TOWARDS A MULTIDISCIPLINARY INTEGRATED EXPLORATION PROCESS FOR GOLD DISCOVERY

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ABSTRACT

Surface geological and geochemical mapping have been key technical contributors to many gold discoveries over the past 25 years. However, in the last ten years there has been a growing emphasis on using geophysical techniques to compliment them in covered terrains. As the search for gold deposits under covered areas expands, there will be increasing emphasis on integrating the geoscientific disciplines in such a manner as to optimise the exploration process to decrease the time and cost of discovery. Successful integrated exploration requires putting mappable petrophysical property contrasts into a geological and geochemical process for the different tectonic environments of major gold ore types.

The geological and geochemical context of epithermal (high and low sulphidation), intrusion related and mesothermal gold deposits is described prior to the discussion of relevant petrophysical property contrasts and geophysical observations. Emphasis is placed on deposits in the circum Pacific region and Western Australia.

INTRODUCTION

The integration that this paper seeks to explore is that between geological and geochemical processes, petrophysical property contrasts, mineralisation and observations that can be made on geophysical survey data. Integration and optimisation of the different geoscientific disciplines will become more important in successful exploration programs of the future, in the search for gold deposits.

Despite gold's exceptional physical properties (electrical conductivity, density etc.), it has never occurred in such concentrations as to alter the macroscopic physical properties of the rocks. Hence direct detection of gold by geophysical techniques in large tonnage deposits has never been reported. Prior to the mid-1980s, gold exploration was dominated by surface geological mapping, prospecting and surface geochemical exploration methods. Since the mid-1980s, geophysical surveys have assumed an increasing importance in mapping lithology, structure and alteration in gold exploration programs. In Western Australia, this is evident by the availability of high resolution regional aeromagnetic surveys, which have provided valuable insights into the geometry of structure, lithology and alteration. This has been followed by exploration initiatives by several state geological surveys in Australia, whereby detailed regional aeromagnetic survey data has been provided to the exploration industry for as little as 1 cent per line km, as well as other valuable information. The value of this information has been demonstrated by the discovery of new gold mineralisation in hitherto unknown major shear systems in the Gawler Range province of South Australia.

Large multisensory airborne geophysical surveys have provided excellent multipurpose databases, which have led to the discovery of not only gold, but water, which is critical to the development of the gold deposit (Cuneen, pers. comm., 1997). They (in particular airborne electromagnetics) have also provided information which allows an environmental bench mark of the subsurface to be established very efficiently. Regional detailed multisensory surveys have been flown in India, Botswana, Namibia, Thailand and Malaysia, to name a few of the countries. Hence multisensory airborne geophysical surveys compliment gold exploration by facilitating the discovery of water and the management of the exploration environment.

Regional geochemical surveys have provided more direct indications of gold and have led to recent gold discoveries in Batu Hijau (Indonesia) and Mt. Bini, Papua New Guinea (PNG). Sillitoe (1995) in a study of the discovery record for precious and base metal deposits in the circum-Pacific region in the last 25 years, concluded that geochemistry was a principal discovery technique in about 70% of the discoveries. In a similar manner to the quality regional airborne geophysical surveys, these data sets also provide environmental base line surveys for future land use. It will not always be a good guide to gold mineralisation in covered areas. To rely exclusively on geochemistry in areas of thick cover and weathering is not a wise strategy for future exploration.

Airborne radiometric and hyperspectral remote sensing data sets provide low cost data sets which characterise the regolith in term of mineral and/or vegetation assemblages. Likewise low cost digital elevation models are becoming more available which also assists in regolith characterisation. Such information is useful for planning and interpreting

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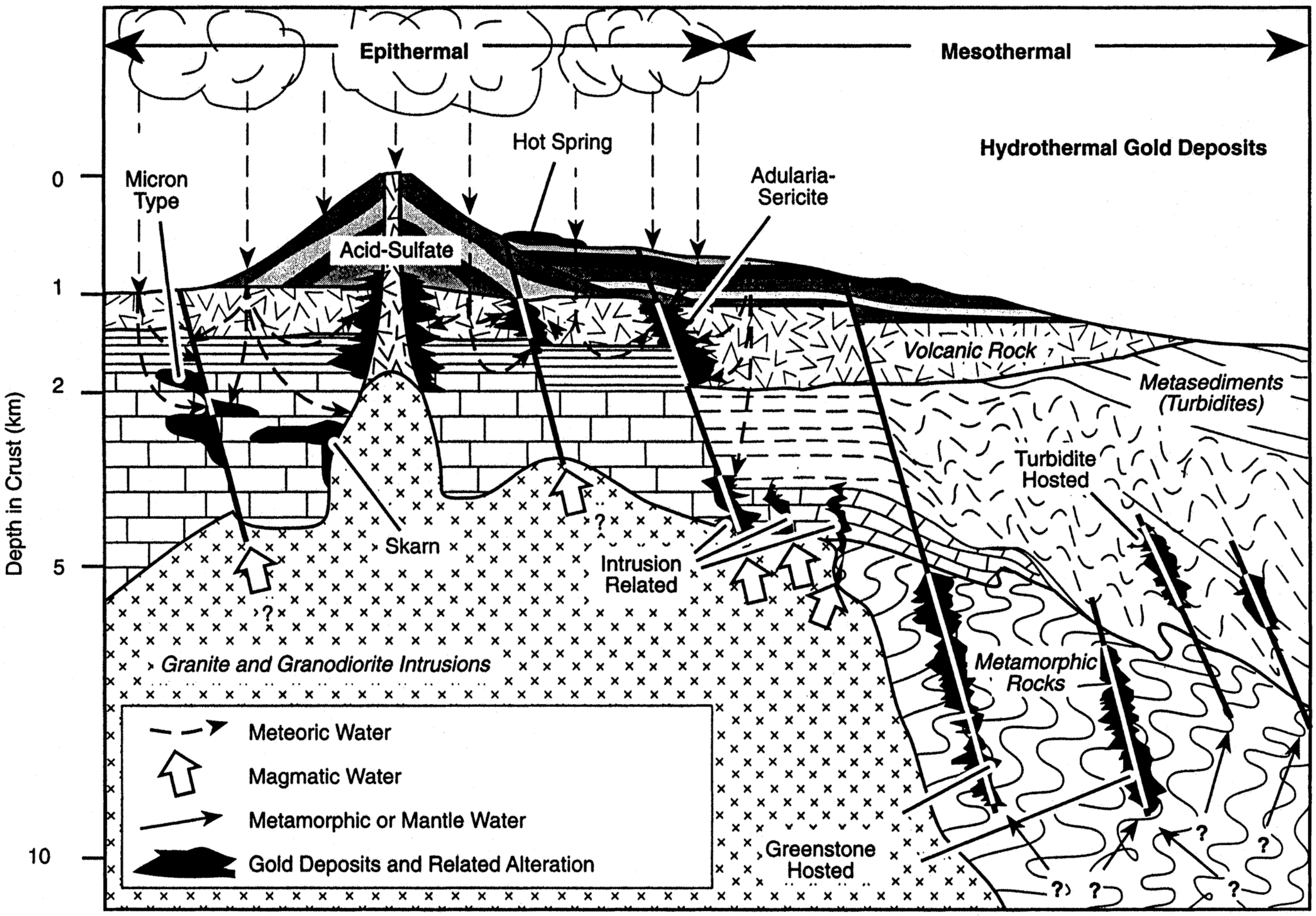

Figure 1: *Depositional environment for hydrothermal gold deposits (modified from Kesler, 1994).*

surface and subsurface geochemistry surveys. The future integration of electromagnetic, magnetic, radiometric and hyperspectral (line scanning) measurements into a fixed wing platform will see vast amounts of data (450–500 data bands) collected in a single flight or pass. Smart methods of extracting information out of these massive data sets efficiently and effectively will be required.

In order to be smarter in the ways that information is extracted from the old and new multisensory data sets, there has to be increased understanding of the petrophysical contrasts which result from geological and geochemical processes that operate in the different mineralised environments. With this last point in mind, this paper will describe the geological context for epithermal, porphyry gold and mesothermal gold systems (Figure 1), before describing the use of geophysics in these systems.

