

1 INTRODUCTION

This manual accompanies a 2 day short course designed to aid ore discovery by exploration geologists involved in the exploration for and evaluation of epithermal and porphyry deposits. The lectures expand themes introduced in short courses provided with the late Terry Leach from 1992-8 and this manual updates the notes written in association with those short courses (Corbett and Leach, 1998). The short course lectures and these notes focus upon tools available to exploration geologists in the field and the **exploration implications** of the models presented herein.

Geological models considered herein evolved from the analysis of many field examples and have been tested and modified by application during mineral exploration over many years (Corbett, 2009a, 2013b; Leach and Corbett, 1993, 1994 1995, 2008, Corbett and Leach, 1998). Early studies of SW Pacific rim ore systems synthesised this author's field structural analyses with petrology by Terry Leach on magmatic arc geothermal and ore systems (Mitchell and Leach 1991), whereas this current work includes ore systems from the entire Pacific rim and elsewhere such as locally Tethyan magmatic Arcs. These geological models are expected

to provide a framework for the prioritisation of portfolios of mineral exploration projects as an aid in the allocation of limited exploration (financial and human) resources. It is stressed these conceptual geological models should be subject to progressive modification as new data or ideas come to hand.

Section 1 seeks to introduce the terminology used for epithermal and porphyry deposit types considered in detail (figure 1.1) and also provide a brief overview of the geological settings in which these deposits form.

1.1 SETTING OF EPITHERMAL-PORPHYRY ORE DEPOSITS

Epithermal and porphyry ore deposits develop in response to plate tectonic processes, typically as partial melting related to subduction gives rise to magmatism mainly within compressional, and locally transpressional, linear magmatic arcs extending into back arc extensional settings. Magmatic arcs are distinguished between island arcs underpinned by oceanic crust such as in the SW Pacific rim, and continental arcs formed at continental plate margins (Pirajno, 1992). Models presented later (section 3.4) suggest transient changes in the nature of convergence,

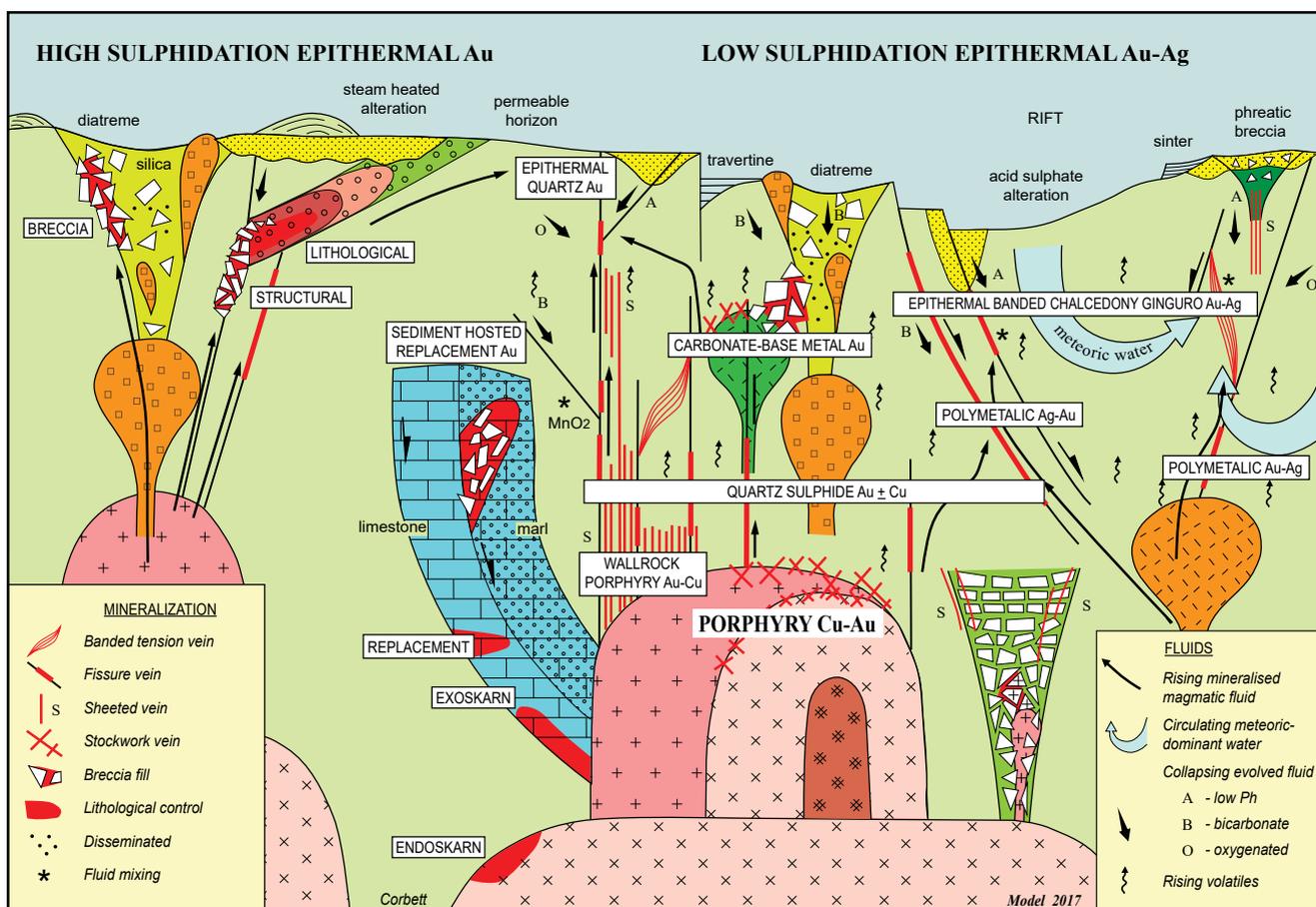


Figure 1.1 Conceptual model for the styles of epithermal Au-Ag and porphyry Cu-Au mineralisation developed in subduction-related magmatic arc – back arc settings.

evidenced by vein configurations, provide extensional environments for ore formation within compressional magmatic arcs, as triggers for the onset of magmatic-hydrothermal processes. Intrusion emplacement is also triggered by rapid uplift and erosion including sector collapse of volcanic edifices (Lihir Is., Papua New Guinea), or thrust erosion (Porgera, Papua New Guinea). It is therefore possible to resolve the space problem associated with the emplacement of porphyry intrusions within compressional settings.

The Pacific rim of fire represents the string of mainly Tertiary and locally older magmatic arcs and related back arcs which overlie the deeper level subduction plate boundaries (figure 1.2). Magmatism in Chile youngs from the deeply eroded Jurassic arcs in the west to active systems in the east, while Cambrian and Ordovician porphyry deposits occur in Eastern Australia. A simplified model for the east Pacific rim suggests the heavier oceanic Nazca Plate is being created at the central Pacific spreading centre and subducted eastwards below the South American continental plate, as uplift and erosion exposes deeper portions of older arcs on the western side (figure 1.3). Subduction draws the wet ocean floor sediments and basalts, with altered hydrous mineral assemblages formed at the mid oceanic ridge, into the hot mantle environment where the high water content promotes partial melting. The subduction rate and inter-related

dip of the downgoing plate influence the development of porphyry Cu deposits, best formed at moderate subduction angles (Sawkins, 1990), as shallow subduction creates insufficient melting and steep subduction promotes rifting in the back arc (Frisch et al., 2011).

In the SW Pacific rim, the Pacific plate is subducting below North Island New Zealand (figure 1.2). An upstanding andesitic magmatic arc on the eastern North Island passes westward to the rifted flat lying Taupo Volcanic Zone, where geothermal studies (Henley and Ellis, 1983; Simmons and Browne, 2000a and references therein) have provided a framework for an understanding of hydrothermal systems in back arc environments (Henley, 1985a). A deep (5-6 km below the surface) batholithic magmatic source was interpreted to provide heat and volatiles which combine with deep circulating meteoric waters within the permeable felsic volcanic pile to provide dilute geothermal fluids (figures 1.4 & 1.5; Henley, 1985 a & b; Corbett and Leach, 1998 and references therein).

The late Terry Leach stressed the profound differences between the New Zealand back arc (or continental rift) and magmatic arc hydrothermal systems using his and others work in the Philippine arc geothermal systems (figure 1.5). The Philippine geothermal systems (Mitchell and Leach, 1991; Corbett and Leach, 1998)

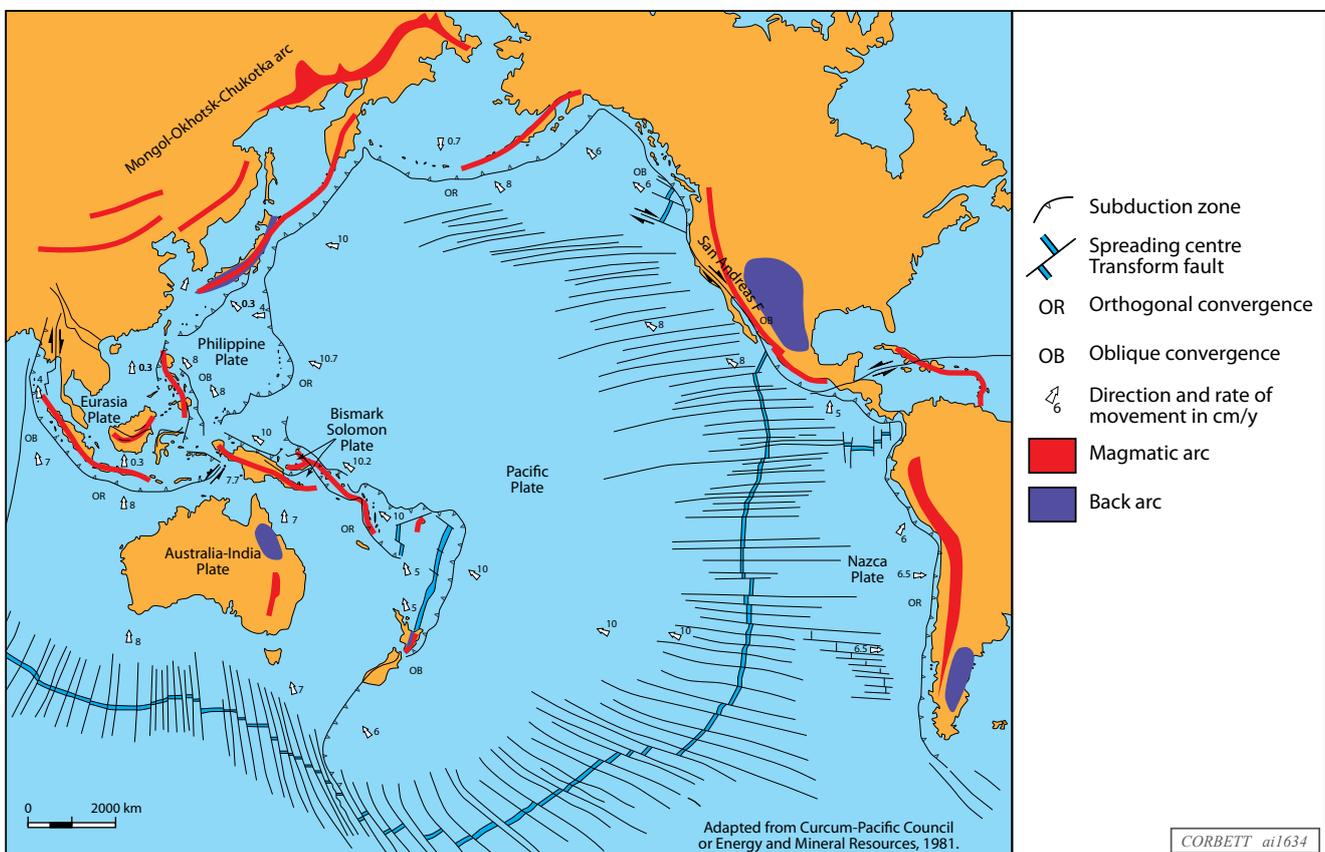


Figure 1.2 Pacific rim tectonic plates, magmatic island arcs, back arcs and spreading centres.

