# Deposit types and paleo-depth extents of Coromandel epithermal Au-Ag deposits

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## Abstract

Known epithermal deposits in the Coromandel region belong to the low-sulphidation type, represented by three subtypes: (1) andesite-hosted epithermal Au-Ag, (2) rhyolite-hosted epithermal Au-Ag, and (3) andesite-hosted polymetallic veins. Paleo-depths for a range of deposits are estimated using various features including: paleo-surface indicators (e.g. sinters), hydrostatic pressures estimated from homogenisation temperature measurements on fluid inclusions, and alteration mineralogy. Paleo-depth estimates to the base of the ore zone for the rhyolite-hosted Coromandel deposits are in the range 200 to 500 m. Andesite-hosted Au-Ag deposits have more variable paleo-depths, and are deeper (up to 950 m) in those deposits with base metals at depth. The majority of Coromandel Au-Ag deposits have limited depth extents (<200 m) of economic grade mineralisation, although Waihi and Karangahake are notable exceptions with depth extents of 575 m and 700 m respectively. Limited depth extents of economic ore are a feature of epithermal systems worldwide and are commonly attributed to gold deposition from boiling fluids. Under hydrostatic conditions in epithermal/geothermal systems, boiling in an up-flowing hydrothermal fluid is controlled by the boiling point for depth (BPD) curve. From fluid inclusion studies of many low-sulphidation epithermal systems, deposition of electrum in economic concentrations appears to be confined to a temperature window of 260 to180$^{o}$C. This means that for dilute, gas-poor fluids that follow the BPD curve, gold deposition is limited to a vertical depth zone of about 400 m, with its upper boundary at about 100 m below the ground surface. The greater depth extent at Waihi and Karangahake, can be explained by mixing of a deep, hot (300$^{o}$C) fluid with cooler (c. 200$^{o}$C) heated ground waters. This has the effect of lowering the 260$^{o}$C isotherm by up to 300 m, thereby increasing the depth range of economic grade gold deposition within the 260 to 180$^{o}$C window of electrum deposition.

## Introduction

Many volcanic-hosted epithermal gold-silver deposits have shallow (<300 m) depth extents, and this is a critical factor in limiting the size of these deposits. The depth extents of epithermal deposits are clearly related to the paleosurface at the time of formation, since the epithermal mineralisation is deposited by hydrothermal waters whose temperature and pressure is controlled by the hydrostatic pressure gradient within the upper 1 to 2 km of the crust (e.g. White and Hedenquist 1990). In geothermal systems, which are present day analogues of epithermal systems, the temperature of the water under hydrostatic conditions is constrained by the fluid vapour pressure existing at a given depth, as represented by the boiling point with depth curve. The upflow zones of geothermal systems have pressure/temperature profiles on or near the "boiling point with depth" (BPD) curve.

Within epithermal deposits, zones of gold-silver ore commonly have sharp lower and upper limits (e.g. Buchanan 1981). These lower and upper limits are generally correlated with a temperature control that may be related to the BPD curve. Seward (1991) determined, with reference to the Rotokawa geothermal system, that adiabatic closed-system boiling from 300$^{o}$C initially increases the solubility of gold as a bisulphide complex, but with continued boiling and loss of $H_2S$ to the steam phase, much of the gold in solution is precipitated over the temperature interval from 250 to 180$^{o}$C. Using reaction path modelling for a Broadlands-Ohaaki deep fluid, Simmons and Browne (2000) confirm that most of the gold in solution is precipitated in boiling from 260 to 180$^{o}$C. Similar temperature windows for gold ore deposition, within a range of 260$^{o}$ to 180$^{o}$C, have been reported from the Waihi deposit (Brathwaite 1999) and other epithermal deposits, such as Hishikari, Japan (Izawa et al. 1990) and Osilo, Sardinia (Simeone and Simmons 1999).

Determination of the paleo-depth (depth below the paleosurface) in epithermal systems, especially in terms of paleo-temperatures of the hydrothermal fluid, is thus a key to locating zones of gold ore within deposits, and to evaluating the potential size of the deposits. The Coromandel Au-Ag province contains a variety of deposits that range from shallow to deep epithermal environments. Here we present data and paleo-depth interpretations for a selection of these.

## Coromandel gold-silver province

The Coromandel gold-silver province (Brathwaite and Pirajno 1993) (Figure 1) contains some 50 epithermal Au-Ag deposits and coincides with the Miocene-Pliocene Coromandel Volcanic Zone (Skinner 1986). Mineralisation is predominantly localised in steeply dipping quartz veins filling extensional fracture systems (Christie and Brathwaite 1986; Brathwaite et al. 1989; Christie et al. 1994). The majority of the quartz veins are hosted by andesite and dacite of the Coromandel Group; rhyolites and basement greywacke are lesser hosts. At some locations (e.g. Neavesville), mineralisation extends from andesite into overlying rhyolitic volcanics and the style of veining changes from relatively thick, continuous veins in andesite to thin stockwork veins in rhyolite (Brathwaite et al. in press).

