Archean gold mineralization synchronous with the final stages of cratonization, Yilgarn Craton, Western Australia

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ABSTRACT

Sm-Nd ages of pegmatite dikes that crosscut gold-bearing structures in the southern Yilgarn Craton, Western Australia, provide minimum age constraints of 2640 ± 11 Ma, 2628 ± 10 Ma, and 2620 ± 36 Ma for gold mineralization at the Westonia and Nevoria (Yellowknife Terrane) and Scotia (Norseman Terrane) gold deposits, respectively. Similarly, a post–gold mineralization dike at Westonia has a U-Pb zircon age of 2637 ± 8 Ma. These constraints are consistent with, and provide further support for, suggestions that the majority of gold deposits in the Yilgarn Craton formed during a regionally extensive gold mineralization event at ca. 2630 Ma (i.e., 2630 ± 10 Ma). In combination with recent geochronological results, these data also provide further evidence that, although mineralization appears to significantly postdate the majority of magmatic and metamorphic activity at higher crustal levels, widespread thermal reworking of the lower-middle crust, involving partial melting, amphibolite to granulite facies metamorphism, and lower crustal granitoid intrusion, occurred concurrently with gold mineralization at ca. 2630 Ma. It is probable that the large-scale hydrothermal fluid flow that produced widespread gold deposition was also part of this tectonothermal event. Models developed for other Archean terranes whereby gold mineralization postdates formation and cratonization of host granite-greenstone terranes, and is therefore unrelated to these processes, are not required to explain the timing of the majority of gold deposits in the Yilgarn Craton.

INTRODUCTION

Understanding of the timing of Archean gold mineralization with respect to tectono-thermal events, such as magmatism or metamorphism, in Archean granite-greenstone terranes strongly influences geological thinking concerning the origin of these enigmatic deposits. Studies from gold deposits within the Abitibi Subprovince, Canada, and gold-tungsten deposits within the Zimbabwe craton have reported 40Ar/39Ar, Rb-Sr, Sm-Nd, and U-Pb ages of hydrothermal phases that are significantly younger (30–100 Ma) than the age of magmatism and metamorphism within the granite-greenstone terranes that host the deposits (e.g., Jemelka et al., 1990; Hanes et al., 1992; Zweng et al., 1993; Darbyshire et al., 1996). These results have been interpreted in terms of “late gold” models where mineralization is considered to have occurred significantly after, and by processes unrelated to, formation and cratonization of the granite-greenstone terranes that host the deposits (e.g., Hanes et al., 1992). This has proven a controversial suggestion, with other workers (e.g., Kerrich and Cassidy, 1994) considering that the younger radiometric ages of gold mineralization are the result of isotopic resetting. In the Yilgarn Craton of Western Australia (Fig. 1), geologic relations and geochronological results in some well-studied areas, such as the Kalgoorlie Terrane, indicate that gold mineralization at higher crustal levels occurred some 70 m.y. after greenstone belt deposition at c. 2700 Ma, and at least 20 to 30 m.y. after major episodes of felsic igneous intrusive activity (2690–2660 Ma) and metamorphism in the surrounding regions (Fig. 2; see references in figure caption). Thus, as gold mineralization postdates these major crust-forming events, the question can be asked: Is mineralization an intrinsic part of the development of the Yilgarn Craton? Or, in line with the “late gold” models discussed above, is mineralization imposed upon granite-greenstone terranes by processes unrelated to cratonization?

AGES OF POST–GOLD MINERALIZATION DIKES

For this study, Sm-Nd isochrons have been used to date samples of garnet-feldspar pegmatites, which demonstrably crosscut, and thus postdate, gold-bearing structures in three different locations, the Westonia and Nevoria deposits in the Yellowknife Terrane, and the Scotia Mine, at the southern end of the Norseman Terrane (Fig. 1). In addition, a U-Pb zircon age for a post–gold mineralization microgranite dike from the Westonia deposit is also reported.

