

Paleoproterozoic gold deposits in the Bald Hill and Coyote areas, Western Tanami, Western Australia

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Abstract Significant gold deposits in the western Tanami region of Western Australia include deposits in the Bald Hill and Coyote areas. The ca. 1,864 Ma Bald Hill sequence of turbiditic and mafic volcanic rocks hosts the Kookaburra and Sandpiper deposits and a number of smaller prospects. The ca. 1,835 Ma turbiditic Killi Killi Formation hosts the Coyote deposit and several nearby prospects. The Kookaburra deposit forms as a saddle reef within a syncline, and the Sandpiper deposit is localized within graphitic metasedimentary rocks along a limb of an anticline. Gold in these deposits is hosted by anastomosing quartz–(pyrite–arsenopyrite) veins within quartz–sericite schist with disseminated arsenopyrite, pyrite, and marcasite (after pyrrhotite). Based on relative timing relationships with structural elements, the auriferous veins are interpreted to have been emplaced before or during the ca. 1,835–

1,825 Ma Tanami Orogeny (regional D₁). Gold deposition is thought to have been caused by pressure drops associated with saddle reef formation (Kookaburra) and chemical reactions with graphitic rocks (Sandpiper). The Coyote deposit, the largest in the western Tanami region, consists of a number of ore lenses localized along the limbs of the Coyote Anticline, which formed during the Tanami Orogeny. The largest lenses are associated with the Gonzalez Fault, which is located along the steeply dipping southern limb of this fold. Gold was introduced at ca. 1,790 Ma into dilatant zones that formed in local perturbations along this fault during later reactivation (regional D₅) towards the end of a period of granite emplacement. Gold is associated with quartz–chlorite–pyrite–(arsenopyrite–galena–sphalerite) veins with narrow (<5 mm) chloritic selvages. A quartz–muscovite–biotite–K–feldspar–(tourmaline–actinolite–arsenopyrite) assemblage, which is interpreted to relate to granite emplacement, overprints the regional greenschist facies metamorphic assemblage. The mineralogical similarity between this overprinting assemblage and the vein assemblage suggests that the auriferous veins at the Coyote deposit are associated with the granite-related metamorphic–metasomatic assemblage. Gold deposition is thought to have been caused by pressure drops within dilatant zones.

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Introduction

The Tanami region, an area comprised mostly of Proterozoic rocks in northern Australia (Fig. 1), has become an important gold producer over the last two decades despite

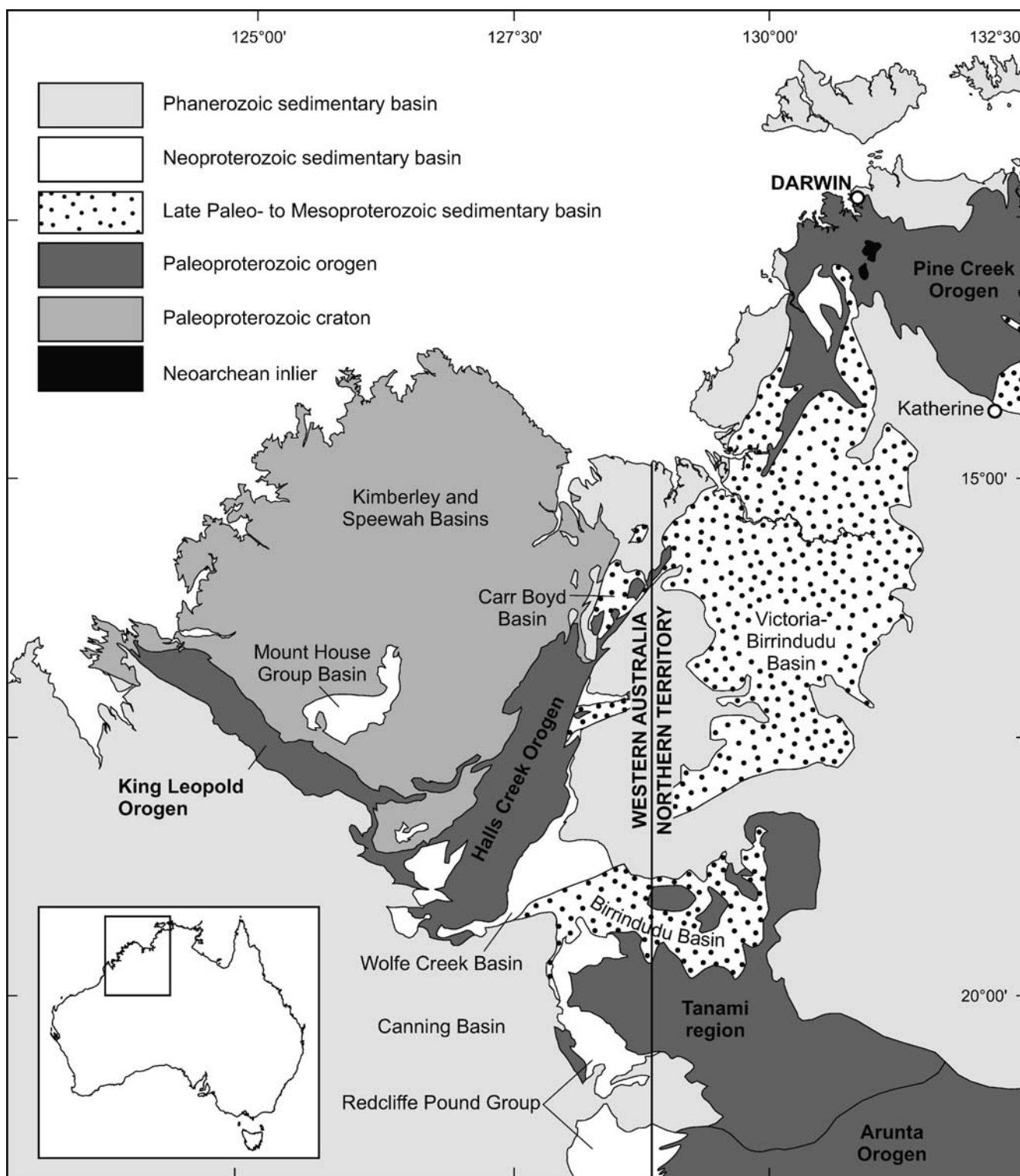


Fig. 1 Regional tectonic map showing the locality of the Tanami region of Western Australia and the Northern Territory (after Bagas and Huston 2005)

extensive cover by Cenozoic regolith. Gold was originally discovered in 1900 (Davidson 1905), but significant production did not begin until 1986 in the Granites goldfield (Mayer 1990). Although most of the 280-tonne

global resource (Huston et al. 2006) was discovered in the Northern Territory, by the late 1990s, significant discoveries were made at the Bald Hill and Coyote areas in Western Australia.

Given the potential of the western part of the Tanami region for gold, the Geological Survey of Western Australia has begun a geological study of the region in cooperation with Geoscience Australia and the Northern Territory Geological Survey. This contribution is to document preliminary findings from studies of oriented diamond core from the Coyote, Sandpiper, and Kookaburra deposits in Western Australia.¹

Structural nomenclature

We present structural chronologies for the Bald Hill and Coyote mineralized areas and then correlate them to a regional chronology established in the Northern Territory (Vandenberg et al. 2001; Crispe et al. 2006). To distinguish local from regional structural chronologies, a letter preceding the structural event number denotes local structural elements. For example, a “F₂” fold in the Bald Hill area is denoted F_{B2}, and a “F₂” fold in the Coyote area is denoted F_{C2}. Structural elements that form part of the regional chronology are denoted by a simple numeric subscript (e.g., D₂). Table 1 lists the geological events in the Tanami region and summarizes the relationships between local and regional structural chronologies.

Regional geology

The Tanami region, which includes Neoproterozoic to Mesoproterozoic rocks in the northwestern part of the North Australian Craton (Crispe et al. 2006; Myers et al. 1996; Fig. 1), is situated between the Paleoproterozoic Halls Creek Orogen to the northwest and the Paleoproterozoic Arunta Orogen (cf. Black and Shaw 1995) to the southeast (Fig. 1). The western Tanami region (Fig. 2) comprises mostly tightly folded greenschist facies metasedimentary and metavolcanic rocks of the Tanami Group (Blake et al. 1979; Cross and Crispe 2006). However, Page et al. (1995) inferred isolated inliers of leucocratic orthogneiss and schistose metasedimentary rocks in the Northern Territory to be Neoproterozoic (ca. 2,510 Ma), and Maidment (2006, personal communication) has recognized that a ca. 1,864-Ma metasedimentary succession crops out in the Bald Hill area (the informally named “Bald Hill sequence”).

The Tanami Group is subdivided into the Dead Bullock Formation and the conformably overlying Killi Killi Formation, and is regionally intruded by pretectonic

dolerite sills (Crispe and Vandenberg, manuscript in preparation). The Dead Bullock Formation, which is present in the eastern Tanami region, is an upward-fining succession of sandstone, carbonaceous siltstone, siltstone, and rare volcanic rocks that are overlain by deeper water chert and banded iron formation. The formation is transitionally overlain by turbiditic sandstone and lesser siltstone of the Killi Killi Formation [Fig. 2; Crispe and Vandenberg, manuscript in preparation; formerly the Killi Killi beds of Blake et al. (1975, 1979)]. The age of the Killi Killi Formation is constrained between ca. 1,838 Ma, which is provided by a tuff in the underlying Dead Bullock Formation, and ca. 1,820 Ma, which is provided by the age of volcanic rocks that overlie the formation and granites that intrude it. These volcanic rocks form part of the Ware Group (present only in the eastern Tanami region), which also includes sedimentary rocks (Crispe et al. 2006; Cross and Crispe 2006).

The Tanami Group was deformed during the ca. 1,835–1,820-Ma Tanami Orogeny (D₁–M₁; Table 1), which involved both disharmonic and angular folding with wavelengths of about 1 km. Accompanying regional metamorphism increases in grade from the greenschist facies in the northwest to the amphibolite facies in the southeast (Crispe and Vandenberg, manuscript in preparation). Complex deformation (D₂ to D₅) in the region between 1,820 and 1,790 Ma (Crispe et al. 2006) was broadly synchronous with a period of widespread compressional deformation through a large part of central and Western Australia (Bagas 2004). Intrusion of synorogenic (D_{2–3}) magmatic suites accompanied the deformation. Widespread ca. 1,790-Ma faults (D₅), which are associated with lode-gold deposits in the Tanami region (Huston et al. 2006), form major north-northwesterly trending structural boundaries (Crispe et al. 2006; Table 1).