The quartz veins strike mainly northeast to east and are generally subvertical to steeply dipping, although some relatively gently dipping to flat-lying veins are known. Vein widths are typically between 1 and 5 m, but may range up to 30 m (e.g. Martha vein zone, Waihi). Vein strike lengths are up to c. 800 m, although large, but predominantly only weakly mineralised quartz vein zones at Tokatea Big Reef (Coromandel) and Big Buck Reef (Waiorongomai) have strike lengths of up to 4.5 km. The veins were mined over a vertical interval typically of 170 to 330 m, but ranging up to 700 m at Karangahake and 575 m at Waihi.

Individual deposits occur as vein systems cropping out in areas up to 3 $km^2$ (Waihi and Karangahake) surrounded by areas of up to 14 $km^2$ of hydrothermally altered rocks. Many deposits contain only two or three major, parallel-striking veins. Although the bonanza-style deposits at Coromandel and Thames have a large number of thin veins, which in some places have a wide range of strike directions (e.g. Hauraki deposit at Coromandel).

Two distinct styles of epithermal gold veins have been recognised (Finlayson 1909; Clarke 1991) as: (1) mainly coarse comb or massive quartz, with coarse free electrum, accompanied by quartz-illite-calcite-kaolinite alteration without adularia, and (2) crustiform fine grained quartz, electrum and sulphides, associated with quartz-adularia-illite (sericite) alteration. The bonanza veins at Thames and Coromandel are examples of the first type, whereas Martha Hill (Waihi) and Golden Cross are examples of the second. The deeper levels of the first type are represented by gold-bearing quartz-sulphide veins on the periphery of porphyry intrusives as at the Sylvia and Monowai deposits (Brathwaite and Pirajno 1993; Brathwaite et al. 1998). Corbett and Leach (1998) have classified the first style (epithermal quartz-gold-silver) as the shallowest level of porphyry-related low sulphidation gold systems, where at depth quartz-sulphide-gold±copper veins are transitional to porphyry Cu-Au mineralisation.

## Mineral deposit types and models

The Coromandel epithermal Au-Ag province contains a variety of types or styles of epithermal deposits, and linkages between the type of deposit and depth extent may be expected. Mineral deposit types have been widely used (e.g. Cox and Singer 1986; Eckstrand et al. 1995), to describe the essential geological and geochemical attributes that are common to a number of similar mineral deposits that are presumed to have been formed by the same genetic process. The main attributes used in classifying a mineral deposit type are: tectonic setting, structural controls, host rock lithology, form of the deposit, main economic elements or minerals, mineralogy of ore and host rocks, and geochemical and geophysical characteristics.

Within the broad class of epithermal ore deposits, two styles have been distinguished: low-sulphidation (also known as adularia-sericite) and high-sulphidation (acid-sulphate) (e.g. Hayba et al. 1985; White and Hedenquist 1990; White et al. 1995). The known Coromandel deposits are all low-sulphidation, although advanced argillic alteration characteristic of high-sulphidation deposits has been recognised at Lookout Rocks near Thames (Merchant 1986; Brathwaite et al. 1998) and at Pumpkin Hill near Tairua (Swindale and Hughes 1968).

Sillitoe (1993) subdivided the low-sulphidation type into three subtypes: (1) sulphide (and base-metal-)-rich associated with sub-alkalic rocks, especially of andesitic to rhyodacitic composition (our Andesite-hosted epithermal Au-Ag deposits), (2) sulphide-poor associated with sub-alkalic rocks, especially of rhyolitic composition (our Rhyolite-hosted epithermal Au-Ag deposits), and (3) sulphide-poor associated with alkalic volcanic rocks. The rhyolite subtype mainly differs from the andesite-rhyodacite subtype in having a low sulphide and base-metal content, but these two subtypes are probably transitional into each other. The relatively base-metal sulphide-rich, andesite-rhyodacite subtype may form at greater depths than the rhyolite subtype. Except for the alkalic subtype, these subtypes are well represented in the Coromandel Au-Ag province.

### Andesite-hosted epithermal Au-Ag

**Synonyms:** Adularia-sericite, quartz adularia or low-sulphidation type.

**Equivalent international model:** "Comstock epithermal veins" (Cox and Singer 1986, Model 25c, p. 150). "Epithermal Au-Ag: low-sulphidation" (Lefebure and Höy 1996, Model H05, pp. 41-43).

**Description:** Au+Ag±Zn±Pb±Cu bearing quartz veins, quartz vein stockworks and hydrothermal breccias hosted in andesitic and dacitic volcanics.

