

Major orogenic gold episode associated with Cordilleran-style tectonics related to the assembly of Paleoproterozoic Australia?

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ABSTRACT

New *in-situ* SHRIMP (sensitive, high-resolution ion-microprobe) U-Pb analyses of hydrothermal phosphates associated with orogenic gold mineralization in the Paleoproterozoic Ashburton and Pine Creek gold provinces of northern Australia provide ages of ca. 1740 and ca. 1730 Ma, respectively. Argon-argon analyses of gold-related hydrothermal micas from the Tanami gold province of northern Australia provide ages of ca. 1730 Ma. It is important to note that late-orogenic events across the western half of Australia coincide with gold metallogenesis across this time interval, in several widely separated provinces. Thus, this orogenic gold episode is interpreted to relate to late-tectonic events during the amalgamation of various continental blocks to form Paleoproterozoic Australia. It is potentially Earth's best-preserved record of orogenic gold formation during a major early Precambrian continental assembly event.

Keywords: Orogenic gold, SHRIMP data, monazite, xenotime, Pine Creek inlier, Ashburton province.

INTRODUCTION

Paleoproterozoic gold provinces of northern Australia (Fig. 1) have been considered separate entities, with different evolutionary paths and metallogenic development. As a result, models for gold-deposit genesis were developed independently and became province-centric. In the Ashburton gold province (Western Australia), the sedimentary rock-hosted gold deposits have features typical of both Carlin and orogenic styles (Young et al., 2003). In the Pine Creek gold province (Northern Territory), contact-aureole or intrusion-related models have been proposed (Wall and Taylor, 1990; Matthäi et al., 1995). Genetic models for these and other Paleoproterozoic gold deposits, such as those in the Tanami gold province, have been constructed without precise geochronology. New geochronological constraints on the timing of mineralization are presented here for the Ashburton and Pine Creek gold provinces. These data are combined with published geochronological data and placed within a geotectonic framework for Paleoproterozoic Australia to demonstrate temporal and possible tectonic links between the three gold provinces discussed here.

GEOLOGICAL SETTING OF DATED GOLD PROVINCES

The Ashburton gold province lies within the Ashburton province, which lies to the south and west of the Pilbara craton in Western Australia (Fig. 1). In the Ashburton province, sedimentary and volcanic rocks were deposited on an Archean to late

Paleoproterozoic basement between ca. 2200 and 1690 Ma (Krapež, 1999). Sedimentation was followed by fold-thrust deformation and peak metamorphism during the poorly constrained 1830–1740 Ma Capricorn orogeny, which involved the Ashburton province, the northern margin of the Yilgarn craton, and the southern margin of the Pilbara craton (Fig. 1). Dextral and sinistral strike-slip deformation, probably linked to indentation by the Yilgarn craton, characterized the final stages of the Capricorn orogeny (Krapež, 1999). The nearest granitoids to the main gold deposits are ~80 km away, and are dated at ca. 1795 Ma (Krapež and McNaughton, 1999).

Several samples of gold ore from the 1.0 million ounce Mount Olympus deposit (24.43°S; 117.89°E) are used for geochronology. The deposit is one of several structurally controlled deposits within a regional-scale northwest-trending dextral-fault system (Young et al., 2003). The deposit is hosted by conglomerate, sandstone, siltstone, and carbonate-bearing rocks of the Mount McGrath Formation. Mineralization consists of submicrometer-sized or solid-solution gold in disseminated arsenian pyrite in quartz-sericite alteration, which postdates regional metamorphic fabrics. The upper temperature and pressure limits for this gold deposition are 350 °C at 1–2 kbar (Young et al., 2003).

The Pine Creek gold province is located in the Pine Creek inlier, Northern Territory (Fig. 1). In the Pine Creek inlier, sedimentary and minor volcanoclastic rocks were deposited on rifted Archean granitic

crust between ca. 2200 and 1870 Ma (Needham et al., 1988). Sedimentation was followed by fold-thrust deformation, peak metamorphism and continental arc-type magmatism during the 1870–1850 Ma Nimbuwah event (Needham et al., 1988), which is correlated to the regional Barramundi orogeny (Etheridge et al., 1987). Widespread, calc-alkalic, post-collisional, variably fractionated and reduced, high-heat-producing granitoids were emplaced during the ca. 1835–1800 Ma Cullen magmatic event (Wyborn, 1988; Stuart-Smith et al., 1993), which was broadly synchronous with the collision of the Kimberley craton into northern Australia (Fig. 1).