EPITHERMAL AND GEOTHERMAL SYSTEMS

Epithermal gold deposits are a subclass of epigenetic gold deposits, which are thought to form at shallow depths (generally less than 2 km) and at temperature ranges from 50–300°C (Lawless *et al.*, 1994). In the last 10 years there has been considerable achievement in the understanding of processes which give rise to epithermal gold mineralisation. This understanding is derived from wide spread application of fluid inclusion and stable isotope studies, detailed investigations into active hydrothermal systems, considerable amounts of mineral exploration for such deposits and the development of numerical modelling algorithms capable of simulation of geological, geochemical and hydrogeological processes that occur within these systems.

It is now commonly recognised that epithermal systems are the shallow portion of fossil geothermal systems, and that porphyry deposits are representative of the deeper portion of these systems, (Sillitoe, 1989; Allis, 1990; Lawless *et al.*, 1994). Mesothermal systems can be significantly deeper (Figure 1). Epithermal gold mineralisation processes can be observed today in waning geothermal systems and are noted major sources of gold production in Japan (Izawa and Aoki, 1991). The essential components of the epithermal system are the same as those of the geothermal systems. Three additional criteria needed to form an epithermal deposit are relevant metals in solution, a mechanism to focus fluid flow which must be coupled to a mechanism to precipitate the carried metals in a restricted space (Hedenquist, 1997). A distinction has been recognised between low-sulphidation (LS) deposits formed from neutral pH, reduced (H_2S rich) hydrothermal fluids (similar to active geothermal systems) and high sulphidation (HS) deposits formed from highly acidic hydrothermal systems with a relatively oxidised state of sulphur (thought to be similar to active volcanic systems) (Arribas, 1995). A spatial and genetic relationship to porphyry systems and magmatic intrusions has been suggested by some authors, whereby HS deposits occur proximal whilst LS form more distally (Sillitoe, 1989; Arribas, op cit).

Numerous geological articles have been published in the last 10 years which either describe specific deposits (e.g., Rye *et al.*, 1990; Jannas *et al.*, 1990) or provide reviews and overviews of styles of epithermal mineralisation (Sillitoe, op cit, White *et al.*, 1995; Simmonds, 1995; Sillitoe, 1993; Mitchell, 1992; Castor and Weiss, 1992). In stark contrast relatively few papers have been published describing the geophysical expressions of epithermal mineralisation. Notable exceptions are the excellent review articles of Allis (1990) and Irvine and Smith (1990) and the work reported on the Hishikari deposit by Johnson and Fujita (1985), Izawa (1990), Hishida (1990) and Kawasaki *et al.* (1986).

Given the relationship between epithermal and geothermal systems, it is informative to review the literature on the application of geophysics to geothermal exploration, which reveals a far greater number of papers, with far greater emphasis on integrated studies (Wright *et al.*, 1985; Reiter and Jordan, 1996; Lagios and Apostolopoulos, 1995; Smith and Braile, 1994; Zohdy *et al.*, 1973; Bibby *et al.*, 1995; Mogillo and Wood, 1995; Van-Ngoc *et al.*, 1995, Thanassoulas, 1991; Hatherton *et al.*, 1966; McEwen, 1970; Mediao, 1970). Common to both HS and LS epithermal and geothermal systems is the occurrence of clays and clay zonations which are difficult if not impossible to map in the field by inspection. The recently developed Portable Infrared Mineral Analyser (PIMA), has been demonstrated to distinguish different clays in the field, which assists in providing vectors to mineralisation (Pontaul *et al.*, 1995).

GEOTHERMAL PROCESSES, ALTERATION PRODUCTS, AND GEOPHYSICS

The essential elements of a geothermal system are a heat source, a fluid to transfer the heat from the source (to the surface) and permeability path for the fluids to convect through or the heat to conduct via, and a reservoir (or host) rock. After a pluton has intruded, (magma temperatures of 400-1200°C), if permeability is present, it will cool spasmodically (predominantly) by convection, and to a lesser degree by conductive heat loss (Cathles, 1970). Meteoric water descending to the intrusion (depths up to 5 km) will become heated, mixed with any fluids derived from the magma, and rise along the permeable pathways due to its lower density and the thermal gradient resulting from the cool water peripheral to the 'hot column' (Wright *et al.*, 1985). As it rises, the water loses heat, and can return down the outer sides of the hot column, hence setting up a convective cell. The area of upflow of the hot column of a hydrothermal system is a function of topography and can vary from 5–10 km^2, in low relief terranes, to 20–25 km^2 in high relief terranes (Allis, op cit).

The movement of these fluids which are hot, briny and are generally chemically reactive (acidic) cause mineralogical and physical alteration of the host rock. The mineral alteration assemblages and degree of alteration are dependent upon temperature (proximity to magma), fluid composition, host rock lithologies, permeability, pressure and time span of the convective cell (Browne, 1978). At low temperatures (below 225°C) clay minerals, quartz and carbonate are typical alteration products. At high temperatures chlorite, illite, epidote quartz and potassium feldspar are products. Kaolinitic and bentonitic clays are commonly derived from felsic rocks whilst chlorites, serpentine and montmorillonite clays are commonly derived from basic rocks. In addition, extra porosity can be caused by alteration (Thanassoulas, 1991).

Cooling of the system may result in the formation of silica which decreases the permeability and porosity of the rock, creating a seal or cap rock which can act to trap the deeper liquids. Steam and gas may move through this trap to produce a hot upper secondary geothermal reservoir (near neutral pH, sodium bi-carbonate - sulphate water) on top of the cap, leaving a sodium chloride hot (acidic) brine below (Wright, op cit). Outflow of this brine can occur at boiling springs and occur at distances of 10–20 km from the hottest part of the system (Kesler, 1982).

The bulk effect of the hydrothermal system on most country rocks is to lower the apparent resistivity of the rocks (Figure 2). This is achieved through the creation of more conductive clay minerals, the increase of porosity and permeability in the rocks, the introduction of hot saline fluids which are relatively less electrically resistive, and the increase in temperature, which causes an exponential decrease in resistivity (Caldwell *et al.*, 1986). Within the system, more intense alteration is dominated by silicification (formation of quartz and andularia) which greatly increases the apparent resistivity of the rocks.

The effect of the hydrothermal alteration on the magnetisation of country rocks is one of (pervasive?) destruction, with the most common mineral product being iron chlorites (Giggenbach, 1981) and leucoxene (Allis, 1990). Allis (op cit, 1990) has reported a wide magnetic low anomaly in the Taupo Volcanic Zone in New Zealand, which has greater areal extent than the resistivity lows associated with the normal active geothermal areas. These are coincident with non magnetic rhyolite intrusion. Rhyolite domes elsewhere in the system have magnetic high anomalies associated with them. This low is interpreted as magnetite destruction alteration by the associated cooler, CO_2 rich, slightly acidic fluids. A similar phenomena is thought to be responsible for the broad magnetic lows coincident with the Olkavia geothermal system in Kenya (Anderson *et al.*, 1987; Leach and Muchemi, 1987), and the Orakeikorako Wairakei and Ngatamarik geothermal systems in New Zealand (Allis, op cit, 1990). The result of this destruction is evidenced in aeromagnetic surveys as magnetic lows or areas lacking magnetic character (see Henrys and Van Dyck, 1987) The exception being in areas of high topographic relief, (typical in Southeast Asian countries) where the geothermal system has only altered parts of the volcanic edifice. Further complications arise when younger magnetic volcanics are deposited on top of the geothermal system, which is seen in some parts of the Philippines. Magnetite is rarely an alteration product (Heald *et al.*, 1987).

The density of contrasts that are created by a geothermal system are dependent on the density of the host rock and the maturity of the geothermal system. Simplistically, there is an early formation of fracture porosity and clays, followed by flooding of the rock with silica (and calcite) as the system cools, which tends to fill the pores. The effect of the former is to decrease the density of the host rocks (generally volcanics) and that of the latter is generally to increase the density of the rock (relative to the altered porous rock and the process is commonly referred to as densification). In rocks with porosity of as little as 0.3%, silica infilling would increase the density by about 0.3-0.4 kg/m^3 (Allis, op cit). Densification is thought to be the cause of positive gravity anomalies in the Imperial Valley and Salton Trough, California (Elders *et al.*, 1971) and the Broadlands field in New Zealand (Hochstein and Hunt, 1970).

