Characteristics of low sulphidation gold-copper systems in the south-west Pacific

T.M. Leach
11 Blake St., Ponsonby, Auckland 1002, New Zealand

G.J. Corbett
29 Carr St., North Sydney NSW 2060 Australia

ABSTRACT

Magmatic-related low sulphidation hydrothermal ore systems at plate margins exhibit distinct spatial and temporal zonations which can be used to aid mineral exploration and development. Low sulphidation systems at all crustal levels exhibit the same paragenetic sequence of events: early breccia formation, followed by quartz - secondary feldspar - sericite/illite veining, then mineralisation, and final argillic overprint. This sequence of events is interpreted to reflect the initial emplacement of melts at high crustal levels, and the progressive cooling of that melt and release of magmatic constituents into a circulating hydrothermal system.

Low sulphidation systems in the south-west Pacific region exhibit a vertical zonation in deposit types : from porphyry copper-gold at deep levels, quartz-sulphide-gold at mesothermal to deep epithermal levels, carbonate-base metal gold at mainly epithermal levels, and epithermal quartz silver-gold at shallow levels. It is interpreted that the characteristics of each of these styles of deposits is produced by mixing with circulating waters of different physio-chemical compositions.

KEYWORDS: *Gold, copper, low sulphidation, SW Pacific.*

INTRODUCTION

Cooling of high level intrusions and their parent melt results in the progressive release of heat, brines, volatiles and metals into the host intrusive and country rocks. This progressive evolution of heat and fluids from the cooling intrusions causes the initial formation of zoned potassic to propylitic alteration, then stockwork quartz veining, and finally a series of overprinting alteration and associated mineralisation events characteristic of porphyry copper deposits (Titley and Beane, 1981)

High sulphidation systems are interpreted to form in response to the disproportionation of reactive magmatic volatiles (mainly SO_2 and Cl) to form hot acidic fluids (Fig 1; Hedenquist, 1987). On the other hand if magmatic fluids and metals are dispersed into the surrounding host rocks through a series of subsidiary structures, reduction of SO_2 and neutralisation of HCl results in the formation of near neutral pH fluids dominated by dissolved salts (e.g. NaCl) and where sulphur occurs mainly as dissolved H_2S. Hedenquist (1987) termed these low sulphidation systems.

Mineralisation in low sulphidation systems can extend up to greater than 5 km from the source high level intrusions. Horizontal zonations in these systems are well documented in the western USA around large porphyry copper deposits such as Bingham Canyon, Nevada. Babcock et al (1992) described mineralisation which is zoned from classical copper hosted in quartz stockwork veining, outwards through vein or lode copper and peripheral Pb-Zn deposits, to distal Au-Ag deposits hosted in reactive sediments.

This paper reviews the temporal and spatial zonation in south-west Pacific low sulphidation systems, and presents possible fluid flow models to explain the observed zonations from environments proximal to the source intrusions, through intermediate levels, to shallow epithermal conditions distal from inferred source intrusions.

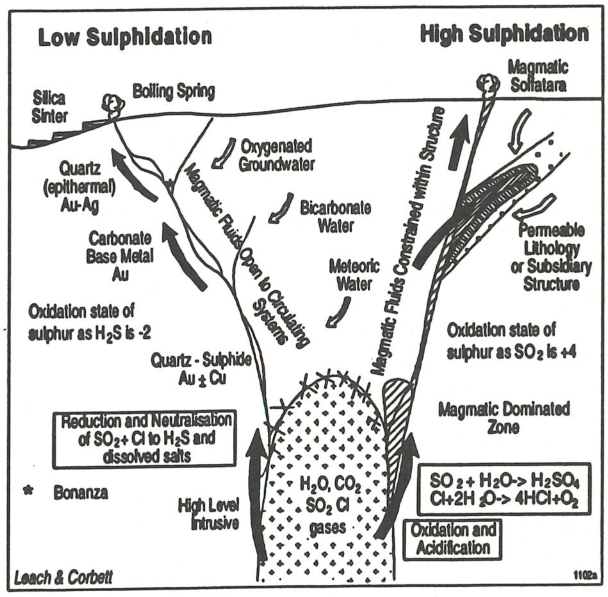

Figure 1 Conceptual model of the derivation and vertical zonations in high and low sulphidation systems.

