Tropicana deposit, Western Australia: an integrated approach to understanding granulite-hosted gold and the Tropicana Gneiss

by

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Introduction

Exploration models for lode gold deposits have emphasized the relatively low prospectivity of regions dominated by high-metamorphic grade gneisses relative to greenschist facies granite–greenstone terranes. The Tropicana Gold Mine, Western Australia, is the first major greenfields gold discovery in upper amphibolite to granulite facies gneissic rocks at the eastern margin of the highly endowed Yilgarn Craton.

Tropicana is a rare example of a world-class (cf. Schodde and Hronsky, 2006) gold deposit hosted in mid-amphibolite to granulite-facies gneisses. Other well-studied gold deposits hosted in high-grade metamorphic rocks include Hemlo in Canada, Renco in Zimbabwe, Challenger in South Australia, and Big Bell and Griffins Find in Western Australia. A protracted history of reactivation, re-equilibration, and remobilization of gold and associated metals in these deposits makes discerning the precise timing of the principal mineralization event(s) challenging. Research has focused on clarifying the timing of alteration, mineralization and deformation and relative to peak metamorphism.

The range of deposit styles are divisible into two categories: a) those deposits formed prior to peak metamorphism (metamorphosed gold deposits); and b) those related to events post-dating peak metamorphism (post-metamorphic gold deposits; Tomkins, 2013). Combined, detailed paragenetic studies, geochronology and theoretical studies suggest that the many gold deposits in high-grade metamorphic rocks can be explained by mineralization at greenschist facies conditions and subsequent metamorphism to mid-amphibolite or granulite facies (e.g. Challenger, Tomkins and Mavrogenes, 2002; Tomkins et al., 2004b; Griffins Find, Tomkins and Grundy, 2009; Hemlo, Tomkins et al., 2004a; Big Bell, Phillips and Powell, 2009). In contrast, multidisciplinary studies support a retrograde timing for shear-controlled gold mineralization at Renco (Blenkinsop and Frei, 1996).

Here we present a summary of studies completed in collaboration with multiple research partners that have placed important constraint on the mineralization, alteration, metamorphic and igneous crystallization events that are represented at the Tropicana gold deposit. Results of the Tropicana studies are placed in the context of the regional seismic line 12GA-T1 in a companion abstract by Occhipinti et al. (2014). The abstract summarizes research outcomes on Tropicana presented in key papers (Doyle et al., 2013; Blenkinsop and Doyle, 2014; Doyle et al., 2015) and readers are referred to those documents as a primary resource.

Project location and resource

The project, located within the remote Great Victoria Desert, is part of the Tropicana Joint Venture, which is 70% owned by AngloGold Ashanti Australia (the manager) and 30% by Independence Group NL (Fig. 1). Economic intercepts returned from diamond and reverse circulation (RC) drilling in mid-2005 at Tropicana prospect and in mid-2006 at Havana prospect formed the foundations for discovery and subsequent resource delineation/definition programs and feasibility studies (Doyle et al., 2007; Kendall et al., 2007). Approval for construction of the project was granted in November