The Tanami region is partly covered by Neoproterozoic to Paleozoic sedimentary rocks, which form part of the Centralian Superbasin (Walter et al. 1995). This superbasin was deformed and segmented during the ca. 550-Ma Petermann and Paterson Orogenies (Bagas 2004) and the ca. 450–300-Ma Alice Springs Orogeny (e.g., Haines et al. 2001). Late brittle north-northeast-trending faults (D₆) cut all units in the region, and the ages of some of these structures may be as young as the Alice Springs Orogeny.

Geology and gold deposits of the Bald Hill area

Deposits in the Bald Hill area (Table 2, Fig. 3), which include the Kookaburra and Sandpiper deposits, as well as a number of prospects, are mostly hosted by the informally named Bald Hill sequence. The sequence is a ~200-m-thick

¹ For the purposes of this discussion, a deposit is a mineralized entity for which Joint Ore Reserves Committee (JORC)-compliant resources or reserves have been established. A prospect does not have an established JORC-compliant resource or reserve.

Table 1 Geological events in the Tanami region and suggested correlations with deformation events in the western Tanami region (modified after Huston et al. 2006)

Rock types	Deformational/metamorphic events
Frederick Suite: magnetic (ca. 1,815–1,790 Ma): peraluminous biotite monzogranite to syenogranite with hornblende in SiO ₂ -poor samples Grimwade Suite (ca. 1,820–1,790 Ma): nonmagnetic, peraluminous biotite monzogranite to syenogranite with hornblende in SiO ₂ -poor samples	D₆(<1,700 Ma) : late thrust, oblique-slip and normal faults that cut earlier structures; ages poorly constrained, possibly as young as the ca. 450–300-Ma Alice Springs Orogeny D₅, D_{C2}, D_{B4}(ca. 1,790 Ma) : shear zones, thrusts and oblique-slip faults; important locus of Au mineralization through Tanami region D ₄ : extension associated with emplacement of Mt Charles Formation in continental rift (?ca. 1,800–1,790 Ma) D₃, D_{B3} : NE- to E-trending angular folds with 100-m wavelength (?ca. 1,810–1,800 Ma) D ₂ : open, angular NNW- to NE-trending folds with wavelengths of 0.5–50 m and 5–10 km (?ca. 1,815–1,800 Ma, may be correlated with Stafford Event in Arunta Orogen)
Ware Group (1,825–1,815): wacke and siltstone (ca. 1,815–1,800 Ma Wilson Formation); conglomeratic sandstone, siltstone, and fine-grained sandstone (ca. 1,825–1,815 Ma Century Formation); volcanogenic sandstone interbedded mainly with felsic volcanic rocks (ca. 1,820 Ma Nanny Goat Volcanics); coarse-grained quartz sandstone and granular conglomerate (ca. 1,825 Ma Mt Winnecke Formation) Birthday Suite: felsic volcanic rocks of the Ware Group and the Winnecke Granophyre; also includes monzogranite and granodiorite; highly magnetic; restricted to NE part of Tanami region	Tanami Orogeny (D₁–M₁, D_{C1}, D_{B2}–M_{B2} ; 1,835–1,825 Ma): Asymmetric, disharmonic folds with wavelengths to 1 km; greenschist to midamphibolite facies metamorphism with highest grades to SE. Prolonged period of deformation that affects the Tanami Group
Tanami Group: turbiditic sandstone and siltstone (ca. 1,835 Ma Killi Killi Formation); siltstone and sandstone (ca. 1,840 Ma Ferdie Member of the Dead Bullock Formation), and fining into graphitic siltstone and banded iron formation (Callie Member of the Dead Bullock Formation) Dolerite sills intrude the Dead Bullock and Killi Killi Formations; peperitic textures locally developed	D_{B1}–M_{B1} : ca. 1,864–1,835 Ma, layer parallel foliation in the Bald Hill area
Ca. 1,864 Ma succession: clastic, volcanoclastic, mafic volcanics, and mafic sills in the Bald Hill area	

Text in bold in the deformational/metamorphic events column refer to deformation events recognized in the Bald Hill and Coyote areas of Western Australia

succession of tightly folded and faulted iron-rich siltstone, graphitic and carbonaceous shale, banded and nodular chert, siltstone, turbiditic sandstone, basalt, and rare felsic pyroclastic rocks (Fig. 3). Although contacts are not exposed, the succession is interpreted to overlie a sequence of thickly bedded, fine- to coarse-grained, detrital muscovite-bearing, turbiditic sandstone, siltstone, and shale to the west that has been intruded by subconcordant dolerite. This entire sequence is in faulted contact with turbiditic sandstone with siltstone and shale, which is typical of the Killi Killi Formation to the east (Fig. 3).

Three deformation events are recognized in the Bald Hill area. The first (D_{B1}) is characterized by layer-parallel faults and tight to isoclinal folds that have been refolded by more open F_{B2} and later folds (Fig. 4a). These early folds are accompanied by an axial-planar cleavage defined by quartz flattening and foliation of sericite and chlorite. The faults

Fig. 2 Maps showing regional geology, mineral occurrences, and total magnetic intensity aeromagnetic response (400-m line spaced data is from the Geological Survey of Western Australia acquisition for the western Tanami region: Geological Survey of Western Australia 2005)

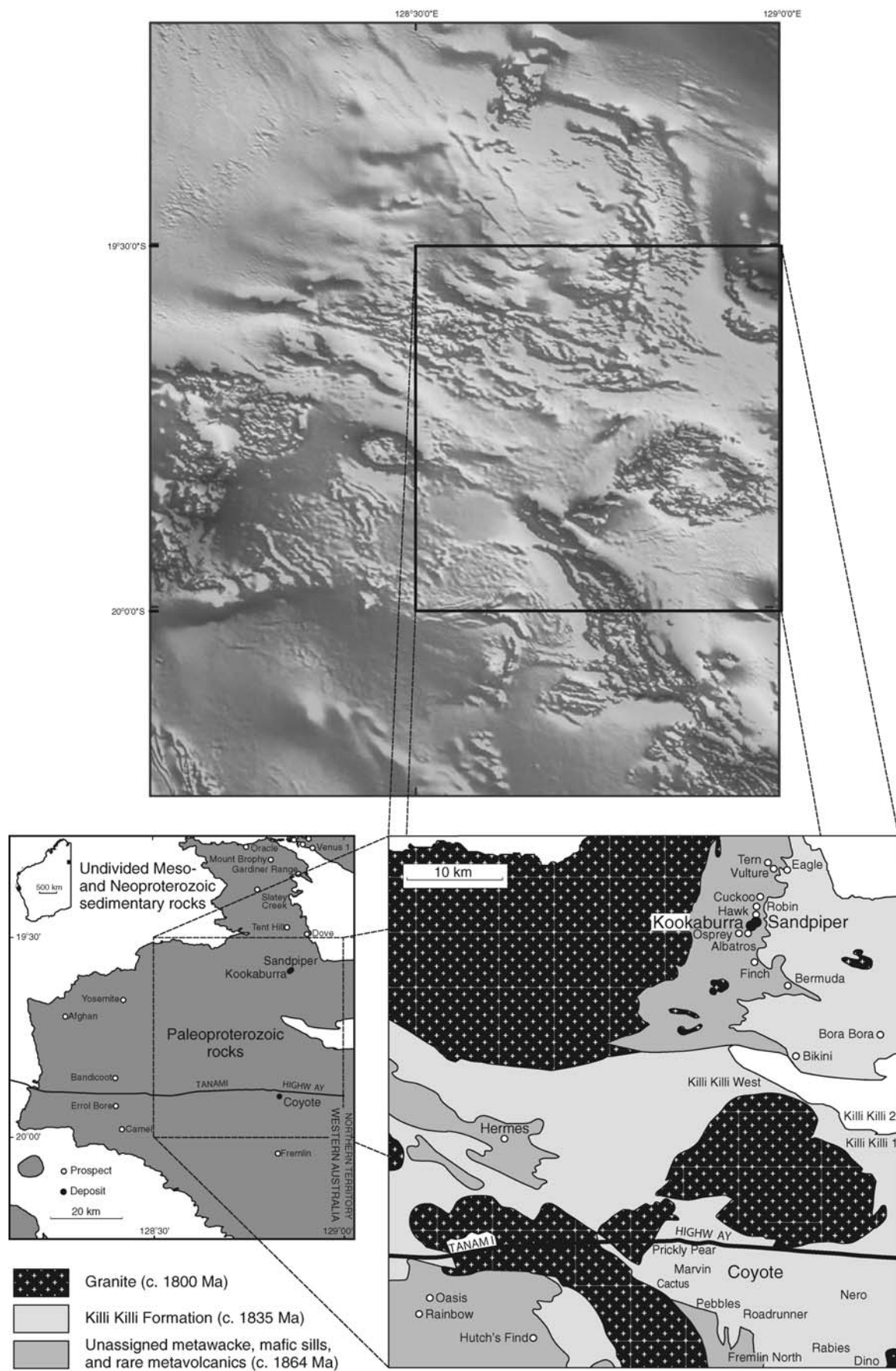


Table 2 Characteristics of the Coyote and Bald Hill areas of the western part of the Tanami region

Deposit	Resource estimates	Host rock and structures	Vein paragenesis and alteration	References
Coyote area				
Coyote	2.66 Mt at 5.24 g/t Au	Immature and graded sandstone, siltstone, and shale of the Killi Killi Formation. Gold is in E-trending quartz veins	Gold in quartz veins associated with minor arsenopyrite, chalcopyrite, pyrite, and bismuthinite	This study
Bald Hill area				
Kookaburra	1.44 Mt at 2.02 g/t Au	Carbonaceous siltstone, chert, mafic volcanic, and subvolcanic (dolerite) rocks. Auriferous veins are in E- to SE-trending faults	Gold mineralization is associated with quartz(–dolomite–sericite–chlorite) alteration. The host rocks are bleached and decarbonized	This study; Hassan (2002)
Sandpiper	1.21 Mt at 2.92 g/t Au			

are associated with a shear fabric and foliation in schists with dips up to 70° to the north. Where a motion sense was determinable in orientated drill core, most D_{B1} shears have an apparent reverse (i.e., north-side up) sense of movement. The faulted contact between the Killi Killi Formation and the Bald Hill sequence is interpreted as a D_{B1} structure.