PARAGENETIC SEQUENCE OF LOW SULPHIDATION SYSTEMS

Low sulphidation systems in the southwest Pacific region exhibit similar paragenetic sequences of events at all crustal levels, and is interpreted to reflect the interaction between melts emplaced at high crustal levels and circulating meteoric waters (Figure 2).

The initial emplacement of intrusions at high crustal levels, causes heating of waters residing in structures and permeable units to produce vertically zoned pebble dykes, fluidised breccias and diatreme-maar complexes, which utilise pre-existing structures (Sillitoe, 1985). The emplacement of melts also provides the heat source for the development of a hydrothermal system, which is dominated by cool dilute meteoric waters. The hydrothermal system circulates to depths along regional and subsidiary structures, intrusive contacts and/or permeable lithologies. These circulating meteoric-dominated waters deposit vein systems dominated by quartz and secondary K-feldspar (Henley and Ellis, 1983). Magmatic volatiles, which progressively evolve from the melt as it crystallises, are entrained in meteoric waters at the base of the convecting hydrothermal system and neutralised and reduced as outlined above. CO_2 is commonly the dominant magmatic volatile phase (with the obvious exception of water vapour) and is the only major magmatic component which is little effected by secondary processes, although some is converted to methane at low temperatures (Giggenbach, 1987). The increase in dissolved gases can decrease the pH of the circulating waters and favour the deposition of sericite/illite over K-feldspar in progressively later quartz veining.

As the intrusive source continues to cool, pressure drops result in the progressive draw-down of near surface bicarbonate condensate and acid sulphate waters. In active Philippine geothermal systems these fluids have been encountered to depths of up to 1.5-2 km, and at cool shallow levels are relatively oxygenated (Reyes, 1990).

Mineralisation at all crustal levels characteristically post-dates the quartz-K-feldspar-sericite/illite veining. Iron sulphides are observed to be overprinted by base and precious metal phases. Crystallisation of the intrusion and most of the volatile phase separation precedes the late stage segregation of metals from the melt (Cline and Bodnar, 1991). Mineralised magmatic fluids are therefore released into structures (and other permeable channelways) which contain : circulating cool dilute meteoric waters at all levels in the system, dilute low pH gas condensate ± acid sulphate waters up to 1.5-2.0 km depth (but predominantly at <1km depth), and relatively oxygenated waters at shallow epithermal levels.

<u>Quartz-Sulphide</u> Au ± Cu vein systems are interpreted to form where mineralised magmatic-dominated fluids are released into structures saturated with respect to dilute (<1-2 wt% NaCl) meteoric waters. <u>Carbonate-Base Metal</u> gold systems are interpreted to form where mineralised fluids migrate into structures containing cool, relatively low pH bicarbonate ± sulphate waters. At shallow levels <u>epithermal gold-silver quartz</u> vein deposits are interpreted to form where magmatic derived mineralised fluids mix with relatively oxygenated surficial waters.

In many of the gold-copper systems in the southwest Pacific region, the style of low sulphidation deposits grades vertically from one type to another. In some cases there is an overprinting of an earlier type of vein system on a later, commonly cooler system.

