Comparison of fluid inclusion data and mineralization processes for Australian orogenic gold and intrusion-related gold systems

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Abstract We have examined the fluid inclusion data and fluid chemistry of Australian orogenic and intrusion-related gold deposits to determine if similar mineralization processes apply to both styles of deposits. The fluid inclusion data from the Yilgarn craton, the western subprovince of the Lachlan orogen, the Tanami, Tennant Creek and Pine Creek regions, and the Telfer gold mine show that mineralization involved fluids with broadly similar major chemical components (i.e. \( \text{H}_2\text{O} + \text{NaCl} + \text{CO}_2 \pm \text{CH}_4 \pm \text{N}_2 \)). These deposits formed over a wide range of temperature-pressure conditions (\(<200\) to \(>500\)°C, \(<100\) to \(400\)MPa). Low salinity, \(\text{CO}_2\)-bearing inclusions and low salinity aqueous inclusions occur in both systems but the main difference between these two types of deposits is that most intrusion-related gold deposits also contain at least one population of high-salinity aqueous brine. Oxygen and hydrogen isotope data for both styles of deposit usually cannot distinguish between a magmatic or metamorphic source for the ore-bearing fluids. However, sulfur and lead isotope data for the intrusion-related gold deposits generally indicate either a magmatic source or mixing between magmatic and sedimentary sources of fluid. The metamorphic geothermal gradients associated with intrusion-related gold deposits are characterized by low pressure, high temperature metamorphism and high crustal geothermal gradients of >30/km. Where amphibole breakdown occurs in a granite source region, the spatially related deposits are more commonly associated with Cu-Au deposits rather than Au-only deposits that are associated with lower temperature granites. The dominant processes thought to cause gold precipitation in both types of deposits are fluid-rock interaction (e.g. desulfidation) or phase separation. Consideration of the physical and chemical properties of the \(\text{H}_2\text{O-NaCl-CO}_2\) system on the nature of gold precipitation mechanisms at different crustal levels infers different roles of chemical (fluid-rock interaction) versus rheological (phase separation and/or fluid mixing) host-rock controls on gold deposition. This also implies that at the site of deposition, similar precipitation mechanisms operate at similar crustal levels for both orogenic and intrusion-related gold deposits.

Key words Fluid inclusions, Isotopes, Orogenic gold deposits, Intrusion-related gold deposits.

1 Introduction

There is considerable debate as to whether or not orogenic gold deposits and intrusion-related gold deposits should be regarded as separate classes of deposits or as variants of the same mesothermal gold system (e.g. Groves et al., 2003). Australia has a range of gold deposits that may be classified as either orogenic-gold or intrusion-related gold deposits. In this study we examine the fluid inclusion data and fluid chemistry of Australian gold deposits to determine if similar mineralization processes apply to both styles of deposits. Orogenic gold deposits typically form along convergent margins during the latter part of the deformational-metamorphic history of terrane accretion (Groves et al., 2003). The deposits have a strong structural control involving faults or shear zones, folds, and/or zones of competency contrast. Host rocks are extremely variable, although there is an overall trend from volcanic- or intrusion-hosted deposits in Archean provinces to sedimentary rock-hosted deposits in Phanerozoic provinces. Although the deposits occur in rocks of metamorphic grade...
varying from subgreenschist to granulite facies, the majority are hosted in greenschist facies rocks. Quartz ± carbonate veins are ubiquitous and the deposits may extend to depths of up to 1 or 2 km, with only subtle metal zoning, and distinctive strong, lateral zonation of wall-rock alteration. A distinctive metal association (Au ± Ag ± As ± Zn ± Bi ± Sb ± Te ± W) is characteristic of orogenic gold deposits, which are associated with near-neutral, low salinity fluids (typically < 10 wt. % NaCl equiv.) with CO₂ contents ranging from 10 to 25 mol. % (Ridley & Diamond, 2000).