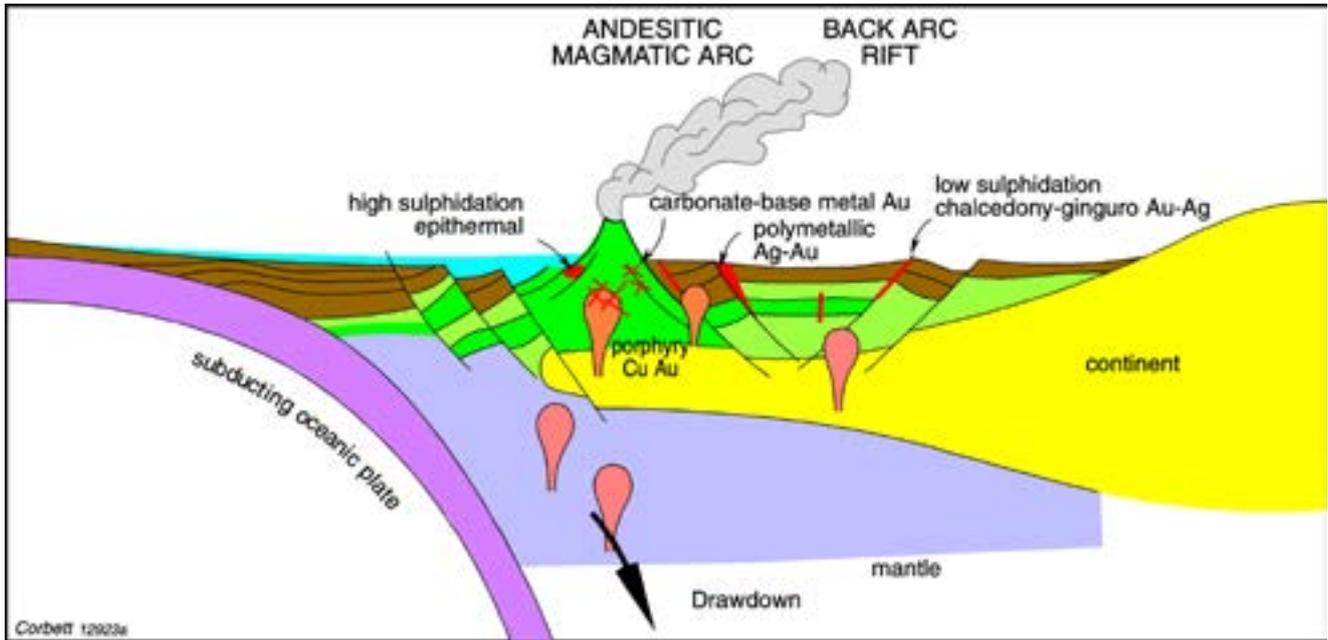


Figure 1.3 Conceptual cross section through a subduction zone, magmatic arc and back arc showing the settings of epithermal and porphyry deposit formation. This cartoon could be analogous to the SE Pacific rim in a section line from the subducting Nasca plate through the east dipping subduction zone below Chile and the Andes magmatic arc, to the Desedo Massif back arc in Argentine Patagonia.

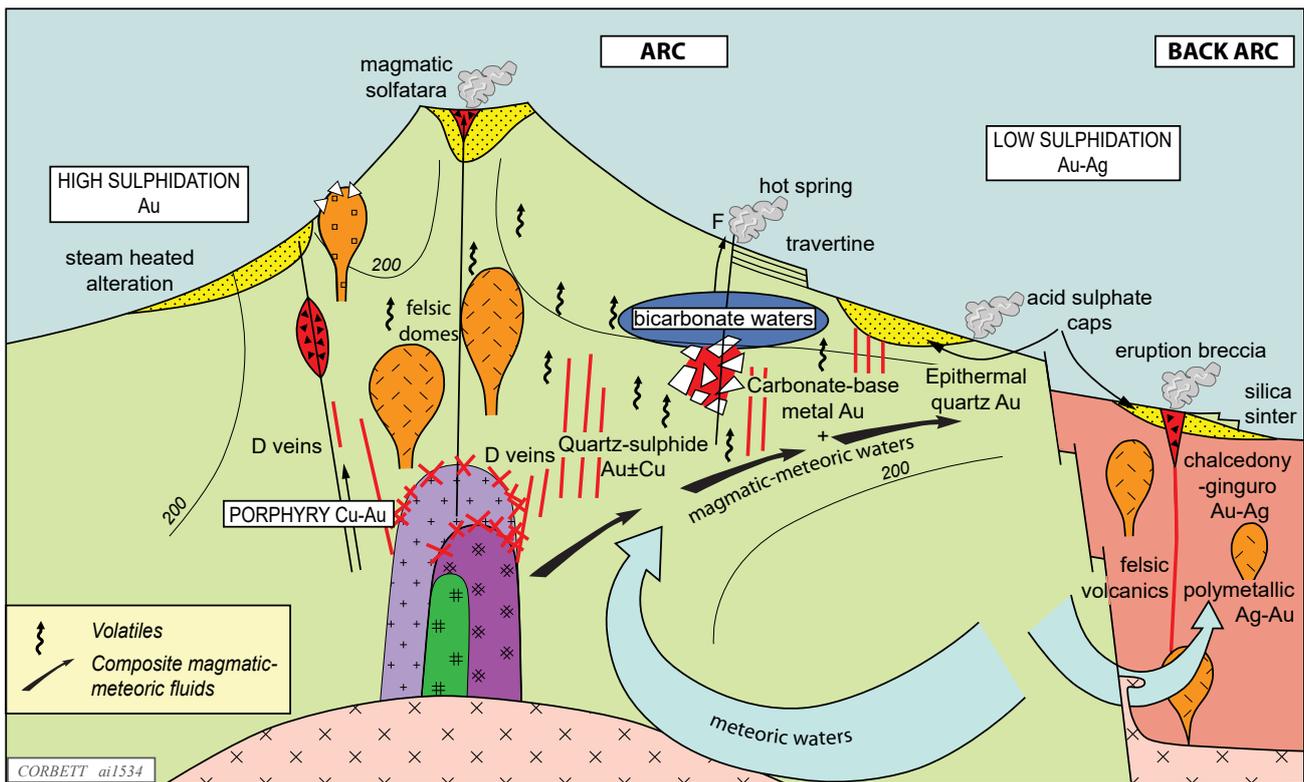


Figure 1.4 Ore systems within subduction-related magmatic arc and back arc settings.

which lie within andesitic arcs, are driven by shallow level porphyry Cu style intrusion heat sources related to deeper magmatic bodies, and feature more saline fluids (figure 1.5). Whereas the New Zealand systems contain only 3-4% magmatic component such as <1000-2000 ppm Cl, the Philippine systems contain up to 50% magmatic component and >10,000-50,000 ppm Cl as reflected in fluid inclusion salinity studies

(Corbett and Leach, 1998 and references therein). Giggensch (1997) also noted the significantly higher CO₂ concentrations in andesitic magmatic arcs (Philippine) than continental rifts (New Zealand) and this CO₂ features in arc-related low sulphidation epithermal deposits. Terry Leach demonstrated that although there is a greater emphasis upon the New Zealand geothermal systems in many published

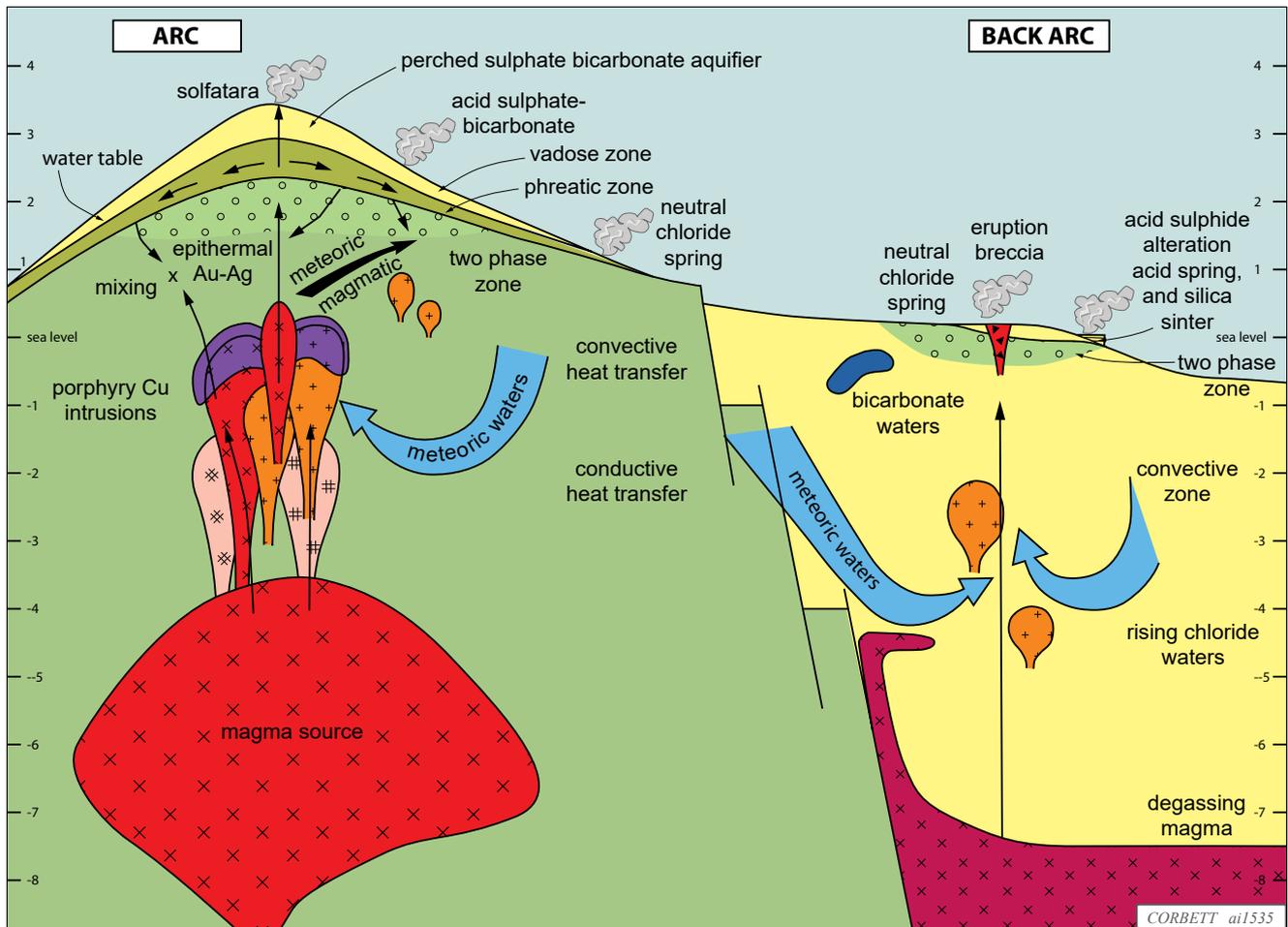


Figure 1.5 Comparison of subduction-related magmatic arc and back arc geothermal systems, drawn at the same scale, from data within Corbett and Leach (1998).

exploration models, the Philippine geothermal systems provide better analogies to many epithermal-porphyry ore deposits. Hence, fluid mixing models, some of which feature CO₂, provide better mechanisms for bonanza Au deposition than boiling models (Leach and Corbett, 2008; section 7.5).

1.2 CLASSIFICATION OF SUBDUCTION RELATED ORE SYSTEMS

A classification, derived from analyses of many exploration projects and mines, aids in the distinction of different Au-Cu deposit types which display varying characteristics such as: zoned wall rock alteration, geochemical and geophysical properties during mineral exploration, metallurgical responses during treatment, and overall value (potential metal grades and size). Linkages occur between deposit types which are presented here (figures 1.1 & 1.4) as points within a continuum of deposit types at varying crustal levels and/or tectonic settings. It is therefore important to distinguish different deposit types, early in any exploration program in order to consider the **exploration implications** of the ore type classification described herein. For instance, exploration methods vary with deposit type and some mineralisation styles

will be prioritised higher than others in different exploration programs.

1.2.1 Evolution of terminology

Waldemar Lindgren (1922) defined the term epithermal as hydrothermal deposits “formed by ascending hot waters near the surface in or near effusive rocks at relatively low temperatures and pressures”, and subsequently placed limits upon epithermal deposit formation as < 1000 m depth and < 200°C temperature (Lindgren, 1933, p. 454-5). As Lindgren’s classification (op cit) appeared to be influenced by shallow level hot spring deposits, the term epithermal is now extended to much deeper crustal levels approaching the porphyry environment, and so includes higher temperature deposits that some workers might have formerly termed mesothermal. The term ‘deep epithermal’ may be employed for deposits such as low sulphidation epithermal quartz-sulphide Au ± Cu mineralisation which are locally analogous to porphyry-related D veins (figure 1.4), in the classification of Gustafson and Hunt (1975).