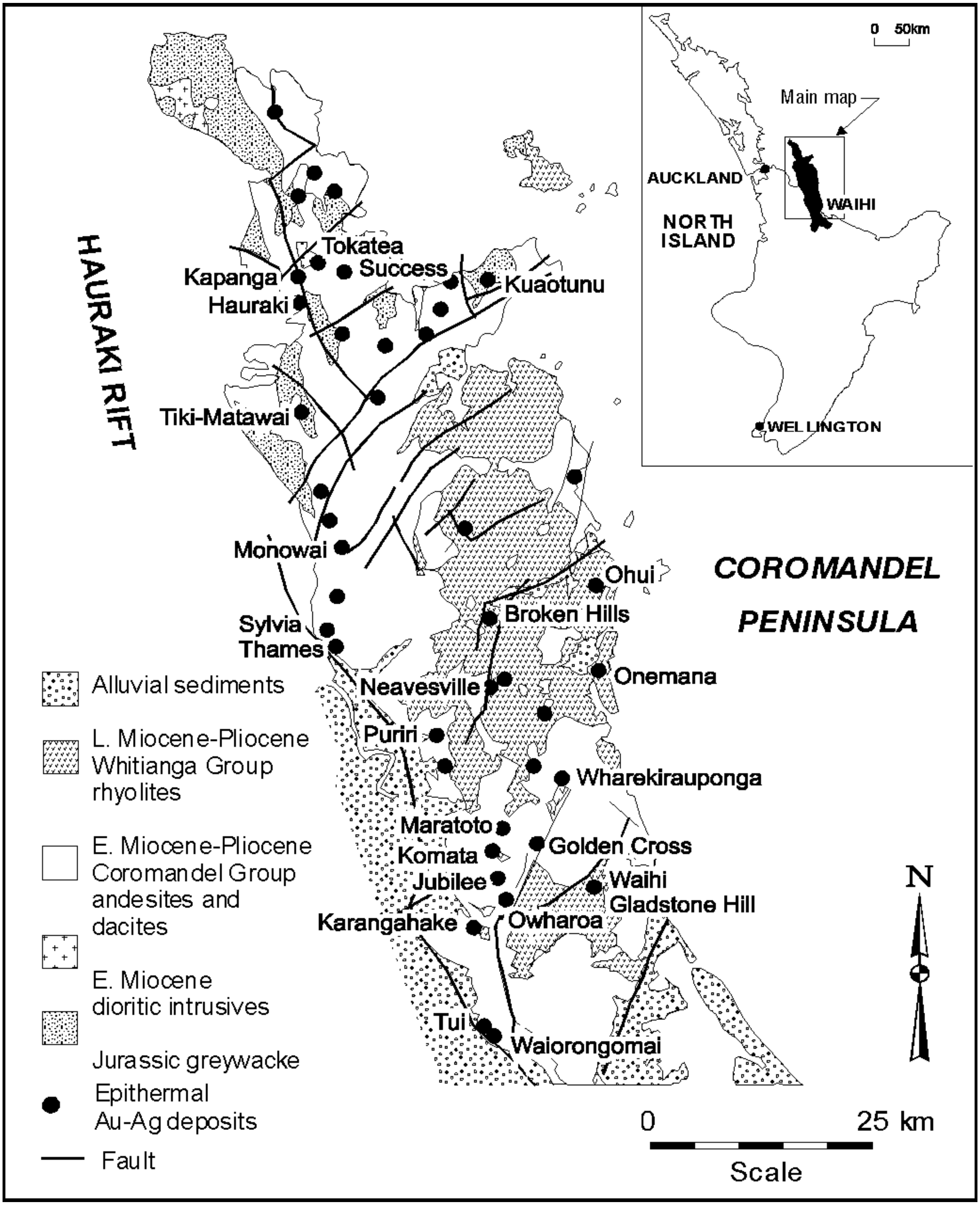

Figure 1. The Coromandel Au-Ag province showing generalised geology and the location of epithermal deposits.

**Main references:** Brathwaite et al. (1989), Brathwaite and McKay (1989), Keall et al. (1993), Mauk et al. (1997), and Simmons et al. 2000.

**Examples:** Waihi, Karangahake and Golden Cross. Overseas examples include Comstock (Nevada), Guanajuato (Mexico - low Au:Ag ratio) and Hishikari (Japan).

**Host rocks:** Andesite and dacitic lavas, breccias and tuffs.

**Mineralogy and texture:** Crustiform quartz-sulphide veins. Main ore minerals are electrum and acanthite with ubiquitous pyrite, and some deposits contain significant sphalerite, galena and chalcopyrite at depth. Quartz and calcite are the main gangue minerals, with Mn-carbonate, adularia and inesite present in some deposits. Bladed quartz and quartz pseudomorphous after calcite are common textures in some veins.

**Alteration:** Quartz-adularia-pyrite ± illite (sericite) adjacent to quartz veins, with propylitic (characterised by chlorite and calcite) and argillic (illite + interstratified illite-smectite + chlorite + pyrite) alteration in outer zones.

**Age:** K-Ar dates for the deposits range from about 14 Ma to 6 Ma and appear to be only slightly younger than the associated andesitic volcanic centres (Brathwaite and Christie 1996).

**Fluid chemistry and source:** Ore deposition at 180 to 260$^{o}$C from low salinity (<2.0 wt% NaCl equiv.), neutral pH fluids of predominantly meteoric origin. Ore with abundant base metals was formed at the higher part of the temperature and salinity ranges. Precipitation was as a result of fluid mixing and boiling.

**Ore controls:** Extensional fault/fracture systems associated with hydrothermal fluid convection driven by cooling subvolcanic intrusives.

