Miner Deposita (2007) 42:3–26
DOI 10.1007/s00126-006-0107-1

ARTICLE

Geological framework of the Archean and Paleoproterozoic Tanami Region, Northern Territory

A. J. Crispe · L. C. Vandenberg · I. R. Scrimgeour

Received: 1 January 2006 / Accepted: 11 October 2006 / Published online: 13 December 2006

Abstract The Tanami Region, a poorly exposed, mostly Paleoproterozoic province within the North Australian Craton, hosts a number of significant gold deposits in diverse settings. Rare exposures of 2,520–2,500 Ma amphibolite facies Archean gneiss and metasedimentary rocks form basement to the thick overlying metasedimentary succession of the 1,880–1,830 Ma Tanami Group. The basal unit of the Tanami Group is the Dead Bullock Formation, a fining-upward deep-water succession dominated by siltstone, carbonaceous siltstone, iron-rich siltstone and mafic sills. Carbonaceous- and iron-rich lithologies in the upper Dead Bullock Formation represent important hosts for gold mineralization. The conformably overlying Killi Killi Formation represents turbiditic sedimentary rocks that are correlated with the widespread Lander Rock beds of the Arunta Region. Sedimentation of the Tanami Group was terminated by regional deformation and greenschist to amphibolite facies metamorphism during the Tanami Event (D_1/M_1), at around 1,830 Ma. The Tanami Group is unconformably overlain by rhyolite, siliciclastic sedimentary rocks, and felsic ignimbrite of the Ware Group that were deposited at about 1,825–1,810 Ma. Subsequent ESE–WNW to SE–NW directed shortening (D_2), followed by NE–SW to E–W directed shortening (D_3), has resulted in open NE F_2- and NW F_3-trending folds in both the Tanami and Ware Groups. Voluminous granitoids, dominated by I-type, biotite granodiorite, and monzogranite were intruded in the interval 1,825–1,790 Ma and have been subdivided using geochemical criteria into the Birthday, Frederick, and Grimwade Suites. Basalt and immature sedimentary rocks of the Mount Charles Formation are restricted in extent to the Tanami mine corridor, and are interpreted to reflect a continental rift succession that was deposited around 1,800 Ma, with an early Archean sedimentary provenance. Steep S to SE dipping F_4-fold structures of Tanami and Ware Group metasedimentary rocks, many spatially associated with 1,825–1,790 Ma granitoid intrusions, indicate a period of SSE-directed regional shortening (D_4) syn-to-post the regional granitoid intrusive phase. A network of N to NW striking faults, several of which are interpreted as oblique thrusts with a component of left lateral movement, indicates a period of D_5 convergence during WSW–ENE to E–W directed shortening. The Tanami mine corridor fault system comprises a network of N, NE to ENE striking D_5 faults that merge with N to NW striking faults and probably accommodated movement between granite core domains. D_5 faulting is associated with the main phase of gold mineralization in suitable structural–lithological traps. The Paleoproterozoic basement of the Tanami Region is unconformably overlain by quartz sandstone, lithic arenite, and conglomerate of the Pargee Sandstone. Pargee Sandstone may represent syn-tectonic sedimentation related to the 1,730 Ma Strangways Orogeny, and is unconformably overlain by the late Paleoproterozoic platform cover succession of the Birrindudu Group. The Paleoproterozoic basement and cover sequences have subsequently undergone several episodes of faulting, collectively termed D_{6+}. The Paleoproterozoic evolution of the Tanami Region is interpreted to have occurred in an intracratonic setting, but was fundamentally influenced by tectonic events in the adjacent Halls Creek Orogen (1,835–1,805 Ma Halls Creek Orogeny) and Arunta Region (1,815–1,800 Ma Stafford

Editorial handling: D. Huston

A. J. Crispe (✉) · L. C. Vandenberg · I. R. Scrimgeour
Northern Territory Geological Survey,
GPO Box 3000, Darwin NT 0801, Australia
e-mail: andrew.crispe@nt.gov.au

Event). The boundaries between the Tanami Region and Kimberley Region to the northwest and the Arunta Region to the southeast are transitional, and are largely defined by the presence or absence of identifiable Dead Bullock Formation.

Keywords Tanami Region · North Australian Craton · Paleoproterozoic · Stratigraphy · Structural geology

Introduction

The Tanami Region (formerly known as the Granites-Tanami Block; Blake et al. 1979; Scrimgeour and Sandiford 1993) is centered 600 km northwest of Alice Springs in northern Australia and forms part of the Paleoproterozoic basement of the North Australian Craton (Fig. 1). It is one of Australia's most productive gold provinces, hosting significant deposits at the Dead Bullock Soak, The Granites, and Tanami goldfields. Gold production in the