Intrusion-related gold deposits are associated with tungsten and/or tin provinces, and typically occur in a continental tectonic setting well inboard of inferred or recognized convergent plate boundaries, in a landward or back-arc position, or within continental collisional settings (Thompson and Newberry, 2000). An additional criterion for distinguishing between orogenic and intrusion-related gold deposits is the timing of mineralization relative to deformation of the host rocks. Intrusion-related mineralization tends to be younger than the penetrative fabric of the host rocks, whereas, orogenic mineralization is synchronous with, or postdates penetrative fabrics and structures. Intrusion-related gold deposits contain a metal suite that includes Au with anomalous Bi ± W ± As ± Mo ± Te ± Sb ± (distal Pb-Zn). The deposits are related genetically to felsic igneous rocks (granite/rhyolite) of intermediate oxidation state (magnetite contents may be low or absent). The deposits exhibit a range of characteristics that vary over a wide range of emplacement depths (< 1 km to > 7 km). Deposits in shallow crustal settings (~ < 5 km) are associated with stocks, sills, dykes and volcanic domes and include systems with epithermal-style veins to breccia and stockwork similar to porphyry-type settings. Deeper systems (~ > 5 km) have characteristics of meso-thermal environments, and are hosted by plutons containing sheeted veins, greisens and disseminated gold. The deposits are characterized by a reduced (pyrrhotite-stable with no magnetite or hematite), low sulfide (5% volume %) ore assemblage. Fluid characteristics also vary with depth. Deposits in shallow environments contain high temperature (> 350 °C), immiscible brine (> 30 wt% NaCl equiv.) and low-salinity (< 5 wt% NaCl equiv.) vapor that commonly contains carbon dioxide. Deposits in deeper environments contain abundant low-salinity, carbon dioxide-rich aqueous fluids (< 10 wt% NaCl equiv.), which in some deposits are post-dated by moderate to high salinity brines (10 to 40 wt% NaCl equiv.). These contrasting fluid types are interpreted to be magmatic in origin and are the result of the complex interplay between exsolution of different volatiles (carbon dioxide, water and chlorine) from felsic magmas emplaced at different crustal levels. A key characteristic of intrusion-related gold deposits is the occurrence of a wide variety of mineralization styles, depending on formation depth, distance from the parent intrusion, and type of structural control.

2 Examples of fluids from Australian orogenic gold deposits

2.1 The Archean Yilgarn Craton

Orogenic gold deposits in the Yilgarn craton in Western Australia (Fig.1) are typified by quartz-dominant vein systems with less than 5% sulfides and up to 15% carbonate minerals.

The vein systems may be continuous along a vertical extent of ~ 1 ~ 2 km with little change in mineralogy although mineral zoning does occur in some deposits (Mernagh et al., 2004). Mafic volcanic and intrusive rocks are by far the most important host rocks to mineralization but at the mine scale several different rock types may host gold mineralization. The metamorphic setting of the Yilgarn gold deposits spans the range from sub-greenschist to granulite facies. However, most of the gold production has come from mid- to upper-greenschist facies domains.

The fluid inclusion data from orogenic gold deposits in the Yilgarn craton of Western Australia has been previously reviewed by (Ho et al., 1990; Ho et al., 1992; Hagemann and Cassidy, 2000). The reviews indicate that these mineral systems contain three main types of fluid inclusions (Fig.2):

(i) CO₂-H₂O inclusions which may contain either a single CO₂ phase or both CO₂ liquid and CO₂ vapor. The carbonic phase may also contain significant amounts of CH₄ as well as other gases (e.g. N₂, H₂S etc.) are rarely observed.

(ii) Two-phase aqueous inclusions with no detectable gases in the vapor phase. These inclusions typically coexist with the CO₂-H₂O inclusions indicating that phase separation has occurred in many of these systems.

(iii) Rare two-phase aqueous inclusions with a CH₄-rich vapor phase. These inclusions may occur as primary or secondary inclusions and are the result of the complex interplay between exsolution of different volatiles (carbon dioxide, water and chlorine) from felsic magmas emplaced at different crustal levels. A key characteristic of intrusion-related gold deposits is the occurrence of a wide variety of mineralization styles, depending on formation depth, distance from the parent intrusion, and type of structural control.
Fig. 2 Representative fluid inclusions from the Yilgarn craton, (a) a three-phase CO₂-H₂O inclusion, (b) a two-phase aqueous inclusion, (c) a co-existing three-phase CO₂-bearing inclusion and two-phase aqueous inclusion, and (d) secondary trail of two-phase aqueous inclusions with a CH₄-rich vapor phase.

Fig. 3 A plot of trapping pressure versus homogenization temperature as calculated from fluid inclusions from selected orogenic gold deposits in the Yilgarn craton.

Some isotopic studies have been carried out at both the district scale and the mine scale (Golding et al. 1990) but the oxygen isotope data are equivocal with respect to the primary source of the fluid. δ¹⁸O values of vein quartz span a range from 8 to 13‰ while δ¹⁸O values from carbonates range from 7 to 14‰. Golding et al. (1990) concluded that the narrow range of δ¹⁸O values of vein quartz for mafic hosted deposits over vertical extents of hundreds of metres indicates a relatively homogeneous source for oxygen and a relatively stable P-T regime during mineralization. The isotopic compositions of the ore fluids indicate that they could have been derived from, or interacted with, seafloor-altered basalts or fault-related regional carbonatization zones. They could only have been derived from felsic intrusions or lamprophyres if modified by subsequent fluid-rock interaction or changing P-T-X conditions.