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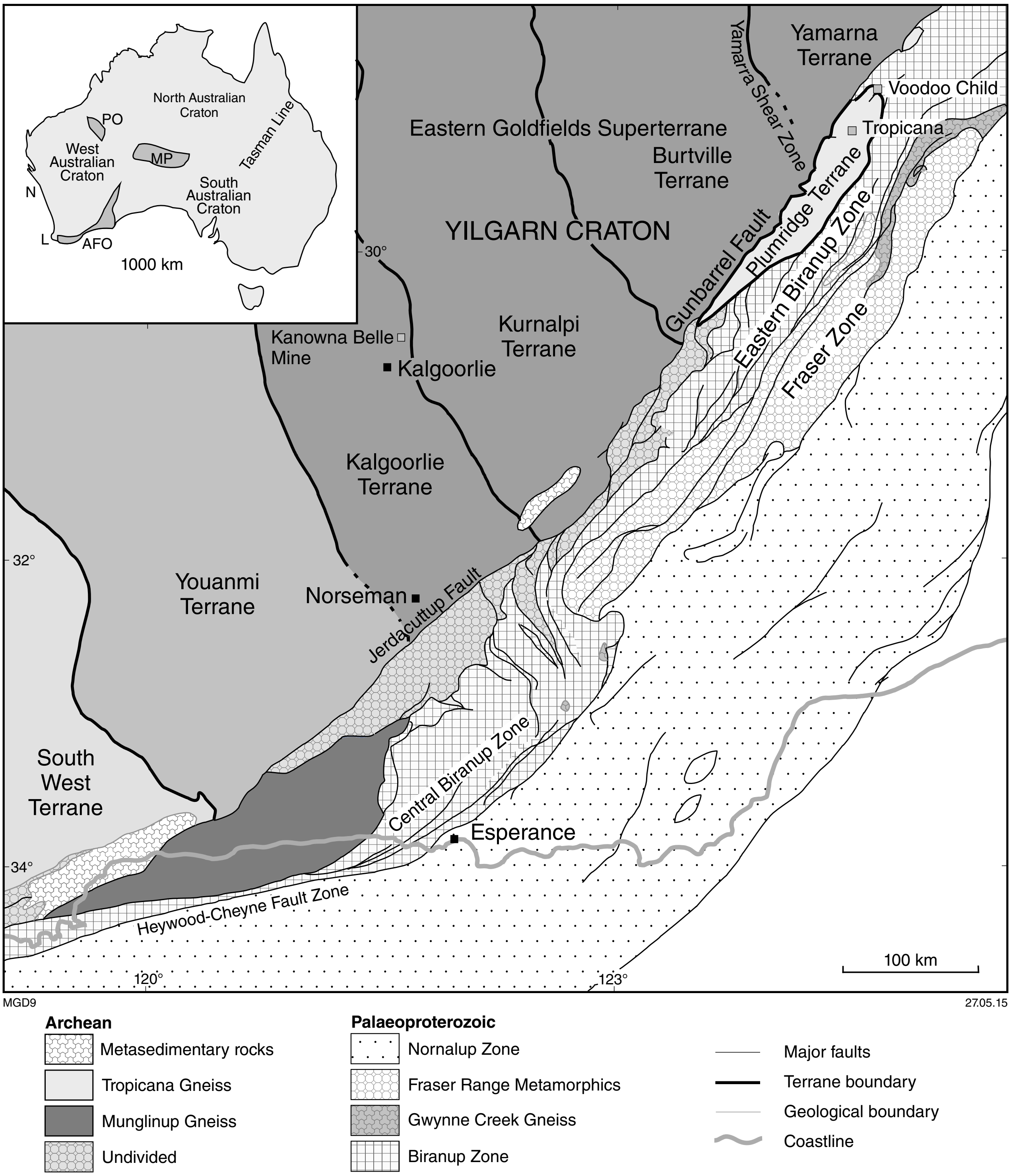

Figure 1. Geological map showing the location of the Tropicana gold deposit in the far northeast of the Albany–Fraser Orogen, and major greenstone-hosted gold deposits in the Yilgarn Craton (modified after Spaggiari et al., 2011)

2010, and construction of the mine commenced in the June quarter of 2011. The first gold pour from openpit mining was completed on schedule in the December quarter of 2013 (Doyle et al., 2013). The approved project will have a 10-year mine life and in the first three years of operation, gold production will be between 470 000 – 490 000 oz/pa at a cash cost of A$580–600/oz.

Reserves as at December 2011 total 56.4 Mt grading 2.16 g/t Au for 3.91 Moz of gold (AngloGold Ashanti Ltd, 2011). In December 2012, the joint venture partners announced an increase in the mineral resource estimate by 1.48 Moz to 7.89 Moz of contained gold, including measured resources of 29.8 Mt at 2.12 g/t Au for 2.03 Moz, indicated resources of 76.4 Mt at 1.95 g/t Au for 4.78 Moz, and inferred resources of 11.9 Mt at 2.83 g/t Au for 1.08 Moz. Mineral resource is inclusive of that mineralization included in ore reserves (AngloGold Ashanti Ltd, 2012; Doyle et al., 2013).