The second deformational event is marked by asymmetrical, angular, tight folds (F_{B2} ; Fig. 4), which have a wavelength of less than a kilometer (e.g., form lines in Fig. 3). The folds are locally overturned, inclined, and southward verging, with local faulted limbs. They plunge moderately towards the east and trend around 120° with an axial–planar cleavage or spaced cleavage that dips steeply to the north-northeast. This cleavage is also defined by quartz flattening and the foliation of sericite and chlorite. In orientated drill core, folded chert bands that plunge around 25° towards 085° define F_{B2} folds. These folds are accompanied by east-southeast-trending, north-northeast-dipping faults that commonly fault synclinal hinges.

A third set of structural elements includes open folds (Fig. 4b) that plunge steeply (around 60°) to the north-northeast (F_{B3}) and an associated vertical cleavage (S_{B3} ; Fig. 5). The last significant structural element is a spaced fracture cleavage (S_{B4}) that dips about 60° towards 220–230°. No macroscale structural elements were observed to be associated with this cleavage.

As chlorite and sericite foliation define both the S_{B1} and S_{B2} fabrics, we interpret D_{B1} and D_{B2} to have developed during greenschist facies metamorphism. As both of the events affect Killi Killi Formation rocks, they are interpreted to have formed prior to or during the Tanami Orogeny, with D_{B2} in response to north-northeast–south-southwest-orientated compression. Ongoing compression during D_{B2} led to overturning of the folds and faulting along fold limbs. The orientation of the F_{B3} folds is indicative of compression in a northerly to northwesterly direction.

The Kookaburra and Sandpiper deposits

Talbot (1910) first recognized gold in the Bald Hill area, reporting grades of about 5 g/t. Glengarry Resources NL and Tanami Gold NL discovered the Kookaburra and Sandpiper deposits in 1996 during a regional geochemical sampling program. The Kookaburra deposit (Fig. 5a) is situated within a F_{B2} syncline that trends southeast and plunges around 50° towards the east (Fig. 6). The irregularly shaped orebody is mostly localized along the southwestern limb and hinge zone of the syncline, although it also extends up the steeply dipping, overturned northeastern limb, possibly along a shear zone. We interpret this geometry to indicate the Kookaburra deposit formed in a saddle reef. In detail, the ore zones are hosted both by basalt and interbedded sedimentary units. Although crosscutting, the ore zones, which range up to 20 m in thickness, broadly follow stratigraphy and are thickest in the hinge of the syncline.

A southeast-trending D_{B2} fault separates the eastern side of the syncline from the Sandpiper deposit to the northeast (Fig. 3). The Sandpiper deposit (Fig. 5b), which is hosted in the hinge and southwestern, overturned limb of a southeast-plunging anticline, consists of a single lens up to 9 m thick. This lens is stratabound within interflow sedimentary rocks between basalt bodies. The host unit contains sericitic graphitic and silicified pelite, chert, and metawacke.

In both deposits, the ore zones consist of anastomosing and folded quartz veins within sulfidic sericite–quartz schist. Other prospects in the area are located in axial planar zones of F_{B2} folds where they intersect southeast-trending faults or fractures and along the boundaries of the Bald Hill sequence.

Vein paragenesis and alteration assemblages

Similar vein parageneses and alteration assemblages characterize the Kookaburra and Sandpiper deposits. Based on outcrop exposures and diamond drill holes, Fig. 6 presents

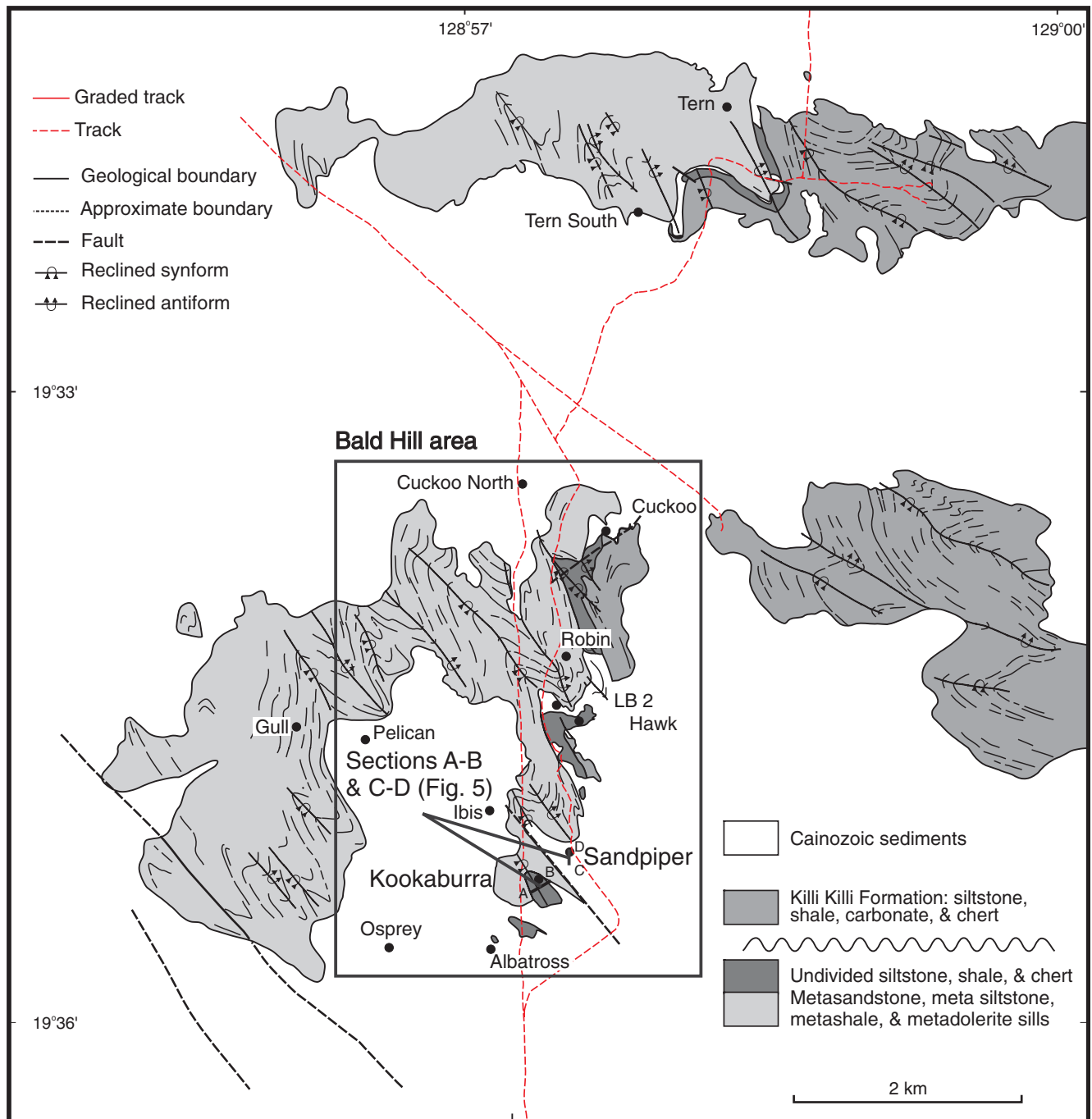


Fig. 3 Geological map of the Bald Hill area showing the location of the Kookaburra and Sandpiper deposits (modified after Beardsmore 2005, personal communication)

the relationship of veins and alteration assemblages to structural elements.

Preore veins and alteration assemblages

The earliest vein set is characterized by 1–3-mm, irregular to folded dolomite veins that are particularly abundant (2–5%) in chloritized mafic igneous rocks. In clastic sedimen-

tary rocks, these veins are associated with a purplish dolomite–hematite-bearing wall-rock assemblage. The dolomite veins are folded and crenulated by F_{B2} folds and form disrupted fragments within D_{B2} shears, suggesting a pre- to syn- D_{B2} timing. Dolomite also fills amygdales in basalt, suggesting that dolomite veins and the chloritic assemblages are the result of spilitic alteration of mafic units shortly after emplacement.

a)

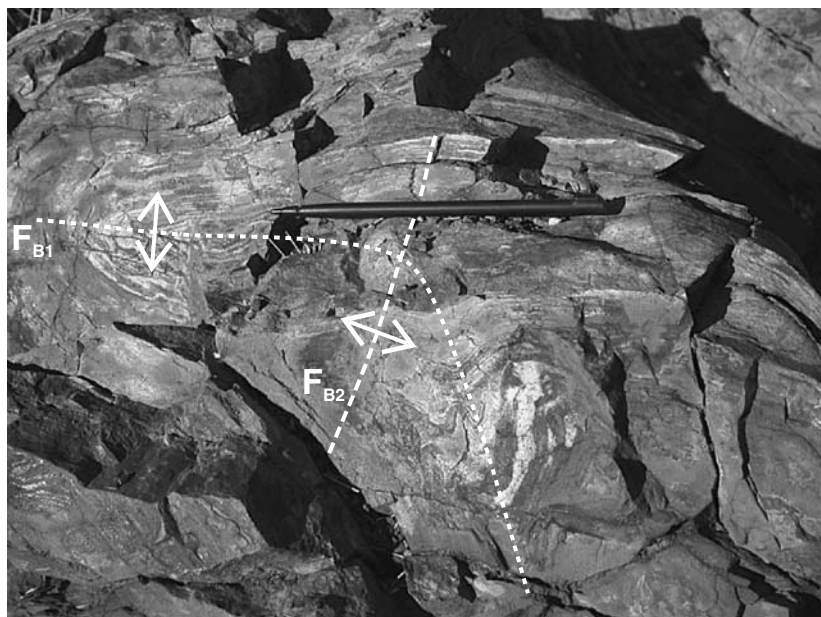
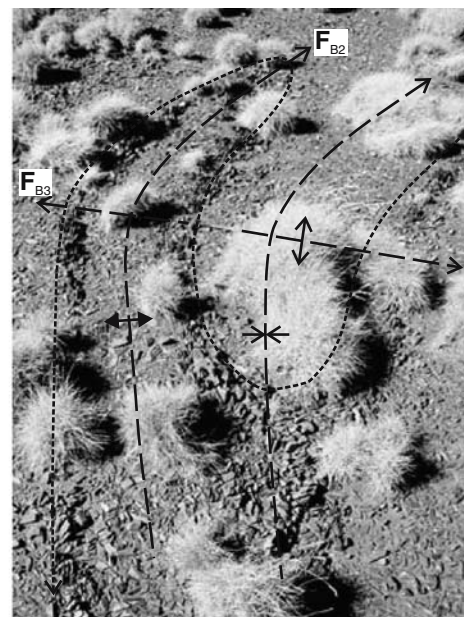