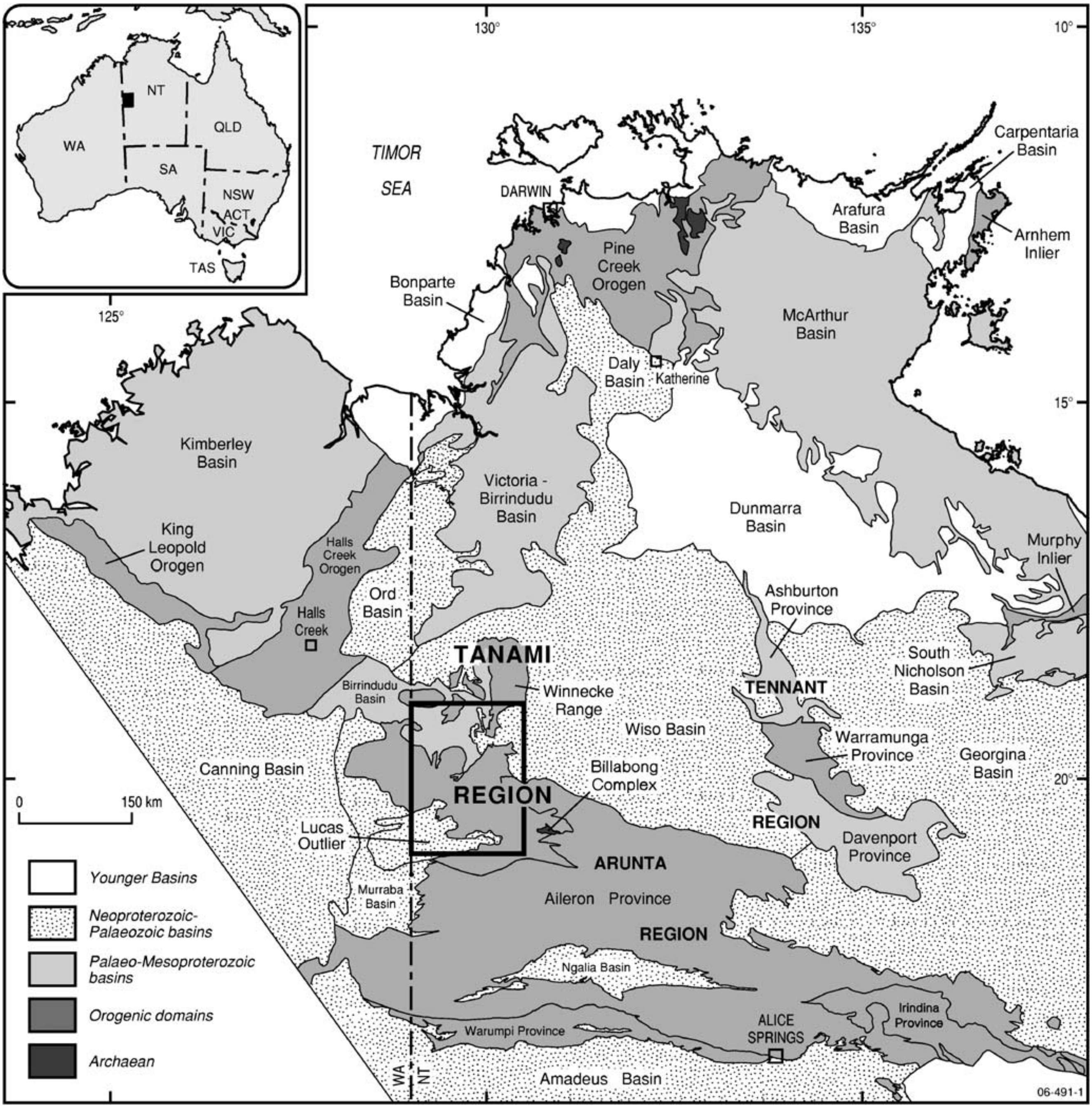


Fig. 1 Location of the Tanami Region

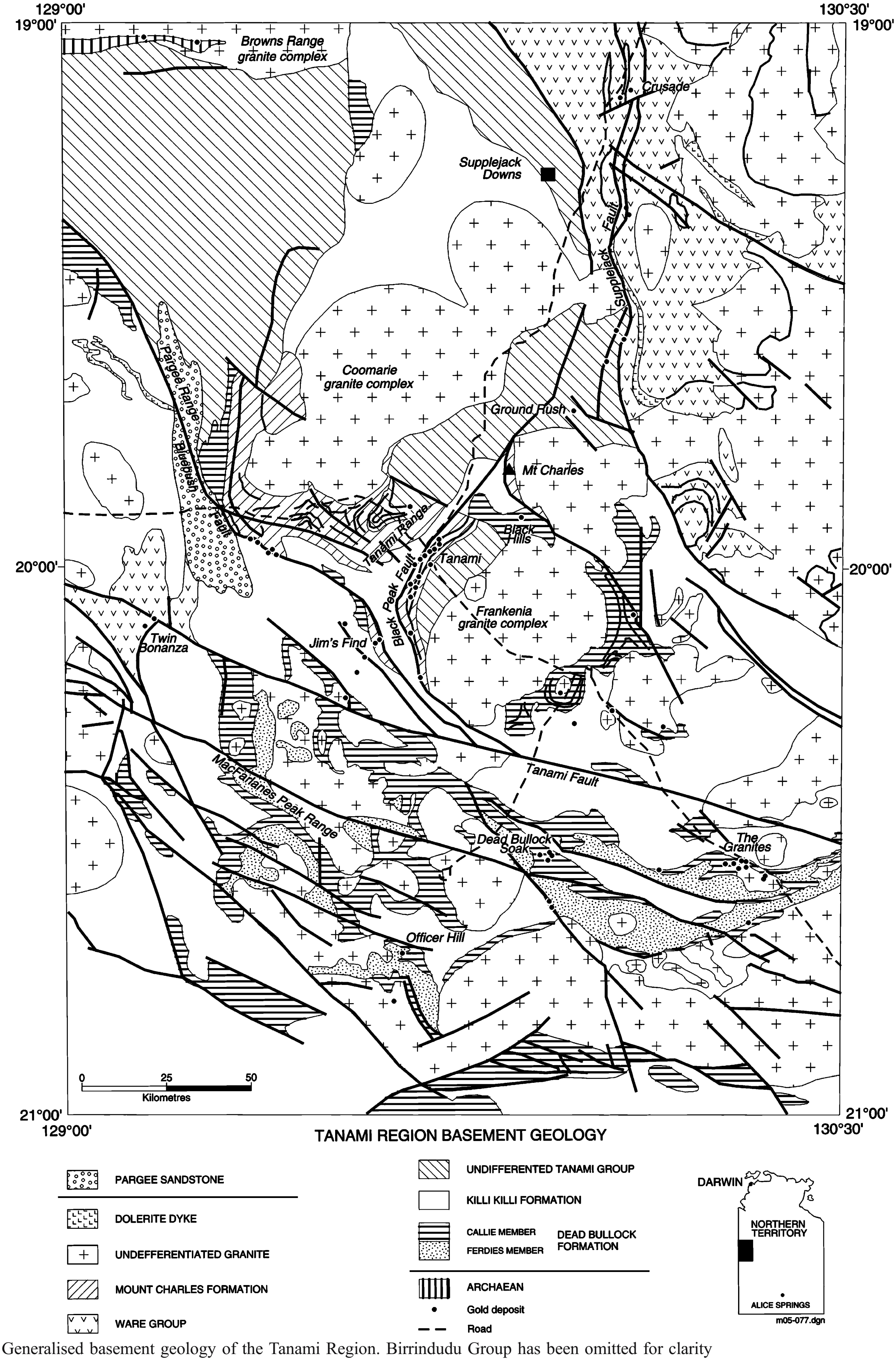


Fig. 2 Generalised basement geology of the Tanami Region. Birrindudu Group has been omitted for clarity