QUARTZ-SULPHIDE GOLD ± COPPER SYSTEMS

Examples

Deposits dominated by quartz and sulphides ± oxides are postulated to form where mineralised fluids are cooled and diluted by circulating meteoric waters. These vein systems occur at all levels in a hydrothermal system, but dominate at mesothermal levels proximal to the source intrusive. Some examples of quartz-sulphide vein deposits in the S-W Pacific region are : Lihir, Hamata, Kerimenge, Kainantu district (PNG); Kidston, Cadia, Lake Cpwal, Ravenswood, Mt. Leyshen (Eastern Australia)

Structural Setting

Quartz-sulphide vein systems exploit pre-existing structures, which have been dilated during mineralisation (Corbett and Leach 1996) as: tension fractures in the orientation of compression (e.g. Arakompa, PNG), arc-parallel structures, (e.g. Bilimoia, PNG), conjugate fractures which rotate to form high grade sigmoids, sheeted fractures (e.g. Kidston), and fluidised and crackle breccias (e.g. Lihir, PNG).

Mineralisation and Alteration Characteristics

The quartz-sulphide vein systems exhibit a common paragenetic sequence of deposition which may be summarised as follows :

i) <u>Breccias</u> ranging from pebble breccias to fluid breccias are a precursor to the hydrothermal system

ii) <u>Quartz veining</u> commonly medium to coarse grained in granular to coxcomb textures with associated pyrite and early K-feldspar/adularia and late sericite. Fluid inclusion data indicates that the quartz has generally been deposited from dilute circulating meteoric-dominated fluids, although at depth hypersaline magmatic derived fluids locally deposit early stage quartz.

iii) <u>Sulphide veining</u> deposited from fluids with a significant magmatic-component and consisting of :

a) *Fe-sulphide/oxides ± magnetite/hematite* veining, commonly massive, and overgrowing or infilling fractures and breccias. Pyrite is almost ubiquitous and the other Fe-sulphides are zoned from proximal to distal environments as :magnetite/hematite, through pyrrhotite, to arsenopyrite/As-rich pyrite, and from early to late in the paragenetic sequence. Inclusions of chalcopyrite and base metals are a precursor to later mineralising events. Limited fluid inclusion data suggests that the Fe-sulphides are deposited from a fluid significantly more saline than the early quartz (Corbett and Leach, 1996)