The rise in Au price in the early 1980’s prompted renewed interest in epithermal Au-Ag deposits to

TERMINOLOGY			REFERENCE
	Epithermal		Lindgren, 1922; Buchanan, 1981
Enargite-gold			Ashley, 1982
		Hot spring gold deposits	Giles and Nelson, 1982; 1982, Nelson and Giles, 1885
High sulphur	Low sulphur		Bonham, 1986, 1988, 1989
Acid sulphate	Adularia-sericite		Hayba et al., 1985 Heald et al., 1987
High sulphidation (based upon oxidation not sulphidation state)	Low sulphidation		Hedenquist, 1987
Alunite-kaolinite ± pyrophyllite	Adularia-sericite		Berger and Henley, 1989
Acid sulphate	Porgera type intrusion-related base metal bearing Au	Adularia-sericite	Sillitoe, 1989
High sulphidation	Low sulphidation		White and Hedenquist, 1990
High sulphidation	Low sulphidation		Sillitoe, 1993
High sulphidation	Intrusion-related: quartz-sulphide Au ± Cu carbonate-base metal Au epithermal quartz Au	Adularia-sericite epithermal Au-Ag	Leach and Corbett, 1993, 1994, 1995; Corbett and Leach, 1998; Corbett, 2002a, 2004
High sulphidation	Intermediate sulphidation	Low sulphidation	Sillitoe and Hedenquist, 2003
High sulphidation		Epithermal banded chalcocopyrite-ginguro Au-Ag	Corbett, 2005a

Table 1.1 Summary of epithermal terminology evolution showing introduction of each new term.

now also include many mined as bulk low grade open pit operations in addition to historic bonanza Au grade underground vein mines. Studies by Buchanan (1981) and Berger and Eimen (1983) in the western US provided analyses of the characteristics of epithermal Au deposits and attempted to develop genetic frameworks to account for features such as vertical zonation in geochemistry as well as the ore, gangue and alteration mineralogy, and the exploration significance of these features. At the same time analyses of active geothermal systems (Henley and Ellis, 1983) contributed towards an understanding of the environments in which epithermal deposits formed. Different classifications of ore deposit styles (table 1.1) emerged based upon wall rock alteration and vein mineralogy as low and high sulphur, along with local alkalic styles (Bonham, 1988). The former two types, originally termed acid sulphate and adularia-sericite (Hayba et al., 1985; Heald et al., 1987), became low and high sulphidation epithermal, initially

(Hedenquist, 1987) related to oxidation state, but later (White and Hedenquist, 1990), based upon the sulphidation state of specific ore minerals. Although these terms continue to be used, this study also focuses upon the nature of ore fluid which provides characteristic ore and gangue mineralogy along with zoned wall rock alteration as more applicable to distinguish deposit types in exploration (table 1.2).

1.2.1.1 Two low sulphidation epithermal deposit groups

By the early 1990's most published literature described low sulphidation epithermal Au-Ag veins as sulphide-poor banded quartz ± adularia veins with laterally zoned wall rock illite alteration, as recognised at mines in Western US (Midas), Japan (Hisikari), New Zealand (Waihi) and Drummond Basin, Australia (Pajingo), and compared these to the studies of the back arc Taupo Volcanic Zone active geothermal systems of

New Zealand (Henley and Hedenquist, 1986). These deposits are herein classed as banded chalcodony-ginguro Au-Ag veins (figure 1.1; section 7.2.2.2) and occupy only a small portion of the epithermal spectrum.

Working in Southwest Pacific rim magmatic arcs in the 1980's, Corbett (Porgera, Papua New Guinea; Fleming et al., 1986) and Leach, each identified sulphide-rich low sulphidation epithermal deposits which did not fit the standard low sulphidation banded vein models (above), and which Leach came to regard as analogous to intrusion-related geothermal systems in the Philippines magmatic arcs (Mitchell and Leach, 1991).

Consequently, in the early 1990's, based upon Southwest Pacific rim exploration studies, and Terry Leach's geothermal experience in New Zealand back arc and the Philippines arc environments, low sulphidation Au-Ag deposits were divided into two groups (figures 1.1 & 1.4; table 1.1, Leach and Corbett, 1993, 1994, 1995; Corbett and Leach, 1998; Corbett, 2013b) developed in two fluid flow trends (figure 1.8).

1. The intrusion-related, sulphide-bearing, magmatic arc Au mineralisation grades from broadly early, deep crustal level and higher temperature, to late, shallow crustal level and lower temperature as:

- quartz-sulphide Au \pm Cu,
- carbonate-base metal Au (including polymetallic Ag-Au veins in Latin America, Corbett, 2002a, 2004, 2005a, 2013b), and
- epithermal quartz Au (Leach and Corbett, 1995), now slightly modified from the original term to account for the empirical dominance of high fineness free Au.

2. The sulphide-poor banded quartz veins, originally termed adularia-sericite style (Hayba et al, 1985), common in extensional rift or back arc settings and listed above, are now termed epithermal banded chalcodony-ginguro Au-Ag veins (Corbett, 2005a), in a move to focus more upon descriptive names using the critical gangue and ore mineralogy (Cooke and Deyel, 2003). Mainly in Latin America, these deposits pass down into the polymetallic Ag-Au veins as Ag-rich vein equivalents of the carbonate-base metal Au deposits. The recent intermediate sulphidation term (table 1.1) is considered below.

1.2.1.2 Porphyry Cu

The porphyry terminology came from descriptions of a common ore type. While veins and supergene enriched caps to porphyry Cu deposits have been worked since pre-history, the 'porphyry copper era' began as early as 1905-10 (Bateman, 1950) with the transition in the Americas from underground mines, to

the exploitation of rich supergene blankets to porphyry Cu deposits, by early open pit operations using steam shovels and train lines (Chuquicamata, Chile from 1915, Bateman, 1950; Bingham Canyon, USA from 1906, Porter et al., 2012). An early categorisation of a porphyry copper deposit is provided (from an engineering perspective) by Parsons (1933) who focused on "their huge size, particularly with respect to horizontal dimensions; the relative uniformity with which the copper minerals are disseminated through the mass; and low Cu per-ton content of the exploitable ore".

Porphyry Cu deposits became significant economic propositions in the southwestern USA and parts of South America as a result in advances in bulk mining technologies after World War II. Geologists therefore sought to better understand these deposits as an aid to exploration. From the 1960's synthesised studies (in Titley and Hicks, 1966; Beane and Titley, 1981; Titley, 1982) provided deposit descriptions and brought together different disciplines in order to develop deposit models. Government sponsored work aided prospecting with an understanding of the weathered surface expression (Jerome, 1966; Blanchard, 1968), especially in view of the economic importance of buried supergene enriched Cu blankets. Data acquired from exploration examples led to the development of early geological models (Lowell and Guilbert, 1970, Sillitoe, 1972), some with a component of paragenetic sequences (Gustafson and Hunt, 1975). The high value of porphyry Cu deposits prompted continued interest as review papers sought to synthesise the progressively evolving understanding of porphyry Cu deposits (Titley and Beane, 1981; Titley, 1993; Corbett and Leach, 1998; Cooke et al., 2002; Seedorff et al., 2005; Sillitoe, 2010; Cooke et al., 2014 and many more). The definition of porphyry Cu deposits with Au or Mo variations is provided below (section 1.2.2.5), and the detailed deposit description in section 5.

1.2.2 This terminology

This section introduces the terminology used herein to describe epithermal and porphyry deposits (figure 1.1) as an aid to the understanding of the exploration tools - alteration, structure and breccias (sections 2-4), prior to the detailed description of each deposit type (sections 5-8) and then prospecting marginal to mineralisation (section 9).

As classified above, epithermal deposits include ore systems developed above the porphyry level. The primary aspect of epithermal classification distinguishes between low and high sulphidation

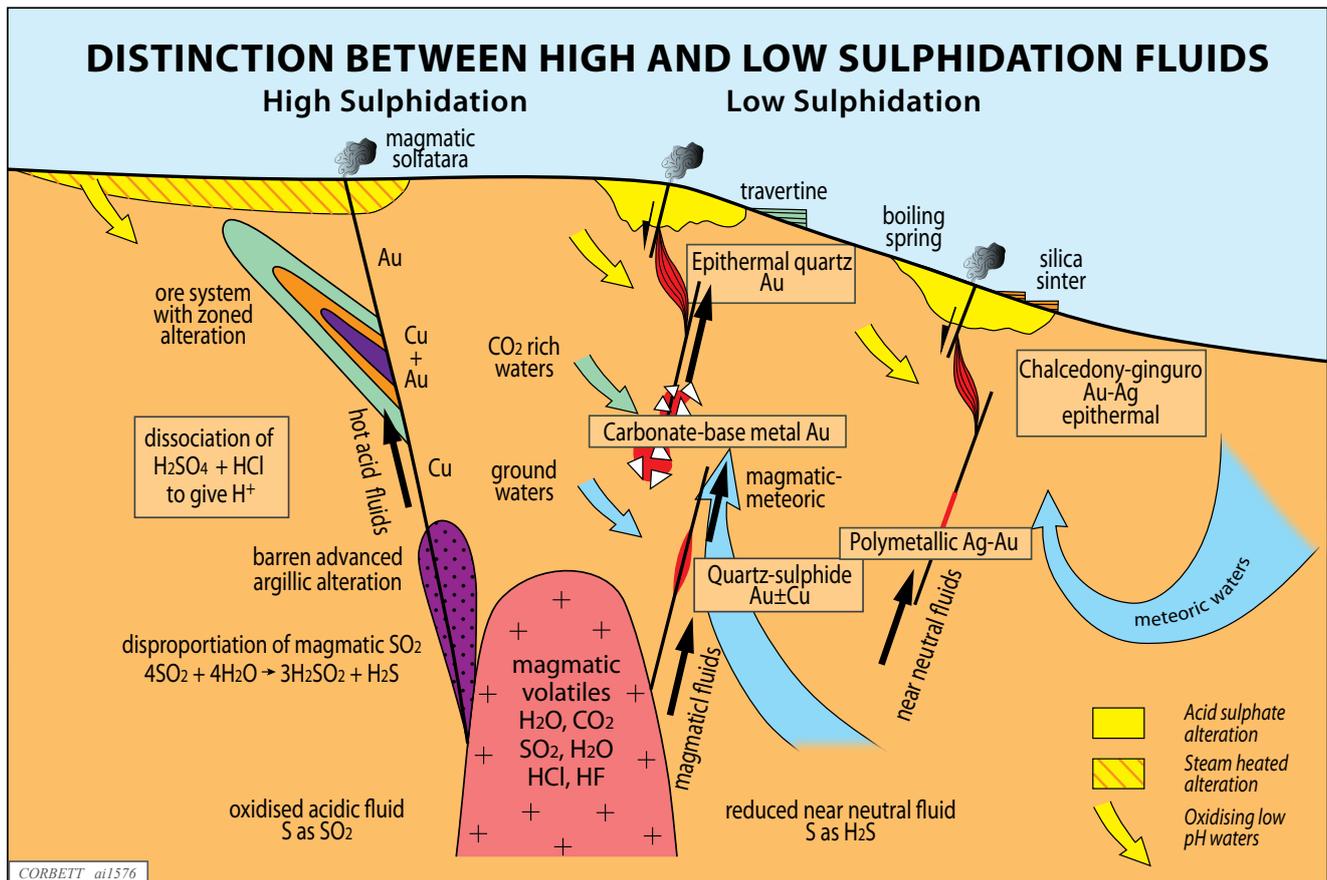


Figure 1.6 Fluid flow paths for low and high sulphidation epithermal Au deposits (modified from Corbett and Leach, 1998).

epithermal mineralisation styles developed from two profoundly different evolving ore fluid types, which might be simplistically considered to originate as open or closed systems (figure 1.6). Low sulphidation fluids develop in an open system characterised by modest reaction with the wall rocks, as rising near neutral magmatic fluids are diluted by variable entrainment within circulating meteoric waters. By contrast, the fluids which deposit high sulphidation epithermal ores might be considered to rise from the magmatic source at depth as a closed bubble, not in equilibrium with the wall rocks, and evolve to take on an acidic character, prior to later cooling and neutralisation by wall rock reaction (section 2.2.4.4). Each epithermal mineralisation style might now be defined as derived from a distinctly different hydrothermal fluid and display characteristic ore and gangue mineralogy as well as wall rock alteration, rather than the original definition based on the sulphidation state of specific ore minerals. Confusion created by the incorrect application of the term intermediate sulphidation is resolved below.

1.2.2.1 Low sulphidation epithermal Au-Ag

Low sulphidation epithermal Au-Ag mineralisation is deposited from evolving near neutral composite magmatic-meteoric ore fluids in which S occurs as H₂S (section 7.1.2). In essence, as an evolving magmatic

fluid, which hosts Au-Ag bearing sulphides, rises, it may combine with varying quantities of shallower circulating meteoric waters and other evolved fluids, which deposit much of the gangue such as quartz, adularia or carbonate. The two low sulphidation epithermal deposit groups introduced above are distinguished by the magmatic versus meteoric contents of the ore fluid. There is a significantly higher magmatic fluid component in the intrusion-related sulphide-rich deposits typical of arcs, and the stronger meteoric component in the sulphide-poor banded quartz vein deposits typical of extensional settings. A comparison of figures 1.1, 1.4 and 1.5 illustrates the settings of the two groups of low sulphidation epithermal Au-Ag deposits in the two tectonic environments (arcs and back arc or rift).