**Geochemical signature:** Anomalous Au+Ag±Zn±Pb±Cu±As.

**Geophysical signature:** Magnetic lows associated with hydrothermal alteration. Resistivity highs from zones of silicification and quartz veining.

**Comment:** The past production and mineralogy of these deposits suggests that there are several variants. Many deposits in the Colville and Coromandel areas have prominent arsenopyrite. Deposits in the southern part of the region (e.g. Komata, Golden Cross, Waihi, Karangahake) have significant calcite. Stibnite is present at Thames. Deposits in greywacke basement and Kuaotunu Subgroup andesite and dacite are characterised by high Au:Ag ratios (1.8) compared with deposits in Waiwawa Subgroup andesite and dacite (average Au:Ag = 0.25) (Brathwaite et al. 1989).

## Rhyolite-hosted epithermal Au-Ag

**Synonyms:** Hot spring Au-Ag deposits.

**Equivalent international model:** "Hot-spring Au-Ag" (Cox and Singer 1986, Model 25a, p. 143-144). "Hot-spring Au-Ag" (Lefebure and Höy 1996, Model H03, pp. 33-35).

**Description:** Au-Ag bearing quartz veins, quartz vein stockworks and hydrothermal breccias hosted in rhyolitic volcanics. These deposits are associated with rhyolitic volcanic centres of the Minden Rhyolite subgroup of the Whitianga Group.

**Main references:** Brathwaite et al. (1989), Rabone et al. (1989) and Brathwaite (1996).

**Examples:** Broken Hills, Wharekirauponga and Komata. Overseas examples include McLaughlin (California), Round Mountain (Nevada) and Delamar (Idaho).

**Host rocks:** Rhyolite flows and associated pyroclastic breccias and tuffs. Overseas examples may be hosted in bimodal basalt-rhyolite suites.

**Mineralogy and texture:** Electrum, acanthite and pyrite in chalcedonic and vuggy quartz veins.

**Alteration:** Classic quartz-adularia alteration, accompanied by or associated with pyrite + chlorite (propylitic alteration), and illite + illite-smectite + pyrite ± kaolinite (argillic alteration).

**Age:** K-Ar ages for the deposits range from 9 Ma to 5 Ma, as for the associated rhyolitic volcanic centres.

**Fluid chemistry and source:** Ore deposition at 180 to 250$^{o}$C from very low salinity (<0.5 wt% NaCl equiv.), neutral pH fluids of predominantly meteoric origin. Precipitation was as a result of boiling and fluid mixing.

**Ore controls:** Extensional fault/fracture systems associated with hydrothermal fluid convection driven by cooling subvolcanic intrusives. Some deposits may be localised along faults related to caldera subsidence.

**Surface expression:** Zones of thin quartz veins and associated silicification, sinters and hydrothermal breccias.

**Geochemical signature:** Anomalous Au+Ag±As±Sb±Hg.

**Geophysical signature:** Magnetic lows associated with hydrothermal alteration. Resistivity highs from zones of silicification.

**Comment:** There are indications of disseminated low grade, large tonnage deposits at Broken Hills, Neavesville and Wharekirauponga that could be economic if they were located in a region where heap leaching of low grade Au-Ag ore was possible (Brathwaite 1996).

## High-sulphidation quartz-alunite epithermal Au

**Synonyms:** Acid-sulphate.

**Equivalent international model:** "Epithermal quartz-alunite Au" (Cox and Singer 1986, Model 25e, p. 158). "Epithermal Au-Ag-Cu: high-sulphidation" (Lefebure and Höy 1996, Model H04, pp. 37-39).

**Description:** Au±Cu±Ag bearing, fine grained replacement quartz and hydrothermal breccias hosted in andesitic and dacitic volcanics.

**Main references:** Merchant (1986), Brathwaite et al. (1989) and Brathwaite et al. (1998).

**Examples:** None known in the Coromandel region, but similar geological environments are present at Lookout Rocks and Pumpkin Hill. Overseas examples include Summitville in Colorado, Nansatsu in Japan, El Indio in Chile, Temora in New South Wales, Yanacocha in Peru and Lepanto in the Philippines.

**Host rocks:** Andesite and dacite lavas, breccias and tuffs associated with dacitic porphyry intrusives.

**Mineralogy and texture:** Gold and pyrite, with enargite, tetrahedrite, chalcocite, covellite and bornite. Commonly associated with vuggy quartz.

**Alteration:** Advanced argillic alteration characterised by quartz-alunite proximal to ore, with pyrophyllite at deeper levels and gibbsite in outer alteration zones.

**Age:** Alunite at Lookout Rocks is K-Ar dated at 11.2 Ma (Brathwaite et al. 1998).

**Fluid chemistry and source:** Advanced argillic alteration produced by highly acid, vapour-rich fluids at 200 to 300°C that were derived from a magmatic vapour phase. Precipitation was as a result of fluid mixing.