2.2 The Palaeozoic western subprovince of the Lachlan orogen

The western subprovince of the Lachlan orogen (Fig. 1), which extends across most of central and western Victoria and into northeast Tasmania, is host to some of the world’s major turbidite-hosted, orogenic gold deposits. It is characterized by a 6 ~ 10km thick Cambro-Ordovician to Devonian turbidite succession consisting of quartz-rich sandstones, mudstones, and carbonaceous shales. This succession is underlain by a 1 ~ 1.5km thick sequence of Cambrian volcanogenic with island-arc affinities (Crawford and Keyes, 1978). Post-tectonic dyke swarms and felsic to intermediate intrusive rocks were emplaced during two broad intervals in the Late Silurian and Devonian and in places are also host to gold mineralization. The orogenic gold deposits are typically hosted within relatively narrow veins that are commonly associated with antiformal structures (domes). The principal quartz vein textures are massive, laminated, and ribbon banded. Recrystallized quartz in early veins is characterized by a milky to light grey appearance, whereas late-stage, fracture-filling veins tend to be more translucent and have evidence of open-space growth of quartz crystals. Gold commonly occurs within massive quartz, in stylolitic seams (indicative of late emplacement or remobilization) or wall-rock breccias.

Three broad classes of fluid inclusions have been recognized in mineralized veins from the western subprovince of the Lachlan orogen (Fig. 5):

(i) Two-phase aqueous inclusions with no detectable gases in the vapor phase. These inclusions are water-rich with a vapor bubble that usually occupies 5 to 10 vol.% of the inclusion at room temperature.

(ii) Water-rich CO₂-H₂O inclusions in which the carbonic phase occupies less than 30 vol.% of the inclusion. In addition to CO₂ the carbonic phase may also contain varying proportions of N₂ and CH₄.

(iii) Two- or three-phase CO₂-H₂O inclusions that are dominated by the carbonic phase. Once again carbonic phase may also contain varying proportions of N₂ and CH₄.

The reported range of trapping pressures and temperatures estimated from fluid inclusion data for selected deposits from the western subprovince of the Lachlan orogen are shown in Fig. 6. Homogenization temperatures vary from 150 to 375°C with the majority of deposits having homogenization temperatures generally below 300°C. Estimated trapping pressures vary from 26 to
300 MPa with the higher temperature deposits having the highest trapping pressures and the lowest temperature deposits having the lowest pressures.

Another interesting observation is that the composition of the carbonic phase appears to change with the estimated depth of formation of the gold deposit. Raman microprobe analysis has shown that fluid inclusions in deposits formed at the deepest crustal levels (i.e., at the highest temperatures and pressures) have CO$_2$-rich vapor phases sometimes containing minor amounts of CH$_4$ as well, while inclusions from deposits at the higher crustal levels (i.e., at lower temperatures and pressures) contain CO$_2$-bearing vapor phases with significant quantities of N$_2$ and CH$_4$ (Mernagh, 2001). This is thought to be due to either more fluid circulating through the host rocks at higher crustal levels, or alternatively, mixing with other fluids enriched in N$_2$ and CH$_4$ that are present in the host rocks at higher crustal levels.

The variation of fluid salinity with temperature for selected deposits from the western subprovince of the Lachlan orogen is shown in Fig. 7. This indicates that most orogenic gold deposits in this region have salinities below 7 mass% NaCl eq. although the higher temperature (deeper) deposits have salinities up to 12 mass% NaCl eq. However, there have not been a large number of fluid inclusion studies in this subprovince and more data is needed to confirm this correlation.

In contrast to the limited number of fluid inclusion studies a large number of oxygen isotope analyses have been carried out in the western subprovince. The majority of δ$^{18}$O values from vein quartz fall into a relatively narrow interval from 12 to 19‰ (Bierlein and Crowe, 2000), which translate to calculated δ$^{34}$S compositions for the ore-bearing fluids of between 7 and 13‰. (Gray et al., 1991) reported remarkably uniform δ$^{18}$O values for over 400 samples from across the western subprovince of the Lachlan orogen, with only a slight systematic increase in isotopic composition across the three structural zones in central Victoria (Stawell zone; 14.7 ± 1.1‰; Bendigo zone; 17.5 ± 1.3‰; Melbourne zone; 19.0 ± 1.6‰). The δ$^{18}$O values from the quartz vein-wall rock pairs in their study define trends indicating greater variation in wall-rock isotopic composition than that found within the veins, leading Gray et al. (1991) to suggest that the fluids responsible for vein quartz precipitation were derived from the host rock. However, Changakakoti et al. (1996) carried out isotopic studies on 10 deposits in central Victoria and reported a clear distinction between the higher temperature Au-As style of mineralization and the lower temperature Au-Sb mineralization. They reported δ$^{18}$O values for deposits with a Au-As association ranging from 14 to 18.5‰ while deposits with a Au-Sb association ranged from 18.6 to 22.9‰.

