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Timing of gold mineralisation in the Pine Creek orogen, Northern Territory, Australia: its significance to the thermal-aureole gold model

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ABSTRACT: For much of the last two decades, gold occurrences in the Pine Creek orogen frequently have been cited as type-examples of high-temperature contact-metamorphic or thermal-aureole deposits associated with granitoid magmatism. Recent fieldwork, coupled with radioisotopic dating of hydrothermal phosphates using SHRIMP, indicates that the age of gold mineralisation is typically younger than the youngest phase of granitoid intrusion, and certainly post-dates the effects of contact metamorphism. This evidence suggests that these deposits are late-stage orogenic gold deposits, formed in the contact-aureole of HHP granitoids, but after peak contact-metamorphism.

1 INTRODUCTION

Recent $^{40}Ar/^{39}Ar$ dating of gold-related biotite and muscovite alteration in the Tanami region (Northern Territory) suggests that the age of gold mineralisation (~1710-16300 Ma; Wygralak *et al.*, 2001) is younger than the two groups of granitoid intrusions (1830-1810 Ma and 1800-1795 Ma; Hendrickx *et al.*, 2000). Previously, the spatial relationship of gold mineralisation to the granitoids was used to suggest a genetic link in this region, as well as in the area of the nearby Pine Creek orogen (PCO) (e.g., Etheridge & Holyland, 1985; Wall & Taylor, 1990).

The $^{40}Ar/^{39}Ar$ dating of hydrothermal biotite and muscovite is problematic due to the potential for resetting. In addition, the indirect paragenetic relationship of alteration minerals to gold mineralisation introduces some uncertainty. Further, many gold deposits, including those studied in the PCO, do not typically contain micaceous alteration minerals that are sufficiently coarse-grained to date effectively.

Consequently, a more robust and direct method of dating gold mineralisation from the PCO was sought. Hydrothermal phosphate geochronology using the Sensitive High-Resolution Ion MicroProbe (SHRIMP) is an emerging technique to date a variety of geological events (e.g., Rasmussen *et al.*, 2001). The method enables the acquisition of texturally well-constrained geochronological data from monazite and xenotime, which are common as accessories in hydrothermal veins. Application of this technique to dating gold deposits in the PCO is used here to test the thermal-aureole model, which stresses a prograde contact-metamorphic timing for gold mineralisation. This model was first proposed by Klomínský *et al.* (1996) and Partington & McNaughton (1997), on the basis of geological evidence, as definitive geochronological data were absent.

2 REGIONAL GEOLOGY

The Paleoproterozoic PCO has a wide variety of mineral deposits including economic deposits of gold, Au-PGE (±U) and U (±Au) (Şener *et al.*, 2002). Gold-only deposits contain 470t Au, making the PCO one of the most economically productive Proterozoic inliers in Australia. The orogen comprises a thick (~10-14km) supracrustal sequence of variably deformed, rift-phase, shallow-water and flysch-type sedimentary rocks (~2.20-1.87 Ga) overlying a rifted Archean granitic basement (~2.68-2.53 Ga).

The sedimentary rock sequence was intruded at ~1.87 Ga by continental tholeiitic dolerite sills (Zamu Dolerite), and then deformed and regionally metamorphosed during the ~1.87-1.85 Ga Nimbuwah event of the Top End orogeny. After deformation, lamprophyres intruded the sequence as dykes that typically pre-date gold mineralisation. A number of granitoid suites intrude the supracrustal sequence, the most voluminous being the ~1.84-1.80 Ga Cullen Suite of fractionated and reduced calc-alkaline, high heat-producing (HHP), I-type granitoids (Klomínský *et al.*, 1996).

3 CHARACTERISTICS OF DEPOSITS

The majority of gold deposits are associated with regional-scale anticlines and, less typically, shear zones. At the deposit-scale, gold mineralisation is generally confined to sub-millimetre stockwork-type quartz veinlets, thicker saddle-reefs and spur-veins, and laminated bedding-concordant veins. There are also parallel and *en échelon* veins in shear zones and ladder, sheeted, and conjugate veins. The veins are hosted typically by greywacke and siltstones/shales, with much of the mineralisation within the more carbonaceous siltstones/shales and in rare silicate-facies BIF, dolomitic siltstones, and dolerite.