**Ore controls:** Extensional fault/fracture systems as pathways for a magmatic vapour-rich phase.

**Geochemical signature:** Anomalous Au+Cu±As.

**Geophysical signature:** Magnetic lows associated with advanced argillic alteration.

**Comment:** No examples of these deposits are known in the Coromandel region, but the characteristic style of alteration associated with these deposits is present in Coromandel Group rocks at Lookout Rocks, Pumpkin Hill and Black Jack (Kuaotunu), and may be undiscovered elsewhere in Coromandel Group rocks (e.g. buried beneath cover rocks).

## Andesite-hosted polymetallic veins

**Equivalent international model:** "Polymetallic veins" (Cox and Singer 1986, Model 22c, p. 125). "Polymetallic veins Ag-Pb-Zn±Au" (Lefebure and Höy 1996 Model H05, p. 67-70). There are also some similarities to "Creede epithermal veins" (Cox and Singer 1986, Model 25b, p. 145).

**Main references:** Weissberg and Wodzicki (1970), Robinson (1974), Merchant (1986), Brathwaite et al. (1989) and Brathwaite et al. (1998).

**Description:** Zn±Pb±Cu±Ag+Au bearing quartz veins hosted in andesitic and dacitic volcanics adjacent to mineralised porphyry stocks.

**Examples:** Sylvia, Monowai, Tui and Waiorongomai.

**Host rocks:** Andesite and dacitic lavas, breccias and tuffs.

**Mineralogy and texture:** Massive and banded quartz-sulphide veins. Main ore minerals are sphalerite, galena, chalcopyrite and tetrahedrite, with minor gold and hessite, and ubiquitous pyrite. Quartz, calcite and anhydrite are the main gangue minerals.

**Alteration:** Quartz-illite-pyrite adjacent to quartz veins, with propylitic (characterised by chlorite and calcite) and argillic (illite + interstratified illite-smectite + chlorite + pyrite) in outer alteration zones.

**Age:** K-Ar ages of the host volcanic rocks are in the range of 12 Ma to 7 Ma.

**Fluid chemistry and source:** Ore deposition at 250 to 320°C from low salinity (<4 wt% NaCl equiv.), slightly acid pH fluids of predominantly meteoric origin. Precipitation as a result of fluid mixing.

**Ore controls:** Extensional fault/fracture systems associated with hydrothermal fluid convection driven by cooling subvolcanic intrusives.

**Geochemical signature:** Anomalous Zn±Pb±Cu±Ag±Au.

**Geophysical signature:** Magnetic lows associated with hydrothermal alteration.

**Comment:** Andesite-hosted polymetallic veins are separated from Andesite-hosted epithermal Au-Ag deposits by their higher base metal content, deeper level of deposition and the higher temperature and salinity of their parent ore fluids.

# Paleosurface indicators

In shallow epithermal environments, evidence may be preserved of the original paleosurface in the form of sinters, hydrothermal eruption breccias, or lake sediments. However, it is often not clear if these features were contemporaneous with and related to the hydrothermal system that formed an individual epithermal ore deposit. Also, silicified sedimentary or volcanic rocks have frequently been miss-identified as sinters in the literature.

For the Coromandel data set, definite sinters have been found near the Broken Hills deposit, and at Ohui and Onemana (Table 1). At Gladstone Hill, recent exploration has identified hydrothermal eruption breccias that fill vent structures (S. Rabone, pers. com. 1998; Weedon, 1999). These vent breccias are overlain by an eruption breccia tuff ring and by sedimentary deposits that fill the eruption crater.

| Deposit | Deposit subtype | Paleosurface indicator | Ore minerals | Zonation with depth | Vertical extent of ore (m) | Paleodepth to base of ore (m) | General depth level |
|---|---|---|---|---|---|---|---|
| Kapanga | Andesite | n | py,el,(aspy,marc, pyrarg,As) |  | 137 | - | S – M |
| Tokatea | Andesite | n | py,el,(hes,sp,gn,cp) | base metals at depth? | 330 | - | M |
| Success | Andesite | n | py,el,(hes,sp,gn,cp) | base metals at depth? | 80 | - | M |
| Hauraki | Andesite | n | py,el,(aspy,sb, marc, pyrarg,As) | shallow sb | 120 | - | S - M |
| Kuaotunu | Andesite | sinter? | py,el,(py,po,sp,gn) |  | 155 | - | S |
| Tiki-Matawai | Andesite | n | py,el,(sp,cp,gn) |  | <50 | - | M |
| Monowai | Polymetallic | n | py,gn,sp,cp,el | base metal-rich | 300 | - | D |
| Sylvia | Polymetallic | n | py,sp,gn,cp,gold,anhy | base metal-rich | 135 | ~800 | D |
| Thames | Andesite | n | py,pyrarg,el,sb,ba, (cp,sp, gn, td, tel) | shallow sb & ba | 150 | ~500 | S - M |
| Broken Hills | Rhyolite | sinter | py,marc,el,ac, (Au-Ag-As-Se s'salts) |  | 170 | ~480 | S - M |
| Ohui | Rhyolite | sinter | py,el |  | <50 | - | S |
| Onemana | Rhyolite | sinter | py,ac,gold,el, (sp, gn,cp) | base metals at depth | >150 | ~200 | S |
| Neavesville | Rhyolite | eruption breccias | py,marc,el,ac,adl, (mo,sp,gn,cp) | base metals at depth | 150 | ~500 | S - M |
| Puriri | Andesite | n | py,ac,el |  | 30 | ~200 | S |
| Wharekirau-ponga | Rhyolite |  | py,el |  | - | - | S - M |
| Maratoto | Andesite | n | py,marc,gn,sp,cp, ac,hes,el |  | 100 | 550-800 | M - D |
| Golden Cross | Andesite | n | py,marc,el,ac,adl, (polybasite,pyrarg) | calcite at depth | 190 | ~350 | S |
| Komata | Rhyolite | n | py,ac,el,adl,(sp,gn,cp) |  | 200 | - | M |
| Jubilee | Andesite | n | py,gn,sp,cp,el |  | 185 | - | M - D |
| Owharoa | Rhyolite | n | py,marc,ac,el |  | 100 | - | S - M |
| Karangahake | Andesite | n | py,ac,el,sp,gn,cp | base metals at depth | 700 | ~900 | S - D |
| Waihi | Andesite | n | py,ac,el,sp,gn,cp, adl | base metals at depth | 575 | 745 | M - D |
| Gladstone Hill | Andesite | eruption breccias | py,ac,el |  | ~230 | 330-400 | S - M |
| Tui | Polymetallic | n | sp,gn,cp,py,(bis,td,gold) | base metal-rich | 260 | ~850 | D |
| Waiorongomai | Polymetallic | n | py,cp,sp,gn,el,(td, hes) | base metal-rich | 80 | ~950 | D |