Hydrogen isotope analysis of fluid inclusion water yielded a very wide spread ranging from +7 to −179‰ (Gray et al., 1991). Inherent in this approach is some uncertainty regarding the origin of the fluid inclusion populations, and hence, both primary and secondary inclusions may be analyzed. The wide range in δD values, which appears incompatible with sole derivation of the fluid from a magmatic or metamorphic source, also supports the hypothesis that the fluids may have originated from the deep circulation of highly evolved meteoric water. However, Goldfarb et al. (1997) have demonstrated that very low and variable δD values can be caused by trapping of meteoric water in secondary fluid inclusions, which formed post mineralization and possibly not until later during the uplift of the metamorphosed host sequence.
3 Examples of fluids from Australian intrusion-related deposits

3.1 The Palaeoproterozoic gold deposits of the Tanami region

The Tanami region (Fig. 1) straddles the Northern Territory-Western Australia border and contains a number of Palaeoproterozoic sedimentary basins that have been intruded by three I-type, granitic suites that range in age from 1825 ~ 1790 Ma. These units are overlain by Neoproterozoic basins and the Phanerozoic Antrim Plateau Volcanics. Gold mineralization is contemporaneous with granite intrusion and is either stratabound within banded ironstones or is associated with dilational quartz-carbonate veins that may occur in either carbonaceous sedimentary rocks or basalt. The majority of the gold occurs as free gold in veins composed of >90 vol. % quartz ± carbonate ± feldspar ± chlorite ± sulfides ± amphibole. Alteration selvages usually only extend up to 10 mm from the veins except at the Tanamigoldfield (thought to have formed at the highest crustal level) where sericitic alteration may extend up to 10 m from the veins.

Four main types of fluid inclusions have been recognised in mineralized veins from the Tanami region (Fig. 8):

(i) CO₂-H₂O inclusions which may contain either a single CO₂ phase or both CO₂ liquid and CO₂ vapor. In addition to CO₂, the carbonic phase may also contain varying proportions of CH₄ and N₂.

(ii) Two-phase CH₄ ± CO₂ ± H₂O inclusions which typically contain <30 vol. % vapor.

(iii) Two-phase aqueous inclusions with no detectable gases in the vapor phase. These inclusions are water-rich with a vapor bubble that usually occupies 5 to 10 vol. % of the inclusion at room temperature.

(iv) Three-phase aqueous inclusions with a halite daughter crystal.

The trapping pressures and temperatures estimated from fluid inclusion data from the Tanami region are shown in Fig. 9. Homogenization temperatures vary from 200 to 430°C. This is similar to the range observed for the Yilgarn craton (Fig. 3) although the trapping pressures, which range from 40 to 290 MPa, are not as high as observed in the Yilgarn craton. In contrast to the fluid inclusions from the western subprovince of the Lachlan orogen (Fig. 5), the higher temperature and higher pressure (i.e. deeper) deposits contain higher amounts of CH₄ in the carbonic phase (CH₄ is the dominant carbonic species in the fluid inclusions at the Groundrush mine), while the lower temperature and lower pressure (i.e. shallower) deposits have CO₂-rich carbonic phases. The presence of CH₄ at deeper levels in the crust may be significant as CH₄-rich fluids unmix over a wider range of pressures and temperatures than for the corresponding CO₂-H₂O system (Naden & Shepherd, 1989), allowing phase separation and gold precipitation to occur at greater depths within the crust.

The δ¹⁸O values of vein quartz from the major deposits in the Tanami region fall into a relatively narrow interval from 11.6 to 19.2‰, which is similar to the range observed in the western subprovince of the Lachlan orogen. Notwithstanding the limited dataset, there appears to be a correlation of δ¹⁸O values with the estimated depth of the deposits (Mernagh and Wygralak, 2006) with the shallowest level deposits of the Tanami Goldfield having values ranging from 15 ~ 19‰. The δ¹⁸O values for quartz translate to calculated δ¹⁸O compositions for the ore-bearing fluids of between 3.8 and 8.5‰. Hydrogen isotopes for the inclusion fluids span the range from ~85 to ~37‰. Therefore,
the isotopic data from the ore fluids in the Tanami region suggest either a magmatic or a hybrid magmatic/metamorphic origin for the fluids. This is in accord with what is expected for intrusion-related gold deposits.

Sulfur isotopes were also obtained from sulfides in pre-ore, ore-bearing, and post-ore veins (Wygralak et al. 2005). Sulfides from pre-ore veins had $\delta^{34}\text{S}$ values ranging from 31 to 37‰, which suggests a sedimentary origin. Sulfides associated with ore-bearing veins had $\delta^{34}\text{S}$ values ranging from 4.2 to 12.3‰, which is interpreted as resulting from mixing of magmatic sulfur with the isotopically heavier sedimentary sulfur. Arsenopyrite and pyrrhotite from post-ore veins gave $\delta^{34}\text{S}$ values ranging from -2.3 to 4.0‰ suggesting a magmatic source for these minerals. These results are also consistent with an ore-bearing, magmatic fluid flowing from an intrusion and mixing with sulfur in the surrounding sediments.