Gold-bearing veins from the 0.3 million ounce Goodall deposit (13.21°S; 131.37°E) are used for geochronology. The deposit is hosted by graywacke, siltstone, and shale of the upper Burrell Creek Formation (1863 ± 7 Ma SHRIMP U-Pb zircon age; Compston and Matthäi, 1994) and is typical of many in the region, hosted by an anticlinal hinge zone in the outer contact-metamorphic aureole of the Burnside Granite (ca. 1800 Ma SHRIMP U-Pb zircon age; Stuart-Smith et al., 1993). Discordant gold-bearing veins and alteration assemblages overprint porphyroblastic cordierite and andalusite in hornfels. The upper temperature and pressure limits for this gold deposition are 320 °C at ~1 kbar (Şener et al., 2003).

The Tanami gold province is located in the Tanami inlier, Northern Territory (Fig. 1). In the Tanami inlier, sedimentary and minor volcanic rocks were deposited on rifted Archean basement after ca. 1880 Ma

(Hendrickx et al., 2000). These rocks were deformed and metamorphosed between ca. 1850 and 1825 Ma (Vandenberg et al., 2001) and emplacement of granitoids occurred at ca. 1830–1790 Ma (Dean, 2001). These events were broadly coincident with those in the Pine Creek inlier.

Gold-related biotite mica from ore-stage quartz veins or from proximal alteration were obtained from the 3.9 million ounce Callie gold deposit (20.49°S: 129.91°E) and were analyzed and interpreted by Wygralak et al. (2001). The deposit is controlled by a series of faults localized in an east-plunging anticline. The upper temperature and pressure limits for this gold deposition are 360 °C and 1–2 kbar (Wygralak et al., 2001).

ANALYTICAL METHOD

In this study, gold-related monazite [(REEs,Th)PO₄, where REEs are rare earth elements] or xenotime (YPO₄) were located from polished thin-sections by using a scanning electron microscope (SEM). Texturally well-constrained phosphates were identified that were contained entirely within gold-stage alteration (Mount Olympus) or quartz veins (Goodall) and that displayed a close spatial association with either gold-stage sulfides or microscopic gold particles. Inclusion-free phosphates of >10 µm diameter were drilled out, mounted in epoxy discs, and analyzed by using *in-situ* SHRIMP II, U-Pb analysis. Monazites were analyzed by following the analytical procedures of Foster et al. (2000), and xenotime analyses used the methods of Fletcher et al. (2004). Ages given are weighted-mean ²⁰⁷Pb/²⁰⁶Pb ages at 95% confidence.

GEOCHRONOLOGICAL DATA

The new geochronological data¹ are summarized in Figure 2. Most analyses of xenotime from Mount Olympus have low levels of common lead (mean ²⁰⁶Pb_c = 0.19%; eight analyses with ²⁰⁶Pb_c > 1% were rejected). The main data group, of 18 analyses, yields a reliable mineralization age of 1738 ± 5 Ma, with a small excess scatter (MSWD [mean square of weighted deviates] = 1.1). This main group excludes a number of older and younger analyses of xenotime, for which, textural relationships with gold-related pyrite indicate pre- or post-gold timings. Approximately half of the analyses for Goodall monazite have unacceptably high contents of common Pb (²⁰⁶Pb_c > 1%) and are not used in age determination. Although the residual data group of 24 analyses is generally discordant (average concordance of 95%), the data are well

grouped, and any offset from concordance may be due to compositional differences between samples and standards. The good grouping is considered to indicate well-preserved U-Pb systems and to give reliable geochronological data. After exclusion of a further ten ages which correspond mainly to a well-defined but localised metamorphic event at ca. 1775 Ma (Shoobridge event of Stuart-Smith et al., 1993), yields a reliable mineralization age of 1727 ± 13 Ma, with a small excess scatter (MSWD = 1.2).