n = not present, y = present, - = no data, ac = acanthite, adl = adularia, anhy = anhydrite, As = native arsenic, aspy = arsenopyrite, ba = barite, bis = bismuthinite, cp = chalcopyrite, el = electrum, gn = galena, hes = hessite, marc = marcasite, mo = molybdenite, py = pyrite, pyrarg = pyrargyrite, sb = stibnite, sp = sphalerite, s'salts = sulphosalts, tel = tellurides, td = tetrahedrite. S = shallow, M = medium, D = deep.

Table 1. Ore zones and paleo-depths in some Coromandel epithermal deposits

## Hydrothermal alteration

Hydrothermal mineral assemblages are indicators of the temperature range and fluid conditions in geothermal systems (e.g. Reyes 1990). Specific mineral assemblages are diagnostic of distinct fluid types that, when integrated with other data, provide broad indicators of depth levels, boiling and mixing zones. At shallow depths and on the margins of geothermal systems, alteration by steam-heated waters produces an argillic illite-smectite-calcite±kaolinite assemblage (e.g. Simmons and Browne 2000). Smectite dominates at <150°C and illite dominates at >220°C. These clay mineral indicator assemblages are listed for a selection of Coromandel epithermal deposits in Table 2.

## Boiling indicators

A variety of mineral indicators are considered to be diagnostic of boiling conditions in epithermal environments. These include: co-existing vapour- and liquid-rich fluid inclusions, adularia, platy calcite, hydraulic fracture vein breccias, and steam condensate argillic alteration (illite/smectite, calcite, kaolinite).

### Fluid inclusion boiling point with depth profiles

Under hydrostatic conditions that prevail in fracture systems open to the ground surface, as in epithermal/geothermal systems, boiling in an up-flowing hydrothermal fluid is controlled by the BPD curve. Fluid inclusion homogenisation temperatures, particularly where there is evidence of boiling conditions from co-existing vapour- and liquid-rich inclusions, are used to determine the hydrostatic pressure and hence the depth below the surface. Fluid inclusion data for a selection of Coromandel epithermal deposits are summarised in Table 2.

Where a fluid inclusion data set over reasonable depth range is available, modal or mean homogenisation temperatures for the different sample depths can be fitted to a BPD curve. The salinity and $CO_2$ content of the water has an effect on the BPD curve (Haas 1971; Hedenquist and Henley 1985), but for dilute and relatively shallow fluids, the BPD curve for pure water is a reasonable approximation. As an example, Figure 2 shows the BPD curve fitted to fluid inclusion homogenisation data for the Neavesville epithermal Au-Ag deposit. The apparent salinities of the fluid inclusions are low, generally <0.3 wt% NaCl equivalent, and $CO_2$ is also inferred to be low. The data are from several different prospects within the Neavesville area, and the uncertainty in fitting groups of temperature data points to the curve may be due to post-mineral fault displacements. This “best fit” plot indicates that the ore zone, as mined in the Ajax no. 2 level, was located at about 400 m below the paleo-water table.

In many low-sulphidation epithermal systems, deposition of electrum in economic concentrations appears to be confined to a temperature window of 260 to180°C. This means that for dilute, gas-poor fluids that follow the BPD curve, gold deposition is limited to a vertical depth zone of about 400 m, with its upper boundary at about 100 m below the ground surface.