### 3.2 The Palaeoproterozoic gold deposits of the Pine Creek geosyncline

The gold deposits in the Pine Creek geosyncline (Fig. 1) are hosted by sequences containing mainly siltstone and greywacke with minor dolomite and tuffaceous sediments. These units were subsequently intruded by the Cullen Batholith and other granitoids. Most of the gold deposits lie along the axial traces of anticlines as concordant and discordant veins, stockworks, saddle reefs, and massive and disseminated replacements. The gold deposits appear to be related to fluid circulation during or shortly after intrusion of the granitic plutons (Sheppard et al. 1990). They are characterized by sulfides, mainly pyrite and arsenopyrite, or base metals such as galena and sphalerite. Other minerals present in lesser amounts include pyrrhotite, tetrahedrite, tennantite, bismuth sulfosalts, carbonate, alkali feldspar and muscovite. Host-rock alteration generally involved the development sericite and silica with chlorite, carbonate, and sulfides being less common.

Four main types of fluid inclusions have been recognised in mineralized veins from the Pine Creek geosyncline (Ahmad et al.; Fig. 11):

- (i) $\text{CO}_2$-$\text{H}_2\text{O}$ inclusions which may contain either a single $\text{CO}_2$ phase or both $\text{CO}_2$ liquid and $\text{CO}_2$ vapor. In addition to $\text{CO}_2$, the carbonic phase may also contain varying proportions of $\text{CH}_4$.

### 3.3 Oxygen isotopes of vein quartz

Oxygen isotope analysis of vein quartz gave $\delta^{18}\text{O}$ values ranging from 12.7 to 16.3‰, which translate to calculated $\delta^{18}\text{O}$ compositions for the ore-bearing fluids of between 8.0 and...
The Paleoproterozoic gold deposits of the Tennant Creek Goldfield

Gold-copper-bismuth mineralization at the Tennant Creek goldfield (Fig. 1) occurs in epigenetic magnetite-chlorite-quartz ironstones, which occur as cross-cutting pipes and ellipsoidal pods within a sequence of Proterozoic tuffaceous metasedimentary rocks and rhyolitic porphyries. Production has mostly come from primary magnetite-rich ironstones such as Juno, Orlando, Peko, Warrego, Gecko, White Devil and TC8. Massive magnetite, with minor chlorite and/or quartz, commonly occupies the centre of the ironstone body. This magnetite core may be surrounded by other zones of talc-magnetite, dolomite-calcite, dolomite-talc-chlorite and chlorite-hematite. At Juno and TC8 gold is generally concentrated in the central massive magnetite-chlorite zone but it may be more widespread in other deposits. Chalcopyrite and bismuth sulfosalts occur as overlapping shells around the core gold-rich zones (Large 1975). Narrow zones of stringer magnetite extend vertically below the deposits and are enclosed within chlorite-rich alteration pipes. The stringer zone consists of varying proportions of magnetite, muscovite and hematite as veins and/or disseminations within a fine-grained chloritic groundmass.

There have been several fluid inclusion studies of mineral deposits in the Tennant Creek goldfield (Khin Zaw et al. 1994; Huston et al. 1993; Skirrow and Walshe 2002) and three main types of fluid inclusions have been recognised in the mineralized veins (Fig. 13):

(i) Two-phase aqueous inclusions with low vapor/liquid ratios and no detectable gasses in the vapor phase. These inclusions homogenize into the liquid phase.

(ii) Two-phase aqueous inclusions with higher vapor/liquid ratios. The vapor phase is NaCl-rich with minor quantities of CO2 and CH4. These inclusions have been further subdivided into D Type Iia, which homogenize to liquid and Type Iib, which homogenize to the vapor phase.

(iii) Multiphase aqueous inclusions which contain liquid, water vapor and one or more daughter minerals. Halite is a common daughter mineral in these inclusions.

The estimated trapping pressures in the Tennant Creek goldfield are not well constrained so only trapping temperatures and fluid salinities are shown in Fig. 12. The data may be divided into two groups which reflect the different results of different authors. (Khin Zaw et al. 1994; Huston et al. 1993) report high salinities from CaCl2-bearing inclusions ranging from 10 to 50 mass% NaCl eq. However, (Skirrow and Walshe 2002) report salinities ranging from 0 to 11 mass% NaCl eq. for N2-CH4-bearing inclusions intimately associated with gold and native bismuth and claim that the higher salinity fluids results from subsequent mixing of this low- to moderate-salinity fluid with Ca-Na-Cl brines. It is also interesting to note that most of the deposits have inclusions with homogenization temperatures spanning the range from 250 to 450°C, which is generally higher than observed for the lode gold systems above. However, Huston et al. (1993) also caution that homogenization temperatures above 400 oC are an artefact of heterogeneous trapping and should not be interpreted as representative of the trapping temperatures.