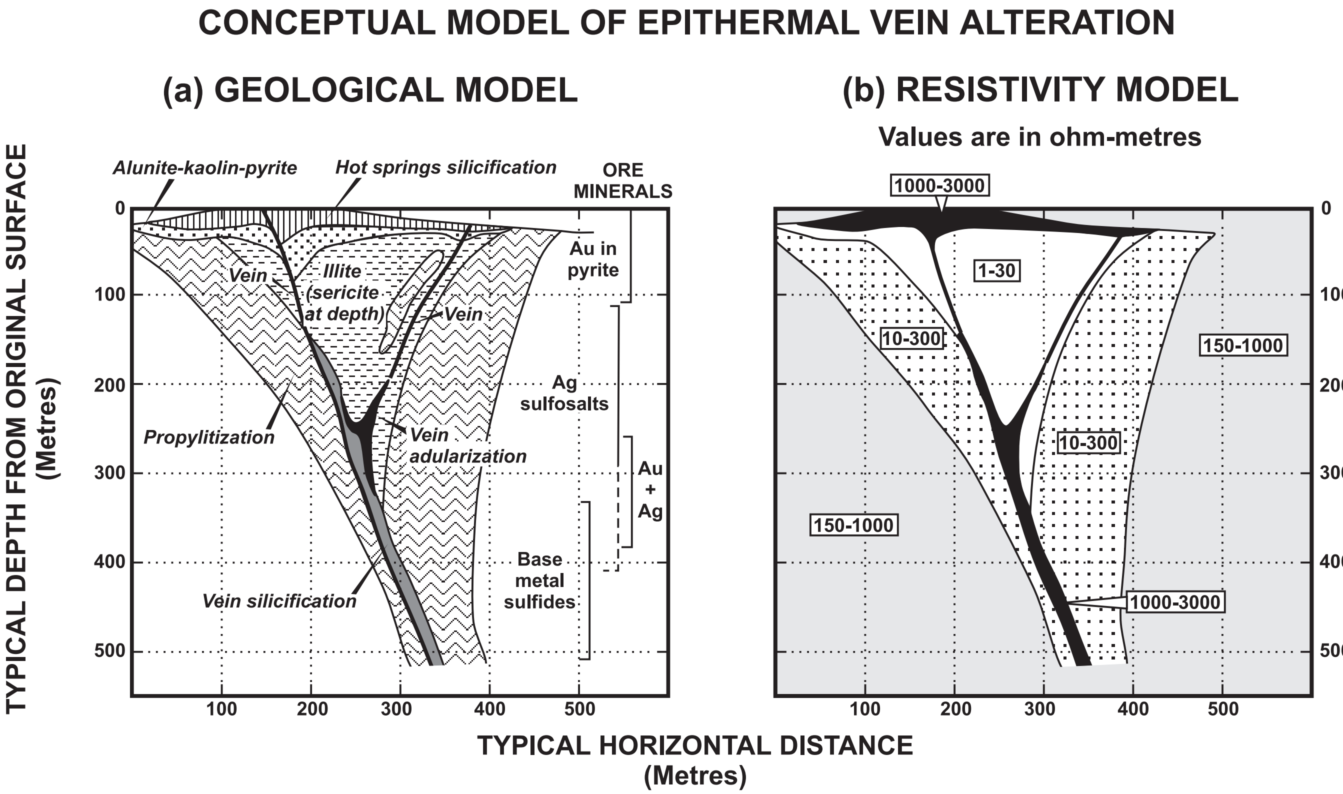

Figure 2: *Schematic illustration of cross-sections of (**a**) a low sulphidation epithermal gold deposit (**b**) electrical resistivity associated with the different alteration types.*

Gravity lows have been observed with some other epithermal systems, such as the Geyser system in California (Delinger and Kovach, 1981) and the Ngawha system in New Zealand (Allis, 1981). To summarise, if the host rocks have relatively high primary porosity and are of low density (e.g., sediments, volcaniclastics) then densification will likely cause a positive density contrast. Hence positive gravity anomalisms will be expected. If the host rocks are dense then a gravity low will be expected from the creation of secondary porosity and silica infilling. This will be enhanced if the host rocks are particularly brittle favouring significant fracturing. Information from gravity surveys has also been used to map rhyolite domes and hydrothermal alteration (McDonald and Muffler, 1972), buried silicic magmas at Mt. Hannah, California (Isherwood, 1976) and the often vertical faults which are commonly encountered in hydrothermal systems (see Edquist, 1976; Ross and Moore, 1985).

EPITHERMAL PROCESSES, PRODUCTS AND GEOPHYSICS

LS epithermal deposits

Examples of LS deposits include the Stockwork form McLaughlin deposit in USA (Buchanan, 1981), Golden Cross in New Zealand (White *et al.*, 1995) and the vein type Hishikari deposit in Japan (Izawa *et al.*, 1990).

The LS deposits form as relatively hot, mildly acidic solutions rise along permeability paths, with accompanying cooling and neutralisation. In this near neutral environment calcite and pyrite have a widespread thermal stability field spanning 40–300°C; adularia, amphiboles, epidote, biotite and illite are stable at temperatures above (approx.) 200°C and smectite, opal and dolomite are stable at temperatures below 200°C, and mainly opal at temperatures below 100°C (Reyes, 1990). Following from these stability fields, it is observed that the principal upflow zones can be dominated by adularia and calcite, and there is progressive change towards the cooler margins which reflects this relative thermal stability of clays. Silica precipitates from these solutions at temperatures less than 300°C as quartz, and then progressively less ordered polymorphs such as chalcedony, cristobalite and finally amorphous silica. Mineralisation is associated with sulphides such as pyrite, sphalerite and chalcopyrite and quartz, adularia and sometimes carbonate (Buchanan, 1981). The form of the alteration system can vary but is typically of mushroom shape, with a significantly wider subhorizontal near surface alteration zone comprising sinter and opaline silica and/or advanced argillic alteration, although the presence/absence of a silica cap today is a function of erosional level.

The stockwork form McLaughlin mine in California, occurs at the thrust faulted contact between serpentinite melange (footwall) and bedded siltstones, mudstones and sandstones. Differential movement at the fault zone produced a permeable cataclasite which focussed fluid flow.

Silica-carbonate-clay alteration is observed in the serpentinite and silicification in the sediments. Pyrite alteration was abundant early, and there is an association of gold with pyrite. Gravity, ground magnetics, seismic and IP surveys were completed over the deposit, with only IP giving anomalism which was indicative of the mineralised system. Apparent resistivity highs indicative of a near surface depth-limited resistive "body" coincides with the silicification and overlying volcanics. An induced polarisation high is coincident in part with the mineralisation but is wider, perhaps reflecting a more widespread pyritisation with/without non economic gold.

The Misima (Western Pacific) LS epithermal mineralisation (also referred to as "Umuna"; Adshead and Appleby, 1996) occurs within the tabular Umuna Fault Zone (UFZ), and overlaps with extensional deformation and potassic-rich magmatism. The mineralisation post dates the magnetite-garnet rich skarn mineralisation ("Boiou"-type), and recent work indicates that these mineralisation styles originated from independent hydrothermal systems (Adshead and Appleby, op cit). The mineralisation occurs continuously over the length of the UFZ, and the line of lode was marked by a discontinuous resistant ridge of massive fine gained silicification including stockwork. The economically significant portions of the UFZ occur in the highly brecciated tabular zone and includes and extends below the above mentioned veins. Deep weathering and oxidation is an important factor in economic viability. The gold is associated with base metal sulphides, and the UFZ is marked by extensive clay alteration beneath the abundant quartz veining. Metamorphic magnetite is invariably destroyed by the alteration, and interestingly graphitic schists within and adjacent to the UFZ are locally extremely carbonaceous, suggesting sporadic graphite enrichment. In the immediate hanging wall of the deposit there is about 200 m thick section of graphite, which appears to permeate through cracks and faults within the larger subvertical fault system (White, pers. comm.). The prerequisites for this style of mineralisation are the more competent and hence brittle deforming (and in part magnetic) Ara schist being in contact with microgranodiorite or extensive zones of vertical permeability (De Keyser, 1961). Magnetic susceptibility measurements and airborne magnetic surveys have possibly mapped the magnetite destruction (formation of leucoxene) of the Ara schist in the north west striking portion of the UFZ, and the east west striking portion of the UFZ as a distinct magnetic linear (Logan, 1989). Airborne radiometric surveys revealed a strong component of variation reflecting vegetation, but principal component analysis reportedly reduced this influence (Logan, op cit), showing potassic high anomalism over parts of the mineralised system.