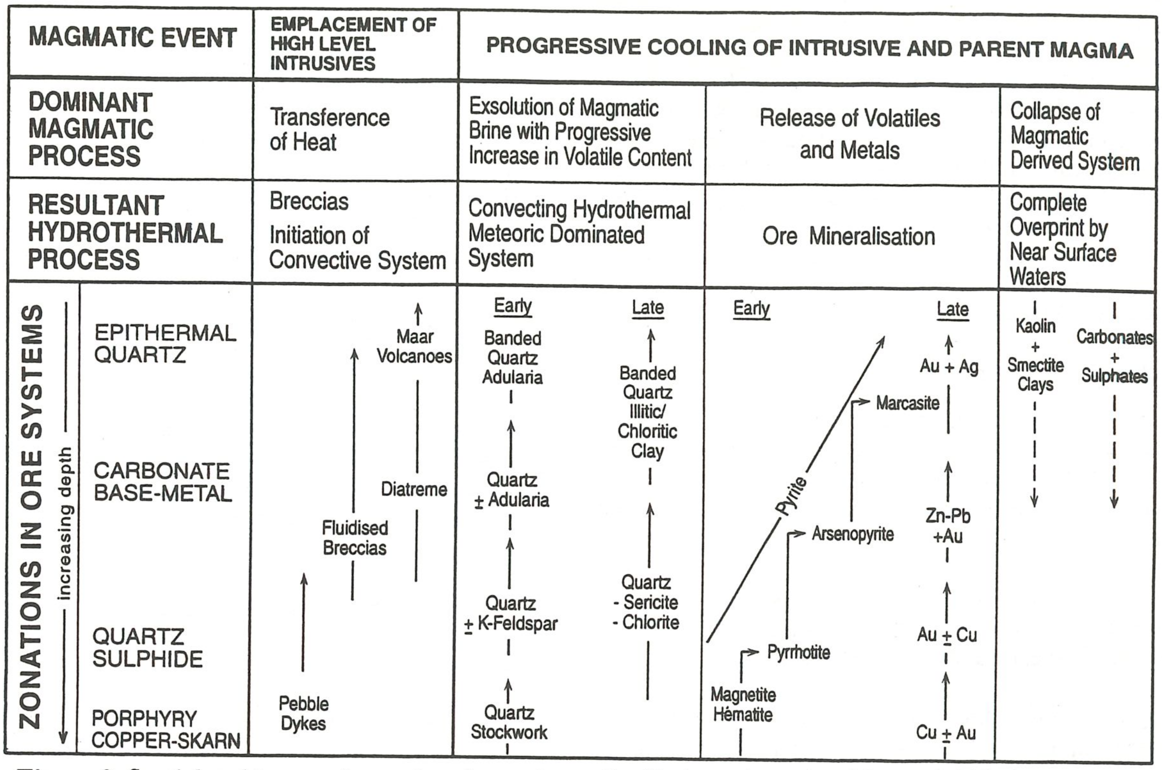

Figure 2 Spatial and temporal zonations in southwest Pacific intrusive-related low sulphidation systems.

b) *chalcopyrite* veining commonly overgrows pyrite and infills fractured, brecciated/shattered pyrite, although in some cases chalcopyrite is intergrown with pyrite. The sulphides are typically accompanied by Bi- or Ag-telluride (e.g. Arakompa) mineralisation, and in some cases W-Sn phases (e.g. Bilimoia), depending on the composition of the source intrusion (Corbett *et al*, 1994)

c) in some cases the sulphide event has been postdated by carbonate-base metal veining (e.g. Kidston), in which the carbonate is typically calcite.

At shallow levels, old mineralisation in the quartz-sulphide systems is mainly associated with the sulphide event as a refractory phase in As-rich pyrites at shallow levels; or at deeper levels, as non-refractory inclusions in Fe-sulphides or chalcopyrite where it is commonly related to the Bi-Ag tellurides. Non-refractory gold in the porphyry-related quartz vein systems has a typical fineness range of 850-950, transitional between the fineness of gold in porphyry copper-gold and carbonate base metal gold systems.

CARBONATE BASE-METAL GOLD SYSTEMS

Examples

Carbonate - base metal gold deposits generally develop distal from the source intrusions, at deep epithermal to mesothermal levels, although some are formed under near surface conditions, and others proximal to the source intrusions.

Some significant SW Pacific rim carbonate-basemetal gold systems are : Kelian and Cikotok (Indonesia); Porgera open pit, Mt. Kare, the Morobe Goldfield group of deposits, Busai and Kulumadau on Woodlark Is., and Maniape at Kainantu (PNG); Gold Ridge (Solomon Is.); Acupan and Amatok (Philippines); Mt. Terrible (NSW).

Structural Settings

Carbonate base metal deposits are best developed in transpressional settings in which fluids have been bled from magmatic source below to higher crustal levels. Pre-mineral structures control fluid flow, and fracturing about the margins of breccia bodies, such as maar volcano/diatreme breccias, are ideal loci for fluid flow. Thus an ideal setting for carbonate base metal gold mineralisation might be fracturing near the intersection of major through-going structures and diatreme/maar complexes e.g. Upper Ridges and Kerimenge, or at the contact of veins with diatreme pipe margins e.g. Acupan. Maar volcano/diatreme breccias are clay altered and do not fracture well in the upper and low temperature clay portions of pipe-like bodies, restricting fluid flow to pipe margins. Only in deeper portions of diatreme breccias where higher temperature clay alteration is more competent do maar volcanoes host gold mineralisation e.g. Montana Tunnels (Sillitoe *et al* , 1985).

Rock competency is a critical factor in fracture development and hence mineral deposition. The baked contact alteration zones, in otherwise unconsolidated sediments, around the high level intrusions at Porgera host brittle fracturing. Similarly, at Kelian, brecciated intrusive margins within incompetent "muddy breccias" (van Leeuwen *et al* , 1990) host gold mineralisation.