Khin Zaw et al. (1990) also carried out electron microprobe analysis of salt precipitates from decrepitated fluid inclusions. The analyses showed that the ore depositing fluids had slightly higher Ca2+ and K+ contents than the fluids that deposited the ironstones but both the gold and copper depositing fluids had similar Na+, K+, and Ca2+ compositions. They concluded that the composition of the Tennant Creek fluids were comparable with that of modern oilfield basinal brines. On the other hand, (Skirrow and Walshe 2002) argue that a low salinity reduced fluid was responsible for the deposition of the Cu- and sulfide-rich deposits while a low-salinity oxidized fluid was responsible for the formation of the Au-Bi style of deposits at Tennant Creek.

Studies of sulfur isotopes in the Tennant Creek goldfield have found consistent zonation patterns between Au-, Bi-, and Cu-rich zones. Wedekind (1990) found a consistent sulfur isotope zonation in the gold-rich zone and also noticed that the gold grade increased as the δ34S values decreased. These observations are consistent with reports by (Large 1975) that the gold-rich zone at Juno had low δ34S values. Huston et al. (1993) also reported that the gold-rich zones at the base of the deposits had δ34S values between 0 and 4‰ whereas the Cu-rich zones had δ34S values generally above 4‰.

3.4 The Telfer gold mine

The Telfer gold mine in Western Australia (Fig. 1) is
centred on the gently-dipping, north-east limb of a north-west trending elongate dome, which is one of two domal structures (the Main and West Domes). Mineralization is largely restricted to the siltstones and sandstones of the Telfer and Malu Formations. It occurs in stratiform and stratabound pyrite-quartz-chalcopyrite-gold reefs and associated veins. Primary ore minerals are quartz and pyrite with minor chalcopyrite, bornite, chalcocite and pyrrhotite. Sulfides occur in the reefs and also in the adjacent host-rocks either disseminated or as euhedral crystals. Gold is present as microscopic inclusions in pyrite, commonly associated with chalcopyrite and mostly within the quartz veins and reefs (Goellnicht et al. 1989).

Six types of fluid inclusions have been reported from mineralized veins at the Telfer gold mine (Goellnicht et al. 1989):

(i) \( \text{CO}_2 - \text{H}_2\text{O} \) inclusions which may contain either a single \( \text{CO}_2 \) phase or both \( \text{CO}_2 \) liquid and \( \text{CO}_2 \) vapor.
(ii) \( \text{CO}_2 - \text{H}_2\text{O} \) inclusions which also contain a halite crystal.
(iii) \( \text{CO}_2 - \text{H}_2\text{O} \) inclusions which contain multiple daughter crystals.
(iv) Two-phase aqueous inclusions
(v) Two-phase aqueous inclusions which also contain a halite crystal.
(vi) Two-phase aqueous inclusions which contain multiple daughter crystals.

The variation of fluid salinity with temperature for the fluid inclusions from the Telfer gold mine is shown in Fig. 12. Homogenization temperatures range from 150 to 440°C with the very saline, multisalt inclusions homogenizing at the highest temperatures. These high homogenization temperatures and fluid salinities are comparable with some types of Sn-W and Mo sheeted vein deposits (see Spooner 1981). (Goellnicht et al. 1989) interpret this data as being due to mixing of hot, high salinity, magmatic fluids with cooler, lower salinity waters. Lead isotope data from pyrites in the deposit (Goellnicht et al. 1989) are interpreted to indicate a mix of local sediment derived lead and possible magmatic lead.

4 A comparison of fluids from orogenic and intrusion-related gold deposits

A comparison of the temperature, salinity and gas contents of fluid inclusions from the above deposits is shown in Fig. 14. As shown in this figure, there are many similarities between the fluids from orogenic and intrusion-related gold deposits, which has prompted some authors to suggest that they be considered as a single mineral system (Walshe et al. 2005). Both types of deposit form over a similar range of temperatures and pressures, although intrusion-related deposits emplaced in the shallow crust appear to have higher temperature fluids than similar orogenic gold systems. Both types contain \( \text{H}_2\text{O} - \text{CO}_2 \pm \text{CH}_4 \pm \text{N}_2 \) fluid inclusions and low salinity fluids are observed in both systems.