Airborne magnetic data has provided highly relevant exploration data in epithermal gold exploration in Queensland, Australia. At the Pajingo deposit, Webster and Henley (1989) have reported that the Scott lode (which contains the bulk of the mineralisation) is localised in a dilational site formed by the intersection of an east-west normal fault and north-west transcurrent shears both of which are observable on imagery of airborne magnetic data. At My Leyshen there is a remarkably distinctive magnetic low which is due to remanent magnetisation of the premineralisation magnetite-biotite alteration in the diatreme complex that hosts the LS epithermal mineralisation (Sexton *et al.*, 1995). The remanent magnetisation reflects the Permo-Carboniferous magnetic field reversal which occurred at the time of alteration and allows fast and effective mapping of similar hydrothermal alteration to be accomplished using magnetics. Webster and Henley (op cit) report the recognition of intersecting structures that are observable in airborne magnetic data sets which are interpreted to be responsible for site preparation for the diatreme complex. Airborne radiometric anomalies have mapped potassic alteration at Pajingo and Conway, but not at Wirralie due to transported superficial cover.

Airborne geophysics surveying over the LS vein style Mt. Muro deposit in Kalimantan, has revealed a complex magnetic pattern in which it is difficult to recognise any feature related to mineralisation, although magnetite destruction is commonly noted with the vein systems. However, the radiometric (particularly the potassium channel) data has mapped the alunite alteration associated with some of the known mineralised vein systems surprisingly well despite the great variation of vegetation cover (Moyle, pers. comm.). Similar magnetite destruction has been observed in Waihi, Komata, Karangahake and Golden Cross mining centres in New Zealand (Webster and Henley, 1989), and in the Bimurra and Conway alteration systems in Queensland (Smith and Irvine, 1990).

Geophysical mapping of the vein style epithermal mineralisation system at Golden Cross has been documented by Collins (1989). The mineralisation is hosted in intermediate volcanic rocks, which is unconformably overlain by unmineralised and unaltered andesitic rocks that are up to 60 m thick. Propyllitic alteration is observed over several hundred of metres, which reduce the apparent resistivity of the rock to about 10 ohm-m, and destroy the magnetic texture of the host rock. The more localised argillic alteration has interpreted apparent resistivities as low as 1 ohm-m, whilst the central silicification has high apparent resistivities. Dipole-dipole and gradient array IP, mapped the quartz stockwork (containing 2.3mt of 2.8g/t gold) but gave no clear indication of the deeper richer subvertical feeder zone (containing 3mt of 7.2g/t Ag). The destruction of magnetic texture is observable in aeromagnetic data. The density of the host rock is likely to be of the order of 2.5 g/cm^3, and the volumetrically significant propyllitic alteration is measured to be 2.23 cm^3 (de Ronde, 1985). This alteration is directly mappable on detailed gravity surveys as a 30 um/s^2 low in the Bouguer gravity.

The well documented and understood geophysical responses of the rich vein style epithermal deposits in the Kyushu district of Japan,

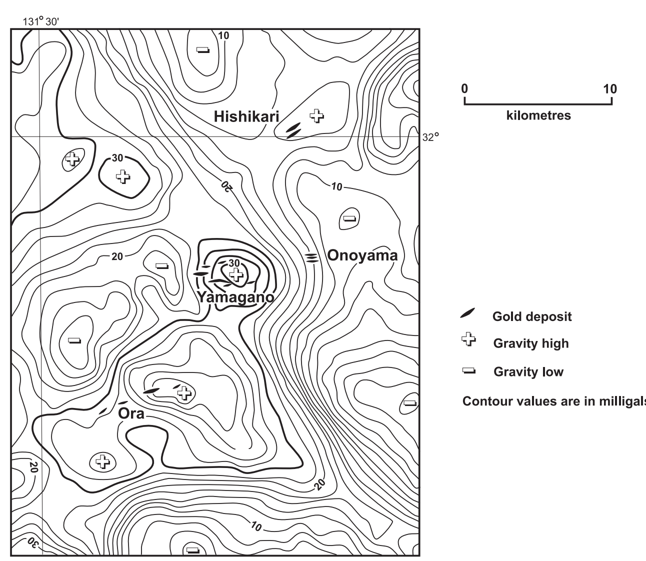

Figure 3: *Bouguer gravity contours over the Kyushu district of Japan (after Kawasaki et al., 1986).*

introduced another important geophysically mappable feature which focuses fluid flow. Most of the quaternary and some Pliocene deposits are coincident with gravity highs (Figure 3), which are readily observable as in raw Bouguer gravity contour maps, or as residuals. The gravity highs result from the discrete uplifting of the denser basement rocks, which has the effect of focussing lateral fluid flow. This is facilitated by an aquatard in the graben structure which inhibits vertical upflow. A similar phenomena is mappable using gravity surveying, in some of the sediment-hosted micron gold deposits in Nevada (Wright, pers. comm.).

HS epithermal deposits

HS epithermal deposits are thought to form following the emplacement of an oxidised intermediate calc-alkaline magma within the top few kilometres of the surface. Hydrothermal fluids derived from the magma are hot, rich involatiles (H_2S, HCI, SO_2), highly saline and increase in acidity as they rise due to early disassociation (Hedenquist, 1997). Hence early alteration involved acidic leaching of the country rock and formation of a core of vuggy and massive silica which is in

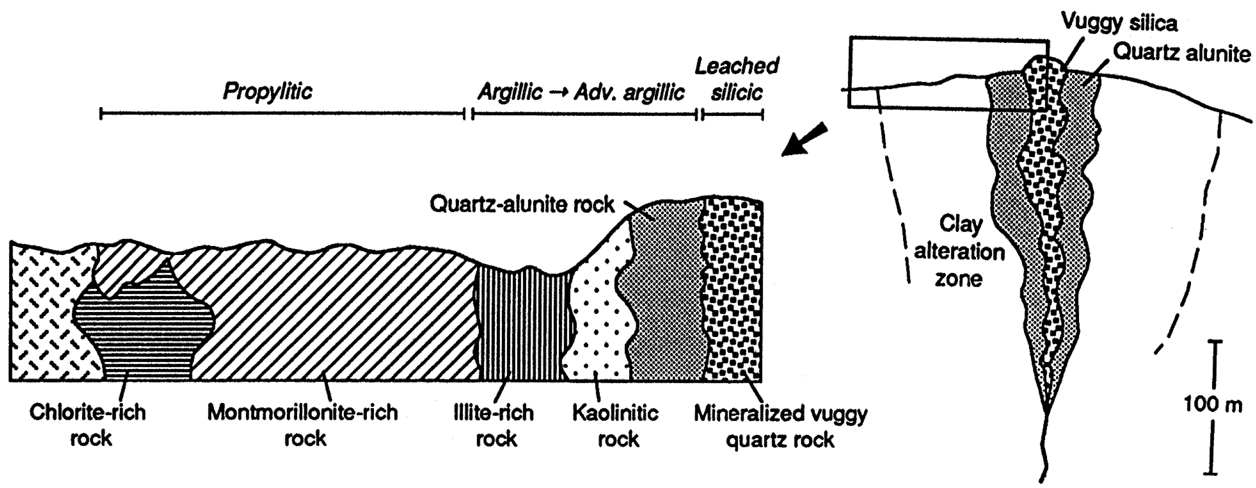

Figure 4: *Characteristic zonation of a high sulphidation epithermal gold vein (after Arribas, 1995).*