Regional geological setting

Exposures of Precambrian basement rocks are scarce within the northern and central parts of the Albany–Fraser Orogen due to widespread sand cover and locally extensive Tertiary and Permian sedimentary sequences. Acquisition of detailed proprietary magnetic, gravity and airborne EM datasets to supplement lower resolution pre-competitive geophysical data has underpinned interpretations of the regional geology in this region. When combined with geochronological and geochemical studies of rocks sampled from geographically disparate outcrops and exploration drillholes, an incomplete but robust geological and tectonic history can be resolved.

The Tropicana Gneiss (Tropicana domain, of Doyle et al., 2013) includes lithologically diverse associations of orthogneiss and subordinate paragneiss that form part of the eastern margin of the Yilgarn Craton (Doyle et al., 2009; Blenkinsop and Doyle, 2014). The domain is characterized by a gravity high and dominantly north-northwest to northeast-trending magnetic pattern that marks the position of Neoarchean reverse (thrusts) faults that define multiple duplexes, including the Tropicana, Iceberg, and Madras duplexes of Blenkinsop and Doyle (2014).

The Tropicana Gneiss hosts the Tropicana gold deposit and at this latitude is approximately 27 km wide, but has a near surface expression that is greater (~35 km) to the south, and is narrow (a few kilometres) and discontinuous to the north around the Hercules prospect (Blenkinsop and Doyle, 2014). The Tropicana Gneiss is interpreted to extend over a strike length of at least 80 km, although it is obscured by Paleoproterozoic rocks of the Voodoo Child Domain in the Voodoo Child and Hercules prospect areas, 50–70 km north of the Tropicana mine (Blenkinsop and Doyle, 2014).

The Tropicana Gneiss comprises a fault-bound assemblage of rocks with a distinct geological history and is ascribed to the Plumridge Terrane of the Yilgarn Craton by Blenkinsop and Doyle (2014). Structural and lithostratigraphic elements in the Yamarna and Burtville Terranes of the Yilgarn Craton cannot be traced eastward into the Tropicana Gneiss on the basis of magnetic and gravity datasets, although relationships are obscured by thick (>300 m) sedimentary sequences (Paterson Formation) which fill the Gunbarrel Basin. In seismic line 12GA-T1, crustal elements of the Yamarna Terrane are interpreted to extend below Tropicana Gneiss — the contact between the two being marked by an approximately 300 m-thick east-dipping detachment fault, the Plumridge Detachment (Occhipinti et al., 2014).

The Gunbarrel Basin is bound along its eastern margin by the steeply west-dipping, Phanerozoic, Gunbarrel Fault which cuts and displaces Neoarchean and Proterozoic faults and shears dissecting the Tropicana Gneiss. Shears within the Tropicana Gneiss are characterized by sericite–chlorite-dominant assemblages indicative of greenschist facies conditions, in contrast to the upper amphibolite to lower granulite-facies mineral assemblages which characterize peak metamorphism in the gneissic rocks (Doyle et al., 2013; Blenkinsop and Doyle, 2014).

To the east and northeast of the gold mine, the Tropicana Gneiss is in faulted contact with the Black Dragon domain (c. 1800 Ma rocks; Blenkinsop and Doyle, 2014) and Voodoo Child domain (c. 1760 Ma; Bunting et al., 1976; Kirkland et al., 2011; Less, 2013) of the Biranup Zone (Blenkinsop and Doyle, 2014; Occhipinti et al., 2014). Diverse associations of metasedimentary and igneous rocks ranging from c. 1800 to 1620 Ma were ascribed to the Biranup Zone (e.g. Spaggiari et al., 2009; Kirkland et al., 2011; Spaggiari et al., 2011). Hf-isotopic signatures and enclaves of Archean basement are interpreted to record a source incorporating both Archean crust and juvenile mantle-derived components for the Biranup Zone (Kirkland et al., 2011). The Biranup Zone is interpreted to record either an arc to back-arc setting on the active craton margin, or to have been emplaced in post-orogenic extensional basins (e.g. Bunting et al., 1976; Kirkland et al., 2011).

Tropicana geology

Mineral resources at the Tropicana Gold Mine encompass four mineralized zones distributed along an approximately 5 km strike length. They are, from north to south, the Boston Shaker, Tropicana, Havana and Havana South Zones (e.g. Doyle et al., 2007, 2009, 2013; Fig. 2). Mineralization has been intersected along strike to the northwest and southwest of the current mining operation, and intersected down dip of the Havana Zone to a maximum vertical depth of about 1 km.