However, as well as one or more populations of low salinity fluids, most intrusion-related deposits also contain at least one population of high-salinity aqueous brines. The fluid inclusion characteristics of intrusion-related deposits change with depth (Baker, 2002) has suggested that this is related to the solubility of \( \text{CO}_2 \) in magmas. The low solubility of \( \text{CO}_2 \) in magmas will result in the early exsolution of the gas and the formation of low-salinity, \( \text{CO}_2 \)-rich aqueous fluids. In some of these deeper deposits, the \( \text{CO}_2 \)-bearing fluids are postdated by moderate- to high-salinity brines (10 ~ 50 mass% NaCl eq.). Intrusion-related deposits that form at shallow crustal levels will exsolve early, immiscible, low-salinity \( \text{CO}_2 \)-bearing inclusions and high salinity aqueous inclusions. These inclusions may be postdated by \( \text{CO}_2 \)-absent, low-salinity aqueous inclusions. These characteristics are consistent with well accepted magmatic-hydrothermal models in which chlorine-rich aqueous fluids exsolve from a magma and partition into immiscible brine and vapor (Cline and Bodnar 1989).

5 The geodynamic setting of associated magmatic intrusions

A petrogenic grid has been used in Fig. 15 to show the \( P-T \) space for the source regions of the granites that are spatially related to the intrusion-related gold deposits at Telfer, the Tanami region, the Pine Creek geosyncline and the Tennant Creek goldfield.

These intrusions have similar characteristics in that they show field evidence for magmatic fractionation. They are dominated by granodiorite to granite (sensu stricto) and are compositionally characterised by high K and low Ca contents (Budd et al. 2001). These characteristics were suggested by Wyborn (2004) to indicate a higher temperature source region, in which breakdown of biotite was the main melt producing reaction. The compositions did not indicate that breakdown of amphibole had played a major role. Where amphibole breakdown
Fig. 15 A plot of pressure versus temperature showing the approximate stability fields of magmas of various composition. The solid lines with arrows represent selected continental geotherms. The biotite out’ and hornblende out’ curves mark the upper stability limits for these minerals respectively. The quartz + albite + K feldspar + H2O curve represents the upper limit for water-rich felsic magmas. The stability limits for garnet-plagioclase and clinopyroxene-orthopyroxene are shown by the solid lines. See text for details.

occurs in a granite source region, the spatially related deposits are more commonly associated with Cu-Au deposits rather than Au-only deposits that are associated with lower temperature granites (Fig. 15; Wyborn, 2004).

The quartz-rich nature of the granites and the dominance of high SiO2 compositions (> 68 wt % SiO2) indicate that these granites formed at pressures < 10 kbars (Johannes and Holz 1996). These granites are also characterized by Sr-depleted, Y-non-depleted trace element patterns further supporting formation pressures < 10 kbars (Wyborn et al. 1992). From this petrogenetic grid (Fig. 15) the geothermal gradients at the time of formation of the granites is interpreted to be greater than 300/km.

The metamorphic geothermal gradients in the Proterozoic Pine Creek, Tanami, Tennant Creek and Telfer regions are also characterized by low pressure, high temperature metamorphism (Oliver et al. 1998; McLaren et al. 2003). All these regions are dominated by andalusite/sillimanite indicating high crustal geothermal gradients of > 300/km. The geothermal gradients for the orogenic gold deposits considered in the paper are also high. The Archaean Yilgarn Craton (Binns et al. 1976) and the Palaeozoic subprovince of the western Lachlan orogen (Collins and Hobbs 2001) are dominated by low pressure, high temperature metamorphism.

The pressure temperature plot (Fig. 16) for the fluid inclusions also indicates that most deposits form where geothermal gradients are greater than 30/km. Therefore high geothermal gradients are common to all the discussed deposits regardless of their ‘orogenic’ or ‘intrusion-related’ classification. Such unusually high geothermal gradients indicate input of heat at the time of mineralization (Thompson, 1981).

It is possible therefore that in low pressure and high temperature terrains that, as the crust heats up, gold deposits can form during prograde metamorphism. At deeper crustal levels a specific type of granite also forms in these terrains resulting in overlapping characteristics of the resultant deposits, thus supporting the concept of Walshe et al. (2005) that the deposits are part of a continuum.

6 Gold precipitation mechanisms

Gold is precipitated from the ore-bearing fluids in response to changes in the physio-chemical conditions of the fluid at the site of ore deposition. These specific changes in ore fluid chemistry, pressure, and/or temperature can result from a number of physical processes including:

(a) cooling during the rise or throttling of the ore-bearing fluid
(b) the mixing of two or more different fluids
(c) interaction between the ore-bearing fluids and their host rocks, and
(d) phase separation in response to a pressure decrease during the rise of the fluid or dilation during faulting.

Geochemical modelling has demonstrated that rock-buffered, gold-bearing fluids are undersaturated with gold at high temperatures (> 400°C) which enables gold to be transported over long distances without precipitation (Bastrakov and Shavarov 2005). The chemical changes responsible for precipitation of gold from ore-bearing fluids depends primarily on the nature of the gold complex in solution and, to a lesser extent, on the redox state of the fluid with respect to the sulfate-sulfide buffer.