Little gold mineralisation occurs in the immediately adjacent vein host rocks, except in silicate-facies BIF. Mineralisation is dominated by pyrite and arsenopyrite, with accessory pyrrhotite, chalcopyrite, galena, and sphalerite. Gold normally occurs within arsenopyrite as 1-5µm inclusions or within fractures in other minerals (5-50µm), and is typically 650-850 fine. Rare native bismuth, bismuthinite and galenobismutite occur as complex, presumably contemporaneous intergrowths, which have been used to argue a magmatic origin for the gold mineralisation. Sericite-chlorite alteration and silicification, with less common carbonate alteration, are typical.

Available fluid inclusion and stable isotope data are equivocal, although some authors use such data to suggest a magmatic component to the ore fluids (e.g., Ahmad *et al.*, 1993). The $\delta^{18}O$ and δD data fall within the area of overlap between magmatic and metamorphic fields, consistent with either mixed magmatic-metamorphic or purely metamorphic fluids. Sulphur isotope values correspond to regional sources and fall within the range defined for orogenic gold deposits (Ridley & Diamond, 2000). The main ore stage is dominated by a low to moderate salinity, two-phase aqueous fluid and deposited ore at a P-T of 180-320°C and ~1kbar (Ahmad *et al.*, 1993), which is typical of some epizonal orogenic gold deposits.

Matthäi *et al.* (1995), Klomínský *et al.* (1996) and Partington & McNaughton (1997) indicate that initial lead isotope ratios obtained from gold-related sulphide minerals are broadly similar, and these contrast with the range of initial lead compositions displayed by the granitoids. This suggests an insignificant contribution of magmatic lead to the mineralising fluids (Partington & Williams, 2000).

4 DISTRIBUTION OF DEPOSITS

The majority of gold deposits occur in the central region of the PCO (Fig. 1), near or within thrust faults, ramp anticlines, and strike-slip shear zones (Partington & Williams, 2000). However, unlike Archean greenstone-hosted gold deposits, they do not show a strong spatial association with major shear-zones. Broadly, fault-related deposits can be separated into small deposits, with epizonal textures characterizing veins hosted by reactivated N-trending thrust faults, and mesozonal vein-mineralisation hosted within NNW-trending shear zones. The former are considered here to be related to late-stage brittle-faulting and the latter to earlier transpressional deformation.

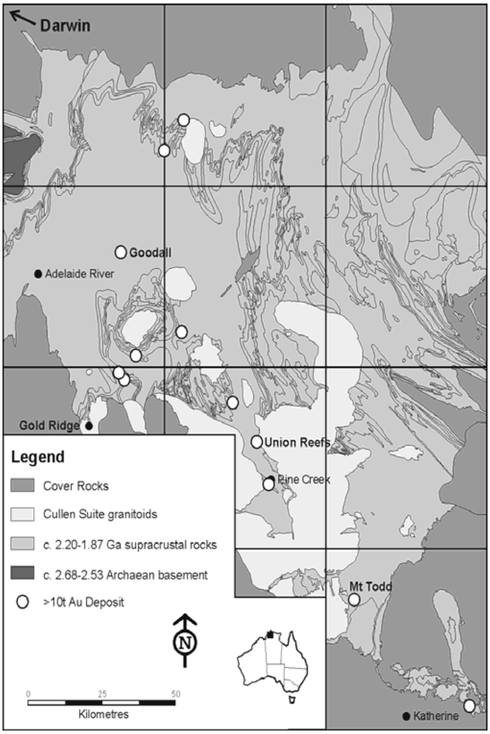

Figure 1. Regional geology of the Central Region of the Pine Creek Orogen showing the distribution of major gold deposits.

The lithostratigraphic distribution of gold deposits reveals a strong association with flysch-type facies of the Finniss River Group (~1.88-1.87 Ga) and the sedimentary rocks of the South Alligator River Group (~1.90-1.88 Ga). The ~1.88 Ga Mount Bonnie Formation is the most productive unit in terms of contained resources normalised by area of outcrop, due to the variability of rheology and chemistry of its component rock types.