The dominant lithological associations in the hangingwall to mineralization are garnet-bearing gneiss, amphibolite and granulite, with subordinate chert, banded iron-formation (grunerite–quartz±garnet), quartzofeldspathic gneiss and anatexite facies (Fig. 3). Ore zones are hosted by a range of gneissic rocks, but predominantly within quartzofeldspathic gneiss and compositionally similar anatexite facies; particularly K-feldspar-dominant (syenitic) facies. The footwall package comprises

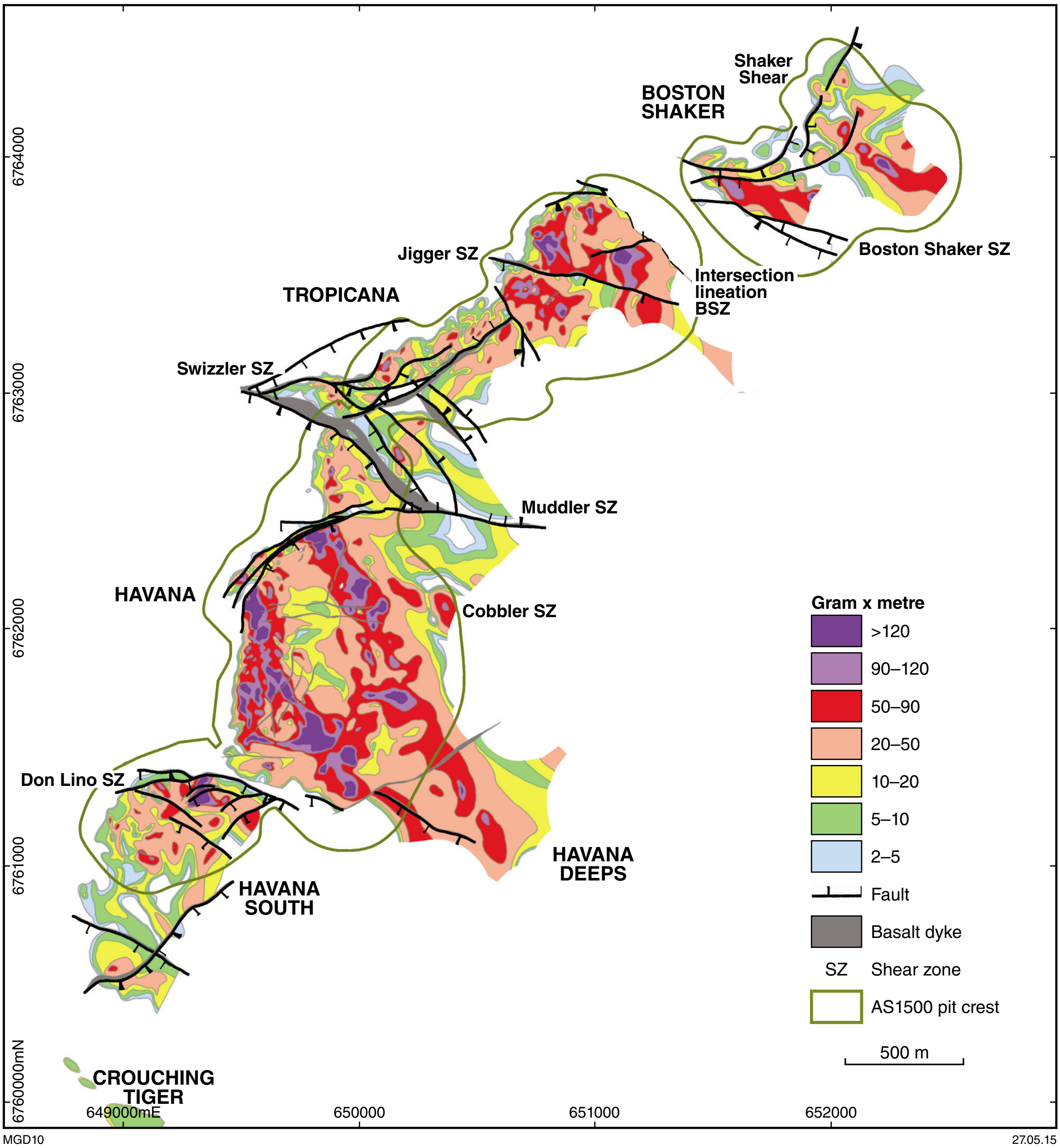

Figure 2. **Structural domains and mesoscopic shear zones of the Tropicana gold deposit, superimposed on a grade (g/t Au) X thickness (m) plot. GDA/UTM grid (after Blenkinsop and Doyle, 2014)**