Cooling is unlikely to be a major depositional mechanism in orogenic gold deposits, given there is a lack of evidence for large thermal gradients in these systems, but it may play a role in zoned intrusion-related deposits, particularly in relation to the deposition of distal Pb and Zn.

Fluid mixing can be a very efficient way of changing the chemical equilibrium of the ore-bearing fluid, which would then lead to gold precipitation. However, given the need for very large
Fluid-rock interaction occurs in many gold deposits as shown by wallrock sulfidation adjacent to veins and even larger alteration haloes around some deposits. Wallrock sulfidation can reduce the activity of H$_2$S in the fluid, which in turn can reduce the solubility of gold by several orders of magnitude (Bastrakov et al. 2004). However, fluid-rock interaction is likely to be most efficient when only one fluid phase is present (i.e. when phase separation has not occurred). Therefore, we suggest that fluid-rock interaction is likely to be the major gold depositional mechanism at P-T conditions above the H$_2$O-CO$_2$ solvus in Fig. 16.

At P-T conditions below the H$_2$O - CO$_2$ solvus in Fig. 16 the ore-bearing fluids lie in the two-phase region and will undergo phase separation. Although a series of complex physical and chemical changes occur during phase separation (Drummond and Ohmoto 1985), one of the most important reactions is the partitioning of H$_2$S and other volatile species into the vapor phase. This once again reduces the activity of H$_2$S in the fluid and leads to gold precipitation. Phase separation has been proposed as the dominant process that leads to the formation of high-grade (10s - 100s g/t Au) orebodies that contain free gold, commonly within quartz-vein arrays or breccias encompassed by weakly mineralized alteration haloes. Therefore, we suggest that phase separation is likely to be the major gold depositional mechanism at P-T conditions below the H$_2$O-CO$_2$ solvus in Fig. 16.

This also implies that at the site of deposition, similar precipitation mechanisms operate at similar crustal levels for both orogenic and intrusion-related gold deposits. Note also that Fig. 16 indicates that most orogenic and intrusion-related gold deposits form under conditions with high crustal geotherms, which may be necessary to promote extensive fluid flow. Fig. 16 also indicates that most of the Australian intrusion-related deposits have P-T conditions near or below the H$_2$O - CO$_2$ solvus. It must also be kept in mind that the solvus in the H$_2$O-CO$_2$-NaCl system will shift to higher temperatures with increasing CO$_2$ concentration or if other gases such as CH$_4$ are added to the system. Thus it appears likely that phase separation is the dominant gold precipitation mechanism in most high crustal level intrusion-related gold deposits. However, some orogenic or intrusion-related gold deposits that form deep in the earth’s crust will be at P-T conditions above the H$_2$O-CO$_2$-NaCl solvus and, in this case, fluid-rock interaction leading to desulfidation would be the dominant gold precipitation mechanism.

7 Conclusions

The fluid inclusion data considered in this paper show that the Australian orogenic and intrusion-related gold deposits formed over a wide range of temperature-pressure conditions (< 200 to > 500°C, < 100 – 400 MPa) and that they involve fluids with broadly similar major chemical components (i.e. H$_2$O + NaCl + CO$_2$ ± CH$_4$ ± N$_2$). Low salinity, CO$_2$-bearing inclusions and low salinity aqueous inclusions occur in both types of deposit. However, an obvious difference between these two types of deposits is that most intrusion-related gold deposits also contain at least one population of high-salinity aqueous brine. The fluid inclusion characteristics of intrusion-related gold deposits also change with depth due to the complex interplay between exsolution of volatiles (e.g. carbon dioxide, water and chlorine) from felsic magmas emplaced at different crustal levels.

Oxygen and hydrogen isotope data for both styles of deposit are usually equivocal between a magmatic or metamorphic source for the ore-bearing fluids. However, sulfur and lead isotope data for the intrusion-related gold deposits generally indicates either a magmatic source or mixing between magmatic and sedimentary sources of fluid.

The metamorphic geothermal gradients associated with intrusion-related gold deposits are characterized by low pressure, high temperature metamorphism and high crustal geothermal gradients of > 30/km. Where amphibole breakdown occurs in a granite source region, the spatially related deposits are more commonly associated with Au-Cu deposits rather than Au-only deposits that are associated with lower temperature granites.

The dominant processes thought to cause gold precipitation in both types of deposits are fluid-rock interaction (e.g. desulfidation) or phase separation. An examination of the impact of the H$_2$O-NaCl-CO$_2$ system on the nature of the dominant gold precipitation mechanisms at different temperatures and pressures (i.e. different crustal levels) infers different roles of chemical (fluid-rock interaction) vs rheological (phase separation and/or fluid mixing) host-rock controls on gold deposition. This also implies that at the site of deposition, similar precipitation mechanisms operate at similar crustal levels for both orogenic and intrusion-related gold deposits.

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