Fig. 4 Structures seen around the Bald Hill area: **a** photograph showing the relationship between a tightly isoclinal F_{B1} fold and angular F_{B2} fold plunging 25° towards 105° in laminated, ferruginized pelite interbedded with chert from the Killi Killi Formation (sample from near the Northern Territory border east of the Kookaburra area at MGA 499998E

b)



7835559N); **b** refolded (F_{B3} plunging steeply east-northeast, hammer is parallel to the F_{B3} fold axis) early (F_{B2}) folds plunging to the southeast in the Kookaburra area (photograph taken facing towards the south at MGA 487124E 7840210N)

Syn-ore veins and alteration assemblages

In outcrop, quartz veins were commonly emplaced parallel to bedding and have been used to recognize bedding trends in areas with few outcrops. Veins range from a few centimeters thick to tens of meters thick and are typically located at lithological contacts between dolerite, metawacke, and pelite. Some of these veins are folded by F_{B2} , forming saddle reefs. In other cases, they transgress bedding,

forming steeply inclined veins in F_{B2} -fold axial planes or subhorizontal veins perpendicular to the direction of maximum D_{B2} extension. These relationships suggest that the veins formed prior to or during D_{B2} . In core, this vein set consists of quartz–dolomite veins that are folded by F_{B2} folds; other veins are commonly located within D_{B2} shear zones, implying formation synchronous with D_{B2} . These shear zones also contain disseminated sulfide that is aligned parallel to and overprints the S_{B2} shear fabric.

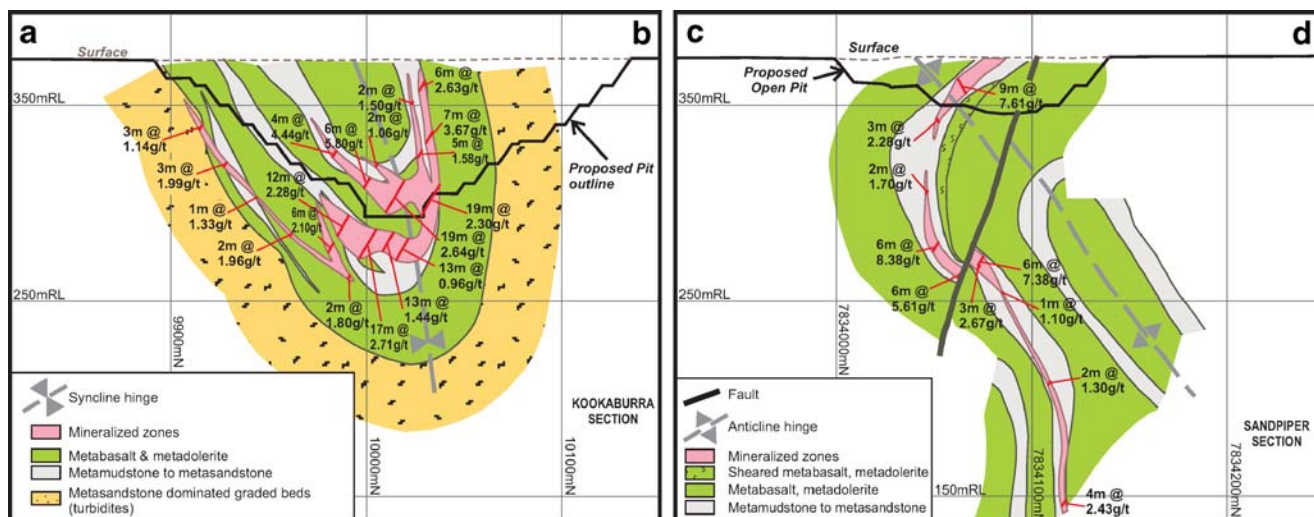
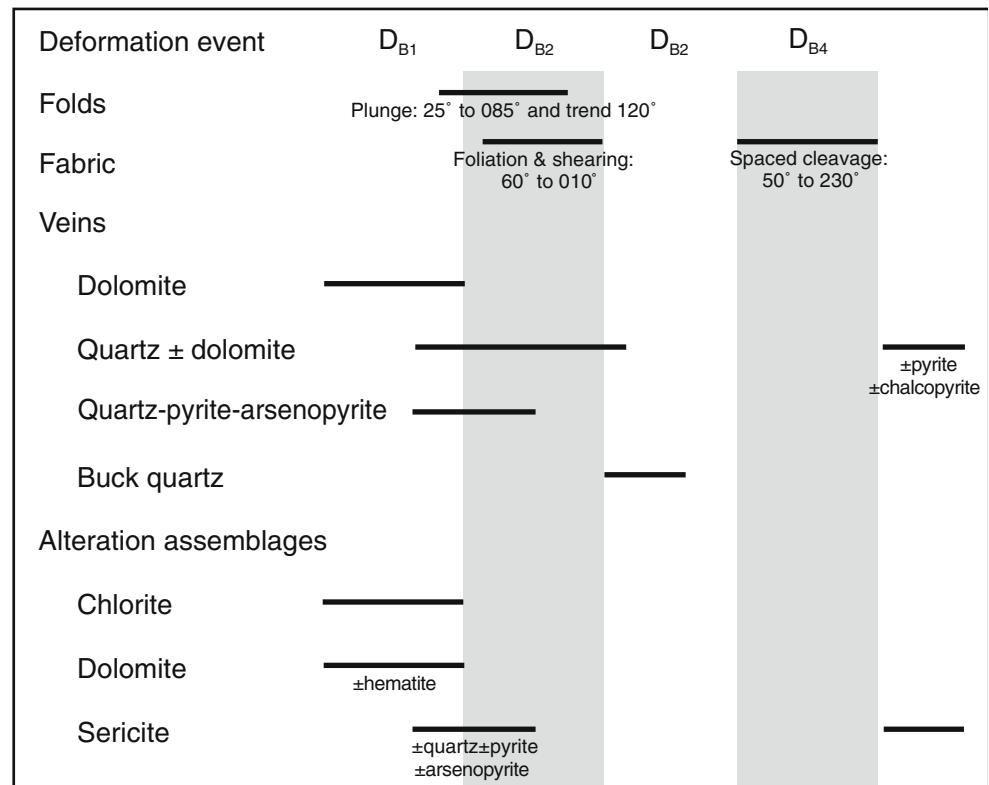


Fig. 5 Cross-sections of the Kookaburra (**a**) and Sandpiper (**b**) deposits showing grades of gold mineralization (after sections and data from L. English of Tanami Gold NL). Locations of these cross sections are shown in Fig. 3

Fig. 6 Relationship of vein paragenesis and alteration assemblages to structural elements at the Kookaburra and Sandpiper deposits



The earliest veins within ore zones consist of 3–10-mm-wide, folded and anastomosing quartz(–pyrite–arsenopyrite) veins that are cut by up to 500-mm-thick, planar buck quartz veins (Fig. 7a). Assays suggest that the earlier veins contain gold (average ~5.5 g/t Au), whereas the later buck veins do not. In detail, the quartz(–pyrite–arsenopyrite) veins contain variable amounts of sericite, potassium feldspar, and marcasite, and minor to trace quantities of biotite, actinolite, apatite, sphalerite, and pyrrhotite. The marcasite typically has a lamellar habit, suggestive of replacement after original pyrrhotite. Pyrite typically overgrows arsenopyrite both in mineralized veins and in the wall rock.

These veins both cut and are folded and sheared by the dominant fabric (S_{B2}) in altered wall rock, suggesting that they developed pre- to syn-kinematic with respect to D_{B2}, (Fig. 6). This structural timing is similar to pre- and syn-D_{B2} quartz veins and pyritic shears outside of the ore zone. The relationships suggest that gold was introduced before or during D_{B2}, which we equate to the ca. 1,835–1,825 Ma Tanami Orogeny (regional D₁). However, this inference has not been tested with geochronology. The Sandpiper deposit also contains minor calcite–galena veins. Although quartz is absent, these veins have a similar structural timing to the gold-mineralized veins, suggesting co-genesis. In addition to galena, these veins contain minor sphalerite.

Quartz(–pyrite–arsenopyrite) veins are associated with sericite–quartz(–biotite–sulfide) schist (Fig. 7a). This rock

type has a fabric, defined by sericite and biotite, with a similar orientation to axial planar cleavage related to F_{B2}, and D_{B2} shearing. Many of the disseminated sulfides within this schist, including pyrite, marcasite (after pyrrhotite), galena, chalcopyrite, and sphalerite, commonly form lenticular aggregates parallel to this fabric. Arsenopyrite typically forms euhedral porphyroblasts commonly with nonfoliated quartz and sericite pressure shadows that contain pyrite and, in some cases, marcasite. The fabric commonly wraps around arsenopyrite porphyroblasts, suggesting an early kinematic timing for arsenopyrite introduction. Overall, the common association of the sulfide and phyllosilicate assemblage in wall rocks to the veins suggests that these minerals formed pre- to synkinematically with the mineralized veins.

The buck quartz veins cut the fabric in the sericite–quartz(–biotite–sulfide) schist, suggesting a post-D_{B2} timing. These veins have a simple mineralogy, with only minor dolomite and pyrite, and very rare arsenopyrite and pyrrhotite.