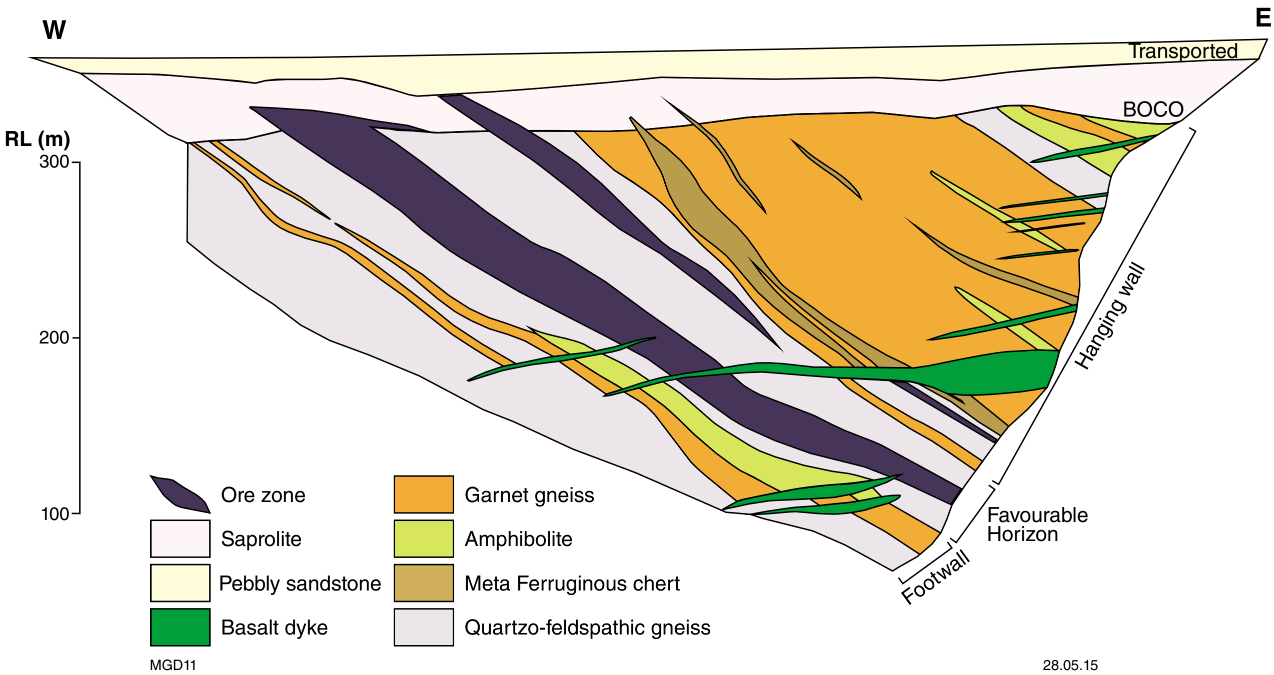

Figure 3. Schematic east–west cross-section of the Tropicana deposit (based on Doyle et al., 2007)

amphibolite, granulite, and both garnet-bearing and felsic gneiss associations. On the basis of lithogeochemistry, the host sequence is interpreted to be dominated by rhyolitic to basaltic metavolcanic rocks (Doyle et al., 2013).

Partial melting of the host sequence has produced anatexite patches, bands and veins (1–20 cm wide). Anatexite and leucosomes are texturally continuous with the gneissosity or intruded parallel to the axial plane of intrafolial folds indicating syndeformational emplacement during peak metamorphism at granulite facies (Doyle et al., 2007; Blenkinsop and Doyle, 2014). Both the host rocks and ore zones are cut by basalt to dolerite intrusions with chilled or weakly sheared margins. Several attempts to date the dykes have been unsuccessful and, on the basis of regional magnetic interpretations, they are ascribed to the c. 1210 Ma (Qiu et al., 1999; Wingate et al., 2000) Gnowangerup–Fraser Dyke Suite providing a minimum age for mineralization (Doyle et al., 2007).