1.2.2.1.1 Low sulphidation fluids

The synthesis (Corbett and Leach, 1998) of studies from the back arc Taupo Volcanic Zone geothermal in New Zealand (Henley and Ellis, 1983; Simmons and Brown, 2000a; Simpson et al., 2001 and references therein) with Philippine arc geothermal systems (Mitchell and Leach, 1991; Reyes, et al., 1993; Gigenbach, 1997; Corbett and Leach, 1998) provides three fluid types (figure 1.7):

- Neutral chloride
- Bicarbonate waters

	Low sulphidation	High sulphidation
Fluid	Dilute, S as H ₂ S	Saline S as SO ₂
Wall rock alteration	Local early propylitic with dominance of zoned argillic illite Gp with quartz, carbonate, pyrite	zoned advanced argillic - argillic as vuggy silica->alunite Gp->kaolin Gp->illite Gp, and abundant pyrite
Ore minerals	Low sulphide < 2% (locally <5%) Pyrite, sphalerite (variable Fe:Zn), galena, chalcopyrite, Ag sulphosalts	Enargite-pyrite with low temperature luzonite and varying to covellite, chalcocite, bornite, chalcopyrite at depth
Economic metals	Au>Ag less common Cu Zn Bi Te	Au>Ag+Cu
Au metallurgy	Generally good poor where Au encapsulated in fine As pyrite	Good in oxide ores Enargite hosts refractory Au Uncommon good Cu ores at depth
Gold fineness Ag:Au	Variable with style of low sulphidation including high and low fineness end members	In SW Pacific Ag-poor Latin America Ag-bearing and locally Ag>>Au
Controls	Ore shoots controlled by lithology, structure, styles and mechanisms of Au deposition	Permeability by host rock structure and dome/breccias

Table 1.2 Comparison of low and high sulphidation epithermal, modified from Corbett & Leach (1998).

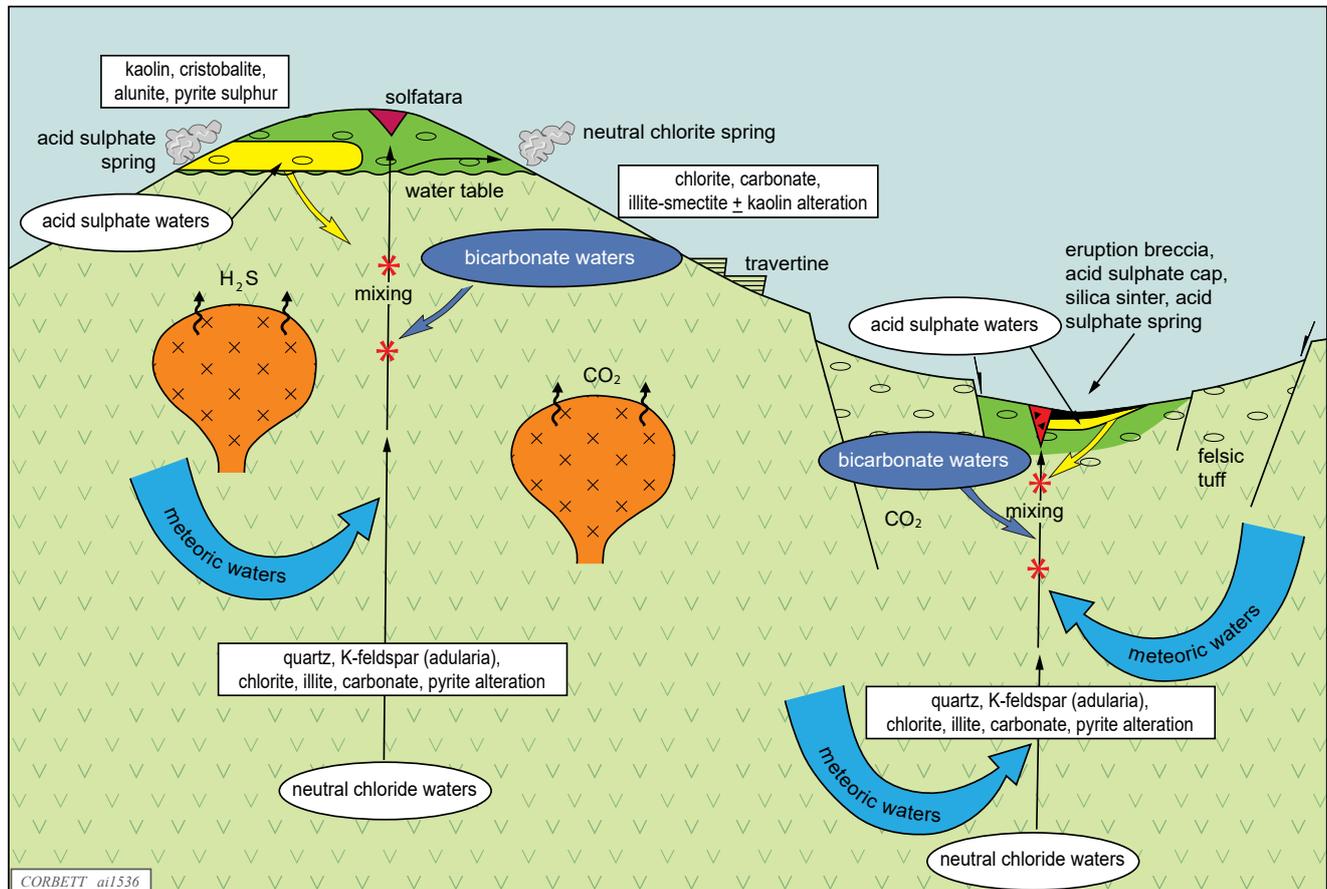


Figure 1.7 Evolved low sulphidation style hydrothermal fluids in magmatic arc and back arc settings.

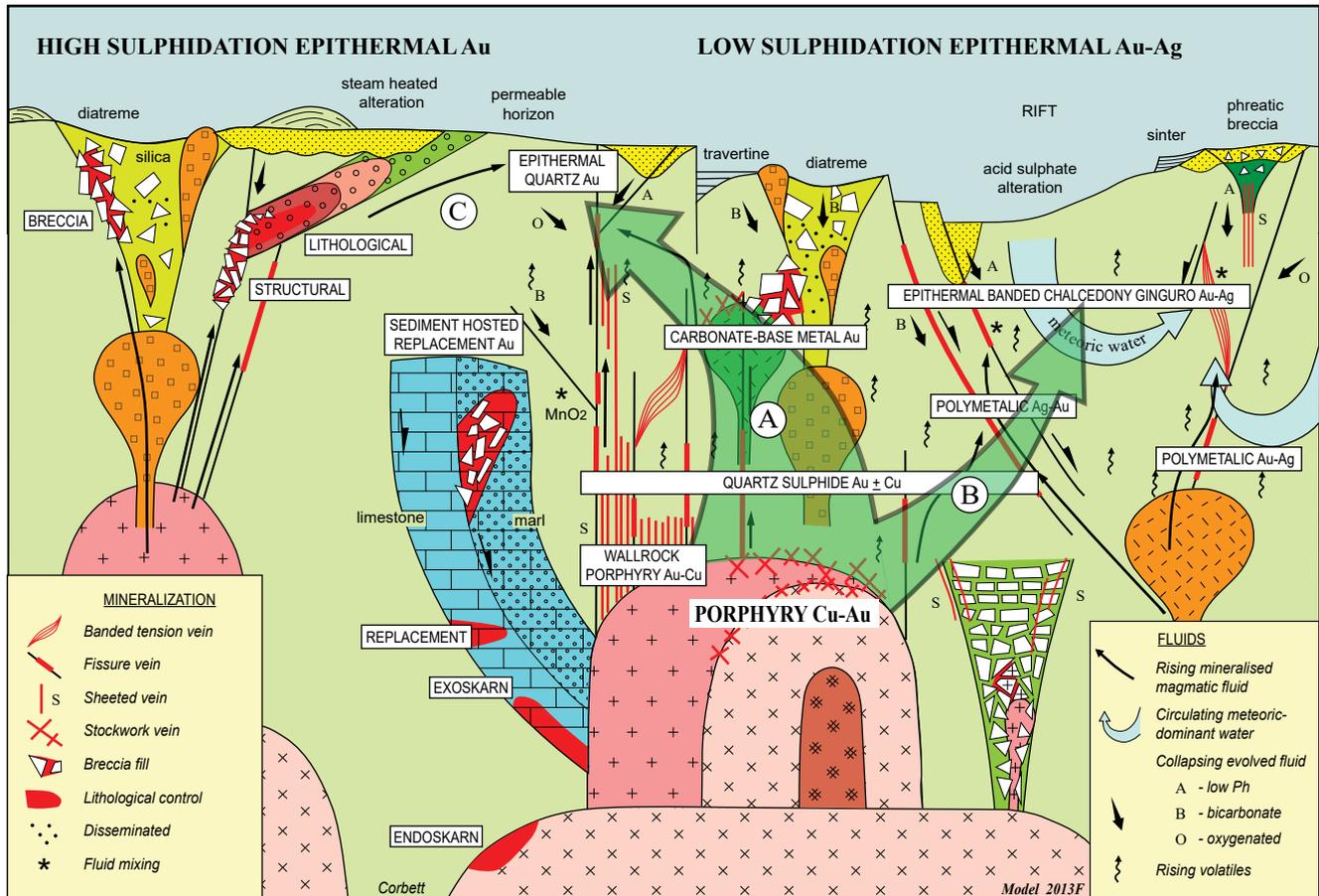


Figure 1.8 Low sulphidation epithermal Au fluid flow trends recognised in different terrains. In path **A**, typically in compressional magmatic island arcs of the Southwest Pacific rim, ore fluids deposit mineralisation in order characterised as: quartz-sulphide Au ± Cu, overprinted by carbonate-base metal Au which in turn evolves to epithermal quartz Au. In path **B** developed in strongly extensional settings such as the Sierra Madre of Mexico, Southern Peru or Argentine Patagonia, quartz-sulphide Au evolves to the polymetallic Ag-Au variant of carbonate-base metal Au, and then banded chalcedony-ginguero Au-Ag veins as substantial meteoric waters deposit chalcedony-adularia and the sulphide vein portion evolves to form ginguero bands. Chalcedony-ginguero Au-Ag veins also occur in the SW Pacific where they bottom as base metal sulphide-rich quartz veins. Fluid flow path **C** represents the rare case where a high sulphidation fluid might become sufficiently neutralised to form a lower sulphidation fluid and deposit ores typical of carbonate-base metal Au and epithermal quartz Au mineralisation.

- Acid sulphate waters

Neutral fluids which rise by convective flow from buried magmatic source rocks contain CO₂ and Cl, in far greater proportions in arc (Philippine) than rift (New Zealand) environments (above and Corbett and Leach, 1998; Simmons and Browne, 2000a; Giggenbach, 1997). In arc environments deep hydrothermal fluids rise and react with the wall rock to provide alteration assemblages grading from potassic to propylitic at depth and chlorite-zeolite at shallow levels (Corbett and Leach, 1998). In shallow level outflow zones, when vapour pressure of the rising fluid eventually exceeds confining pressure, water vapour and other gasses (mainly CO₂ and lesser H₂S) exsolve from the hydrothermal fluid. Then in the two-phase zone, absorption of CO₂ by ground waters produces moderately low pH bicarbonate waters (Corbett and Leach, 1998). In magmatic arcs the abundant bicarbonate waters may vent to form surficial travertine deposits, and are apparent on the margins of the rift Ohaaki-Broadlands geothermal system in New

Zealand (Hedenquist, 1990; Simmons and Browne, 2000a), where Terry Leach (pers. commun.) noted fluid mixing provided the deposition of anomalous gold. At shallow levels in the vadose zone (aerated region above the saturated phreatic zone, figure 1.5) H₂S gas derived from the deeper two-phase zone is oxidised to produce acid sulphate waters, which contain sulphuric acid, while oxidation of H₂S in the atmosphere produces native sulphur and steam (Corbett and Leach, 1998). Thus, there are two end member (bicarbonate and acid sulphate) evolved waters derived from the original neutral chloride precursor (figure 1.7). The bicarbonate waters, which are more abundant in arc than rift settings and associated with the formation of carbonate-base metal Au deposits, show empirical relationship with high level felsic (dacite) domes as a possible link to the magmatic source for CO₂ and H₂S. There is an **exploration implication** that elevated Au grades result from the effective destabilization of bisulphide complexes which transport Au, as oxidising low pH bicarbonate and acid sulphate waters mix with