Existing geochronological data for the Callie gold deposit define mineralization ages broadly similar to those given above. ⁴⁰Ar/³⁹Ar analyses of alteration and vein-hosted biotite yield ages of ca. 1730–1666 Ma (Wygralak et al., 2001) and converge on ca. 1730 Ma (Skirrow et al., 2002). Given that the conditions of gold mineralization (generally >300 °C) are higher than the blocking temperatures for biotite (~300 °C), it is likely that the ⁴⁰Ar/³⁹Ar ages record minimum ages of mineralization (Wygralak et al., 2001). However, even these ages cannot be directly correlated with ages based on the U-Pb in phosphate because there is an ~1% uncertainty in the decay constants for the argon system (Min et al., 2000). The ca. 1730 Ma ⁴⁰Ar/³⁹Ar age could be equivalent to ca. 1740 Ma, and hence within range of the Ashburton SHRIMP U-Pb age, but this possibility is uncertain. The argon data, however, do indicate a broadly contemporaneous gold event in the Tanami inlier, linked to convergence at 1740–1730 Ma (Fig. 1).

COINCIDENT TECTONIC ACTIVITY

The dynamic Paleoproterozoic evolution of the Australian continent was dominated by the amalgamation of various Precambrian provinces over several million square kilometers (e.g., Myers et al., 1996). However, models proposed for the assembly of proto-Australia and other Paleoproterozoic continental blocks remain the subject of debate. The absence of blueschists, accretionary complexes or mélangé zones, belts of magmatic arc-type rocks, and ophiolite complexes, typical of modern-style subduction tectonics, together with the occurrence of bimodal igneous rocks, in many Australian Paleoproterozoic provinces has been used to support models of vertical accretion and reworking in an intracratonic setting (e.g., Etheridge et al., 1987). However, there has been increasing recognition of evidence for convergent-margin tectonism, leading to plate-tectonic models involving subduction, collisional,

and/or escape tectonics (e.g., Myers et al., 1996; Krapež, 1999; Giles et al., 2002). Despite this growing consensus, precise tectonic models for the assembly of proto-Australia prior to ca. 1700 Ma are evolving and still subject to some debate.

In one model—based primarily on the geology of Paleoproterozoic provinces within Western and Southern Australia (Krapež, 1999; Krapež and Martin, 1999)—the Pilbara and Gawler cratons are considered to have been initially contiguous; this model proposes eastward indentation during 1740–1700 Ma following oblique convergence at 1830–1740 Ma. This indentation of a Yilgarn foreland indenter into a Pilbara-Gawler hinterland is interpreted to have initiated (1) a sinistral strike-slip megashear extending through the Capricorn orogen and (2) associated fault-bounded escape corridors, including one through the Ashburton gold province. The indentation phase is broadly synchronous with the new dates for gold mineralization.

An alternative model envisages long-lived but episodic accretionary events and magmatic arc development associated with north-dipping subduction at the then southern margin of a north Australian continental block from 1800 to 1730 Ma (e.g., Giles et al., 2002). In this scenario, the Gawler craton is considered separate from the Yilgarn and Pilbara cratons. Collision of the south Australian continental block with the southern margin of the north Australian block (Fig. 1) is interpreted to have occurred at 1740–1730 Ma (Giles et al., 2002). During this time, an episodic extensional stress regime is interpreted to have developed in the north Australian block, caused by rollback of the subducting slab. This regime is interpreted to have resulted in lithospheric thinning, mafic underplating, and elevated heat-flow across much of northern Australia, in addition to emplacement of several granitoid suites within terranes proximal to the collision front (Giles et al., 2002; Betts et al., 2002).

Despite these conflicting models, there is consensus that Paleoproterozoic proto-Australia was amalgamated by ca. 1700 Ma, with periods of transitory shortening and basin inversion throughout northern Australia between ca. 1750 and 1720 Ma (e.g., Krapež, 1999; Krapež and Martin, 1999; Jackson et al., 2000; Betts et al., 2002; Giles et al., 2002); the period covering the ages of gold deposits dated in the Ashburton, Pine Creek, and Tanami gold provinces.

A MAJOR GOLD EPISODE?

The new geochronological data, coupled with existing ages of gold mineralization, suggest that 1750–1720 Ma represents a widespread gold mineralization episode in northern Australia. Coincident and broadly similar tectonic activity during this interval suggests a common cause. Specifically, the broad coincidence of ages of deposits in gold provinces several thousand kilometers apart with the late deformation events that affected their hosting and surrounding provinces suggests the involvement of a major hydrothermal gold event linked to continent-scale tectonism. It is evident that, whichever tectonic model is accepted, this period represents the near-final amalgamation of Archean and Paleoproterozoic crustal domains, with attendant postcollisional continent-scale tectonism, high heat-flow, and basin inversion related to compressional and transpressional deformation, in addition to episodic extension and local basin formation.