The ore envelope modelled at a ≥0.3 g/t Au is subparallel to dominantly east- to southeast-dipping (~40°) gneissosity and enveloping surfaces of garnet-bearing gneiss divisions in the footwall and hangingwall. Mineralization is localized in shear-controlled lenses that are characterized by biotite–sericite–pyrite–chlorite±calcite±siderite mineral assemblages that are consistent with upper greenschist facies conditions at the time of economic gold mineralization. In lithons between shears, biotite–sericite–pyrite alteration has moved out from fractures and altered metamorphic mineral assemblages. Greenschist facies retrogression is widespread but variable in rocks distal to mineralization.

Gold typically occurs as fine-grained (10–30 µm) inclusions in pyrite and less commonly in fractures cutting K-feldspar, quartz, and monazite. Stylolitic dissolution fabrics, crackle-breccia facies, and shears, fractures and veins with biotite–pyrite±sericite fills are widespread, particularly in higher grade zones, and cut and/or displace peak-metamorphic fabrics (Blenkinsop and Doyle, 2014). Accessory minerals include pyrrhotite, chalcopyrite, electrum and telluride minerals (calaverite, petzite, sylvanite, altaite), and trace minerals include molybdenum, bismuthinite, sphalerite, galena, and bornite.

There is evidence for more than one phase of mineralization, probably at different gold grades, and reactivation of mineralized structures is common. Occurrences of visible gold associated with high-grade intercepts are localized on late sericite fractures which cut across anatectic segregations, gneissic bands and rare deformed quartz veins, and overprint earlier biotite–sericite–pyrite-dominant assemblages.

Tropicana structure

The structural architecture and history of the Tropicana Deposit has been described in detail by Blenkinsop and Doyle (2014) and is summarized below.

Gneissic banding (mm-to-cm scale) is readily measurable in drillcores and available outcrops. The banding is tight to isoclinally folded with east- to southeast-dipping hinge surfaces and gently south-plunging hinges. Many of these folds are rootless, consistent with the development of gneissic banding during early deformation accompanying metamorphism at amphibolite to granulite facies, as supported by leucosomes that are observed both parallel to the banding and localized along D_1 fold closures (Doyle et al., 2007).

Mapping of outcrop 4 km northeast of the deposit (Fox-Wallace, 2010; Fox-Wallace et al., 2013) defined D_2 folds that are represented in the Tropicana Gold Mine model at the scale of hundreds of metres in the footwall to ore. The D_2 folds are interpreted to record a west to northwest-verging thrust system that is developed regionally during D_2.

The mineralized shear zones developed during D_3 at c. 2520 Ma (see below) during the Tropicana Event (Doyle et al., 2013; Blenkinsop and Doyle, 2014). D_3 shear zones (mm-to-cm wide) are defined by assemblages of biotite, pyrite, sericite, and chlorite and cut across the gneissic banding, although they are generally subparallel to the gneissosity. The shear zones envelop lithons ranging in scale from centimetres to tens of metres in length that are brecciated and fractured. Shear sense indicators include S–C and S–C fabrics, sigma porphyroclasts and oblique foliations, and when linked with mineralogy define a coherent kinematic history. Biotite–pyrite-dominant fabrics as ascribed to D_3 are overprinted by later sericite and/or chlorite fabrics. Gentle folding of the gneissic host postdates D_1 and D_2, and is ascribed to D_3. The typical southeast plunge of the high-grade shoots at Havana is parallel to common intersections of the biotite–pyrite shear zones and hinges of F_3 folds.

In the Tropicana Zone, high-grade ore shells dip more easterly, giving an easterly trend to their intersection. The change in plunge could be a consequence of: a) an initial variation in geometry inherited from D_1 and D_2; or b) reorientation by D_4 or D_5 in the Tropicana Zone, which is distinguished from the other zones by a higher density of late shear zones.

Sericite–chlorite dominant fabrics overprint the biotite–pyrite shears and are characterized by distinct fabrics and kinematics (D_4, D_5). Asymmetric folds with fold hinge surfaces which dip south, and the south-dipping shears are consistent with late deformation events comprising dextral shear on south- and southwest-dipping zones, and are ascribed to D_5.