Ninety-percent of the gold deposits in the central region lie within 2.5 km of granitoid contacts when evaluated in 3D, which corresponds to the limit of the contact-aureoles. Further, gold mineralisation is specifically concentrated in, and just beyond, the biotite-albite-epidote zone of the contact aureole (Fig. 2), with only 10% of gold deposits in the inner, 0.5-km-thick, hornblende-hornfels zone. This strong spatial association of mineralisation to granitoids has been used to support a genetic link between the granitoid intrusions and the gold deposits (cf. Partington & McNaughton, 1997). Despite this, no gold deposits are located within the granitoids, nor in related extrusive rocks of the Edith River Group, in contrast to sheeted vein systems in granitoids that characterise many intrusion-related gold provinces (e.g., Lang *et al.*, 2000).

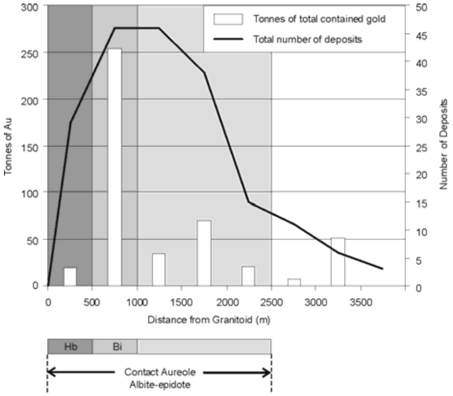

Figure 2. Distribution of gold deposits away from granitoid contacts (in 3-D), showing the position of the hornblende (Hb) and biotite (Bi) zones of the albite-epidote contact-metamorphic aureole.

5 AGE OF MINERALISATION

5.1 *Geological evidence*

Many of the geological timing constraints on gold mineralisation in the PCO are equivocal. However, gold mineralisation is dominantly epigenetic and confined to quartz-sulphide±carbonate veins, which clearly formed after the intrusion and deformation of the Zamu Dolerite, regional metamorphism, and cleavage development, as defined by cross-cutting relationships. This indicates a post-1.85 Ga age for all gold deposits in the region.

Gold-bearing veins at the Toms Gully deposit are cut by lamprophyric and granitic dykes that are contemporaneous (Sheppard *et al.*, 1991) with the 1831 ± 6 Ma Mount Bundey Granite (Geoscience Australia), which demonstrates that mineralisation pre-dates one of the earliest granitoid phases. Mutually cross-cutting relationships between Sn-Ta-bearing pegmatites and gold-bearing quartz veins at Mount Shoobridge suggest a late-stage magmatic timing. However, gold mineralisation along the sheared sedimentary rock-granitoid contact at Bonrook provides evidence for post-intrusion gold deposition, as does comparable mineralisation at the Gold Ridge Au-PGE deposit. Similarly, alteration along faults within a granitoid, which are related to a structure that localises gold mineralisation at Golden Honcho, also suggests a post-intrusion timing.

Despite these conflicting relationships from small and/or atypical PCO gold occurrences, there is significant evidence for a post-contact metamorphic timing for many of the larger and more typical gold deposits in the orogen. Textural evidence from veins and alteration at Cosmo Howley, Enterprise, Mount Todd and Woolwonga shows that gold mineralisation post-dates contact metamorphism (Etheridge & Holyland, 1985; Kavanagh & Vooys, 1990; Matthäi *et al.*, 1995; Hein, 2003). Importantly, the syn-flexural slip folding saddle-reefs at many of these larger deposits are unmineralised, except where they are cut by later generations of gold-bearing quartz veins.