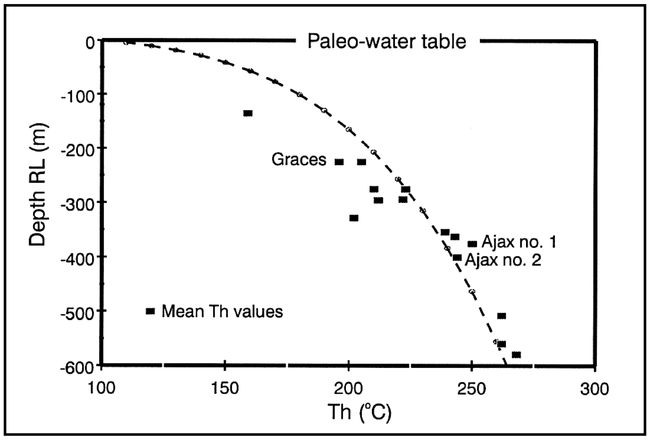

Figure 2. Fluid inclusion homogenisation temperatures (Th) for vein quartz samples versus depth from the Neavesville Au-Ag deposit, in relation to the BPD curve (dashed) for pure water. Graces and Ajax samples are from old mine workings; most other samples are from drill holes.

## Depth extent of economic ore

The vertical extent over which ore was mined in historic underground mining operations provides a measure of the depth extent of economic ore in Coromandel gold-silver deposits. This data, as extracted from Fraser and Adams (1907), Fraser (1910), Bell and Fraser (1912), Henderson and Bartrum (1913) and Downey (1935), is presented in Table 1. Separate mining claims have been grouped to make up individual deposits, as previously described by Brathwaite (1981).

The majority of the deposits have ore zones with depth extents of less than 200 m, including significant producers such as Kapanga, Hauraki, Kuaotunu, Sylvia, Thames, Komata and Golden Cross. Since most of the ore zones crop out at the surface, part of the original ore zone has likely been eroded and for many deposits these are minimum depth extents. Waihi and Karangahake are notable exceptions with depth extents of 575 m and 700 m respectively.

Some ore zones show transitions at depth into Au-poor base metal sulphides (sphalerite, galena and chalcopyrite). This deep base metal sulphide mineralisation was probably deposited at a higher temperature (260-320°C) than the overlying ore zone. For example at Waihi, electrum-base metal sulphide ore deposited at 190 to 255°C passes down into electrum-barren base metal sulphides that were deposited at 255 to >300°C (Brathwaite 1999). In other deposits, notably Golden Cross, the ore-bearing quartz vein diminishes rapidly in thickness at depth, with no significant change in ore mineralogy.

In the historic mining literature, ore zones are commonly described or shown on mine longitudinal projections as having flat-lying bases. As noted by Buchanan (1981) and others,

| Deposit | Alteration minerals | Fluid inclusions | | | References |
|---|---|---|---|---|---|
| | | Vapour-rich[1] | Th °C | Salinity | |
| Kapanga | ill | - | - | - | Fraser & Adams 1907; Downey 1935 |
| Tokatea | ill | n | 200-260 | 0.5-4 | Fraser & Adams 1907; Downey 1935; Christie 1982 |
| Success | ill | - | - | - | Fraser & Adams 1907; Downey 1935 |
| Hauraki | ill-sm, kaol | - | - | - | Fraser & Adams 1907; Downey 1935; Robson & Stevens 1993 |
| Kuaotunu | ill-sm, kaol | n | 220-270 | - | Fraser & Adams 1907; Downey 1935; Parkinson 1980; Christie 1982 |
| Tiki-Matawai | ill-sm, kaol | - | - | - | Fraser & Adams 1907; Downey 1935; Robson & Stevens 1993 |
| Monowai | ill | - | - | - | Downey 1935; Roberts 1989 |
| Sylvia | Ill-sm-cc | n | 250-320 | 1-3 | Downey 1935; Brathwaite et al. 1998 |
| Thames | ill-sm-cc | n | 200-240 | - | Fraser 1910; Downey; 1935; Merchant 1978 |
| Broken Hills | adl-ill | y | 200-250 | 0.3-2 | Bell & Fraser 1912; Moore 1979; Christie 1982 |
| Ohui | adl-ill | - | - | - | Bell & Fraser 1912; Merchant et al. 1988 |
| Onemana | adl-ill, kaol | - | - | - | Robson & Stevens 1991; Brathwaite & Boswell 1997 |
| Neavesville | adl-ill | y | 195-250 | 0.1-0.9 | Downey 1935; Barker et al. 1980; Christie 1982; Brathwaite unpub. |
| Puriri | ill-sm | y | 207-218 | - | Downey 1935; Torckler 1989 |
| Wharekiraupонga | adl-ill | y | 180-250 | 0.2-0.9 | Rabone et al. 1989; Moore 1985; Christie unpub. |
| Maratoto | adl-ill | y | 220-300 | 0-3 | Bell & Fraser 1912; Main 1979; Christie 1982 |
| Golden Cross | adl-ill | y | 170-220 | 0-2 | Bell & Fraser 1912; Keall et al. 1993; Simmons et al. 2000; Simpson et al. in press |
| Komata | adl-ill | y | 235-265 | 0.5-3.5 | Bell & Fraser 1912; Christie 1982; Wayper 1988 |
| Jubilee | adl-ill | - | - | - | Bell & Fraser 1912; Rabone 1975 |
| Owharoa | adl-ill | - | - | - | Bell & Fraser 1912; Rabone 1975 |
| Karangahake | adl-ill | n | 230-280 | 0.7-3.2 | Henderson & Bartrum 1913; Christie 1982; Brathwaite 1989 |
| Waihi | adl-ill | y | 190-255 | 0.3-1.7 | Bell & Fraser 1912; Christie 1982; Brathwaite & McKay 1989; Brathwaite 1999 |
| Gladstone Hill | adl-ill | y | 200-250 | 0.1-0.5 | Oldfield 1990; Weedon 1999 |
| Tui | adl-ill | n | 280-310 | 1-6 | Robinson 1974; Christie 1982; Bates 1989 |
| Waiorongomai | ill | y | 230-280 | 1-4 | Cartwright 1982; Christie 1982; Bates 1989 |