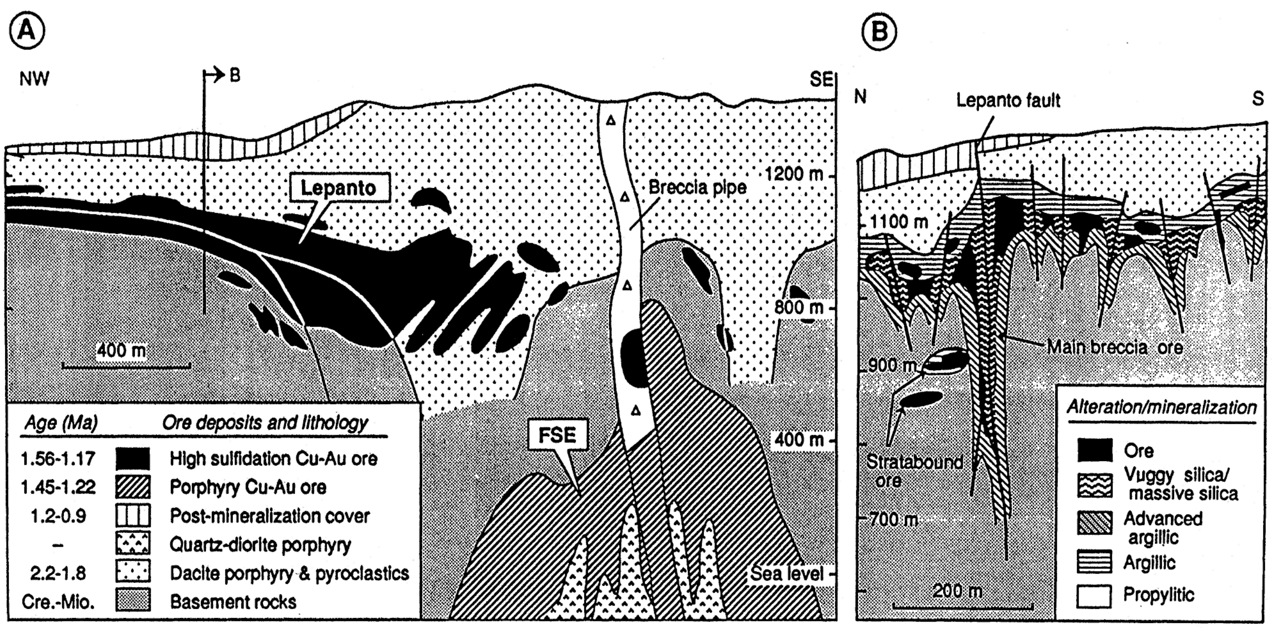

Figure 5: *The Lepanto epithermal gold deposits (Philippines) showing subvertical and subhorizontal controls in mineralisation longitudinal (**a**) and transverse (**b**) sections through the deposit (after Arribas, 1995).*

sharp contact with the advance argillic assemblage of quartz, alunite, kaolinite, dickite and pyrite. This characteristic zoning extends outwards through an argillic and finally propyllitic stage (Figure 4). Ore forming is thought to take place as a later stage alteration which occurs under less acidic, more reducing and cooler conditions. The ore is mostly contained within the vuggy/massive silica. In fact several stages are normally involved, as the systems can be affected by another intrusive event; clogging of the pores and pressure build up and release. Three end members of HS deposits have been recognised.

1. Irregular, disseminated silicified ores, such as Gidginbung, NSW.
2. Cavity filling veins with sericite and clay rich haloes (e.g., El Indio).
3. Characteristic zoned alteration (Figure 4) with a silica core, such as that described above, and seen in the Nansatu deposit in Japan.

The last member is the most common, and results in stratabound and/or subvertical ore geometries (permeability control), which can contain breccia bodies, veins, small vein stockworks and disseminated ores impregnating country rock. The Lepanto deposit in the Philippines is a classic example of the subvertical control, derived from faulting and sub-horizontal control due to permeability along the competency contrast across an unconformity, giving rise to a distinctive mushroom shaped ore distribution (Figure 5).

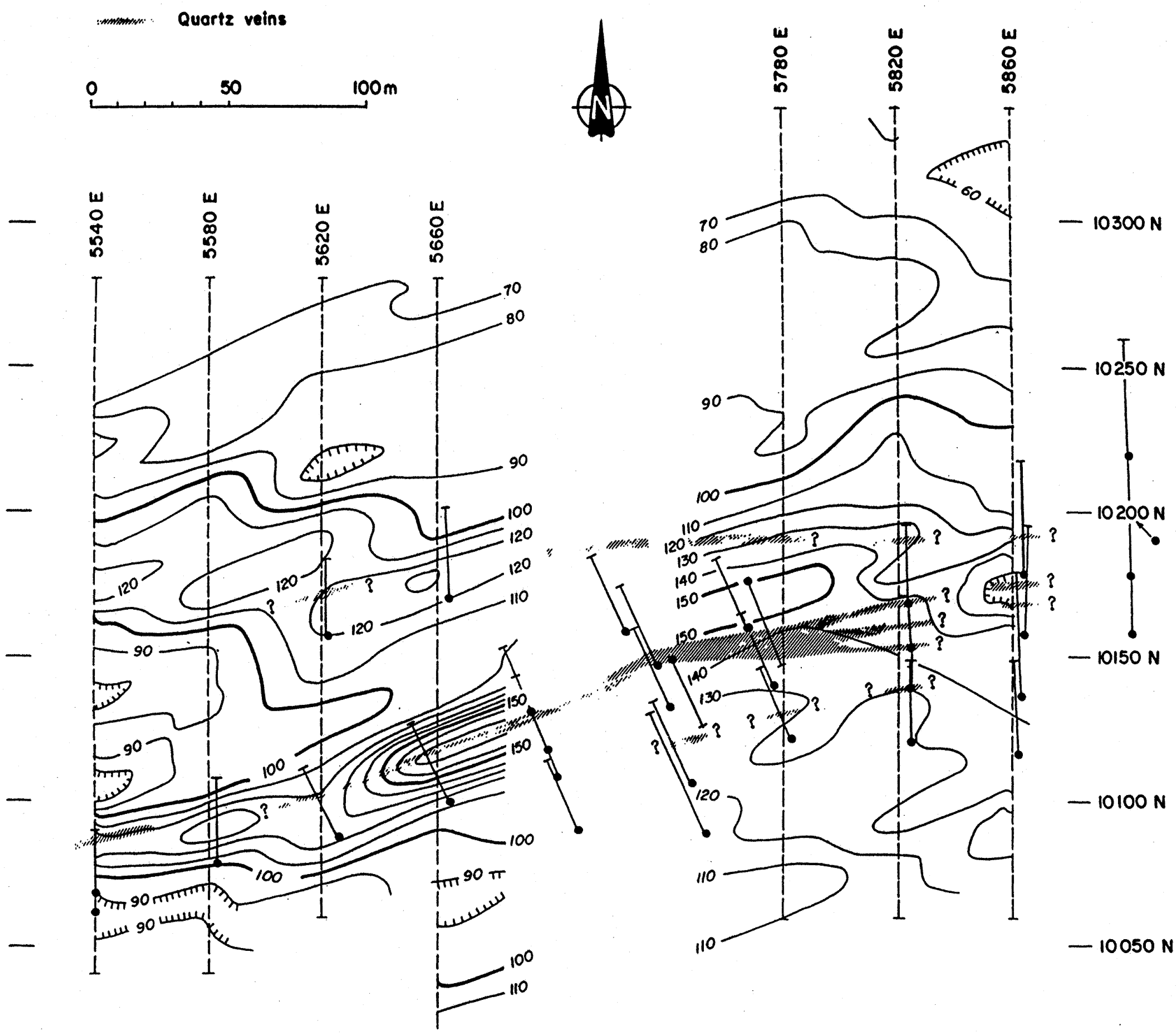

Figure 6: *Inductive source resistivity survey method and results at Mt. Aubrey, NSW (after MacNae and Irvine, 1988).*

MacNae and Irvine (1988) report on two different approaches to map thin (about 5 m thick) auriferous epithermal quartz veins within and under weathered and altered rock (apparent resistivities of 10 ohm-m), in very poor outcrop (but thin transported overburden) conditions, at Mt. Aubrey, NSW. The conventional galvanic gradient array resistivity (GGR) and inductive source resistivity (ISR) methods were used successfully to achieve this result (Figure 5). The ISR measurements were made using a 800 by 600 m loop as the source and the UTEM III system, with its unique saw tooth current waveform. The inductive loop source is a better source for setting up the secondary electric fields beneath relatively more conductive weathered areas, as no galvanic contact is required, the primary electric field is horizontal, its strength (at late times) is independent of the conductivity of the overburden, and in many cases a greater survey area can be measured from one transmitter set up. Topographic effects of the more resistive bedrock surface beneath conductive overburden will be observed in both surveys.

At the Gidginbung deposit near Temora, NSW, a characteristic destruction of magnetic minerals is observable in airborne magnetic data as a loss of magnetic texture in high frequency enhancements of the data. A central core of pervasive silicification occurs over an area of 300 by 100 m, and this core hosts the bulk of the mineralisation. This is surrounded by a much more extensive zone of Advance Argillic alteration, extending outwards, of the order of 100 to 200 m from the core. Propyllitic alteration generally occurs further out, but can occur as patches within the Advanced Argillic. MacNae and Irvine have documented the application of ISR mapping, to successfully map out the silicified zone under relatively thick (up to 100 m) conductive (10 siemen) cover.