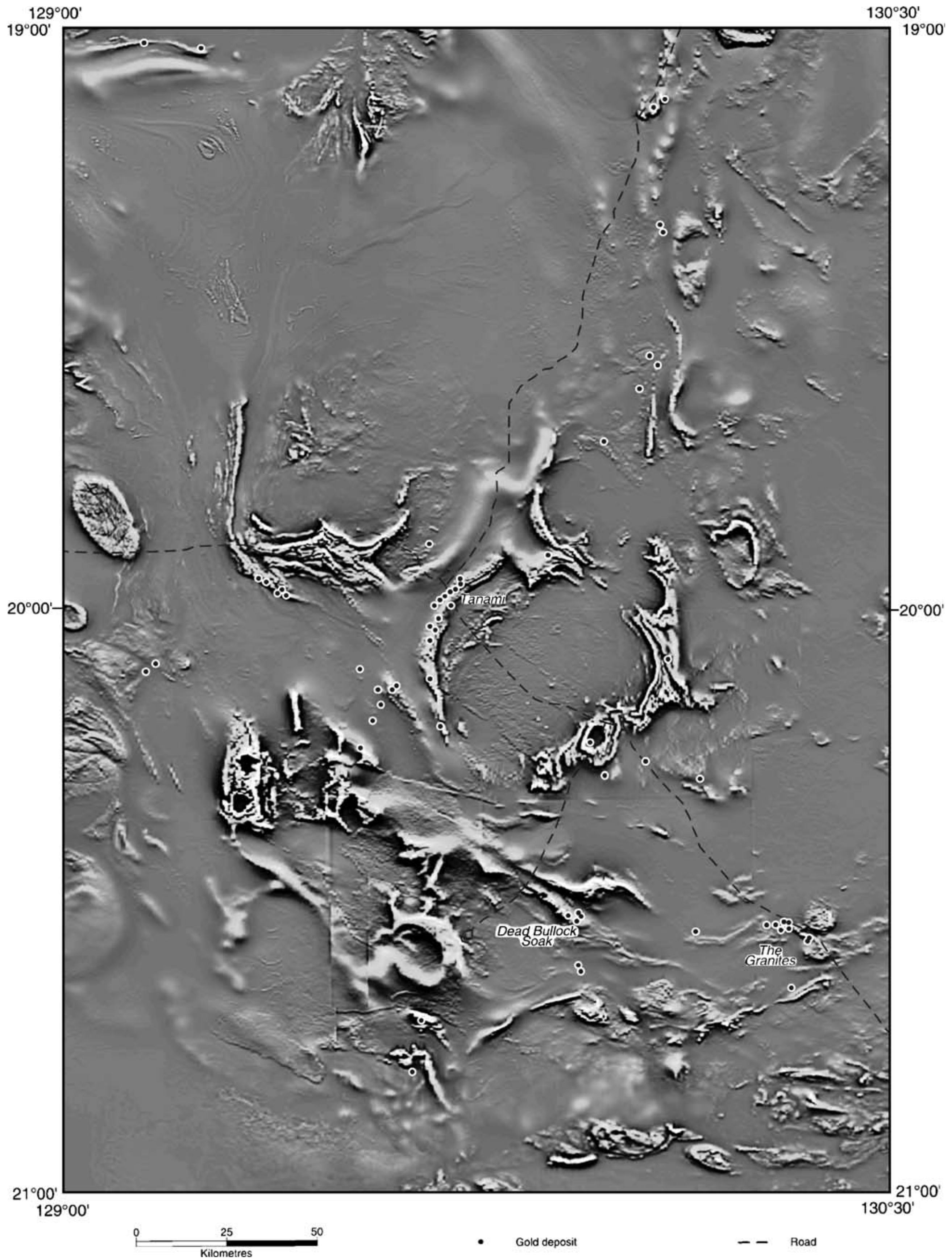


Fig. 3 First vertical derivative magnetic image of the Tanami Region

Tanami Region to date is an estimated 4.8 M oz Au with a remaining known resource of approximately 7.7 M oz Au (Wygralak et al. 2005). The area is dominated by sand plain with subdued topography, but is largely underlain by Paleoproterozoic rocks similar in age and history to other Paleoproterozoic terrains in northern Australia. Outcrop is generally sparse and deeply weathered, creating significant difficulties in the development of regional stratigraphic and structural frameworks.

Geological setting and previous studies

The Tanami Region forms part of the North Australian Craton (Myers et al. 1996), which includes the Paleoproterozoic basement of the Halls Creek and Pine Creek Orogens, and the Tennant Creek and Arunta Regions, and younger platform cover successions, which include the McArthur and Victoria-Birrindudu Basins (Fig. 1). Archean crust is interpreted to underlie much of the NAC, but is only exposed in the Pine Creek Orogen and Tanami Region (Page et al. 1995).

The Tanami Region lies between two neighboring regions of Paleoproterozoic basement: the Aileron Province of the Arunta Region to the southeast and the Halls Creek Orogen to the northwest (Fig. 1). Metasedimentary successions in the Aileron Province (Scrimgeour 2004) have ages in the range 1,860–1,750 Ma, and were variably affected by multiple tectonic and magmatic events in the interval 1,810–1,570 Ma, probably in response to plate margin processes (Collins and Shaw 1995; Scrimgeour 2003). In contrast, the Tanami Region was less strongly affected by these events. The Halls Creek Orogen has sedimentary and igneous protolith ages in the range 1,915–1,790 Ma and is interpreted as a collisional zone between the Kimberley Craton and the North Australian Craton (Myers et al. 1996; Sheppard et al. 1997, 1999; Griffin et al. 2000). Early tectonism in the Western and Central zones of the Halls Creek Orogen from 1,865 Ma to 1,850 Ma, has been attributed to accretion of exotic terranes and an island arc onto the Kimberley Craton (Sheppard et al. 1999; Griffin et al. 2000). The Eastern zone of the Halls Creek Orogen belongs to the North Australian Craton, and the amalgamation of the cratons is interpreted to have occurred during a collisional event in the interval 1,835–1,805 Ma (Myers et al. 1996; Sheppard et al. 2001; Bodorkos et al. 2002).