Postore veins and alteration assemblages

Planar, 1–10-mm, quartz–dolomite–pyrite–chalcopyrite veins that are located along or cut the D_{B4} spaced cleavage characterize the last and third significant vein set. These veins are associated with sericitic alteration selvages that commonly pick out the S_{B4} fabric. This assemblage is

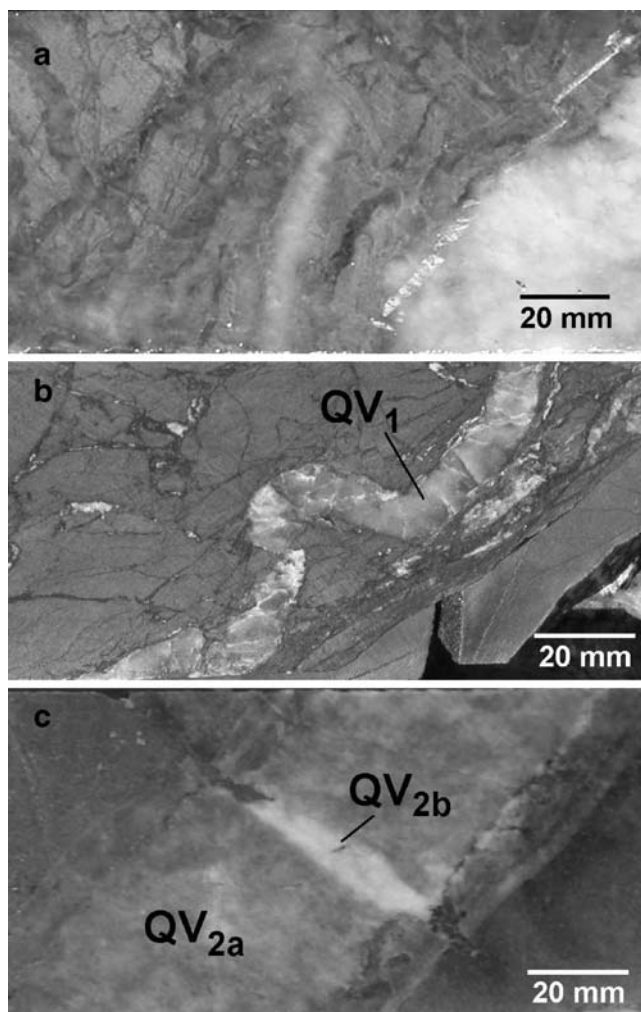


Fig. 7 Photographs of rock relationships at the Kookaburra and Coyote deposits: **a** anastomosing auriferous veins within sericite-quartz schist with disseminated arsenopyrite and pyrite (Kookaburra deposit: LKD100 at 176.0 m), **b** folded early quartz vein (QV₁) near the contact between turbiditic sandstone and siltstone from (Coyote deposit: CYDD87 at 255.2 m), and **c** stage QV_{2a} vein cut by tension gash containing stage QV_{2b} auriferous quartz-chlorite-sulfide assemblage (Coyote deposit: CYDD87 at 296.4 m)

similar to late (regional D₆₊) quartz–dolomite-base metal sulfide veins that cut auriferous veins at the Callie deposit (Wygralak et al. 2005).

The composition of ore-forming fluids

Mineralized veins from the Sandpiper deposit contain abundant clusters of primary, vapor-rich (typically 100 vol% vapor) fluid inclusions in the cores of large (<0.5 mm), clear, quartz crystals. They are irregular to rounded in shape and range in size up to 20 μ m. There are also rare, coexisting aqueous inclusions containing approximately 5 vol% vapor and a small halite crystal. Raman microprobe analysis of the vapor-rich fluid inclusions indicates that they may be divided

into two groups. The first group is CO₂-rich (>90 mol% CO₂) with minor N₂ and CH₄, whereas the second group is CH₄-rich (>59 mol%) with moderate N₂ (<21 mol%) and CO₂ (<35 mol%). The microthermometric data reflect the Raman analyses with some inclusions exhibiting homogenization a few degrees above the CO₂–CH₄ critical temperature (–82.1°C) and others showing CO₂ final melting near the CO₂ triple point (–56.6°C). The latter inclusions exhibited total homogenization between –50.2 and 29.5°C. The aqueous inclusions exhibit final ice melting from –43.1 to –17.2°C, indicating that the fluid was enriched in Ca²⁺. L+V→L partial homogenization took place over the range from 103 to 195°C, whereas total homogenization occurred by melting of the halite crystal over the range from 207 to 291°C. This indicates that the aqueous inclusions had salinities between 32.2 and 37.5 wt.% NaCl equiv. using the equation of Knight and Bodnar (1989).

Partially recrystallized quartz veins from the Kookaburra deposit exhibited clusters of, possibly, secondary, vapor-rich (>90 vol% vapor) fluid inclusions and rare aqueous inclusions with up to 40 vol% vapor, in the cores of relict quartz grains. Raman microprobe analysis of the vapor-rich fluid inclusions indicates that some are CO₂-rich (>98 mol%) with minor N₂±CH₄ and others are CH₄-rich (>99 mol%) with minor CO₂. Microthermometric analysis of the CO₂-rich inclusions showed CO₂ final melting between –56.6 and –58.8°C, which is in good agreement with the Raman microprobe analyses. These inclusions exhibit CO₂ homogenization over a wide range from –8.3 to 15.6°C, which may indicate pressure fluctuations or partial re-equilibration. The aqueous inclusions exhibit final ice melting from –9.9 to –3.2°C, which indicates fluid salinities from 5.2 to 13.8 wt.% NaCl equiv. using the equation of Bodnar (1993). These aqueous inclusions homogenized to the liquid phase from 212 to 350°C, with the majority homogenizing below 270°C.

Deposits of the Coyote area

The Killi Killi Formation hosts the Coyote deposit and several nearby prospects. Locally, this unit, although dominated by immature graded-metasandstone (meta-wacke), contains significant siltstone lenses and dolerite. Even though the Coyote deposit is the only deposit for which JORC-compliant mineral resources have been established (Table 2), other significant prospects in the area include the Pebbles and Rabies prospects, which are located about 6 km southwest and about 13 km southeast of the Coyote deposit, respectively (Fig. 2). These prospects have similar parageneses to the Coyote deposit and are not discussed here. The Coyote deposit is located in an area of no outcrop and is covered with both in situ and transported

Cenozoic regolith to a depth of up to 40 m. As a consequence of regolith cover, all geological data at the deposit are based on drill hole and closely spaced magnetic geophysical data.

Geological setting of the Coyote deposit

Gold mineralization in the Coyote area is located between 1 and 4 km northeast of the (regional D₆) Trans-Tanami Fault (Fig. 2), which is a late north-northwesterly striking, brittle, dextral, strike-slip fault. The Coyote deposit contains one main (Gonzales) and several satellite (Speedy and Buggy)

ore lenses that are associated with the Coyote Anticline (Fig. 8). The host rocks consist of a monotonous sequence of fine- to coarse-grained immature, graded sandstone interlayered with lesser (10–30%) siltstone, and rare carbonaceous shale mafic and dolerite. A relatively thick (locally >10 m) siltstone-rich unit, the “marker siltstone,” has been used as a marker to establish the geometry of the Coyote Anticline.

The Coyote Anticline is a close to tight, overturned, angular fold with an amplitude of about 400 m. The southern limb of the anticline dips steeply to the south or is subvertical, whereas the northern limb dips around 40° to the north

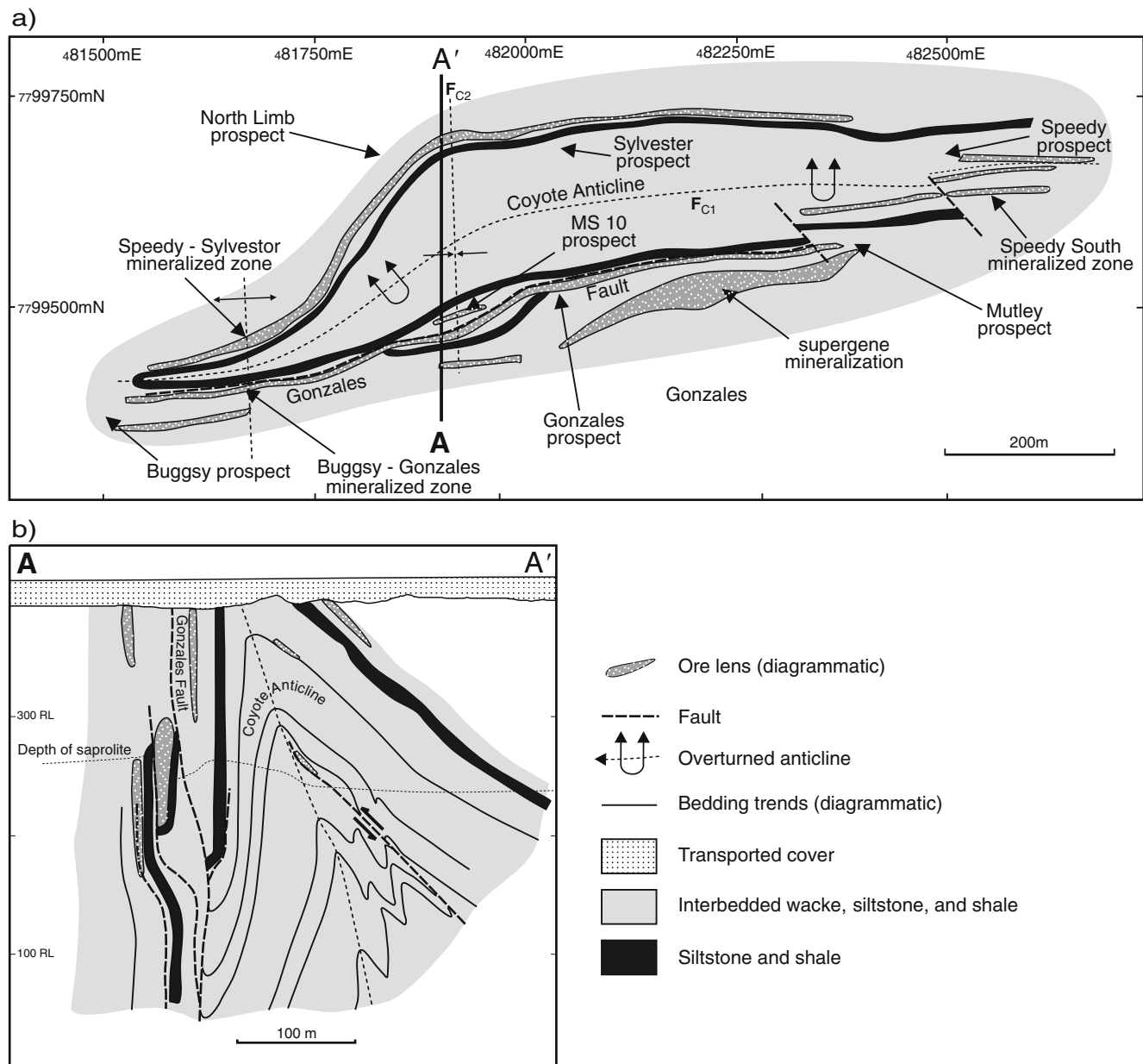
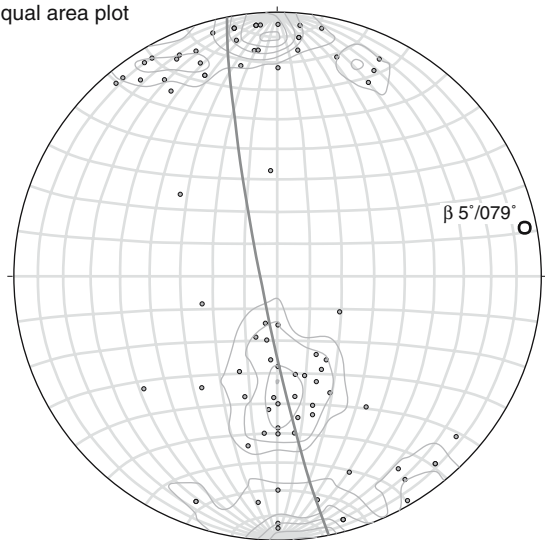
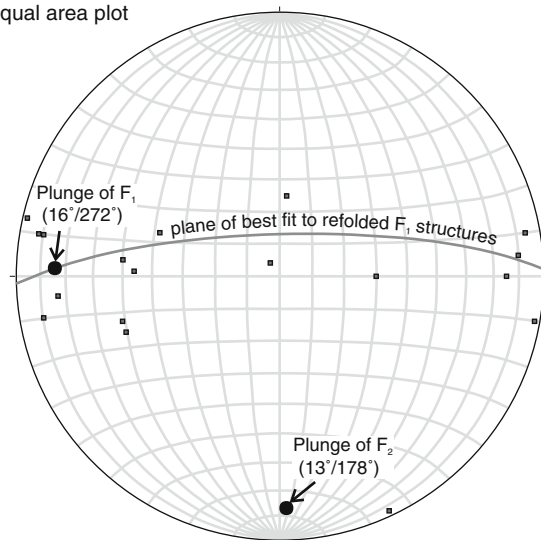