n = not present, y = present, - = no data, [1] = apparent salinity (wt% NaCl equivalent), adl = adularia, cc = calcite, ill = illite, kaol = kaolinite, sm = smectite.

Table 2. Alteration and fluid inclusion data for some Coromandel epithermal deposits

these flat bases are generally at the same elevation throughout an individual mining field and may be correlated with the level of first boiling in the upflow zone of a geothermal system. In the Coromandel deposits, ore zones with flat-lying bases are indicated from old mine plans for Kuaotunu, Thames, Komata and Golden Cross. In some other deposits, ore zones were reported to diminish in strike length with depth (e.g. Komata, Downey 1935). This second type of ore zone geometry may better fit with the vertical cone-shaped boiling zones described from the Broadlands-Ohaaki geothermal field by Simmons and Christenson (1994).

The greater depth extent of the Waihi deposit can be explained by mixing of a deep, hot (300°C) fluid with cooler (c. 200°C) heated ground waters (Brathwaite 1999). This has the effect of lowering the 260°C isotherm by up to 300 m, thereby increasing the depth range of economic grade gold deposition within the 260 to 180°C window of electrum deposition. A similar model can be applied to other low-sulphidation epithermal deposits with large depth extents of economic ore.

## Paleo-depth estimates

Estimates of the vertical distance from the paleo-surface, or paleo-water table, to the base of the ore zone for some of the deposits are listed in Table 1. For other deposits, the available data is insufficient to attempt to quantify the paleo-depth, although most can be categorised in terms of shallow (<300 m), medium (300-500 m) or deep (>500 m). Some deposits span two of these depth zones. The estimates are based on one or more of the parameters: (1) paleo-surface indicators, (2) hydrothermal alteration, and (3) hydrostatic pressures derived from fluid inclusion homogenisation temperatures.

For the Andesite-hosted deposits, paleo-depth estimates range from 200 to 950 m, and are deeper in those deposits with base metal sulphides (sphalerite, galena and chalcopyrite) at depth. The Rhyolite-hosted deposits are shallower, with estimated paleo-depths of 200 to 500 m. This feature of Rhyolite-hosted deposits being shallower appears to be a stratigraphic control, because rhyolitic volcanics generally occur at shallower stratigraphic levels than andesites within individual volcanic centres of the Coromandel Volcanic Zone.

## Conclusions

- Known epithermal deposits in the Coromandel region belong to three subtypes of the low-sulphidation type:

  (1) andesite-hosted epithermal Au-Ag;

  (2) rhyolite-hosted epithermal Au-Ag; and

  (3) andesite-hosted polymetallic veins.
- Although no examples of the high-sulphidation type of epithermal deposits are known in the Coromandel region, there is potential for their occurrence, as evidenced by the presence of characteristic advanced argillic alteration at Lookout Rocks and Pumpkin Hill.
- Paleo-depth indicators for the epithermal deposits include: paleo-surface indicators (e.g. sinters), hydrostatic pressures estimated from fluid inclusions, and alteration mineralogy. Paleo-depth estimates for rhyolite-hosted deposits are 200 to 500 m, whereas andesite-hosted Au-Ag deposits are more variable, and deeper (up to 950 m) in those with base metals at depth.
- The majority of Coromandel Au-Ag deposits have limited depth extents (<200m) of economic grade mineralisation, although Waihi and Karangahake are notable exceptions with depth extents of 575 m and 700 m respectively.
- Limited depth extents of economic ore, fluid inclusion data, and modelling of gold deposition in active geothermal systems suggest that deposition of electrum in economic concentrations is confined to a temperature window of 260 to180°C. Under boiling conditions in low-salinity, low-gas systems, gold deposition is therefore generally limited to a vertical depth zone of about 400 m, with its upper boundary at about 100 m below the ground surface.
- The greater depth extent at Waihi and Karangahake resulted from the mixing of a deep, hot (300°C) fluid with cooler (c. 200°C) heated ground waters, lowering the 260°C isotherm by up to 300 m.

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