Tropicana geochronology

The structural and mineralization history of the Tropicana deposit has been established through integration of structural, paragenetic, and geochronological studies. The event history and significance for interpretation of the region are summarized from Doyle et al. (2013), Blenkinsop and Doyle (2014), and Doyle et al. (2015).

SHRIMP U–Pb analysis of zircon and monazite from gneiss hosting the Tropicana gold lodes yield a weighted mean $^{207}Pb/^{206}Pb$ age of 2638 ± 4 Ma. In samples for which both zircon and monazite have been analysed, the ages returned are within error. The centre of some zircon grains yield ages in the range 2.6 – 2.7 Ga, in contrast to monazite which lacks evidence for Pb inheritance. The absence of an inherited Pb component in monazite analyses from the sample pairs implies that the U–Pb system in monazite was completely reset during metamorphism at c. 2638 Ma, or that both zircon and monazite record the magmatic age, and the older zircon ages are from xenocrysts.

Metamorphic zircon is typically characterized by Th/U ratios less than 0.1 (e.g. Rubatto et al., 2001, and references therein). Th/U ratios for zircons in the Tropicana samples are in the range of 1.3 – 0.2, favouring interpretation as an igneous crystallization age.

The timing of peak granulite-facies metamorphism is poorly constrained between c. 2638 and 2520 Ma. Cooling trajectories based on the maximum and minimum uplift rates published in the literature allow the peak of granulite metamorphism recorded at Tropicana to be from close to the host rock emplacement age, to only a few million years prior to mineralization (Doyle et al. 2015).

The oldest statistically significant population of rutile ages (2521 ± 5 Ma) is interpreted to record the formation of tungsten-rich rutile during mineralization at a temperature below the 500–550°C blocking temperature (Doyle et al., 2015). Re–Os of pyrite from Tropicana returned an age of 2505 ± 50 Ma and overlap with those from less precise Pb/Pb pyrite analyses (2.4 – 2.5 Ga). The pyrite dates are within error of the biotite analyses from biotite–pyrite assemblages hosting gold (Blenkinsop and Doyle, 2014).

The dehydrated nature of granulite-facies gneisses under retrograde conditions suggests mineralizing fluids were introduced from an external source at c. 2.5 Ga. The fluid-induced event (Tropicana Event, Doyle et al., 2013) produced a mineral assemblage indicative of greenschist-facies conditions and impacted on the retrograde path from peak metamorphism. Economic gold mineralization is interpreted to have formed during the event during northeast–southwest directed shortening.

The Tropicana Gneiss was exhumed into the greenschist facies window during the Neoarchean and remained relatively unaffected during the Albany–Fraser Orogeny. Evidence for Stage I (1345–1260 Ma) or Stage II (1215–1140 Ma; Clark et al., 2000) of the Albany–Fraser Orogeny is limited. At Tropicana, the Albany–Fraser Orogeny cannot have reached temperatures of about 350°C for an extended period of time, as biotite and rutile ages are robust. The Tropicana Gneiss is interpreted to have represented a ‘relatively’ stable structural region during the Proterozoic Eon. Deformation was localized along its margins, between constituent structurally bound blocks, and within discrete high-strain mylonitic shear zones that cut both the Archean and Proterozoic domains.

Discussion

The history of the Tropicana Gneiss of the Plumridge terrane falls into two principal periods (Doyle et al., 2013; Blenkinsop and Doyle, 2014; Fig. 4). During the first period, emplacement and metasomatism of the precursor mafic to felsic rocks at c. 2636 Ma was followed by amphibolite to lower granulite facies metamorphism in the period c. 2636 to 2520 Ma. This was followed by