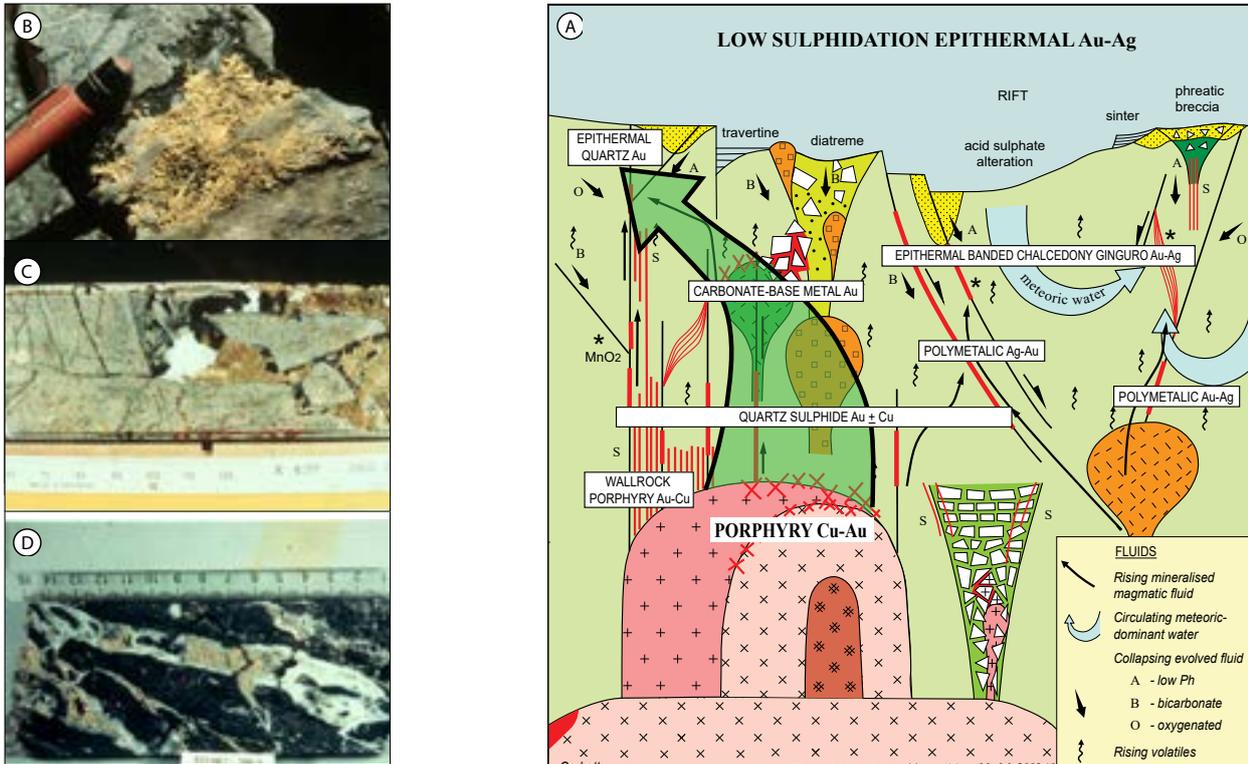


Figure 1.9 Low sulphidation epithermal Au mineralisation styles develop within magmatic arcs as the ore fluid evolves from early to late and deep to shallow crustal levels.

A - Modified figure 1.1 to illustrate the fluid flow and paragenetic sequence for the formation of mineralisation styles.

B - Quartz-sulphide Au + Cu mineralisation is characterised by quartz and coarse crystalline auriferous pyrite, from Bilimoia, Papua New Guinea.

C - Carbonate base-metal Au comprises early pyrite (of the quartz-sulphide Au + Cu event) followed sphalerite (here dark Fe-rich) with lesser galena and later carbonate, here as open space breccia fill, from Kelian, Indonesia.

D - Epithermal quartz Au mineralisation is characterised by bonanza grade high fineness yellow free gold with quartz and green roscelite (V illite) gangue, from Porgera Zone VII, Papua New Guinea.

rising ore fluids (section 7.5; Leach and Corbett, 2008). The term steam heated is commonly used in the geological literature to describe the evolved waters and associated wall rock alteration in both shallow crustal level low and high sulphidation epithermal regimes. However, here steam heated is reserved for alteration in the uppermost portions of high sulphidation epithermal Au-Ag deposits whereas acid sulphate describes the near surficial acid waters and associated alteration in low sulphidation epithermal terrains (figures 1.1, 1.4, 1.6. & 1.7).

1.2.2.2 Styles of low sulphidation epithermal Au-Ag mineralisation

Different styles of low sulphidation Au-Ag mineralisation are derived from two hydrothermal fluid flow trends which broadly equate to compressional magmatic arcs and more strongly extensional settings, such as back arc environments, or intra-arc rifts, but not restricted to these settings (figure 1.8). As mentioned earlier, the terminology is introduced here, while deposit types, associated wall rock alteration and the **exploration implications** of this classification are considered in detail in later chapters.

1.2.2.2.1 Quartz-sulphide Au ± Cu

with local As, Hg and Sb mineralisation varies from Cu-rich at depth to Au-rich at elevated crustal settings, and is the earliest deposited of the sulphide bearing low sulphidation epithermal Au styles, where it may display an association with intrusion source rocks (figures 1.1 & 1.4; table 1.2; Leach and Corbett, 1993, 1994, 1995; Corbett and Leach, 1998; Corbett, 2013b). These deposits occur over a considerable vertical range and so include very deep level batholith intrusion-related quartz-sulphide deposits regarded as orogenic by some workers (Lang and Baker, 2001), through to mineralisation deposited within typical epithermal crustal levels (Nolans & Mt Wright Australia, Round Mountain, Nevada), and rising to near surficial settings such as the giant Ladolam deposit, Lihir Is., Papua New Guinea (Corbett et al., 2001 and below). Gold occurs in association with sulphides. Mineralogy is dominated by quartz with (auriferous) pyrite, the latter varying to include low temperature marcasite and arsenian pyrite at a shallow crustal level, while at a deep crustal level sulphides include high temperature pyrrhotite, chalcopyrite and locally specularite or magnetite. Quartz varies from chalcedony or opal at shallow crustal levels, to mostly slow cooled coarser grained crystalline or comb quartz in vein deposits developed at deeper crustal levels.

Quartz-sulphide veins are transitional to many D veins formed marginal to porphyry intrusions (in the classification of Gustafson and Hunt, 1975) but not including enargite veins described by those workers (figure 1.4). Variable Au grades include supergene Au enriched ores (Section 7.6.2).

1.2.2.2.2 Carbonate-base metal Au,

originally defined in the southwest Pacific rim (Leach and Corbett, 1993 1994; 1995; Corbett and Leach 1998), and later recognised elsewhere, including the related (table 1.4) polymetallic Ag-Au deposits of Latin America (Corbett, 2002a, 2004, 2005a), have been some of the most important Au and Ag producers in those regions and host significant unexploited resources. The carbonate-base metal Au and polymetallic Ag-Au deposits contain early lower precious metal grade quartz-sulphide Au ± Cu mineralisation and display strong associations with felsic high level intrusions, typically rhyolite-dacite domes, and also phreatomagmatic breccias for the carbonate-base metal Au deposits. Extensional listric

faults dominate as settings for polymetallic Ag-Au vein deposits. These deposits are characterised by Au-Ag in association with pyrite-galena-sphalerite and lesser chalcopyrite and tennantite-tetrahedrite with gangue dominated by quartz-carbonate. The elevated Ag content of polymetallic Ag-Au deposits is commonly hosted within Ag sulphosalts such as tennantite-tetrahedrite (freibergite) at deeper crustal levels rising to argentite-acanthite at elevated settings. The polymetallic Ag-Au deposits, which may also be enriched in barite, display an argentite-acanthite rich epithermal end member and, with the addition of chalcedony from meteoric waters, evolve at high crustal level extensional settings into banded chalcedony-ginguro Au-Ag mineralisation. As illustrated in figure 1.9 the carbonate-base metal Au deposits evolve to epithermal quartz Au mineralisation.

Consequently, there are two low sulphidation epithermal end members at shallowest crust levels readily distinguished at by mineralogy and Ag:Au ratio (figures 1.1 & 1.9; tables 1.3-5). Epithermal quartz

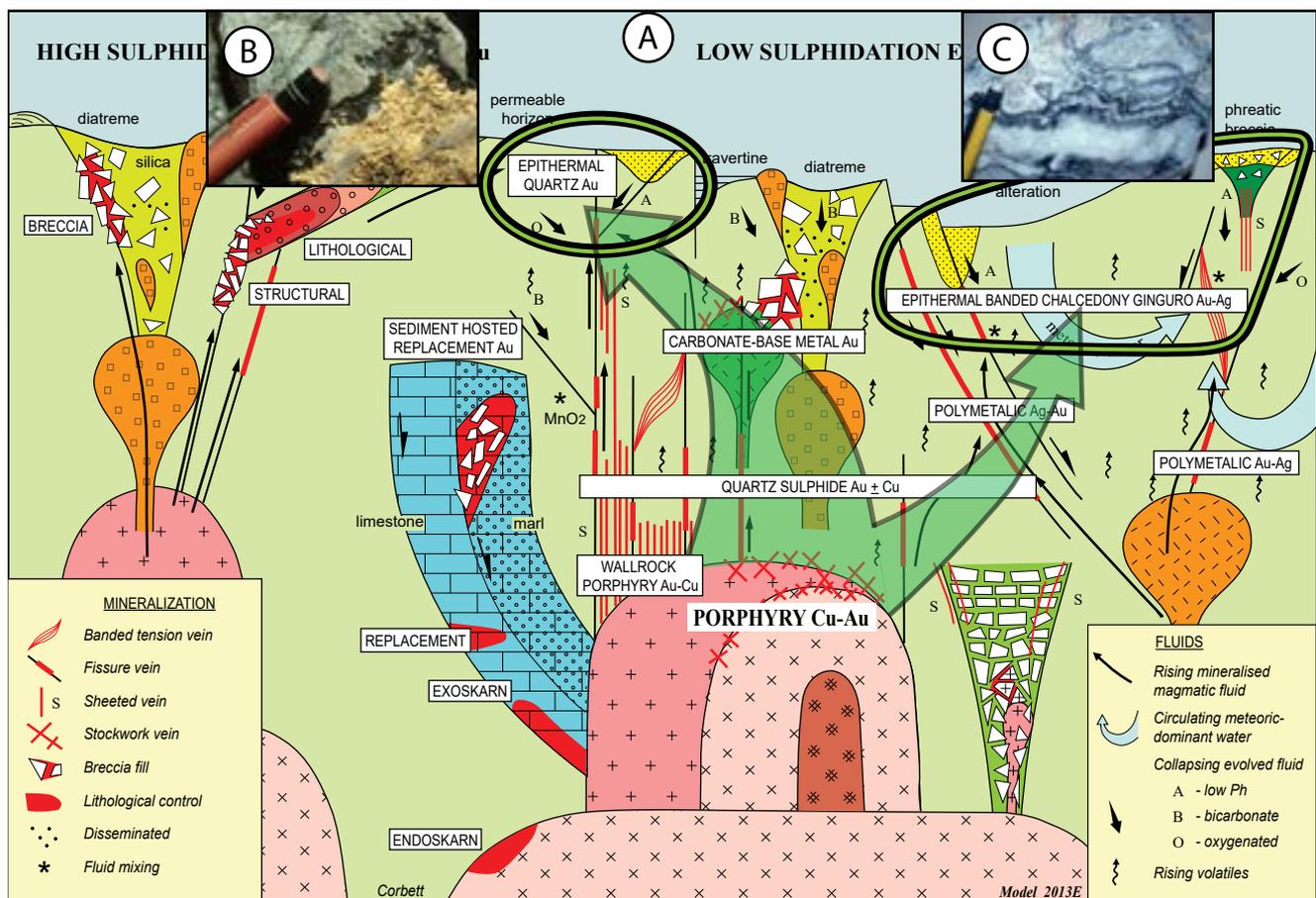


Figure 1.10 Two low sulphidation epithermal bonanza Au end members.

A - Graphic combines the two fluid flow trends in figures 1.9 and 1.11 which evolve to host bonanza Au.

B - In magmatic arcs, epithermal quartz Au mineralisation is characterised by high fineness free Au and little gangue, from Porgera Zone VII, Papua New Guinea

C - In strongly extensional settings such as back-arcs or rifts, banded chalcedony-ginguro Au-Ag mineralisation contains low fineness Au with abundant Ag, typically within the black sulphidic ginguro bands, which are locally interlayered with the poorly mineralised banded chalcedony, local adularia and quartz after platy calcite gangue, from Hishikari, Japan, 948 g/t Au & 3,720 g/t Ag.