Sm-Nd Dating of Post-Gold Pegmatite Dikes

All pegmatites analyzed exhibit similar mineralogy, consisting of quartz, K-feldspar (generally microcline), albite, garnet ± muscovite. Sm-Nd analytical results for mineral separates are listed in supplementary data Table A.1 Results of the regression of data from each sample is listed in Table 1.

Westonia. Regression of all Sm-Nd analyses for sample 93-1148 from Westonia produces an age of 2640 ± 11 Ma with a mean square of weighted deviates (MSWD) of 0.7 (all Sm-Nd ages are quoted at 95% confidence levels). This is interpreted as the age of pegmatite intrusion and is in good agreement with the U-Pb zircon age for emplacement of comagmatic microgranite dikes detailed below. An additional sample (91-1147) from this deposit appeared to have suffered disturbance of the Sm-Nd systematics and does not provide an estimate of the timing of pegmatite intrusion.

Nevoria. Regression of all analyses for three samples (93-1144, 93-1145, 93-1146) of pegmatite from the Nevoria deposit yields an age of 2623 ± 8 Ma, but with a high MSWD (139). Both albite aliquots analyzed from sample 93-1144 lie off the regression line, and removal of these from the regression produces an age of 2626 ± 18 Ma with a substantially lowered MSWD (4.7). The reason for discordant albite analyses in sample 93-1144 is unclear but is probably the result of localized isotopic remobiliza-


Table A.1 Resultsoftheregressionofdata

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tion. Regression of data from sample 93-1146 alone yields an age of 2628 ± 10 Ma, with a low MSWD (0.11). This is within uncertainty of the age obtained by regressing all Nevoria data and is considered the best estimate for the age of the pegmatite intrusion.

**Scotia.** Regression of all analyses for sample 91-237 from the Scotia deposit gives an age of 2616 ± 54 Ma, although the high MSWD (112) indicates significant nonanalytical scatter in this sample. Removal of two garnet aliquot analyses from the regression lowers the MSWD to 12, corresponding to an isochron age of 2620 ± 36 Ma. However, as there is little independent reason to remove these aliquots from the regression other than to reduce the scatter about the line of best fit, and as the improved MSWD values are still greater than acceptable values for a Model 1 isochron, this age can only be considered an estimate for the age of pegmatite intrusion, although it is within error of ca. 2600 Ma 40Ar/39Ar ages from muscovite from pegmatites in the Scotia mine.

**DISCUSSION**

Isotopic dating of hydrothermal minerals from gold deposits within the Yilgarn Craton has provided evidence for a craton-wide episode of gold mineralization at ca. 2630

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**Figure 1.** Radiometric ages of gold mineralization in the Yilgarn Craton. Gold mineralization age sources: Golden Mile—Kent and McDougall, 1995; Griffin’s Find—Barnicoat et al., 1991; Matilda—Kent and Hagemann, 1996; Reedy’s—Wang et al., 1993; Victory—Clark et al., 1989. Granitoid age sources: Hill et al., 1992; Wiedenbeck and Watkins, 1993; Qiu et al., 1995; I. H. Campbell, 1994, personal commun.

**Figure 2.** Comparison between the timing of gold mineralization within the Yilgarn Craton and the timing of magmatic and metamorphic events within the Kalgoorlie Terrane. Data sources: Campbell and Hill, 1988; Hill et al., 1992; Kent and McDougall, 1995.