IP surveys were used to map the alteration of the Rhyolite Creek epithermal system, Victoria (Irvine and Smith, op cit). The mineralisation occurs within stockwork veins, which contain 10–30% pyrite, and in some instances can be massive over thicknesses of 1 m. This occurs within an upthrust block of Cambrian andesite, dacite and phyllite volcanics. The mineralisation zone coincides with high chargeabilities (50–100 msecs) and low apparent resistivity (10 ohm-m).

The Nena copper-gold resource (32 mt of 2.3% Cu, 0.58g/t Au, 3.6g/t Ag: Hall *et al.*, 1990), in the Frieda River district of Papua New Guinea, occurs on the eastern boundary of 13 × 4 km block of Advanced Argillic alteration, within pyroclastic rocks in an area of 200 × 200 m. The breccia is always silicified, and a zonation of silica/pyrite/alunite/kaolinite has been noted from inner to outer zones. The mineralisation occurs in the pyrite-alunite zone, and the very fine grained pyrite can be massive and/or laminated. The Advanced Argillic alteration is mapped as a magnetic low. The higher grade massive pyrite associated mineralisation is mapped by both electromagnetic and IP surveys (Holzberger *et al.*, 1996).

PORPHYRY RELATED GOLD DEPOSITS

Gold has been recognised as an important byproduct of certain mineralised porphyry systems for at least 20 years (Kesler, 1973). Gold rich porphyry copper systems are thought to represent the shallow end member of a continuum with the deeper end member porphyry copper molybdenum deposits (Cox and Singer, 1988). Gold rich porphyry systems appear to be more commonly associated with alkaline igneous (c.f. calc-alkaline) and form mostly in island arc settings, where the crust is

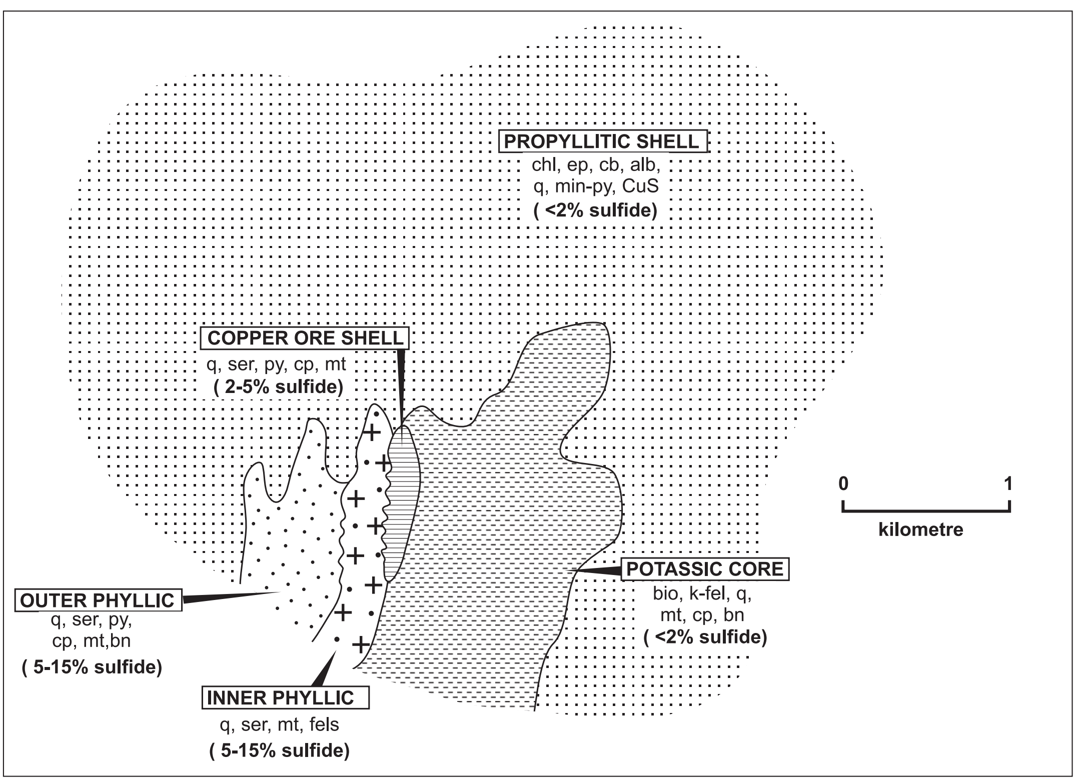

Figure 7: *Mineral alteration zoning in a porphyry gold-copper system.*

thinner and there tends to be less crustal input into the hydrothermal system. Original magmas tend to be oxidised, and the mineralised environments tend to contain reduced rocks. The largest and richest gold rich porphyry copper mineralisation systems are associated with multiphase intrusions, such as Grassberg, Bingham and Panguna.

The development of a porphyry mineralisation system is generally thought to follow the emplacement of a high level intrusive magma, which can be emplaced in areas of dilation or structural weakness. Fluids derived from the magma create additional permeability, and are high temperature (600°C) and very high salinity. Somewhat simplistically, the fluids cool to form a high temperature central potassic core, composed of biotite, k-feldspar, quartz, magnetite, chalcopyrite and bornite (Figure 7). Enveloping this, a lower temperature propyllitic zone is formed, consisting of chlorite, epidote, carbonate, albite, quartz and minor pyrite, with copper sulphides being absent. This basic concentric zonation can be overprinted with phyllic alteration creating a strongly seriticized rock, which can be delimited into an inner zone of quartz, sericite and magnetite, and an outer zone of quartz, sericite, pyrite and chalcopyrite, minus magnetite and bornite.

Generally copper ore grade is associated with the phyllic/potassic core contact. Gold appears to be introduced early and tends to occur in the potassic core. It can also occur late, and this could result in remobilisation of the earlier gold mineralisation. Redistribution of copper ore by supergene enrichment can result in a redistribution of copper ore to form a economically significant, shallow subhorizontal richer cap (0.7–1% Cu) (Titley and Marozas, 1995). Weathering of porphyry copper deposits can result in leached caps which are lower in copper than surrounding rocks, but can be enriched in gold (Learned and Boissen, 1973). Gold has been observed to form small grains along the margins of high temperature minerals, especially bornite (Cuddy and Kesler, 1982). Clark and Arancibia (1995) have argued for a pre-potassic alteration, magnetite rich alteration, suggesting it be recognised as separate M-vein event. The magnetite can occur as both veins and pervasive wall-rock alteration, and reportedly occur in sulphide poor assemblages

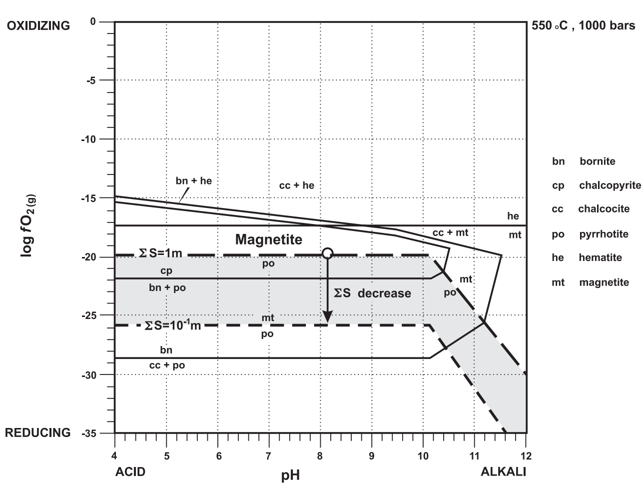

Figure 8: *Schematic illustration of the stability fields of the principal sulphur species at 500°C and 1000 bars pressure.*

which are rich in gold (Kesler, 1997). Magnetite forms preferentially to pyrite in systems with low total sulphide activity (Figure 8) and high oxygen fugacity, and magnetite can coexist with chalcopyrite and/or bornite carrying gold (Kesler, 1997). It is feasible that magnetite can coprecipitate with gold at lower temperatures (250–300°C) from oxidised low total sulphur activity solutions, which would explain late stage gold veining.

Advanced argillic alteration is formed later in some porphyry systems under unusually acidic conditions, and results in such minerals as pyrophyllite, kaolinite, andalusite and alunite, along with pyrite, enargite and tennantite (minus chalcopyrite and bornite) forming a lithocap (Kesler, op cit). This is similar to alteration in HS epithermal gold systems. As a result of this advanced argillic alteration, the copper and gold can be remobilised into the pyrite-chalcopyrite-quartz-magnetite assemblage.