Paleoproterozoic orogenic rocks of the Tanami Region are unconformably overlain by late Paleoproterozoic gently folded sedimentary rocks of the Birrindudu Group of the Victoria-Birrindudu Basin, which crop out more extensively to the north (Figs. 1, 2). The Birrindudu Group comprises three units including, from the base: the Gardiner Sandstone, the Talbot Well Formation, and the Coomarie Sandstone (Blake et al. 1975, 1979). The Gardiner and Coomarie Sandstones form most of the main ridges in the area. The Tanami Region is overlain to the east by Cambrian sedimentary rocks of the Wiso Basin, to the west by the Paleozoic and Mesozoic rocks of the Canning Basin, and to the southwest by gently folded sedimentary rocks of the Neoproterozoic Murraba Basin.

First-edition mapping of the Tanami Region was undertaken by the Bureau of Mineral Resources (now Geoscience Australia) in the 1970s, leading to the first geological framework for the region (Blake et al. 1973, 1975, 1979). Subsequent studies have focused mainly on the major gold deposits worked since 1986 (Mayer 1990; Scrimgeour and Sandiford 1993; Cooper and Ding 1997; Tunks and Marsh 1998; Smith et al. 1998). In this paper, we summarize the findings of regional geological mapping of the Tanami Region undertaken by the Northern Territory Geological Survey in collaboration with Geoscience Australia since 1999. These more recent investigations have benefited from the use of publicly available regional magnetic and gravity data sets (Figs. 3, 4). More detailed descriptions of this work, including details of individual outcrops, geochemistry of intrusive rocks, and geochronology can be found in Hendrickx et al. (2000a); Vandenberg et al. (2001b,c), Smith (2001); Dean (2001); Cross and Crispe (2006), and Crispe and Vandenberg (in preparation).

Stratigraphy

A summary of the Paleoproterozoic stratigraphy of the Tanami Region and its relationship to structural and igneous events is given in Fig. 5.

Archean basement

Rocks of possible Archean age crop out on the southern margin of the Browns Range granite complex (Browns Range Metamorphics; Blake et al. 2000) and to the east in the De Bavay Hills region (Billabong complex; Page et al. 1995). Zircons of the latest Archean age occur in sedimentary and granitic units as detrital grains or xenocrysts indicating that underlying Neoarchean rocks are likely to be widespread (Cross and Crispe 2006). These rocks form the basement to the overlying Paleoproterozoic stratigraphy of the Tanami Region.

Browns Range metamorphics

The name Browns Range metamorphics was applied by Blake et al. (2000) to metamorphosed arkosic sedimentary rocks exposed near the Browns Range granite complex in Western Australia. The Browns Range metamorphics