Deposit type	Typical Ag: Au ratio	Characteristic
Quartz-sulphide Au ± Cu	1	Quartz and Fe sulphides typically pyrite, varying to marcasite / arsenian pyrite at high levels. Chalcopyrite specularite or pyrrhotite common at depth.
Carbonate-base metal Au	2-10	Fe/Mn/Mg/Ca carbonate with pyrite, sphalerite > galena and quartz. MnO if weathered.
Polymetallic Ag-Au	Commonly >100	Banded veins with layers of quartz, Fe/Mn/Mg/Ca carbonate, and sulphides as pyrite, sphalerite, galena. MnO if weathered.
Epithermal quartz Au	<1	High grade, high fineness, free Au, commonly with quartz and locally banded chalcedony.
Epithermal chalcedony-ginguro Au ± Ag	2-10 commonly >10	Banded veins comprising interlayered chalcedony, ginguro and local adularia and quartz pseudomorphing platy calcite.
Sediment hosted replacement Au	<1	Impure limestone replaced by siliceous arsenian pyrite commonly as breccias and with stylonites. Jasper common.

Table 1.3 Field characteristics of different low sulphidation epithermal Au-Ag styles.

	Carbonate-base metal Au	Polymetallic Ag-Au
Metal	Au-rich	Generally Ag > Au local Zn
Au fineness	Moderate	Low
Form	Breccias, fracture/veins local fissure veins	Generally as fissure veins, commonly in listric faults
Relationship to other deposits	Significant early quartz-sulphide. Overprinted by epithermal quartz Au±Ag	Minor early quartz sulphide. Evolve to chalcedony-ginguro in higher portions of strongly dilatant systems
Setting	Magmatic island arcs	Extensional arc and back arc
Relation to intrusions	Many deposits associated with diatreme flow dome complexes, also marginal to intrusions	Felsic domes common at prospect scale
Dilution	May be stopped out by late breccias	Common dilution of ore grade by post-mineral quartz
Ore fluid transport	Bisulphide dominant	Chloride locally important

Table 1.4 Essential differences between the low sulphidation carbonate-base metal Au and polymetallic Ag-Au deposits.

Au mineralisation (below) is characterised by high fineness free Au and commonly very little gangue, while banded chalcedony-ginguro Au-Ag mineralisation is characterised by high Ag in ginguro bands and abundant gangue of chalcedony and quartz and other minerals such as adularia (figure 1.9).

1.2.2.2.3 Epithermal quartz Au

mineralisation (originally defined as epithermal quartz Au-Ag in Leach and Corbett, 1995; Corbett and Leach

1998) typically forms at shallow crustal levels within magmatic arcs overprinting quartz-sulphide Au ± Cu and carbonate-base metal Au deposits, and hosts high fineness locally bonanza grade free Au typically with very little gangue, although chlorite is locally abundant (described in section 7.2.1.3). Some deposits comprise high fineness Au within banded chalcedony-adularia veins (Sleeper, Nevada; Gosowong, Indonesia), while others are strongly anomalous in Te (Emperor, Fiji), locally with Bi such as quartz-tellurobismuthite

Characteristic	Epithermal quartz Au	Epithermal chalcedony-ginguro Au-Ag
Visible Au	Abundant	Present
Ore mineralogy	Free Au local Te and Bi minerals	Electrum, silver sulphosalts and Ag-bearing sulphides local Se minerals
Au fineness	High	Low
Ag: Au ratio	Low	High
Gangue quantity	Commonly low	Generally high gangue which may dilute ore
Gangue type	Quartz, local clay or chlorite	Banded chalcedony with local quartz pseudomorphing calcite and adularia. Common post-mineral calcite
Setting	Magmatic arc	Extensional settings which are most common in rifts, (back arc and intra arc)
Associated mineralisation	Commonly overprint low sulphidation quartz-sulphide and carbonate base metal Au	Commonly pass downwards to polymetallic Ag-Au in Latin America or base metal sulphides in the SW Pacific

Table 1.5 Comparison of the two end members of low sulphidation epithermal Au-Ag mineralisation.

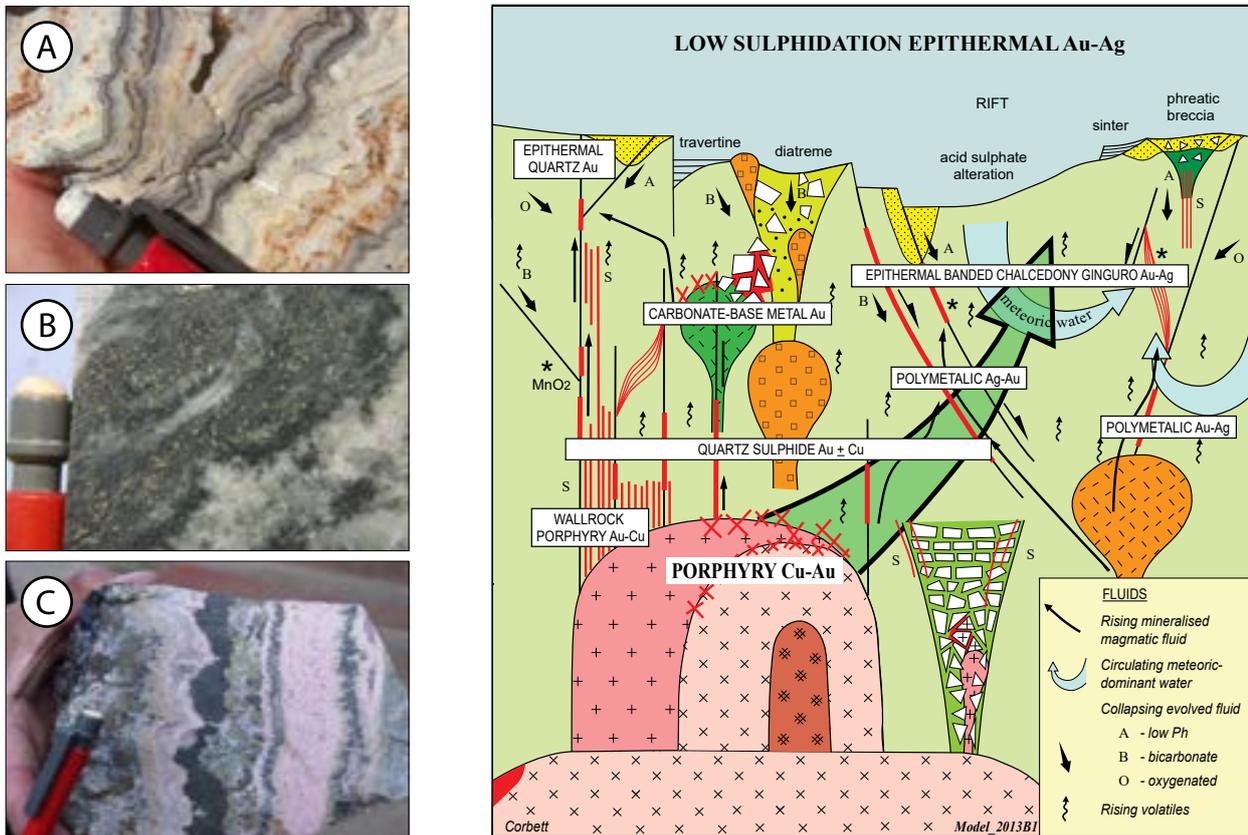


Figure 1.11 Evolution of low sulphidation epithermal mineralisation styles within strongly extensional settings such as back arcs or rifts (Sierra Madre of Mexico, Southern Peru or Argentine Patagonia).

A - In strongly extensional settings the banded chalcedony-ginguro Au-Ag veins develop as the ore fluid evolves and combines with meteoric waters which deposit chalcedony, adularia and quartz after platy calcite interlayered in veins, such as this example from Golden Cross, New Zealand. Note the symmetry in the bands and central open space as these veins grow inwards as open space fill.

B - Some polymetallic Ag-Au deposits evolve to host late stage mineralisation characterised by argentite-acanthite, pyrite and white Fe-poor sphalerite, such as this example from Juevos Verde, Argentine Patagonia.

C - Polymetallic Ag-Au mineralisation is characterised by pyrite (as part of the early quartz-sulphide Au + Cu component, locally with barite) along with sphalerite (here yellow low to moderate Fe), galena and Ag sulphosalts with gangue of quartz and carbonate (here rhodochrosite). This sample from Caylloma mine, Peru, assayed 30,00g/t Ag, contained mostly within dark freibergite, the Ag-rich tetrahedrite.

(Bilimoia, Papua New Guinea) and chlorite gangue (Cracow, Australia).

1.2.2.2.4 Epithermal banded chalcedony-ginguro Au-Ag

mineralisation (figures 1.10 & 1.11) develops by the combination of mineralised ginguro bands of magmatic origin, with bands of gangue deposited from dominantly meteoric waters, comprising chalcedony (low temperature quartz), adularia (as low temperature K-feldspar) locally with platy calcite pseudomorphed by quartz (Corbett, 2005a). Chalcedony is deposited from cooling fluids at a higher temperature and evolution from amorphous silica may evolve to quartz over time (section 2.1.7). Veins typically form in strongly extensional settings such as back arcs and intra-arc rifts. The term ginguro is derived from the early Japanese miners who recognised best Au-Ag occurred within bands or breccia fill of black metallic material comprising fine pyrite, Ag sulphosalts such as argentite-acanthite, along with electrum and gold with minor chalcopyrite. Sado gold mine began production in 1452 and for many years the shogunate of Japan was based on Sado Island at the source of income. These deposits are therefore generally Ag-rich.

In Latin America many polymetallic Ag-Au deposits are capped by epithermal banded chalcedony-ginguro Au-Ag veins and some SW Pacific rim epithermal banded chalcedony-ginguro Au-Ag veins pass downwards to sub-economic base metal bearing quartz + carbonate veins similar to polymetallic Au-Ag mineralisation (Waihi, New Zealand; Kupol, Eastern Russia). Epithermal banded chalcedony-ginguro vein systems are recognised in active near surficial settings as hot spring deposits and may display an association with eruption breccia pipes (section. 4.4.6).

1.2.2.2.5 Sediment hosted replacement Au

deposits occur throughout the Pacific rim and so a derivation of the 'sediment-hosted disseminated precious metal deposit' terminology (Bagby and Berger, 1985, Berger and Bagby, 1991) provides a preferred (Cooke and Deyel, 2003) descriptive term, rather than the commonly used Carlin-style terminology (Cline et al., 2005 and references therein), named after the district in Nevada from where these deposits were originally well documented. Sediment hosted replacement Au deposits are now interpreted (Leach, 2004) to develop at elevated crustal settings by a combination (Corbett and Leach, 1998) of several features. Dilatant structures facilitate transport of low sulphidation epithermal quartz-sulphide style ore fluids from magmatic source rocks at depth to higher crustal levels where they react with permeable

impure limestone and mineral deposition occurs by sulphidation reactions (Leach, 2004). These deposits are characterised by microfine refractory Au encapsulated within typically arsenian pyrite which varies from pseudomorphous lithological replacement to breccia fill and feature anomalous Hg and Sb, in addition to As, as an indication of the interpreted formation at elevated crustal settings.

1.2.2.3 High sulphidation epithermal Au mineralisation

The high sulphidation epithermal Au terminology developed from a focus on the high sulphur content, to the sulphidation state of the ore minerals (above), but might now be better defined in the field by exploration geologists on the basis of the characteristic zoned alteration developed by the reaction of hot acidic fluids with wall rocks and enargite-bearing ore minerals with barite-alunite gangue. The hot, acidic, magmatically-derived, ore fluid is saline, hosts sulphur as SO₂ and is extremely oxidising (below). There is a variation in Ag content, from virtually absent in most SW Pacific deposits, to Ag-rich and locally dominant in value over Au in some Latin American deposits, although the terminology herein focuses upon Au. Cu is locally economic as Cu-rich, As-poor, sulphides (covellite-chalcocite) dominate at depth (Cukaru Peki, Serbia).