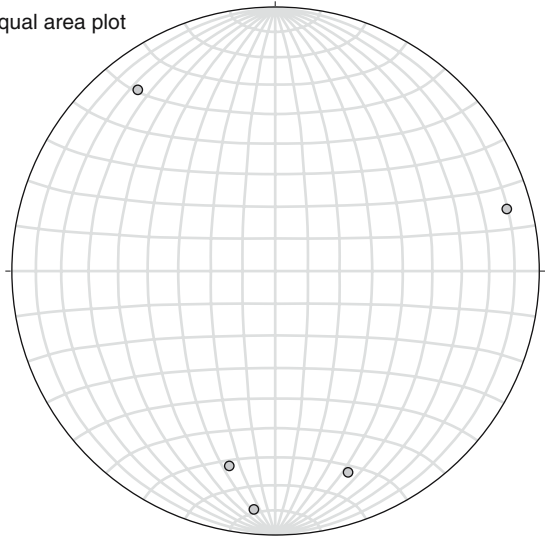
Fig. 8 Diagrams showing the geology of the Coyote area: **a** plan, and **b** cross-section (A–A' in **a**)

a) Equal area plot

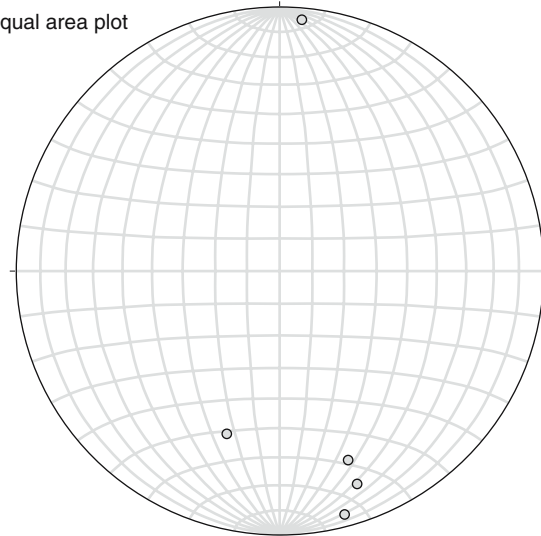
○ n (poles to bedding) = 86
 Poles to bedding contour interval = 2.0% per 1% area

b) Equal area plot

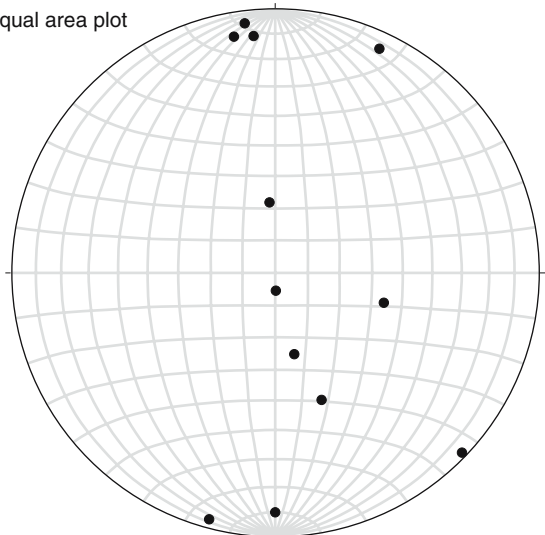
■ n (minor fold plunge) = 18

c) Equal area plot

○ n (arsenopyrite-bearing veins) = 5

d) Equal area plot

○ n (auriferous veins) = 5

e) Equal area plot

● n (chalcopyrite-bearing veins) = 12

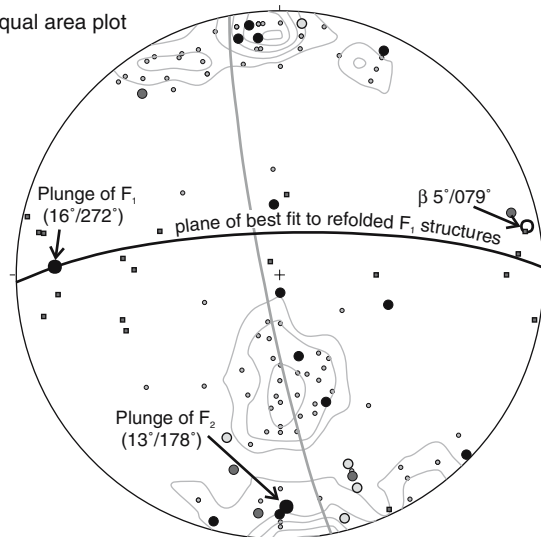
f) Equal area plot

Fig. 9 Pi diagrams showing poles to: (a) bedding; (b) folds; (c) chalcopyrite-bearing quartz veins; (d) auriferous quartz veins; (e) pyrite-bearing quartz veins; (f) arsenopyrite-bearing quartz veins. Data collected from orientated diamond-drillhole core CYDD 31, 85, 87, and 122. The location of the drillholes are shown in Fig. 8a

(Figs. 8 and 9a). This anticline and other early folds (F_{C1}) in the Coyote area plunge shallowly to the west (Fig. 9b).

A near vertical to steeply north-dipping shear zone, the Gonzales Fault, is oriented subparallel to the axial surface of the Coyote Anticline and cuts its southern limb (Fig. 8). The orientation of the fault in combination with the angular, asymmetrical, and overturned shape of the anticline suggest that the fold formed synchronously with near layer-parallel reverse faulting along its southern limb. This fault does not predate the fold because it cannot be traced around the fold. Changes in the sense of movement, including extensional (south side down) and transpressional dextral movements observed in the fault, indicate that there have been multiple movements along the Gonzales Fault.

The Coyote Anticline and ore lenses plunge 10–15° to the southwest around Buggy and to the west-southwest around the Speedy (Fig. 8). The curved trace of the fold suggests refolding (F_{C2}) around northerly trending axes that indicate compression in an easterly direction, which is similar to that expected for D_5 elsewhere in the Tanami region (Huston et al. 2006). During this easterly compression, it is envisaged that the Gonzales Fault was reactivated as a transpressional fault with dextral movement. Dilational zones would have formed at local perturbations along the fault during this movement, localizing fluid flow to form ore lenses such as the Gonzales lens.

Linear, northwest-striking reverse faults, which are spaced around 300 m apart, crosscut F_{C1} and F_{C2} folds and mineralized zones (Fig. 8). These faults suggest compression orientated in a northeast–southwest direction, which might relate to the ca. 550 Ma King Leopold Orogeny, which was associated with compression orientated in a northeast–southwest direction in the Halls Creek Orogen (Tyler et al. 1998).

Veinigen paragenesis and alteration assemblages

The Coyote deposit contains three sets of quartz veins that were localized mostly siltstone and formed before (QV_1), during (QV_2), and after (QV_3) gold mineralization.

Early-stage veins (QV_1)

The earliest quartz veins are layer-parallel, commonly located in siltstone beds near the contacts with competent sandstone beds. These veins also contain minor chlorite and minor dolomite; narrow (<5 mm) chloritic zones are

locally developed in the wall rock to the veins. Although these early veins are generally folded or crenulated, nearby contacts between sandstone and siltstone are not folded (Fig. 7b), suggesting that the contacts are bedding-parallel shears and that the early quartz veins were folded in response to this shearing or flexural slip. These veins are commonly found near anticlinal hinge zones, but do not appear to be significantly mineralized in gold. We interpret these veins and folds to be related to progressive bedding plane slip during the development of the F_{C1} Coyote Anticline, and are probably not related to an earlier event.

Gold-stage veins (QV_2)

The early folded veins (QV_1) are cut by both laminated quartz–chlorite veins with minor sulfide minerals and by planar, auriferous quartz veins with minor chlorite (after biotite), dolomite, and sulfide minerals. Both of these vein types are hosted mostly by siltstone, commonly within a few centimeters of contacts with siltstone, and are crosscut by late-stage quartz veins (QV_3).

The only real difference between the laminated veins and auriferous veins is the presence of gold in the latter type. Both vein types are present in brittle faults, although they are rarely sheared, and they are locally associated with chlorite(–sericite–biotite) alteration selvages that extend, at most, 10 mm into the host siltstone. These vein types probably represent the same generation (QV_{2a}), as they do not cut each other.