**U-Pb Zircon Ages of Westonia Microgranite Dike**

Zircons separated from a post–gold mineralization microgranite dike sample (86-305) from Westonia were analyzed on the SHRIMP I ion-microprobe (Compston et al., 1984). Zircons from this sample have been previously analyzed, with an age of 2637 ± 7 Ma reported by Hill et al. (1992). For this study, the sample was reanalyzed using the more homogeneous SL 13 zircon standard. Full analytical U-Pb data are available as supplementary data Table B. Zircons from sample 86-305 have suffered variable degrees of Pb loss, with most analyses showing some discordance (Fig. 3). However, a population of zircons can be identified with indistinguishable 207Pb/206Pb ages (within 2σ errors) and a weighted mean 207Pb/206Pb age of 2637 ± 8 Ma (95% confidence limits). A discordia regression line (Fig. 3) has intercepts at 2636 ± 16 Ma and 10 ± 236 Ma with no excess scatter (MSWD = 1.01). The upper intercept age agrees well with the weighted mean 207Pb/206Pb age of this population, and the lower intercept, albeit with a large uncertainty, coincides with intense modern weathering of the Yilgarn Craton. This is evidence that Pb loss within zircon analyses that define the principal population occurred during modern times and that these zircons did not suffer significant Proterozoic or Phanerozoic Pb loss. Thus, the 208Pb/206Pb weighted mean age of 2637 ± 8 Ma for the principal population is considered the best estimate of the age of emplacement of the microgranite dike.

**DISCUSSION**

Isotopic dating of hydrothermal minerals from gold deposits within the Yilgarn Craton has provided evidence for a craton-wide episode of gold mineralization at ca. 2630
Ma (i.e., 2630 ± 10 Ma). At present, gold deposits from five widely spaced locations have radiometric ages of ca. 2630 Ma (Fig. 1; see references in figure caption). These deposits formed at a range of crustal depths (from greenschist to granulite metamorphic grade; Barnicoat et al., 1991; Groves, 1993; Kent and McDougall, 1995). Geologic and geochemical similarities (and systematic variations with changing pressure-temperature conditions) between these and other, as yet undated, deposits suggests that the majority of gold deposits within the Yilgarn Craton formed at ca. 2630 Ma during a crustal-scale episode of hydrothermal fluid flow (Groves, 1993). One or more younger gold deposits also are present in the craton (e.g., Mount Charlotte deposit, Kalgoorlie Terrane; Kent and McDougall, 1995). However, these deposits appear to be relatively restricted and probably formed as a result of relatively localized processes.

Sm-Nd isochron ages for pegmatites that crosscut, and thus postdate, gold mineralization in three locations in the southern Yilgarn Craton provide minimum estimates for the timing of mineralization. Thus, at the Westonia, Nevoria, and Scotia deposits, gold mineralization occurred at or before 2640 ± 11 Ma, 2628 ± 10 Ma, and 2620 ± 36 Ma, respectively. The suitability of the Sm-Nd technique for dating the primary crystallization of these rocks is confirmed by the 2637 ± 8 Ma U-Pb zircon age of a microgranite dike comagmatic with pegmatite intrusion at the Westonia deposit. These results are also similar to the 2620 ± 6 Ma Pb-Pb whole rock isochron age reported by Bloem et al. (1995) for post-gold pegmatite intrusion at the Corinthia mine, also located within the Yellowdine Terrane (Fig. 1). Although the ages for post-gold pegmatite intrusions strictly provide only minimum constraints for the timing of mineralization, they are consistent with mineralization at these deposits occurring during a regionally extensive gold mineralizing event at ca. 2630 Ma (Fig. 1). Furthermore, at the Corinthia deposit, Bloem et al. (1995) argued that pegmatite intrusion occurred either immediately after mineralization or during the final stages of hydrothermal activity. The presence of sillimanite veinslets within sample 93-1147 from Westonia also implies that pegmatite intrusion occurred at, or soon after, amphibolite facies peak metamorphism and synmetamorphic gold mineralization.