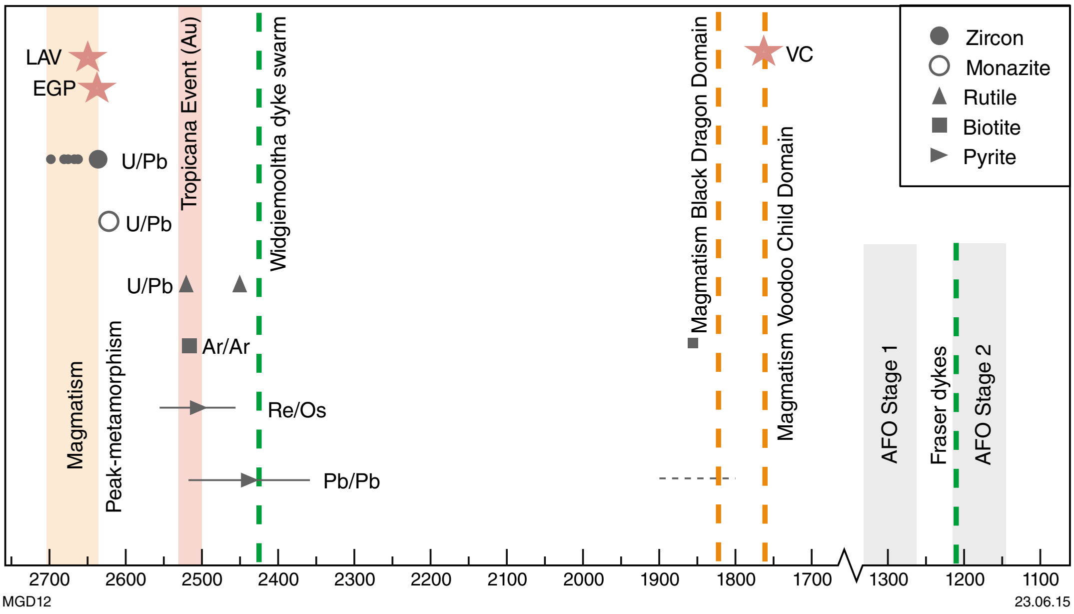

Figure 4. Summary of principal events at the Tropicana gold deposit, Biranup Zone and Albany–Fraser Orogen (AFO). The principal gold events in the Eastern Goldfields Province (EGP), Laverton District (LAV) of the Yilgarn Craton, and Voodoo Child (VC) are also illustrated (after Doyle et al., 2015).

exhumation and juxtaposition of the Archean lower crust against and over upper crust of the Yilgarn Craton. The Plumridge Detachment marks the contact between the Tropicana Gneiss and underlying elements of the Yamarna Terrane (Occhipinti et al., 2014). The second period was associated with northeast–southwest shortening and produced mineral assemblages diagnostic of greenschist facies conditions (Blenkinsop and Doyle, 2014). The age of this deformation and mineralization event, the Tropicana Event, is latest Archean (c. 2520 Ma) and generated economic concentrations of gold at the Tropicana mine. Thrusts mapped in the Tropicana Gold Mine area have listric geometries and merge into the Plumridge Detachment at depth (Occhipinti et al., 2014).

The age of mineralization in the Tropicana Gneiss contrasts with that of peak gold mineralization in the Yilgarn Craton. Mineralization was diachronous across the craton and in the Laverton greenstone belt occurred at c. 2.65 Ga, whereas in the Eastern Goldfields Superterrane, the Southern Cross and Murchison Domains mineralization occurred at 2.64 Ga (e.g. Salier et al., 2005). The Tropicana mineralization occurred at c. 2.5 Ga, a period that coincides with a subordinate peak in juvenile continental crustal production and gold deposit formation (e.g. Goldfarb et al., 2001, 2005).

The timing of the Tropicana mineralization is similar to that recognized in the Eastern Dharwar Craton, India (e.g. Sarma et al., 2008). In the Dharwar Craton, gold ores at Hutti and Kolar were broadly coincident with widespread syntectonic plutonism preceding final stabilization of the craton by c. 2420 Ma (Krogstad et al., 1989). The current study suggests that the final stages in cratonization of the Yilgarn Craton in Australia may have extended into the early Paleoproterozoic and, if so, was preceded by thermal reworking of the lower–middle crust.

The similarity in the position of Tropicana gold deposit and the granulite-hosted Renco gold deposit in Zimbabwe relative to their adjacent cratons is striking. Both comprise shear-hosted ore zones that dip moderately away from the craton and post-dates peak metamorphism (Blenkinsop and Doyle, 2014). They are type examples of Tomkin's (2013) post-metamorphic gold deposit category found in highly metamorphosed terranes.

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