISLANDS

PAPUA NEW GUINEA

VANUATU

INDIAN OCEAN

Moonmera

Coalstoun

AUSTRALIA

NEW ZEALAND

0 2000 4000km

HYRY PROVINCES OF THE WORLD
HYRY Cu-Au DEPOSITS SHOWN

PLAN 1