The process for the formation of high sulphidation epithermal Au deposits varies dramatically from low sulphidation ore fluids. A fluid rich in magmatic volatiles (SO₂, CO₂, H₂S, HCl and HF), and including brine, is interpreted (Corbett and Leach, 1998 and references therein) to vent from a magmatic source at depth and rise rapidly up a dilatant structure to an elevated crustal setting without significant interaction with ground waters or wall rocks, essentially as a bubble. This closed system is diametrically opposed to the open system involved in the formation of low sulphidation epithermal deposits. In the formation of high sulphidation epithermal deposits, the volatile-rich fluid, which would have been pressurised and near neutral pH at porphyry levels, becomes progressively depressurised as it rises rapidly, like a bubble, up the host structure causing volatiles to progressively come out of solution. As the temperature of the rising fluid falls below 400°C, vapour phase magmatic SO₂, exsolved from the depressurised fluid, undergoes disproportionation to yield H₂SO₄ (sulphuric acid) and H₂S (Rye et al., 1992). Consequently, an originally hot near neutral fluid becomes progressively more acidic as it rises and so by the stage it has reached epithermal levels it might be characterised by a pH of 0-2 and temperature of 250-300°C. This environment in which

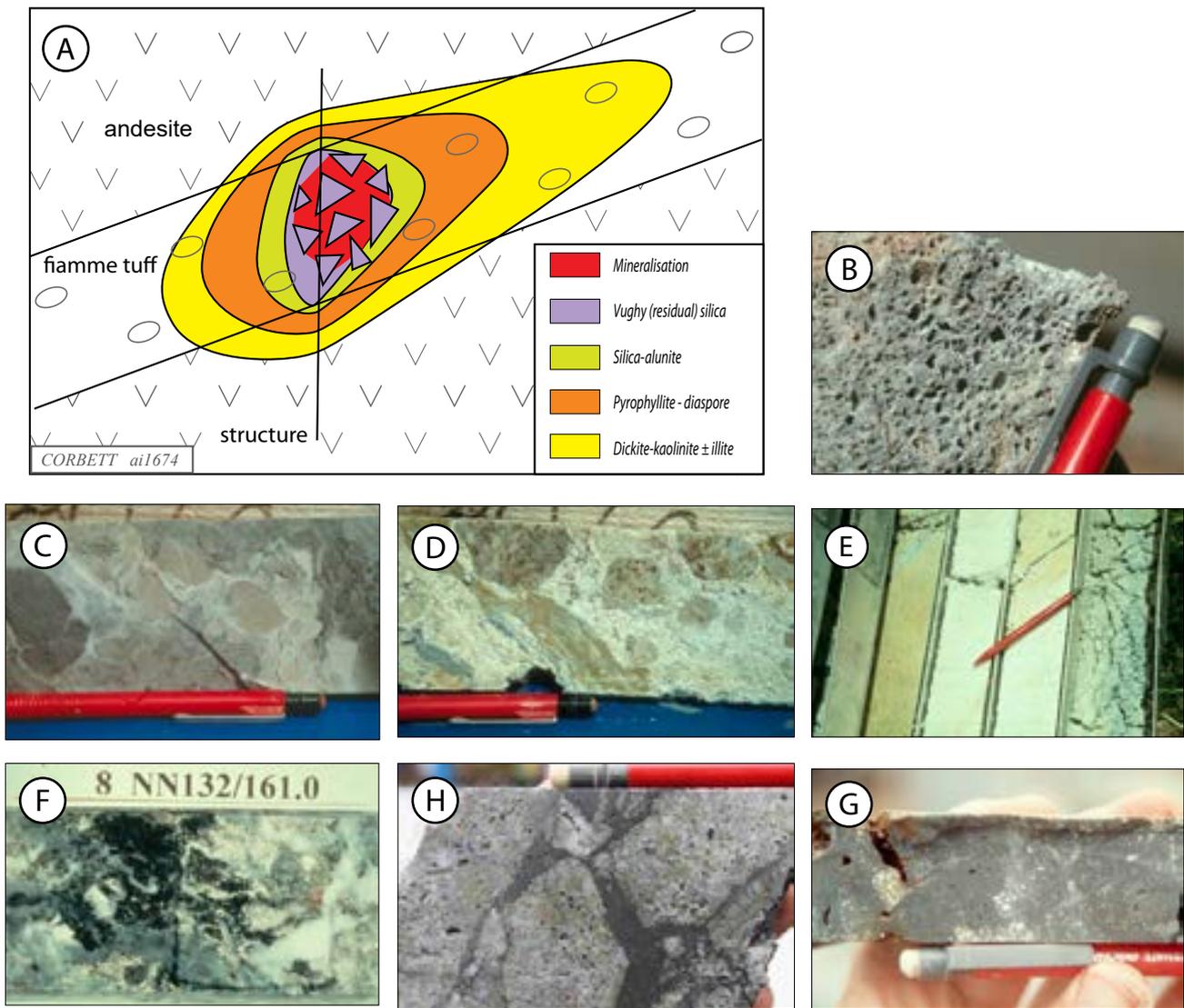


Figure 1.12 High sulphidation epithermal Au mineralisation is associated with characteristic zoned advanced argillic alteration grading outwards from the core of the alteration system.

A – Graphic illustrates the localisation of a high sulphidation epithermal system at the intersection of a feeder structure and permeable lithology which then controls fluid flow (see figure 1.1) and alteration zonation. Mineralisation overprints the competent residual vuggy silica.

B - Vuggy silica at the centre of the advanced argillic alteration zone, from Sappes, Greece.

C - Silica-alunite grading outwards from the centre, from Sappes, Greece.

D - Pyrophyllite-diaspore in the outer portion of the advanced argillic alteration, from Sappes, Greece.

E - Dickite-kaolinite grading outwards to illite then more marginal smectite discernible as a swelling clay as the argillic halo to advanced argillic alteration, from Sappes, Greece.

F - Mineralisation post-dates alteration as breccia fill (black) enargite with additional (white) alunite, from Nena, Papua New Guinea.

G - Disseminated enargite-pyrite within vuggy silica, from Mt Kasi, Fiji.

H - Enargite-pyrite vein cuts vuggy silica, from Cerro Quema, Panama.

fluid evolution occurs provides a distinct gap between any high sulphidation epithermal Au deposit and its underlying intrusion source (figures 1.1 & 1.4), in the order of several hundred metres. The **exploration implication** is that high sulphidation epithermal Au deposits should not immediately overlie source intrusions as illustrated in some ore deposit models. However, many high sulphidation epithermal Au deposits may sit on top of older intrusions, possibly telescoped in conditions of rapid uplift and erosion (Caspiche, Chile; Wafi-Golpu, Papua New Guinea).

In the epithermal regime the hot acidic fluid is

progressively cooled and neutralised by wall rock reaction to provide the characteristic zoned advanced argillic hydrothermal alteration grading outwards from residual (vuggy) silica to mineral assemblages dominated by alunite, pyrophyllite, dickite and so on with variations described in detail later (section 2.2.4.4; figure 1.12). The hot acidic fluid breaks up into two phases. A faster moving volatile-rich phase reacts with the wall rocks to provide the characteristic zoned advanced argillic alteration by progressive wall rock reaction. The slower liquid-rich phase deposits later Au-Ag mineralisation within sulphides comprising pyrite and enargite, or luzonite, its low temperature

polymorph, along with barite-alunite gangue discussed in detail later (section 8.3; figure 1.12). At epithermal crustal levels hydrothermal fluid flow in the wall rocks is controlled by permeable lithologies, breccias or structure (figure 1.1, section 8).

The early 1980's term 'acid sulphate, which is now replaced by high sulphidation for epithermal Au deposits of that type, is maintained for kaolin-alunite bearing blankets of alteration developed near the palaeo surface as caps to low sulphidation Au-Ag deposits (section 2.2.4.5). Similar near palaeo surficial caps to high sulphidation epithermal Au deposits are termed steam heated alteration, characterised by cristobalite, kaolin and powdery alunite and basal silica ledges (figure 1.1; section 2.2.4.5). Near surficial acidic fluids responsible for kaolin alteration styles locally collapse into deeper levels in the hydrothermal system where they might mix with rising ore fluids and

promote the development of high precious metal grade mineralisation discussed herein.

1.2.2.4 Does intermediate sulphidation exist?

The acidic fluids associated with high sulphidation epithermal Au deposits locally become cooled and neutralised to form lower sulphidation states late in the paragenetic sequence, and/or at the margins of some high sulphidation epithermal Au deposits (fluid flow path C in figure 1.8). This has been described for Link Zone at the margin of the Wafi high sulphidation Au deposit, Papua New Guinea (section 8.6.6; Leach, 1999) and at El Indio mine district, Chile (section 8.6.1; Corbett and Leach, unpubl. reports, 2000 in Heberlein, 2008). At the Viento vein system, El Indio, (figure 1.13), there is a progressive change along strike in ore mineralogy, from typical high sulphidation enargite-luzonite in the south, to carbonate-base metal

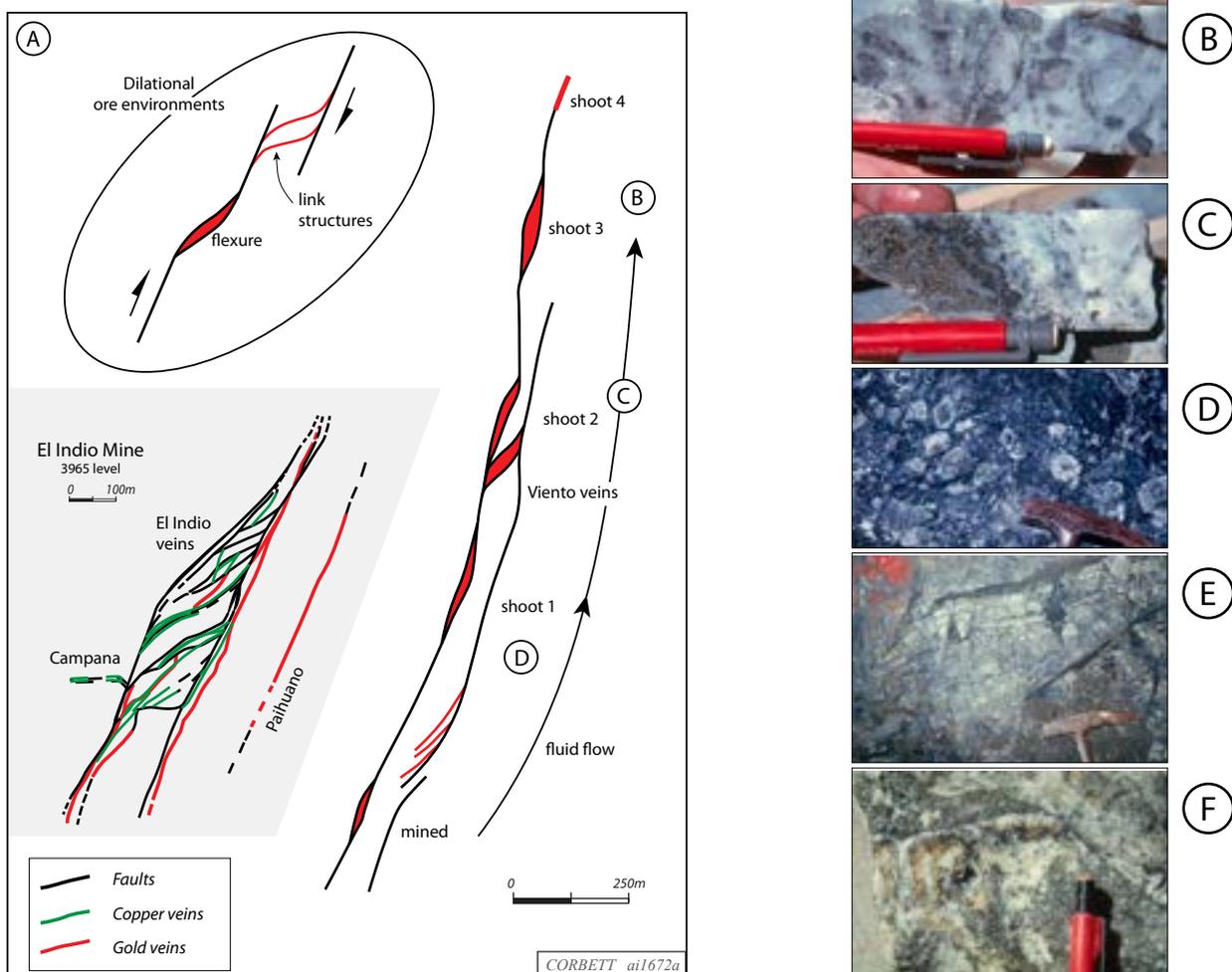


Figure 1.13 Transition from high to lower sulphidation at the El Indio-Viento veins, Chile, showing the trend in mineralogy in space and time.

A - Sketch map of the El Indio-Viento vein system showing the sigmoidal loop mapped by Stan Caddy at El Indio, from Jannas et al. (1990), and the Viento veins with ore shoots, from Corbett unpubl. reports (2000) in Heberlein (2008).

B - Quartz-Au (shoot 4).

C - Quartz-rhodochrosite-sphalerite-galena (shoots 2 & 3).

D - Enargite-luzonite (mined & shoot 1).

E - Banded enargite-pyrite ore at the El Indio veins shown in green on the graphic.

F - Bonanza quartz-Au El Indio ore shown in red in the graphic.

Au style (pyrite, galena, sphalerite and rhodochrosite) in the centre and epithermal quartz Au (quartz with high fineness free Au) in the north, all overprinting advanced argillic alteration of the high sulphidation Au event (figure 1.13; Corbett and Leach, unpubl. reports, 2000 in Heberlein, 2008). Similarly, the adjacent El Indio veins are zoned in time as an early copper stage, transitional stage and later gold stage (Jannas, 1995 in Heberlein, 2008) as the bonanza quartz Au event overprints the enargite-bearing Cu event (section 8.6.1). These are examples of fluid evolution from high to lower sulphidation both overprinting in time and marginal to the high sulphidation system. Typical carbonate-base metal Au and epithermal quartz Au mineralogy also overprint advanced argillic alteration in settings of fluid evolution from high to lower sulphidation at Orcopampa (section 8.6.2; Salazar et al., 2009) and the La Zanja districts in Peru (section 8.6.3; Corbett, unpubl. reports, 2014).