DISCUSSION

The geochronological data demonstrate that deposits of the Ashburton, Pine Creek, and Tanami gold provinces are not temporally related to the main periods of granitoid magmatism in these provinces. It is also apparent that they formed during the latter stages of an Australia-wide orogenic event at ca. 1750–1720 Ma that resulted in amalgamation of the north Australian, west Australian, and south Australian continental blocks. The best analogs are orogenic gold provinces (e.g., Groves et al., 1998) in which gold deposits were deposited broadly contemporaneously over extensive regions and show gross spatial relationships to granitoids, although they may predate (e.g., Victorian Goldfields, Australia) or largely postdate (e.g., Eastern Goldfields, Western Australia) adjacent granitoids (Groves et al., 1998). Such deposits formed from a distal and deep, auriferous, low-moderate salinity $\text{H}_2\text{O}-\text{CO}_2 \pm \text{CH}_4$ fluid source, as is also indicated for the Ashburton, Pine Creek, and Tanami deposits, although the precise fluid source is equivocal.

Of particular interest to understand the controls on gold mineralization and the variable endowment of the Paleoproterozoic gold provinces are the models of Betts et al. (2002) and Giles et al. (2002) that involve rollback of the slab subducting beneath the north Australian block. This process would cause enhanced subcontinental convection and lithospheric thinning along the southern margin of the north Australian block, resulting in elevated lower- to middle-crust

heat flow that is needed to trigger flux of large volumes of auriferous fluid required to form world-class orogenic gold deposits (e.g., Goldfarb et al., 2001). In this model, the Tanami gold province would have been proximal to this accretionary margin, whereas the Ashburton and Pine Creek gold provinces would have been distal to such an accretionary margin. It is important to note that of these gold provinces, the Tanami has the largest known gold endowment.

Orogenic gold provinces formed during distinct periods in Earth history, broadly coincident with major orogenic and continental crust-forming events (e.g., Goldfarb et al., 2001). Phanerozoic, particularly Mesozoic to Cenozoic, analogs define elongate, semicontinuous provinces, whereas Archean and Paleoproterozoic provinces have been partly dismembered by later events. The remarkable preservation, since the Paleoproterozoic, of northern Australia makes its newly understood gold provinces potentially Earth's best-preserved record of orogenic gold-deposit formation in a major early Precambrian continental-assembly event. However, further robust dating is required to determine whether the dated deposits, other deposits in the same provinces, and deposits in other Paleoproterozoic gold provinces formed in a single event or represent different evolutionary stages in an evolving orogenic province undergoing an extended and complex period of postcollisional crustal responses. Such responses include extension or transtension as a result of tectonic escape and intermittent compression and transpression caused by the jostling of crustal domains during the waning stages of continental assembly. Experience in most Phanerozoic Cordilleran settings suggests that a 20 m.y. period (the approximate uncertainty in duration of the proposed Paleoproterozoic gold event) may encompass several gold events within a single accreting margin (Goldfarb et al., 2001). Further dating will not only resolve the metallogenic history, but also help to constrain the tectonic history of Paleoproterozoic proto-Australia.

ACKNOWLEDGMENTS

D.M. Compston, M.A. Etheridge, N.J. McNaughton, N.M. Vielreicher, and A.S. Wygralak provided useful comments. Sponsorship was provided by Northern Gold NL, Sipa Resources International NL, and Newcrest Ltd. Staff at the Centre for Microscopy and Microanalysis (University of Western Australia) and the Western

Australian SHRIMP facilities, operated by a Western Australia university–government consortium with Australia Research Council (ARC) funding, provided technical support. The original manuscript was improved by the comments of R.J. Goldfarb and P. Brown.

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Figure 1. Paleoproterozoic reconstruction of proto-Australia at 1750–1700 Ma, showing age and direction of proposed collisions of continental blocks. Also shown are dated Paleoproterozoic gold provinces with approximate ages. NAC—north Australian continental block; SAC—south Australian continental block; WAC—west Australian continental block. Outlines of continental blocks adapted from Betts et al. (2002) and additional data derived from Myers et al. (1996), Krapež and McNaughton (1999), and Giles et al. (2002).

Figure 2. Concordia plots for two gold deposits of Pine Creek and Ashburton regions, with corresponding scanning-electron (SE) images of representative monazite and xenotime. A: Data obtained from Goodall deposit. B: Data obtained from Mount Olympus deposit. BSE—backscattered electron; SE—secondary electron; MSWD—mean square of weighted deviates.