5.2 *Isotopic dating*

Preliminary U-Pb age data for the sedimentary rock-hosted Goodall deposit (Quick, 1994) were obtained by Compston & Matthäi (1994), who separated monazite, xenotime and zircon grains from a gold-bearing quartz vein. Interpretation of the zircon data suggested a maximum depositional age of 1863 ± 7 Ma for the contact-metamorphosed host-rock (Compston & Matthäi, 1994). Additionally, 24 analyses were made on two large grains of monazite (D.M. Compston, oral commun., 2003). From interpretation of these data, 15 analyses provided a pooled mean ^{207}Pb/^{206}Pb age of 1810 ± 10 Ma, which was reported as the age of gold mineralisation by Compston & Matthäi (1994), but could equally be the age of incorporated contact-metamorphic grains (cf. Rasmussen *et al.*, 2001). Two of the lead analyses were older (~1900 Ma) and seven were younger (1750-1624 Ma). The analyzed sites had concentrations of 350 to >2500 ppm U and common lead was low, indicating reasonably reliable results (D.M. Compston, pers. comm., 2003). The xenotime yielded five ages ranging from 1831 to 1637 Ma (D.M. Compston, oral commun., 2003).

Methodology used in this earlier work is considered inappropriate, as it failed to establish the textural relationships between the monazite and gold mineralisation at Goodall. To overcome this problem, monazite grains were located in polished-section using a SEM at the Centre for Microscopy and Microanalysis at the University of Western Australia. Only those monazite grains completely enclosed by vein quartz, and clearly showing an association with vein-stage pyrite and microscopic gold, were analysed (Fig. 3). Only one monazite grain or cluster of sufficient diameter (>10µm) for SHRIMP analysis was located in each polished-section examined.

The resulting data provide a pooled mean ^{207}Pb/^{206}Pb age of ~1750 ± 40 Ma for Goodall, which corresponds broadly to the ages of the seven younger monazites in the previous study. The large error is attributed to few measurements (14 analyses) and small, inclusion-rich grains, with low to moderate uranium concentrations (~110-730 ppm). However, as analysed monazite is texturally related to gold, this age is considered the best current estimate for gold mineralisation at Goodall. Importantly, the age is younger than the last phase of granitoid intrusion.

To test whether other large gold deposits in the PCO might be of similar age, a pilot study of monazite grains located in high-grade mineralisation from the Union Reefs deposit was also undertaken. Although few grains were located, preliminary indications are that the age of mineralisation for this deposit falls between 1800 and 1700 Ma. Current data are imprecise and overlap with the youngest possible age of granitoid intrusion. Further work on this and other deposits is in progress.

In addition, monazites from the Gold Ridge Au-PGE deposit (Şener *et al.*, 2002) provide preliminary age data on one of the more atypical gold occurrences. Their analysis yields younger ages of ~1610 ± 80 Ma. The large error is again attributed to few measurements, relatively low uranium counts and the effects of pitted and imperfect grains. Despite this, the pooled age is sufficiently young to demonstrate that this mineralisation style also post-dated contact metamorphism.

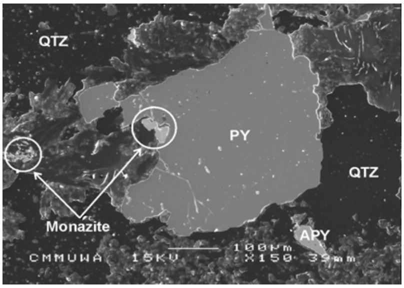

Figure 3. Example of hydrothermal monazite dated in this study. Pyrite (PY), accessory arsenopyrite (APY) and monazite are closely related in vein-quartz (QTZ) and gold (located just off image).

6 DISCUSSION AND CONCLUSIONS

Current field and geochronological data suggest that many gold deposits in the PCO are younger than the youngest phase of the Cullen Suite granitoids and post-date peak contact metamorphism. Despite this, the broad spatial relationship between gold deposits and the granitoid intrusions suggests that the mineralisation is influenced by the distribution of the granitoids. This is probably a result of the mechanical behavior of the contact aureole with respect to regional stresses, combined with post-crystallisation thermal effects of the HHP granitoids (e.g., McLaren *et al.*, 1999).

The deposits are best viewed as a variant of the orogenic gold, rather than intrusion-related, deposit type. In addition to their post-magmatic timing, they lack the endocontact sheeted vein systems, regional metal zonation and spatial relationship with major Sn and W deposits shown by intrusion-related gold deposits. Thus, proposed intrusion-related or contact-aureole models for the formation of the gold deposits in the PCO must be seriously questioned.

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