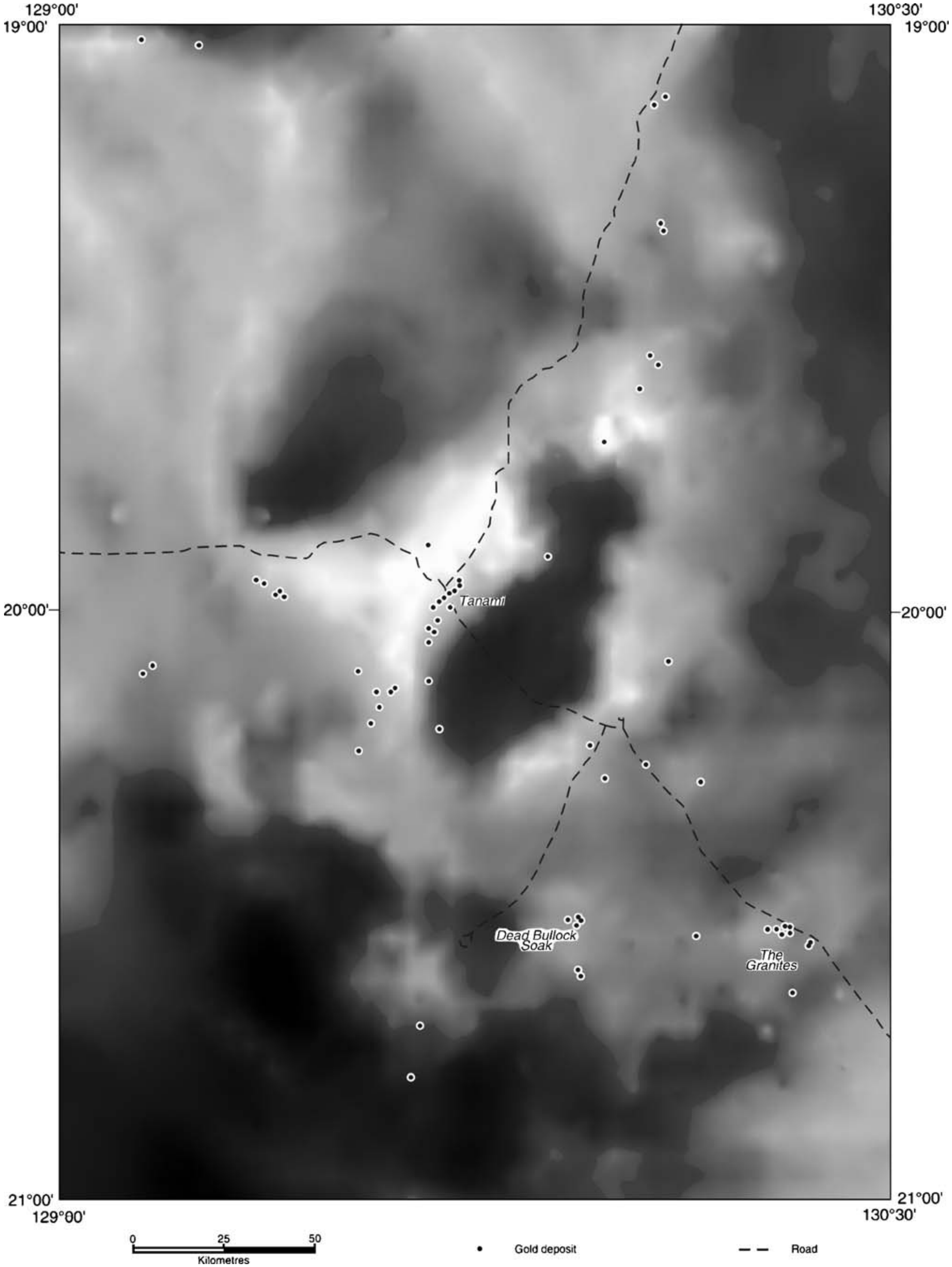


Fig. 4 Bouguer gravity image of the Tanami Region

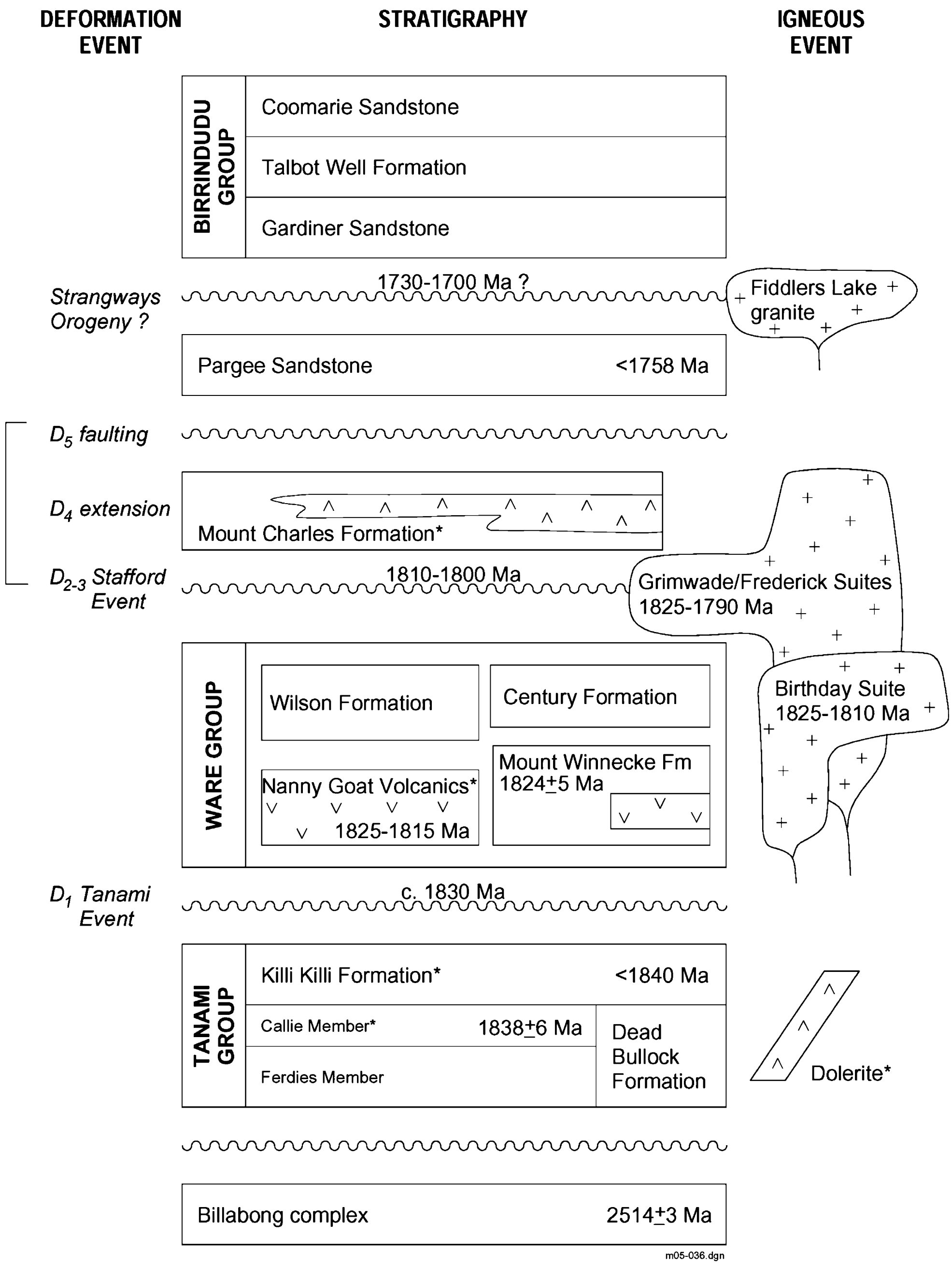


Fig. 5 Schematic summary of stratigraphic, igneous and structural events in the Tanami Region. *Asterisks* denote units hosting significant gold mineralization

within the Northern Territory occur along the southern margin of the Brown Range granite complex and include quartzofeldspathic gneiss and muscovite schist intruded by aplite and pegmatite. The muscovite schist contains possible relict low-angle cross-bedding. SHRIMP geochronology on complex zircon populations by Page et al. (1995) led to an interpreted late Neoarchean (2,510–2,500 Ma) age for the Browns Range metamorphics, although this interpretation is now in some doubt (Cross and Crispe 2006). Page et al. (1995) considered the entire Browns Range granite complex to be Archean, but more recent geochronology and geophysical interpretation suggests that most of the complex comprises granite with emplacement ages of 1,805–1,780 Ma (Smith 2001).

Billabong complex

Approximately 50 km east-southeast of The Granites is a region of interpreted Archean basement informally known as the “Billabong complex” (Page et al. 1995). It comprises an area of high magnetic response associated with high Bouguer gravity responses. The complex crops out approximately 10 km southeast of the DeBavay Hills as a series of small, smooth, low pavements that consist of banded granitic gneiss. A SHRIMP U-Pb zircon age of 2514±3 Ma has been obtained from this granitic gneiss (Page et al. 1995).

Tanami Group

The Tanami Group (Blake et al. 1973, Tanami Complex of Blake et al. 1975) comprises two formations that were deposited in the interval 1,880–1,830 Ma (Cross and Crispe 2006). The lower unit (Dead Bullock Formation) is a fining-upward package in which feldspathic sandstone and siltstone grade up into siltstone, chert, and iron-rich siltstone, with rare tuffaceous volcaniclastic beds. The upper unit is a thick package dominated by turbiditic sandstone and siltstone (Killi Killi Formation). A lower quartzite unit that was interpreted by Cooper and Ding (1997) to unconformably overlie the Archean Billabong complex, and stratigraphically underlie the Dead Bullock Formation near the DeBavay Hills, is now considered to represent thickened and sheared quartz veining at the contact between the Billabong complex and Tanami Group rocks.