The greatest volume percentage of sulphides is known to occur in the phyllic zones, with 10-15% pyrite and chalcopyrite (Figure 7). The core has a typically lower volume percentage of sulphides, ranging between 3 and 4%. The propyllitic zone has the lowest levels of sulphides, ranging up to 2% (Guilbert and Parth, 1986). The later argillic and advanced argillic alteration tends to reduce the total sulphide content.

The classical picture of porphyry copper deposits as being magnetic lows, is not translatable to porphyry copper-gold systems, as can be easily deduced from the above discussion. In fact the reverse may be nearer the truth for the Island Arc porphyry copper-gold systems. Spectacular dipolar and semicircular magnetic highs are coincident with the Grassberg and Ertzberg (Irian Jaya) igneous complexes (Potter, 1996). At Grassberg, a long wavelength (of the order of 20 km) high amplitude magnetic anomaly (Figure 9) is sourced by the magnetite bearing Kali, Dalam (both 6–7 weight percent magnetite, magnetic susceptibility 4.4 cgsu) and main Grassberg (12 weight percent, magnetic susceptibility 9.8 cgsu) intrusive. Strongly magnetic mineralised skarns also occur adjacent these intrusives, which adds to the complexity and amplitude of the magnetic anomaly pattern. The host rocks consist of weak to non-magnetic sediments and limestones. The Ertzberg complex has a complex anomaly of amplitude between 1200 to 1440 nT. The size of these anomalies and subsequent analysis, convinced Freeport that a regional survey using a line spacing between 800–1600 m was all that was needed to detect similar systems (Potter op cit).

The Dinkidi (Philippines) porphyry copper-gold deposit sits within a large (approximate dimensions, 3 km × 3 km) strongly magnetic dioritic and monzonitic intrusive complex, which contains between 5–7 weight percent magnetite (Garret, 1996). The mineralisation controlling structures are mapped by a combination of topographic features and linear magnetic lows. The main high grade mineralisation occurs in a quartz-calcite-sulphide zone (which rings a core zone which is relatively depleted in sulphides) and a footwall calc-silicate-magnetite skarn. An IP anomaly is coincident with the main mineralisation (Garrett, 1996).

The Mt. Bini (PNG) porphyry copper-gold deposit occurs adjacent to the large (approximate dimensions, 10 × 4 km) magnetic dioritic Bavu Igneous Complex (BIC), which was identified and mapped by a regional aeromagnetic survey (Leamen, 1996). The emplacement of the BIC is thought to be controlled by a structural corridor which is subparallel to the direction of subduction, and also is easily recognisable on regional aeromagnetic and topographic data. The Mt. Bini intrusion occurs on the southeast flank of the BIC, and several stages of alteration and mineralisation have been documented. Magnetite occurs as cross cutting (the potassic alteration) stockwork veins at levels of up to 5 weight percent, as irregular quartz stringers in the phyllic zone, with

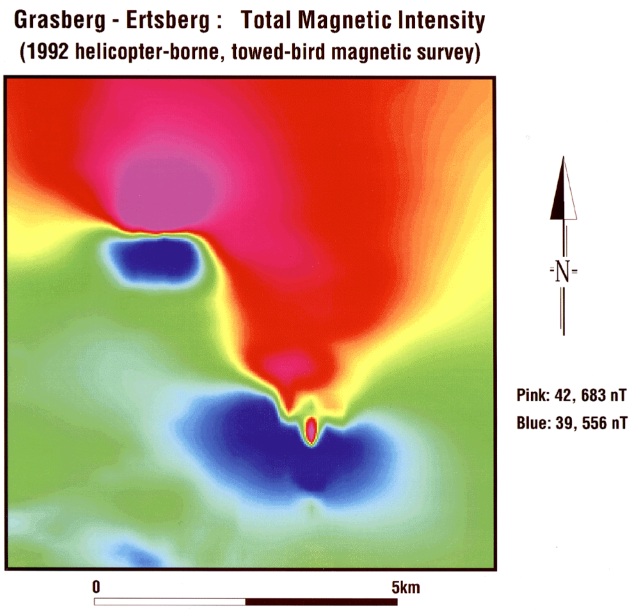

Figure 9: *Airborne magnetic anomalies over the Grassberg and Ertzberg gold-copper porphyry complexes (after Potter, 1996).*

pyrite, chalcopyrite and molybdenite and late stage magnetite-quartz-chalcopyrite veins associated with the later intermediate Argillic and propyllitic alteration. The net result is a coincidence of observed magnetic high anomaly with the mineralisation. The margins of the 0.3% copper contour is defined by the margins of potassic alteration which sits within the area of observed magnetic anomalism.

The Horse/Ivaal and Koki porphyry copper-gold resources occur within the dioritic Frieda River complex. Their locations are controlled by the intersection of northeast trending transfer fault zones (with their local scale equivalents) and west-northwest to northwest trending regional structures that are readily observable in images of regional aeromagnetic data. A characteristic zonation going from central potassic-albite, albite-biotite ± magnetite to quartz/sericite-chlorite to a broad outer propyllitic zone is observed. All of these areas are identified as magnetic highs, which is interpreted to be the result of hydrothermal magnetite (4-5 weight percent) in the potassic alteration zones. They also occur as clear magnetic anomalies on a regional scale (Holzberger *et al.*, 1996).

The Batu Hijau porphyry copper-gold deposit on the island of Sumbawa has a distinctive magnetic anomaly, similar to that noted above. Magnetite is associated with the potassic alteration of the intrusives and the propyllitic alteration of the wallrocks, producing a magnetic high which is coincident with the 0.5% copper contour of the deposit. The high is observable both in ground and airborne magnetic data. A discrete IP anomaly is coincident with the magnetic high and the mineralisation. Interestingly this high is surrounded by a 500 m wide annular shaped low response and then, further out, an annular IP high. This 200 m wide latter response is thought to be due to the outer pyritic halo. Argillic zones and clay weathering along structures show as low apparent resistivities (Maula *et al.*, 1996).

MESOTHERMAL LODE GOLD DEPOSITS

Mesothermal lodge gold deposits, for the purpose of this paper, will be restricted to quartz vein related gold which occur in greenstone belts. Emphasis will be given to those that occur in the Archaean of Western Australia and South Australia.

The gold deposits typically occur proximal to, but rarely within, major or first order faults. The economic gold mineralisation occurs within secondary or lower order faults which are splays off the first order fault (Clout *et al.*, 1990). There appears to be no particular style of kinematic structure that is more favourable, and low mean rock stress is envisaged as focussing fluid flow (Groves *et al.*, 1995). The gold mineralisation can occur within a number of rock types, but more commonly in the more competent rocks with alteration zones commonly enriched in CO_2, S, K, ±Na, ±Ca (Groves *et al.*, 1995). The main gold mineralisation event is thought to occur at a late stage (Groves *et al.*, 1995).

The deposits are envisaged to occur at crustal depths ranging between less than 5 km to about 20 km, from deeply sourced overpressured low salinity fluids. The fluid flow is focussed into zones of low mean stress which is consistent with the observation that the deposits occur in competent (or at the contact of such competent rocks with ductile) units in greenstone belts that are sub-perpendicular to the inferred craton scale late east-west compression.

In greenschist facies, mafic lithologies, a distinctive alteration assemblage has been observed by several authors (Williams, 1985, 1994; Clark, 1987). The geophysical significance of this alteration assemblage lies in the fact that the enveloping magnetite stable alteration can occur in sufficient quantities and thicknesses to give rise to mappable magnetic anomalies, either in borehole, ground and/or airborne magnetic data sets. In the North Orchin and Orion mineralisation systems, the strike of the magnetic anomaly defines the strike of the structure, and the dip of mineralised structure is predicted from mathematical modelling of the observed magnetic response (Figure 9). The discordance of the geometry of the causative magnetic source and the mapped geometry of lithologies allows easy recognition of the anomaly as a mesothermal gold target.