Mineral deposition varies from lode-style in feeder structures (e.g. Ivanhoe and Busai on Woodlark Island); to more progressive open space deposition (e.g. Kelian and Porgera), typically in dilational structures subsidiary to the fluid upflow zones or as fissure veins (e.g. Acupan). While bonanza gold grades are common in lode mineralisation, high grade fracture gold may form close to fluid upflow zones (e.g. Kelian) or by repeated deposition in dilational structures (e.g. Maniape).

Mineralisation and Alteration

Zonations in mineralisation and veining with depth in carbonate-base metals is illustrated in Figure 3. A generalised paragenetic sequence of veining, alteration and mineralisation in carbonate - base metal systems may be summarised as follows :

i) As for quartz-sulphide systems, veining and mineralisation is preceded by a breccia event such as fluidised, intrusive, or diatreme breccias.

ii) Quartz veining which precedes metal deposition, is commonly polyphasal and associated with early adularia and/or late sericite/illitic clay. Fluid inclusion data indicates that the quartz is deposited from relatively hot (250-350°C) but dilute (<2-4 wt% equivalent NaCl) fluids (Leach and Corbett, 1994).

iii) Sulphide deposition post dates quartz and consists of early pyrite, followed by sphalerite and galena, and then by copper phases (mainly chalcopyrite then tennantite). The base metal sulphide mineralisation commonly extends into the carbonate event. Sphalerites are dark Fe-rich at deep hot levels, proximal to source intrusions, and pale Fe-poor at shallow, cool, more distal environments. Pyrrhotite ± magnetite occur at depth, pyrite is almost ubiquitous, and marcasite is locally encountered at shallow levels. Sulphides and/or quartz dominate at depth, whereas carbonates increase in abundance at progressively shallower levels. Zinc and lead dominate over copper, although copper is the dominant base metal phase proximal to the source intrusions.

iv) Carbonates overgrow the sulphides and are progressively zoned Fe- (siderite), Mn- (rhodochrosite) mixed Mn-Fe-Ca-Mg (kutnahorite, ankerite), Mg- (dolomite, Mg-calcite) and Ca- (calcite) from shallow and/or cooler levels, distal from the intrusive source, to deeper levels, proximal to the inferred source intrusive. A similar zonation in active geothermal systems reflects progressive neutralisation of descending gas condensate fluids (Mitchell and Leach, 1991). Carbonates occur as banded colloform to crustiform veins at shallow levels and massive granular veins at depth. Fluid inclusion data indicate that the carbonate and sphalerite in many deposits were deposited at similar temperatures as early quartz veining, however from a fluid of significantly higher salinity (<4-6 wt% equivalent NaCl; Leach and Corbett, 1994).

Gold mineralisation predominantly occurs during base metal sulphide deposition and extends into the carbonate event. The gold is typically in the native state either as inclusions in pyrite or base metal sulphides, intergrown with carbonate, or infilling fractures and vughs in earlier quartz. Some gold mineralisation also develops during the early stage quartz veining, especially where abundant pyrite/arsenopyrite is present (e.g. at Kerimenge, Syka and Bloom, 1990 and Porgera, Richards, 1992). The average fineness of the gold in carbonate-base metal systems typically lies within the range of 700-850, intermediate between epithermal Au-Ag systems and quartz-sulphide veining marginal to porphyry systems (Corbett and Leach, 1996)

Late stages of activity are dominated by surficial fluids with kaolin, interlayered clay, gypsum, quartz deposition and alteration. Gold mineralisation may locally persist into the initial stages of this late event.