**Relationship Between Magmatism, Metamorphism, and Mineralization**

Although gold mineralization demonstrably postdates granitoid intrusion and greenstone belt metamorphism within the more shallowly exhumed regions of the Yilgarn Craton, such as the Kalgoorlie Terrane (Fig. 2; Clark et al., 1989; Kent and McDougall, 1995), there is now an emerging amount of geochronological data to suggest that regional gold mineralization at ca. 2630 Ma was synchronous with an episode, not previously well recognized, of partial melting and granitoid intrusion and amphibolite-granulite metamorphism within the more deeply exhumed parts of the craton. This is in agreement with the "crustal continuum" model for lode gold mineralization of Groves (1993), who postulated synchronous gold mineralization over a large area of the Yilgarn Craton in conjunction with deep crustal metamorphism. Granitoid rocks of ca. 2630 Ma age have been reported in a number of areas within the Yilgarn Craton (Fig. 1), although they appear volumetrically minor with respect to granitoids intruded between 2690 and 2660 Ma (e.g., Hill et al., 1992; Weidenbeck and Watkins, 1993; Qiu et al., 1995). These rocks are predominantly located in the southern and western parts of the craton, in areas such as the Yellowdine and Murchison Terranes. The greenstone belts in these regions are characterized by amphibolite or granulite metamorphism, suggesting that the ca. 2630 Ma granitoids are largely restricted to relatively deeply exhumed parts of the craton (compared to regions such as the Kalgoorlie Terrane that are dominated by greenschist facies assemblages; e.g., Ridley, 1993). Radiometric ages of ca. 2630 Ma for pegmatites from the southern Yilgarn Craton detailed in this study and in Bloem et al. (1995)

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**Figure 3.** $^{207}Pb/^{235}U$ vs. $^{206}Pb/^{238}U$ plot for zircons from microgranite sample 86-305 from the Westonia deposit.
provide further evidence for the presence of felsic melts within the crust at a time coincident with gold mineralization. Furthermore, the pegmatite ages reveal that at least some felsic magmatism at this time was spatially associated with gold mineralization and that intrusive activity continued until after the cessation of gold deposition.

Available data on the timing of metamorphism in the Yilgarn Craton, albeit limited, suggest that granulite and amphibolite metamorphism in the more deeply exposed segments of the crust occurred at a time broadly synchronous with gold mineralization. Textural and structural studies show that gold mineralization hosted within amphibolite and granulite facies greenstone belts is texturally synmetamorphic, whereas mineralization hosted within greenschist facies greenstone belts is postmetamorphic (e.g., Groves, 1993). U-Pb zircon and titanite dating by Nemchim et al. (1994) indicates that granulite metamorphism within the southwestern Yilgarn Craton occurred between 2650 and 2630 Ma, and Barnicoat et al. (1991) identified granulite metamorphism synchronous with gold mineralization at 2636 ± 3 Ma at Griffin’s Find, also in the southwest part of the craton (Fig. 1).

Partial melting and intrusion of granitoids and metamorphism within the more deeply exposed segments of the Yilgarn Craton at ca. 2630 Ma constitute the last major tectono-thermal event currently recognized within the craton. Regionally extensive gold mineralization at ca. 2630 Ma was contemporaneous (within the resolution of current dating techniques) with this widespread tectono-thermal episode, which suggests that the major crustal fluid flow considered responsible for gold mineralization (Groves, 1993) was probably an intrinsic part of the thermal reworking of the crust at this time. Thus, although gold mineralization demonstrably postdates greenstone belt deposition and metamorphism and granitoid intrusion within the more shallowly exposed levels of the crust, mineralization appears to be synchronous with metamorphism and granitoid intrusion at deeper crustal levels during the final stages of cratonization. Therefore, the regional episode of gold mineralization at ca. 2630 Ma appears to be an intrinsic part of the final stages of cratonization of the Yilgarn Craton.

This model contrasts with “late” gold models invoked for some deposits in the Canadian and Zimbabwe cratons where the young radiometric ages of mineralization cannot be related to a consistent and widespread episode of partial melt emplacement and/or metamorphism. Instead, the young ages for mineralization may be the result of isotopic resetting (Kerrich and Cassidy, 1994) and/or related to postaccretive activity unrelated to the final stages of development of these cratons. By analogy with the proposed model for mineralization in the Yilgarn Craton, it is proposed that the regional episodes of gold mineralization in these terranes may also be integral parts of the final stages of cratonization.

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