Sulfide minerals in these veins, which are characterized by strained granoblastic quartz, include variable amounts of arsenopyrite, pyrite, and chalcopyrite. Other minerals in the veins include tourmaline, sericite, biotite, and potassium feldspar. However, gold is associated with a volumetrically minor and later paragenetic stage (QV_{2b} ; Fig. 7c) containing less-strained quartz with variable amounts of arsenopyrite, magnesian calcite, potassium feldspar, biotite (commonly altered to chlorite), pyrite, galena, sphalerite, chalcopyrite, and bismuth minerals (native bismuth, bismuthinite, and hedlyite [$Bi_{14}Te_6$]). The later paragenetic assemblage is in brittle fractures or tension gashes with normal movement that cut the earlier paragenetic stage. Fractures containing the later paragenesis extend up to several centimeters into the host rock, commonly offsetting the margin of the vein and diffracting steeply into the country rocks (Fig. 8c). Biotite and chlorite commonly fill the fractures where they intersect the country rocks. The tensional gashes have either dilational or constrictional bends and are commonly shallowly dipping and at a high angle to the earlier paragenetic stage.

Other than the lack of gold, the main difference between the auriferous veins and the laminated veins is the lack of

this later paragenetic stage (QV_{2b}) in the laminated veins. This suggests that, although arsenic and some base metals were introduced more extensively during the initial formation of these veins, gold deposition is restricted temporally and spatially to the development of the second paragenetic stage, possibly as the consequence of relaxation of or changes in the orientation of the stress regime. The gold-bearing paragenesis also transgresses structures associated with D_{C2}, so the change in the stress regime is late- to post-D_{C2}.

The poles to chalcopyrite, arsenopyrite, and auriferous veins on an equal-area stereographic projection (Schmidt) concentrate close to the plunge direction of F_{C2} (Fig. 9c,d,f). This indicates that the mineralized veins formed perpendicular to S_{C1}, associated with F_{C2} folds (i.e., along S_{C3} extensional structures), and that the mineralization most likely took place during D_{C2}. The cluster of poles for the chalcopyrite-bearing veins towards the center of Fig. 9e plot near the poles to the bedding along the northern and shallower limb of the Coyote Anticline. This is thought to be associated with local openings along bedding planes along the northern limb of the anticline during D_{C2}.

Late-stage veins

The main set of postgold veins consists of nonmineralized buck quartz veins (QV₃). These veins are generally planar, cut the earlier vein generations, and are associated with regional, northwest-striking, regional D₆ faults. Other late veins include calcite veins that fill late fractures.

Alteration

Weathering extends to a depth of up to 170 m in the Coyote area, obscuring alteration assemblages and their relationship to mineralized zones. Although extensive weathering creates uncertainty, our work suggests that metasomatic alteration can be related to discrete tectonothermal and hydrothermal events. The regional metamorphic assemblage is dominated by the assemblage quartz–muscovite–chlorite–potassium feldspar, with the relative proportion of these minerals determined by lithology. A later assemblage of quartz–muscovite–biotite–potassium feldspar containing minor, but variable, tourmaline, actinolite, and arsenopyrite overprints this metamorphic assemblage. This later assemblage is interpreted to be related to the emplacement of the granites that surround the western part of the Coyote area (Fig. 2). Within the thermal aureole of the granites, porphyroblastic biotite and andalusite form part of this assemblage. The mineralogical similarity between this assemblage and the vein assemblage suggests the Coyote auriferous veins are associated

with the granite-related metamorphic–metasomatic assemblage; however, additional work is required to confirm this.

In addition to these assemblages, which affect most or all rocks at the Coyote deposit, other more localized alteration assemblages include quartz–sericite–pyrite–chlorite (most abundant; commonly highly siliceous), quartz–dolomite (spotting and veining), quartz–potassium feldspar (uncommon), graphite, and chlorite(–biotite). With the exception of the last assemblage, none of these assemblages can be related to the auriferous veins, although some may be related to late dolomite-bearing veinlets. The most visible and extensive metasomatic product is coarse (to 20 mm) arsenopyrite porphyroblasts, constituting up to 2% of the rock. Although locally associated with auriferous zones, the arsenopyrite porphyroblasts are extensively developed outside of these zones, both in sandstone and in siltstone. Although arsenopyrite porphyroblasts are not always closely associated with silicate alteration assemblages, their crosscutting habit shows that they were formed after deposition of the host rocks and are probably associated with subtle and extensive arsenic metasomatism.

Locally developed alteration assemblages appear to be structurally controlled. For example, northwest-trending normal faults that dip to the southwest are heavily fractured and have a pervasive quartz–dolomite alteration. Larger fault zones, such as those on the Gonzales Fault, are also silicified and dolomitized. Siltstone and shale beds that are intersected by these faults are both intensely fractured along bedding and intensely chlorite(–sericite–biotite)-altered. This assemblage, which is associated with auriferous veins, is more extensive in siltstone and shale relative to sandstone. The brittle component of the Gonzales Fault is patchily calcite-altered, whereas other faults are annealed with quartz and chlorite.

Genetically, the chlorite(–biotite) alteration assemblage may be the most important. This assemblage commonly forms narrow (<10 mm) selvages adjacent to auriferous veins. In addition, biotite, which is commonly altered to chlorite, is an important accessory mineral to both paragenetic stages in the auriferous veins. High-grade auriferous veins are also present within a chloritic shear along the contact between siltstone, shale, and sandstone. In this case, chlorite also replaces biotite both in the wall rock and in the shear. These relationships suggest that biotite was initially stable but became unstable and was replaced by chlorite during gold introduction. Portable Infrared Mineral Analyzer analysis showed that high-grade gold is spatially associated with the introduction of magnesian chlorite. Such a relationship could suggest mineralization taking place under a regime of decreasing temperature.

The composition of ore-forming fluids

Strained, granoblastic quartz crystals in QV₂ veins contain trails and clusters of pseudosecondary or secondary fluid inclusions. As Mernagh and Wygralak (2006) present complete results of fluid inclusion studies of the Coyote deposit, only a summary is provided here. Four types of inclusions were identified based on microthermometric and Raman microprobe analysis. Type A inclusions contained CO₂-rich liquid±vapor phases with small amounts of CH₄ or N₂. Liquid H₂O and/or accidentally trapped graphite were present in some of these inclusions. Type A inclusions have salinities of 3–7 wt.% NaCl equiv. based on clathrate melting temperatures. The majority of these inclusions homogenized or partially homogenized (i.e., L+V→L) over the range 290–360°C.

Aqueous type B inclusions contain 10–30 vol%, CH₄-rich vapor with minor CO₂ and occasional accidentally trapped graphite crystals. Clathrate-melting temperatures indicate salinities of 1–13 wt.% NaCl equiv., and these inclusions homogenized in the range 255–389°C, with a mode at 310°C.

Type C inclusions are monophase, CH₄±N₂±CO₂ vapor inclusions, and type D inclusions are two-phase aqueous inclusions. The majority of these inclusions homogenized or partially homogenized (i.e., L+V→L) over the range from 290 to 360°C, but the graphite crystals did not dissolve at temperatures up to 550°C.

Both the graphite-absent and graphite-bearing type B inclusions showed no observable phase changes below 0°C. The first observable phase change was clathrate melting over the range 2.9–15.3°C, equating to salinities between 1 and 13 wt.% NaCl equiv. These inclusions homogenized or partially homogenized [i.e., L+V(L)] over the range 255–389°C, with a mode at 310°C. Once again, the graphite crystals did not dissolve at temperatures up to 550°C.

The type C inclusions could not be completely frozen. Type D inclusions homogenized to the liquid phase over the range from 180 to 420°C, with the majority homogenizing below 320°C.

Correlation and timing of structural and mineralizing events

Vandenberg et al. (2001) and Crispe et al. (2006) have defined a regional structural chronology based on observations in the central and eastern parts of the Tanami region. Because of a lack of data, structural events in the western Tanami region have not been correlated into this regional framework. In the following section, we propose correlations of the local structural chronologies in the Bald Hill and Coyote areas with the regional Tanami chronology. Our

proposed correlations (Table 1) are based on similarities of structural style and, in some cases, geochronological control offered by crosscutting intrusive bodies and the age of mineralization.

We interpret the layer-parallel shear at the top of the Bald Hill succession and associated isoclinal folds, which are the oldest structural elements in the western part of the Tanami region, to predate the earliest regional deformation event of the Vandenberg et al. (2001) chronology. Layer-parallel shears and isoclinal folds, which characterize D_{B1}, are not typical of the tight folds associated with regional D₁. Rather, we suggest that our D_{B1} correlates with an earlier event, possibly the D₁ event of Smith et al. (1998), who reported a weak layer-parallel fabric (their S₁) in the Dead Bullock Soak goldfield that predated folding assigned as the regional D₁ by Vandenberg et al. (2001).

We correlate our D_{B2} and D_{C1} events with the regional D₁ event (Table 1), which has been constrained in age between 1,835 and 1,825 Ma (Vandenberg et al. 2001; Crispe et al. 2006). Folds associated with D_{B2} and D_{C1}, both at the mesoscopic and macroscopic scales, are tight, with an easterly trend (e.g., the Coyote Anticline: Fig. 8), consistent with folds developed during regional D₁. Moreover, in the total magnetic intensity aeromagnetic image (Fig. 2), these folds are cut by granites that have been dated at ca. 1,795 Ma.

According to this correlation and structural relationships observed in drill core, the gold mineralization in the Bald Hill area took place before or during the Tanami Orogeny (D₁), a timing that predates that at Coyote and most other deposits in the Tanami region (cf. Huston et al. 2006). The only other district for which an early timing has been proposed is the Granites district, where Scrimgeour and Sandiford (1993) and Adams et al. (2006) have documented gold mineralization synchronous with amphibolite facies metamorphism and early deformation correlated with the regional D₁ event (Vandenberg et al. 2001).

Our data suggest that mineralization at Coyote took place during D_{C2}, postdating the Tanami Orogeny. We correlated D_{C2} with the regional D₅ event, which involved reverse and oblique-slip faults, as well as buckle folds associated with these faults (Vandenberg et al. 2001; Crispe et al. 2006). Additional constraints on the timing of these events are provided by the age of mineralization, which is interpreted to have formed during D₅ at the Callie deposit, where it has been dated using hydrothermal xenotime at 1,801±19 Ma (Cross et al. 2005).

Five analyses of hydrothermal xenotime from a gold-bearing vein from the Coyote deposit were undertaken using a xenotime standard and gave an age of 1,791±8 Ma (Cross 2004, personal communication; based on data from Armstrong 2002, personal communication), which we interpret as the age of gold mineralization. This ca. 1,791-Ma age overlaps the ages obtained for granite bodies in the

western Tanami region and is consistent with the age obtained for the Callie deposit.