EPITHERMAL QUARTZ GOLD-SILVER SYSTEMS

Examples

There is group of epithermal gold-silver deposits whose characteristics strongly suggest that they are intrusive-related. These include both the distal portions of more mesothermal veins and deposits typical of the classical epithermal Au/Ag deposits (banded quartz-adularia-sericite systems; Bonham, 1986). Intrusive-related quartz gold-silver systems are commonly encountered at shallow or epithermal levels of the hydrothermal systems, at the margins of carbonate-base metal gold systems or in late stage veining which post-dates the carbonate base metal gold event.

Adularia-sericite epithermal deposits have traditionally been characterised by mineral deposition from meteoric fluids (Bonham, 1986), which circulate to depth andso may come under the influence of magmatic fluids. Although most of the quartz-adularia-sericite alteration and veining was probably deposited from meteoric waters, it has been interpreted that the Au/Ag mineralisation was sourced from a substantially magmatic fluid (e.g. Hishikari; Shikazono and Nagayama, 1993). Mineralisation inepithermal quartz veining invariably occurs in thin sulphidic bands associated with sulphides and low temperature clays (see below). Therefore, although boiling was a probable mechanism for the deposition of at least some quartz-adularia and bladed carbonate in epithermal deposits, it is postulated that most of the gold was deposited through quenching mineralised fluids with cool, and probably low pH and oxygenated, surficial waters.

Some significant intrusive-related epithermal Au/Ag deposits in the S-W Pacific region are : Zone 7 at Porgera, Tolokuma, Mt Kare quartz-roscoelite veining (PNG); Emperor Mine (Fiji); Thames and Karangahake (New Zealand).

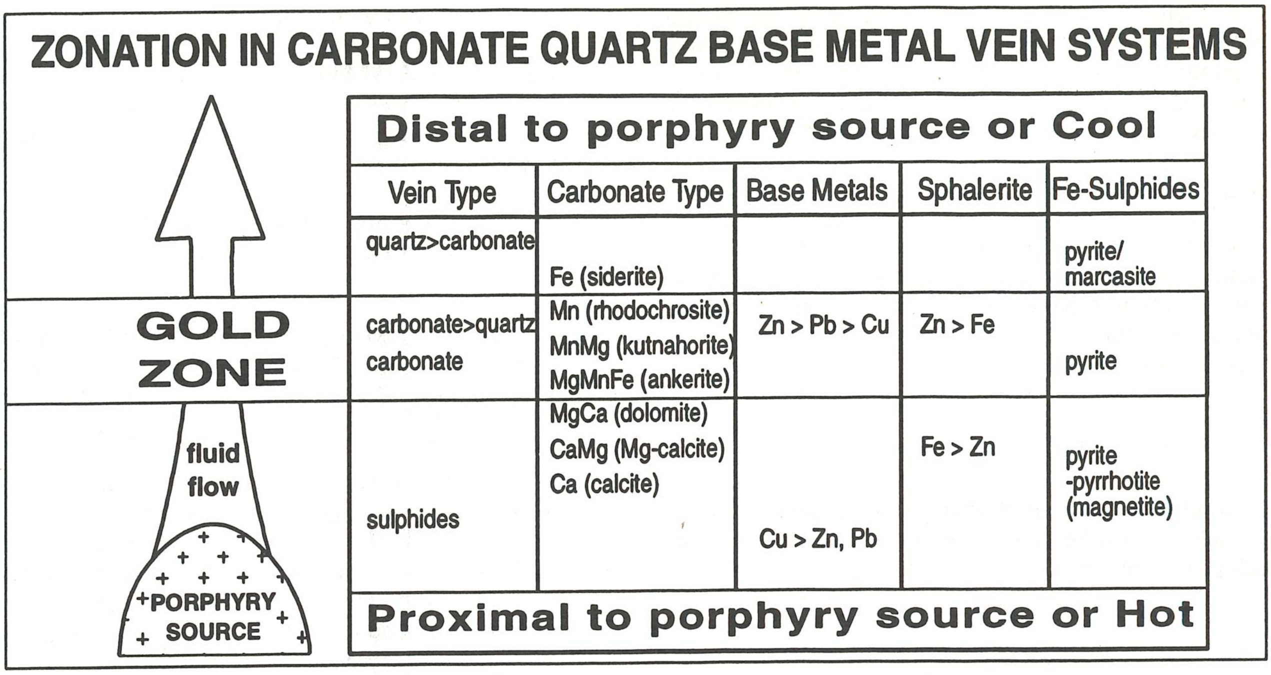

Figure 3 Zonations in veining and mineralisation with depth in carbonate-base metal systems.