Dead Bullock Formation

The Dead Bullock Formation, which is host to significant gold mineralization at The Granites and Dead Bullock Soak, is a deep-water fining-upwards succession in which siltstone, carbonaceous siltstone, and less abundant sandstone of the lower Ferdies Member grade up into chert-bearing iron-rich siltstone and carbonaceous siltstone of the overlying Callie Member. The rocks were previously included in the Mount Charles beds of Blake et al. (1975) and incorporate the informally named Blake beds and Davidson beds of Smith et al. (1998) and the MacFarlane Peak Group and Twigg Formation of Hendrickx et al. (2000a). The base and lower parts of the formation are not exposed and are, therefore, poorly understood. However, lithic sandstone, displaying soft sediment deformation and intraformational breccias have been observed in drill core to underlie the exposed Callie Member at Dead Bullock Soak. In addition, integrated outcrop and geophysical data suggests sediments of the Ferdies Member underlie the more highly magnetic iron-rich siltstone layers of the Callie Member (Vandenberg et al. 2004).

The Ferdies Member comprises feldspathic sandstone and fine-grained sandstone locally interbedded with siltstone, and is equivalent to most of the "Lower Blake beds" of Lambeck (2004) where it is described from drill core. Exposures of Ferdies Member are rare but include deformed feldspathic sandstone near Officer Hill and quartzose psammite east of MacFarlane's Peak Range. Feldspathic sandstone, conglomerate, and siltstone that host the Groundrush deposit have also been assigned to the Ferdies Member (Crispe and Vandenberg 2004). The top of the Ferdies Member is defined as the top of the uppermost sandstone unit within the Dead Bullock Formation.

The Callie Member comprises fine-grained lithologies such as siltstone, chert, iron-rich siltstone, and carbonaceous shale, along with rare tuffaceous sandstone, and is broadly equivalent to the "Upper Blake beds" and "Davidson beds" of Smith et al. (1998) and Lambeck (2004). The Callie Member forms a number of small isolated silicified outcrops, but the best exposures are from mine pits and drill core from Dead Bullock Soak where they are described in detail by Smith et al. (1998), Williams (2002), and Lambeck (2004). Similar lithologies are reported in adjacent regions of Western Australia (Waddell 1999), east and northeast of the Browns Range granite complex in the northern Tanami Region, and in the De Bavay Hills in the east. A sample of tuffaceous sandstone from the uppermost Callie Member in the Black Hills has a SHRIMP U-Pb age of 1,838±6 Ma (Cross and Crispe 2006). The top of the Callie Member is dominated by laminated siltstone and iron-rich chert that is transitional over a short interval into interbedded graywacke and siltstone of the overlying Killi Killi Formation.

Due to structural thinning and thickening, lateral variation and the lack of an exposed continuous section of Dead Bullock Formation, the thickness of the unit is poorly constrained (Lambeck 2004). Estimates from regional geophysical modeling of magnetic and density profiles across the Dead Bullock Formation suggest a minimum thickness of about 1,000 m (Vandenberg and Meixner 2003, 2004). The formation is intruded by dolerite dikes and sills in the Dead Bullock Soak area (Smith et al. 1998) and regionally by numerous 1,825–1,790 Ma granite bodies.

Fresh outcrops at Dead Bullock Soak are of buff to gray, massive to laminated siltstone with interbedded black carbonaceous siltstone, thinly bedded chert, iron-rich siltstone, and minor thinly bedded quartz-rich sandstone. A detailed stratigraphy for the Dead Bullock Formation at Dead Bullock Soak has been published by Smith et al. (1998) and Lambeck (2004). At shallow levels within the Callie deposit mineralization is hosted in the locally named "Callie host unit," which comprises pale siliceous bands that cross-cut bedding within chlorite–sericite schist. At deeper levels the mineralization transgresses into higher levels of the local stratigraphy (Williams 2006). A distinctive unit of "boudin chert" also occurs at the Callie deposit and comprises a carbonaceous metasiltstone with bands of chert nodules up to 5 cm in diameter (Fig. 6).

The upper part of the Callie Member at Dead Bullock Soak comprises fine-grained, variably carbonaceous metapelite (quartz–chlorite–albite–biotite±graphite schist), and

Fig. 6 Dead Bullock Formation chert nodules ('Callie boudin chert', Dead Bullock Soak goldfield, DBD395 drill core, 815 m)

several "BIF" units (mine terminology) up to 20 m thick. The "BIF" units consist of interbedded layers rich in Fe-amphibole and chlorite with 1- to 20-cm-thick laminated chert bands. They host a number of smaller deposits in the Dead Bullock Soak goldfield. These deposits form two groups separated by a 200-m thick dolerite sill. At Dead Bullock Soak, the Callie Member is overlain by the Killi Killi Formation (Madigan beds of Smith et al. 1998), which is a graywacke-dominated succession.

The Dead Bullock Formation at The Granites goldfield has a higher metamorphic grade (mid-amphibolite facies) and has a distinguishable local stratigraphy consisting of three main units: the "footwall schist", "host unit," and "hangingwall schist" (Mayer 1990; Adams et al. 2006). The "footwall schist" comprises at least 120 m of biotite-bearing pelitic schists containing andalusite, cordierite, gedrite and/or garnet (Scrimgeour and Sandiford 1993) with less abundant hornblende- and cummingtonite-bearing schists, metapsammite and rare thin recrystallized chert. Contact metamorphism resulting from the intrusion of a Grimwade suite granite is characterized by fine-grained garnet and andalusite overgrowths (Vandenberg 2002). The "host unit" (5–35 m thickness) consists of three layers of banded hornblende–cummingtonite schist that contain pyrrhotite, arsenopyrite, and loellingite (Adams 1997) and are separated by massive almandine–cummingtonite ± biotite schist, with minor conformable calc-silicate and chert bands. The "hangingwall schist" is more than 150 m thick and consists of biotite–andalusite schist (locally graphitic), thin calc-silicate, laminated chert, and nodular chert bands. Layers become increasingly psammitic at higher levels in the stratigraphy, and the upper part has a gradational contact with the overlying Killi Killi Formation. The ore zone follows the margin of a Grimwade-suite granite body and is associated with a brittle-ductile shear zone, crosscut folded stratigraphy, and contains folded mineralized calcite-quartz veins with alteration zones in which calc-silicate assemblages are aligned in the shear fabric (Scrimgeour and Sandiford 1993; Crispe and Vandenberg, in preparation).

Dead Bullock Formation north of the MacFarlane's Peak Range comprises west-dipping black graphitic phyllite and minor thin-bedded calc-silicate rock. Outcrops 20–30 km east and east-southeast of Browns Range granite complex include metamorphosed interbedded sedimentary chert, fine lithic arenite, and phyllite assigned to Dead Bullock Formation on lithological and structural grounds. Bedding parallel and poddy quartz veins and hematitic breccia are well developed. The metasedimentary rocks here show evidence of deformation at amphibolite facies conditions, with a greenschist facies overprint.