Towards genetic models for the Bald Hill and Coyote gold deposits

Although data collected in this study are not definitive, they place some constraints on models for the genesis of gold in deposits in the Bald Hill and Coyote areas of Western Australia.

Bald Hill deposits

Our studies in the Bald Hill area suggest that gold deposition took place early in the tectonic history of the area (i.e., before or during the ca. 1,835–1825-Ma Tanami Orogeny) and was accompanied by greenschist facies metamorphism. The mineralization was localized by structures that focussed carbonic fluids into dilational or chemically receptive sites. In particular, the mineralized zones at the Kookaburra deposit are within saddle reefs, which are formed with dilational zones in hinges of folds. At Kookaburra, these saddle reefs continue along bedding contacts where bedding slip provided paths for fluid flow.

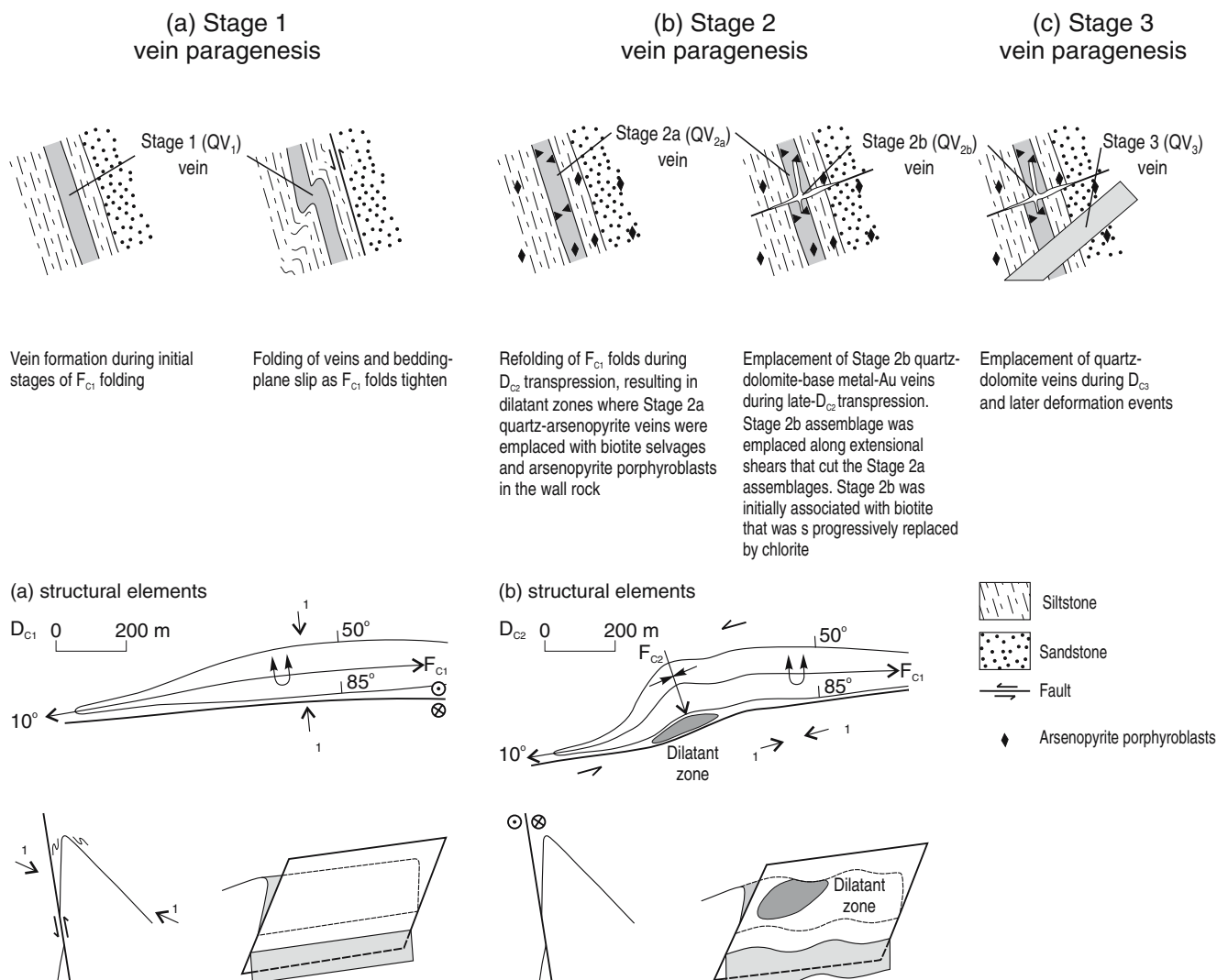


Fig. 10 Preliminary model for the formation of the Coyote deposit: **a** stage 1—development of east-west-trending F_{C1} angular fold at high crustal level, **b** stage 2—refolding of F_{C1} folds about shallowly south-plunging fold axes in response transpression during D_{C2} that reactivated the Gonzales Fault with a dextral sense of motion, and **c** stage 3—late-stage fracturing associated with D_{C3} faulting. Early-stage quartz veins are emplaced and folded during F_{C1} folding. Gold-

stage quartz veins are emplaced in dilational zones developed by interaction of D_{C2} folding with transpressive motion along the Gonzales Fault. Gold was introduced as the D_{C2} event relaxed, allowing gold and quartz to be introduced in late fractures within gold-stage quartz veins. Late-stage quartz and quartz-dolomite veins were emplaced during D_{C3} and later fracturing events

These reefs are generally developed parallel to the plunge of D_{B2} folds.

At the Sandpiper deposit, the geometry of the ore lens is not consistent with saddle reefs. Rather, the ore lenses are stratabound, suggesting either control by the chemistry of the host rock or control by bedding-parallel shears. The host to the Sandpiper deposit contains graphitic shale. As Smith et al. (1998), Huston et al. (2006), and Williams (2006) have suggested that graphitic (or carbonaceous) rocks are very effective chemical traps elsewhere in the Tanami region, the distribution of graphite in the Bald Hill sequence may have been an important gold control at the Sandpiper deposit.

Coyote deposit

Figure 8 illustrates the two major structural elements at the Coyote deposit, the early, shallowly west-plunging Coyote Anticline and the near-vertical Gonzales Fault that shears the southern limb of this fold. We interpret that these two structural elements formed during the Tanami Orogeny (D_1) and synchronous with the D_{B2} event in the Bald Hill area. The earliest generation of folded quartz veins (QV_1) most likely formed at this time (Fig. 10) along bedding-parallel shears. These veins were progressively folded to accommodate bedding-slip as the Coyote Anticline tightened. As this anticline is angular and generally lacks a pervasive axial-planar foliation, we interpret that it formed at a relatively high structural level.

Gold mineralization at Coyote is interpreted to have taken place late during D_{C2} , which corresponds to regional D_5 . Although mesoscopic effects of regional D_2 to D_4 events are not recognized at the Coyote deposit, regional fold interference patterns from aeromagnetic data (Fig. 2) suggest that these folding events have affected the western Tanami region. Cores from deeper diamond drillholes at Coyote have a penetrative foliation that has incorrect vergence for the Coyote Anticline, indicating that the foliation is later than the folding forming the Coyote Anticline.

The D_5 event in the Tanami region resulted in east-southeast-trending dextral brittle-ductal faults and antithetic reverse movement along more northerly trending faults (cf. Huston et al. 2006). In many cases, transpression resulted in reactivations of existing faults, including the Gonzales Fault. We interpret that the flexures indicated by distribution of the marker siltstone and variations in fold axes of F_1 mesofolds also formed at this time (Fig. 10). Interaction between shallowly south-plunging regional F_5 (F_{C2}) folds and dextral reactivation of the Gonzales Fault resulted in local dilatory zones in south-southeast-facing limbs of regional F_5 folds along the northern side of the Gonzales Fault (Fig. 10). Competency contrasts between siltstone and sandstone beds localized dilation and allowed emplacement of laminated quartz-chlorite-pyrite(–arsenopyrite) veins

(QV_{2a}). Arsenic was also introduced during this event, leading to development of arsenopyrite porphyroblasts in both siltstone and sandstone.

Gold was introduced during the late stages of D_5 (QV_{2b}). As the stress field associated with regional D_5 relaxed, the release of pressure allowed the fracturing of the laminated quartz veins (Fig. 10). Moreover, the decrease in pressure allowed the auriferous fluids to effervesce, as indicated by fluid inclusion studies (Mernagh and Wygralak 2006), causing gold deposition as H_2S was partitioned into a CO_2 -rich vapor. This process would have taken place in regions of lowest pressure, mainly along SSE-facing limbs of F_5 folds. It is also likely that the late- D_5 relaxation was accompanied by a decrease in temperature, which may be reflected in the replacement of biotite by chlorite in the late-stage paragenesis of the auriferous veins.

As our model suggests that the gold deposition at Coyote was caused by pressure decrease, other structural environments favorable for gold deposition include dilational zones along bends or perturbations of shear zones active during D_5 . The lack of a distinct lithochemical control (as seen in other Tanami gold deposits) suggests that structural traps were important in localizing gold at Coyote. This structural control may be the most important factor for gold deposition in the Killi Killi Formation, which lacks the chemically reactive rocks that are highly effective gold traps in the Dead Bullock Formation (e.g., Huston et al. 2006).

Conclusions

Geological, geochemical, and structural data from the western Tanami region suggest that gold was localized by structural and chemical factors, possibly at different times in the tectonic history of the area. Using structural correlations, the first gold event is inferred to have happened during the ca. 1,835–1,825-Ma Tanami Event in the Bald Hill area. However, no geochronological data are available to test this inference. During this event, gold is inferred to have deposited in dilational zones associated with saddle reefs or in graphitic rocks that acted as chemical traps.

The second gold event took place at ca. 1,790 Ma and correlates with the main gold event in the east Tanami. This event is associated with the regional D_5 deformation event and occurred at the end of a major period of granite intrusion. At the Coyote deposit, gold was emplaced along dilational zones in the Gonzales Fault as it was reactivated during D_5 . Gold deposition is inferred to have been caused by decreases in fluid pressure, which resulted in effervescence. Unlike elsewhere in the Tanami region, reactions with wall rock played a minimal role in gold deposition. These results imply that no single model should be used in gold exploration in the Tanami region.

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