Structural Setting

This group of deposits display structural characteristics consistent with both magmatic-related deposits and the classical epithermal vein systems. Major structures localise high level intrusions and by rotation create dilational ore hosting environments. Dilational structures are important to transport fluids considerable distances from inferred magmatic sources.. Subsidiary and not major structures commonly host mineralised vein systems. These epithermal deposits may therefore exhibit similar banded ores to the classic epithermal vein systems.

Mineralisation and Alteration Characteristics

The sequence of veining / mineralisation in intrusive-related epithermal Au/Ag systems is summarised as :

i) As in all other magmatic-derived systems, veining and mineralisation is preceded by hydrothermal magmatic derived breccias such as fluidised breccias and in some places diatreme breccias (e.g. Tolokuma). Some epithermal Au/Ag deposits are preceded by carbonate-base metal vein systems (e.g. Porgera and Mt. Kare)

ii) Early veining is dominated by the deposition of quartz-adularia and local quartz after bladed carbonate,

iii) Later veining is dominated by Quartz-Clay (chlorite, illitic/smectitic, kaolin) ± sulphides and contains the bulk of the Au/Ag mineralisation. In environments where hydrothermal fluids are sourced or hosted in basic intrusion/volcanics, the vanadium-rich illite species, roscoelite, may occur instead of the K-rich species (e.g. Porgera, Mt. Kare and Emperor)

Sulphide content is typically low and iron sulphides dominate over trace base metal sulphides. The ore mineralogy is generally Ag-rich. Gold usually occurs as electrum with a low fineness typically less than 600-700 (Corbett and Leach, 1996). The copper dominates over base metal phases which are also silver rich. Silver sulphides and sulphosalts (e.g. argentite, pearsite-polybasite, proustite-parargyrite) are also common, as is native silver.

The most striking feature of the ore mineralogy is the common association with tellurium and in some cases selenium. Whereas Pb- and Bi-telluride phases dominate in intrusive-related mesothermal quartz-sulphide veining, Ag/Au-tellurides (e.g. hessite, calaverite, petzite) are common in the epithermal intrusive-related Au/Ag-quartz vein systems

Hypogene hematite occurs in many of these systems, which in addition to the occurrence of marcasite, is indicative of strongly oxidising environment. The availability of free oxygen in the groundwater provides the most efficient mechanism for scrubbing out gold from metal-bearing fluids (Romberger, 1988), and commonly results in very high to bonanza gold grades.

It is postulated that mineralisation in classical epithermal adularia-sericite systems (e.g. Hishikari, Cracow, Waihi, Golden Cross) is also due to the mixing of magmatic-derived metal-bearing fluids with surfical waters.

CONCLUSIONS

A zonation is recognised in magmatic-related hydrothermal ore deposits at plate margins which range from classical porphyry and skarn copper-gold at depth, through proximal quartz-sulphide gold ± copper and then peripheral carbonate-base metal gold systems, to distal and/or shallow epithermal gold-silver deposits. Each style of these deposits exhibits a paragenetic sequence which reflects the progressive evolution of the magmatic system.

Metals are released late from the cooling melt into permeable chanellways saturated with respect to circulating meteoric waters, gas condensate bicarbonate ± sulphate waters, and oxygenated groundwaters, and results in the formation, through fluid mixing, of zoned quartz-sulphide, carbonate-base metal and epithermal quartz Ag-gold deposits respectively.

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