West of the Tanami mine corridor a succession of purple siltstone with minor graywacke, quartz wacke, and chert is separated from the Mount Charles Formation by the Black Peak Fault. This succession was mapped as Mount Charles beds by Blake et al. (1979) and "Twigg Formation" by Hendrickx et al. (2000a) but is now considered to belong to the Dead Bullock Formation. The unit in this region comprises finely laminated purple siltstone with lesser red- or white-banded thin chert beds and rare chert nodules. Sandstone beds of graywacke and quartz wacke composition are medium-grained and thin- to medium-bedded. Drilling of the formation west of the Tanami mine intersected some graphitic schist (N. Bryce, 2003, personal communication).

A succession of purple siltstone with minor graywacke, quartz wacke, and chert exposed in the Black Hills region is also interpreted to belong to the Dead Bullock Formation. This area contains the tuffaceous sandstone layer that returned a U-Pb SHRIMP zircon age of 1,838.4±6.4 Ma (Cross and Crispe 2006).

The Dead Bullock Formation was probably deposited in quiet marine conditions below storm wave base, with water depth increasing towards the top of the formation. Abundant chert, as layers or nodules, is indicative of very slow sedimentation rates, suggesting the Callie Member may represent a prolonged period of deposition. The presence of black graphitic mudstone and possible banded-iron-formation suggests that the basin periodically became euxinic.

Killi Killi Formation

The Killi Killi Formation (Killi Killi beds of Blake et al. 1972) is a thick succession of monotonous turbiditic rocks that occurs extensively across the Tanami Region, and incorporates the informally named Madigan beds in the Dead Bullock Soak area (Smith et al. 1998). The rocks are typically deeply weathered and crop out poorly as low sand-covered rises and breakaways.

The Killi Killi Formation includes a variety of lithologies ranging from micaceous graywacke, quartz wacke, and lithic graywacke to quartz arenite and lithic arenite, interbedded with siltstone (in part carbonaceous) and mudstone. Most sandstone is medium-grained, although coarse-sandstone to granulestone beds occur locally. A well-developed penetrative slaty cleavage is recognized regionally (see below), and pronounced refraction through interbedded mudstone and sandstone sequences is common. The rocks are generally metamorphosed to greenschist facies except within the contact aureoles of granites and in regions east and south of The Granites goldfield where the rocks are metamorphosed to amphibolite facies. Rare, banded, jasper chert has also been found within the formation (Hendrickx et al. 2000a), which can lead to confusion with Dead Bullock Formation, but Lambeck (2004) noted chemical variations that can be used to discriminate between the units in the absence of other stratigraphic control.

Preserved sedimentary structures are typical of deposition by turbidity currents and include amalgamated sandstone beds, graded bedding, and cross-bedding forming incomplete bouma sequences. Thicker sandstone beds are massive to graded, poorly sorted, and medium to coarse-grained with some containing scattered granule-sized clasts and larger rip-up clasts of mudstone close to the base. Localized thick-bedded, poorly-sorted massive and graded granulestone are interpreted as channel deposits. Siltstone and mudstone beds are generally medium-bedded, massive, planar laminated, or have fine unidirectional cross-laminations. In areas of higher metamorphic grade, siltstone and mudstone are metamorphosed to biotite schist, with varying proportions of andalusite, garnet and/or cordierite. Highly contorted, thin-bedded jasper chert exposed in sub-crop over several square kilometers adjacent to the Bluebush fault may reflect alteration and surface weathering of a fine-grained sedimentary rock (Hendrickx et al. 2000a). The jasper chert unit crops out in the core of a north-plunging syncline and is interpreted to lie in the upper part of the Killi Killi Formation.

As the top of the formation is not exposed, true stratigraphic thickness cannot be calculated. Integrated geological mapping, geophysical interpretation, and modeling suggests the formation is up to 4 km thick, although this does not take into account the possibility of structural thickening or loss of section due to faulting (Vandenberg and Meixner 2003, 2004). The transition from the Dead Bullock Formation to the Killi Killi Formation is interpreted to reflect a rapid increase in sediment input in deep marine conditions, possibly in response to uplift in the source area.

Ware Group

Rocks belonging to the Ware Group crop out most abundantly in the Winnecke Range area (north of area on Fig. 2). The group was deposited in the interval 1,825–1,810 Ma (Cross and Crispe 2006; see below) and is dominated by felsic volcanic rocks and coarse-grained lithic sandstones, with minor siltstone and basalt. It includes the Mount Winnecke Formation (Traves 1955; Blake et al. 1975), Nanny Goat Volcanics (Hendrickx et al. 2000a), Wilson Formation, and Century Formation (Crispe and Vandenberg, in preparation). The relationship with the Tanami Group is not exposed, but an unconformity is inferred based on structural observations (see below). The Supplejack Downs Sandstone, which was previously assigned to this group (Blake et al. 1975), is now assigned to the Birrindudu Group on the basis of lithological and structural similarities to the Gardiner Sandstone.

Ware Group sediments (Century and Wilson Formations) outcrop in the vicinity of the Twin Bonanza prospect in the central west of the Tanami Region. No volcanic rocks are noted in this area. For simplicity, Ware Group has not been subdivided in Fig. 2, although for the distribution of Ware Group units, the reader is directed to the surface geology maps of The Granites and Tanami 1:250,000 map sheets (Crispe 2006,Vandenberg and Crispe, in preparation).

Mount Winnecke Formation

Traves (1955) first described Mount Winnecke Sandstone as ridge-forming sandstone in the vicinity of Mount Winnecke. Mount Winnecke Sandstone was renamed the Mount Winnecke Formation by Blake et al. (1975), who recognized three main lithologies in the unit: rhyolite lava, sublithic arenite, and tuffaceous sedimentary rock. This formation crops out extensively in the Winnecke Range (north of Fig. 2 where the three lithologies are interlayered and folded into kilometer-scale open folds. The dominant (exposed) rock is sublithic arenite, which is medium- to thick-bedded and medium- to very-coarse-grained, with common quartz granule to pebble conglomerate. Cross-bedding is common. Lithic clasts in the arenite are largely derived from felsic volcanic rock (Blake et al. 1979). Rhyolite is typically maroon to purple, and contains small phenocrysts of quartz and K-feldspar.