This relationship is seen in different lithologies and in higher grade metamorphic rocks (e.g., Cox deposit in the Agnew Mining District, Western Australia (W.A.), Chalice deposit in the Norseman field of W.A. [Bonwick, pers. comm.]) but not all mesothermal gold deposits in greenstone rocks have this alteration assemblage. The pyrite stable alteration is harder to map in areas of thick regolith, which is a function of the alteration and host rocks having high apparent resistivity and occurring beneath a conductive overburden. This makes penetration of the energising electric fields into the polarisable body difficult, resulting in low signal levels. Further difficulties arise from poor galvanic contact with the ground and a large number of non gold mineralisation related polarisable sources.

Quartz is a resistate mineral in the tropical-arid weathering environment, which is in contrast to the more common pyroxene, hornblende and feldspar minerals that form the bulk of greenstones. These latter minerals readily weather to form clays, with low apparent resistivities (1–10 ohm-m) which in the prospective Archaean areas of Western

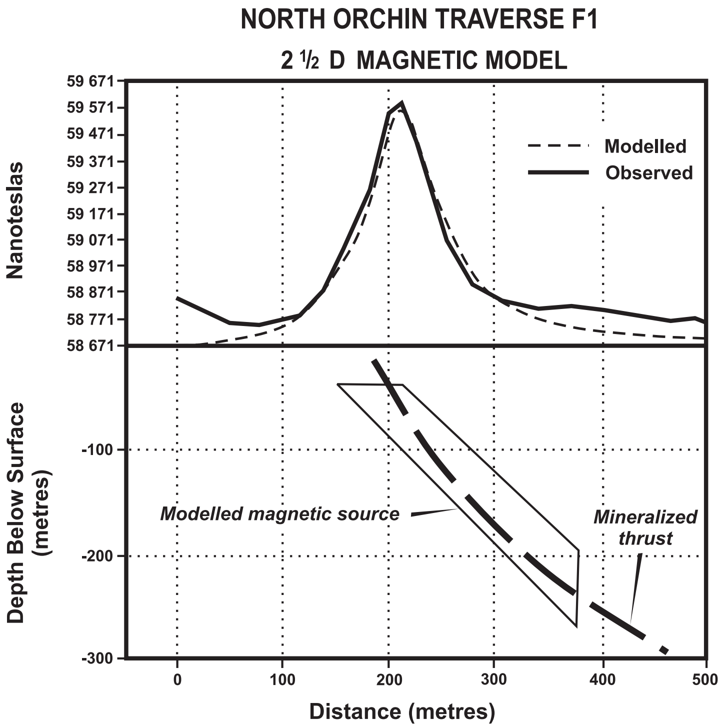

Figure 10: *Expression of the North Orchin and Orion mineralisation in airborne magnetic data (**a**) contour plan (**b**) modelled cross-section (after Williams, 1994).*

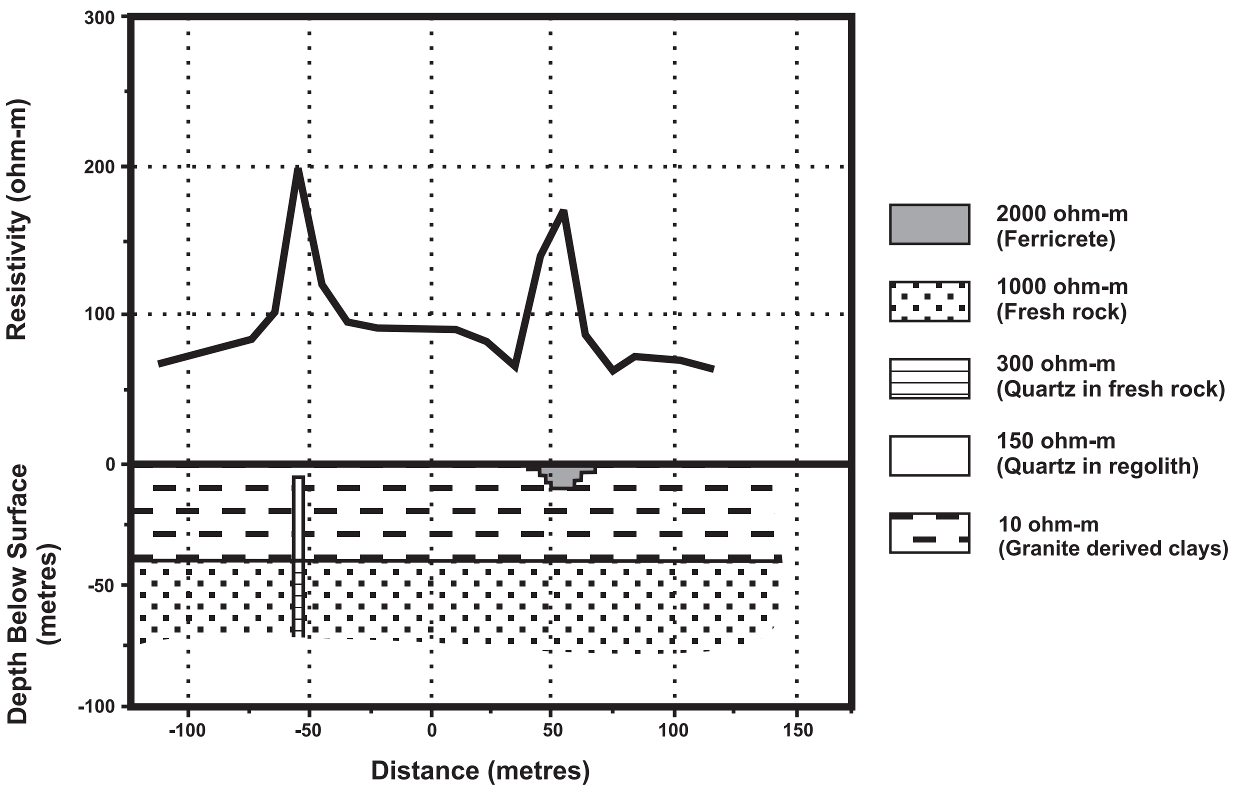

Figure 11: *Electrical geophysical expression of quartz veins in tropical-arid weathering environments (after Williams, 1989).*

Australia range from 30 to 100 m thick. Hence the electrically and physically resistive quartz veins can remain in a 'sea of conductive clay', and hence be detected and mapped by resistivity mapping techniques such as GGR and ISR (Figure 11).

SUMMARY

Successful integrated exploration for hydrothermal gold requires a shared knowledge of relevant geological and geochemical processes, coupled with an understanding of the interplay between mineral products from these processes and petrophysical property contrasts.

Epithermal gold systems are the shallow portions of fossil geothermal systems: the processes tend to result in a decrease in the bulk apparent resistivity of the host rock (due to principally conversion to clay) and a decrease in the bulk magnetisation of the host rock. The change in host rock density is a function of the porosity and degree of silicification. The nature of the gravity anomaly associated with epithermal/geothermal alteration is dependent on the density of the altered rock relative to that of the host rock. Both positive and negative gravity anomalism has been observed. Gravity and magnetics have been useful tools in mapping structuring and predicting areas of fluid flow focussing. On a prospect scale, electrical geophysical techniques have been demonstrated to map electrically resistive auriferous quartz veins.

In some cases airborne radiometrics has been surprisingly successful in mapping some alteration systems, in tropical rain forest conditions.

Intrusion or porphyry related gold/copper-gold mineralisation is noted to occur close to large magnetic (oxidised) intrusions, which are mappable in regional aeromagnetic surveys. Major structures which appear to control these intrusions have also been mapped by airborne magnetic surveys. Magnetite stable alteration has also been mappable in some systems. Pyrite and clay alteration has been mapped using a combination of IP and EM techniques.

The discovery of greenstone belt hosted, mesothermal gold deposits have been predominantly due to geochemical techniques (exp. Western Australia). Airborne magnetics has provided important information on regional and local structural geology and the occurrence of know preferred hosts such as banded iron formations and thick differentiated cholerites. In some cases aeromagnetics has mapped magnetite stable alteration which envelops the relatively thinner auriferous lodes. On a prospect scale, electrical geophysical surveys have been shown to be capable of mapping the physically and electrically resistive auriferous quartz veins in arid weathered terrains.

Surface geological and geochemical surveying have been key discovery techniques for gold exploration in the last two decades. Geophysical surveying has provided valuable supportive information which has allowed important geological elements (structure, intrusions, alteration) to be mapped efficiently. Having a sound knowledge of the 'geological context' of different gold deposits, allied with an understanding of the relationship between geochemical/geological processes and mineralogy/petrophysics will greatly facilitate the efficient and effective integration of the geoscientific disciplines and the optimisation of the exploration process.

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