The term intermediate sulphidation (Einaudi et al., 2003), was defined as ores comprising (low temperature) Fe-poor sphalerite, tennantite-tetrahedrite and lacking pyrrhotite (Sillitoe and Hedenquist, 2003), developed as a stage in the fluid evolution from high to low sulphidation, and therefore overprinting high sulphidation advanced argillic alteration, similar to the examples described above. Using a similar sulphide-bearing and sulphide-poor distinction in Nevada by John (2001), to that previously defined in the SW Pacific rim for low sulphidation epithermal deposits (Leach and Corbett, 1993, 1995, Corbett and Leach, 1998), the intermediate sulphidation terminology has been extended (Sillitoe and Hedenquist, 2003) to include the entire suite of sulphide-bearing low sulphidation epithermal deposits previously classified as low sulphidation carbonate-base metal Au (Leach and Corbett, 1993, 1995; Corbett and Leach, 1998) and including the Ag-rich variant, polymetallic Ag-Au deposits (Corbett, 2002a).

The large group of carbonate-base metal Au (including polymetallic Ag-Au) deposits should not be categorised as intermediate sulphidation. They are derived from a sulphide-rich low sulphidation fluid which has evolved through two low sulphidation fluid flow paths, preceded by quartz-sulphide Au + Cu and followed by either epithermal quartz Au or chalcedony-ginguro Au-Ag mineralisation, as illustrated in fluid flow paths A and B in figure 1.8. Intermediate sulphidation deposits are derived from the fluid flow path C in figure 1.8, overprinting earlier high sulphidation systems with associated advanced argillic alteration. The carbonate-base metal Au deposits are characterised by a range of sphalerite compositions and colour, not restricted to low Fe honey coloured

sphalerite (section 7.2.1.2.1), and some deposits contain pyrrhotite or chalcopyrite, all not consistent with the intermediate sulphidation definition above. For instance the important examples (described as intermediate sulphidation by Sillitoe and Hedenquist, 2003), Porgera, Papua New Guinea and Kelian, Indonesia, each feature black Fe-rich sphalerite and pyrrhotite (Corbett and Leach, 1998). Furthermore, the carbonate-base metal Au deposits are characterised by argillic hydrothermal alteration derived from the interaction of a typical near neutral low sulphidation epithermal fluid with the wall rocks, not the advanced argillic as would be expected in the definition above. The description of carbonate-base metal Au deposits as quartz-poor intermediate sulphidation by Sillitoe and Hedenquist (2003) is similarly incorrect (see quartz in figure 7.15, Corbett and Leach, 1998). Many deposits described as intermediate sulphidation in the geological literature have formed within a typical low sulphidation fluid flow trend not the evolution from high to lower sulphidation.

Consequently, as is the custom in science, this study uses the first published terminology for the large group of deposits categorised as carbonate-base metal Au, (Leach and Corbett, 1993, 1994, 1995; Corbett and Leach, 1998), and including the Ag-rich variant, polymetallic Ag-Au (Corbett, 2002a), each with wall rock argillic alteration rather than intermediate sulphidation.

1.2.2.5 Porphyry Cu mineralisation

The term porphyry Cu \pm Mo \pm Au deposits which came about from mining, has persisted as these deposits represent attractive exploration targets, typically as high total value, bulk mining, low metal grade open pit operations, although many are also worked as underground mines. While the term porphyry Cu herein implies some Au and Mo may be present, mention is made where these add significant value.

Definitions of porphyry Cu deposits in current use focus upon the porphyritic texture of dominantly calc-alkaline intrusions, which host Cu \pm Au \pm Mo mineralisation associated with sulphides (pyrite-chalcopyrite-bornite) as disseminations, breccia fill and mostly within stockwork and sheeted quartz-sulphide veins (figure 1.14). Best mineralisation may occur in the upper margins of plutons or apophyses as vertically attenuated spine-like stocks derived from deeper magmatic source rocks and rising to depths of 1 - 2 km below the palaeo surface. While porphyry deposits typically display characteristic paragenetic sequences

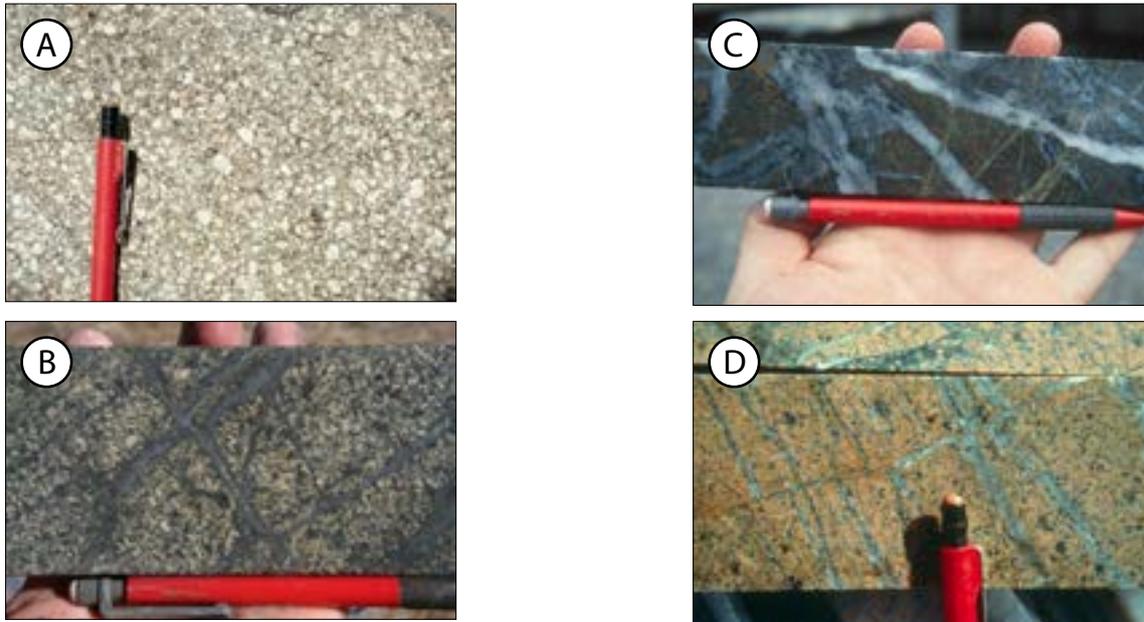


Figure 1.14 Some characteristics of porphyry Cu-Au deposits discussed in detail in section 5.

A - Typical porphyritic host rock, Woodlark Is., Papua New Guinea.

B - Stockwork (M style) laminated quartz-magnetite veins, from Copper Hill Australia.

C - Stockwork of several overprinting vein events from the Ridgeway porphyry, Australia.

D - Wallrock porphyry as interpreted sheeted veins outside the source intrusion, Cadia Hill, Australia.

of zoned hydrothermal alteration and vein styles, best metal grades are associated with those systems which feature multiple intrusions and hence polyphasal mineralisation events, although post-mineral intrusions may stope out ore. (figure 5.1 section 5).

This work expands upon existing porphyry definitions with reference to the **exploration implications** of structure and the paragenetic sequence porphyry alteration and mineralisation expanded from earlier work by Corbett and Leach (1998). Dilatant fracture systems host sheeted quartz-sulphide veins which transport mineralisation from magmatic source rocks at depth to higher crustal level cooler sites of mineral deposition. Porphyry Cu deposits display characteristic hydrothermal alteration which is zoned in space and time analysed as a major component of this study (sections 2 & 5). This zoned hydrothermal alteration, along with marginal veins and pebble dykes may be used as vectors towards buried porphyry targets (section 9). Ore hosting quartz-sulphide veins are also characterised as different vein styles which consistently display the same paragenetic sequence of formation. Spine-like mineralised stocks may cluster above more deeply buried magma sources commonly aligned along regional structures (Goonumbla & Cadia, Australia).

While Mo is recognised in many porphyry Cu deposits, a separate group of porphyry Mo deposits (White et al., 1981) are associated with more granitic porphyry compositions and display variations in form Corbett et al., 2009). Au-rich variants, termed

porphyry Cu-Au deposits are recognised in many settings (Sillitoe, 1993, 2000). Some workers have focused upon K-rich intrusion compositions with Au mineralisation (Müller and Groves, 1993, 2000, 2016), while others consider the influence of oceanic crust in their formation (Cooke et al., 2002; 2014), and arc reversal and remelting of oceanic crust (Solomon, 1990). Gold porphyry deposits, although with local anomalous Cu and Mo, might be distinguished as those mined for only Au, as the primary mineralisation, or a possible overprint (Fort Knox, Alaska, section 5.3.2.3). Suggested Sn and W-rich porphyry styles (Seedorff et al., 2005) would need to display porphyry alteration and mineralisation styles in order to be included in this class.

The term ‘wallrock porphyry deposits’ (Newcrest Mining Staff, 1996) has been used for Au-rich porphyry Cu-Au style mineralisation developed wholly within the wall rocks outside the source intrusion, which may not have been identified, (Cadia Hill & Cadia East, Australia; Gaby, Ecuador; some Maricunga belt occurrences, figure 5.2) as different to the more limited mineralisation normally documented extending from a mineralised porphyry into the adjacent wall rocks. Some deposits classed as Au porphyry might represent intrusion wall rock hosted deep epithermal low sulphidation quartz-sulphide Au ± Cu mineralisation.

1.2.2.6 Skarn

Skarn deposits defined by the characteristic calc-silicate mineralogy (Einaudi et al., 1981; Meinert, 2000; Meinert et al. 2005 and references therein) mostly develop by the metasomatic replacement of carbonate-bearing rocks and display paragenetic similarities to porphyry alteration and mineralisation (Corbett and Leach, 1998) with prograde and retrograde phases often overprinted by epithermal mineralisation, discussed in detail later (section 6).

1.2.2.7 Linkages between deposit types

Linkages or transitions exist between most of the deposits described above as illustrated in figures 1.1 and 1.4. The low sulphidation epithermal deposit types described herein all represent end members within evolving fluid trends. In compressional magmatic arcs, many intrusion-related low sulphidation epithermal Au deposits (Porgera, Papua New Guinea) or districts (Morobe goldfield, Papua New Guinea) contain several of the individual deposit types as: quartz-sulphide Au \pm Cu, carbonate-base metal Au and epithermal quartz Au. Similarly, in Latin American strongly extensional settings, polymetallic Ag-Au mineralisation passes upwards to epithermal banded chalcidony-ginguro Au-Ag veins, while some SW Pacific chalcidony-ginguro veins terminate down-dip as sub-economic base metal bearing quartz veins likened to polymetallic Au-Ag mineralisation. Some districts (Great Basin, Nevada) and deposits contain elements of both low sulphidation epithermal fluid flow trends (Frute del Norte, Ecuador; Gosowong, Indonesia; Karangahake, New Zealand). Transitions are recognised from high to (intrusion-related) lower sulphidation mineralisation (El Indio, Chile) and from deep epithermal intrusion-related low sulphidation quartz-sulphide Au \pm Cu style to porphyry Cu-Au, commonly as wallrock

porphyry Cu-Au. High sulphidation epithermal fluids may overprint earlier porphyry Cu intrusions (Golpu porphyry, Wafi, Papua New Guinea; Hayward et al., 2011; Menzies et al., 2013), but there should be a physical separation between the high sulphidation Au deposit and its source intrusion at depth.

Apparent magmatic arc mineralisation occurs in belts known for orogenic mineralisation such as Yukon-Alaska terrain, where the White project (MacKenzie et al., 2010) displays ore (auriferous pyrite) and alteration (K-feldspar-specularite) mineralogical typical of intrusion-related deep epithermal quartz-sulphide Au mineralisation (Corbett unpubl. reports, 2007-2009), and Fort Knox, Alaska is described as a Au porphyry (Bakke et al., 1998) and skarns occur nearby.

1.3 CONCLUSIONS AND EXPLORATION IMPLICATIONS

Section 1 sought to introduce the terminology used to describe epithermal and porphyry deposit types in order to facilitate the following discussion of the exploration tools - alteration, structure and breccias, and then these deposits will later be considered in greater detail. The **exploration implication** is that the explorationist must understand the style of mineralisation present as the first step in the evaluation of any project, in order correctly interpret field observations as well as geophysical, geochemical and hyperspectral data. Comparisons with known deposits of that style will then facilitate prioritisation of any portfolio of prospects, or identify potential problems (supergene enrichment or refracting hypogene metallurgy), even at the initial stage of an exploration program.