Flow banding and autobrecciation are locally preserved (Blake et al. 1979). At least three rhyolite units occur at separate stratigraphic levels within the Mount Winnecke Formation. The rhyolite is geochemically equivalent to the 1,815 Ma Winnecke Granophyre of the Birthday Suite (Green in Crispe and Vandenberg, in preparation), which intrudes the Mount Winnecke Formation, and is interpreted to be a shallow-level intrusion co-magmatic with the rhyolite. SHRIMP U-Pb zircon dating of a rhyolite from the Mount Winnecke Formation yielded an age of 1,824±5 Ma (sample #87495029, Ozchron database, Geoscience Australia).

Nanny Goat Volcanics

In the northeast of the Tanami Region, the Nanny Goat Volcanics crop out in a north-trending linear belt, incorporating most of the Nanny Goat Creek beds of Blake et al.

(1975). Rock types in this unit are generally of volcanic origin and include quartz-rich ignimbrite, feldspar-rich ignimbrite, rhyolite, basalt, and sandstone. Due to limited outcrop, the relationships between individual mappable units within the formation are not exposed, as is the case for contacts with the Tanami Group. Two samples of Nanny Goat Volcanics have SHRIMP U-Pb zircon-interpreted ages of 1816±7 and 1821±5 Ma (Smith 2001).

Homogeneous fine-grained, pale green and purple quartz-rich ignimbrite, a common constituent of the Nanny Goat Volcanics, is locally interlayered with basalt. The ignimbrite contains small embayed, bipyramidal phenocrysts and broken crystals of quartz, less abundant sericitized feldspar crystals, and minor lithic clasts. The groundmass is composed of fine-grained quartz, feldspar, and amorphous material, and has a well-developed eutaxitic foliation indicative of welding and compaction. Less common is purple feldspar-rich ignimbrite-containing sericitized feldspar phenocrysts up to 2 mm across and less abundant small phenocrysts of quartz. The Nanny Goat Volcanics also contain fine-grained rhyolite lava, some of which is flow-banded and, less commonly, autobrecciated. Other less common facies are volcaniclastic sedimentary rocks interbedded with quartz arenite.

Basalt of the Nanny Goat Volcanics crops out on either side of Nanny Goat Creek near the Crusade prospect. Drill chips from holes around this prospect indicate that the basalt contains plagioclase microlites, magnetite crystals, and small relic phenocrysts that may have been clinopyroxene but are now replaced by fine chlorite. Geochemically, the basalt shows a variably evolved tholeiitic character (Dean 2001). A brecciated contact between quartz-rich ignimbrite and basalt is the site of gold mineralization at the Crusade prospect.

Century Formation

Extending south from Pargee Sandstone outcrop, the Century Formation crops out as an arcuate chain of hills and isolated strike ridges. These were previously mapped as Pargee Sandstone (Blake et al. 1976; Hendrickx et al. 2000a); however, they contain regional deformation features that are not found in the Pargee Sandstone, which has a maximum depositional age of 1,768±14 Ma (Cross and Crispe 2006). The unit is estimated to be approximately 1,200 m thick and consists of quartz arenite, fine-grained lithic arenite, cleaved siltstone, and granular and pebble conglomerate. It has a faulted contact with Wilson Formation to the west, and is interpreted to be overlain unconformably by Pargee Sandstone. The Century Formation is intruded by a rhyolite sill that has subsequently been folded. The formation has a maximum depositional age of 1,823±4 Ma based on SHRIMP U-Pb dating of detrital zircon (Cross and Crispe 2006).

Wilson Formation

The Wilson Formation is an association of graywacke, quartz wacke, and siltstone that crops out in two regions. Near the Crusade prospect, it is identified as granular conglomerate, quartz wacke, graywacke, and minor siltstone locally metamorphosed to phyllite and fine-grained schist. Thicker beds of coarse-grained sedimentary rock have a pale green to tan color, whereas thinner, finer grained bedding layers are leached pale yellow and white. These rocks were previously included within the Nanny Goat Creek beds by Blake et al. (1975). Approximately 140 km to the southwest, in the vicinity of the Twin Bonanza prospect, the Wilson Formation comprises medium- and thick-bedded, purple- and gray-interbedded graywacke and siltstone mapped as Killi Killi beds by Hodgson (1976) and Hendrickx et al. (2000b). Quartz wacke beds are common and contain medium to coarse sub-angular to sub-rounded quartz grains and subordinate lithic grains in a purple iron-rich clayey matrix. Siltstone forms thinner, recessive zones between thicker sandstone beds and possess a strong penetrative cleavage that overprints a much weaker earlier cleavage. Several granulestone beds contain a high proportion of angular volcanic quartz grains and felsic volcanic lithic grains, which indicate derivation from a nearby felsic volcanic source. Total thickness of the formation is estimated to be in the order of 1,000 m.

Contacts between Wilson Formation and other units are not observed; however, the formation has a high magnetic signature, distinct from the lower magnetic signature of the surrounding Killi Killi Formation (Slater 2000a). SHRIMP U-Pb dating of detrital zircon from the Wilson Formation 6 km west of the Twin Bonanza prospect yielded a maximum deposition age of 1815±13 Ma (Claoué-Long et al. 2001). A definitive minimum age constraint is yet to be determined, however a porphyry granite at the Twin Bonanza prospect that has intruded the Wilson Formation (based on magnetic data interpretation) yielded an interpreted SHRIMP U-Pb zircon age of 1,802±8 Ma (Smith 2001). SHRIMP U-Pb geochronological investigation of detrital zircon from a coarse-grained weathered quartz wacke from the Wilson Formation east of the Crusade prospect yielded a maximum interpreted deposition age of 1830.9±6.5 Ma (Cross and Crispe 2006).

Depositional environment of the Ware Group

Blake et al. (1975) proposed a subaqueous depositional environment for the Ware Group based on the intimate association of felsic lava and subaqueous sedimentary rocks and the absence of subaerial pyroclastic rocks in the Mount Winnecke Formation. The presence of volcanic lithic clasts in sandstone of the Mount Winnecke Formation suggests that felsic volcanic rocks were exposed in the region. The lithological association of densely welded ignimbrite, flow-banded and autobrecciated rhyolite with only a small proportion of clastic sedimentary rocks suggests the Nanny Goat Volcanics were deposited in a predominantly subaerial environment. The Wilson Formation consists of interbedded, laterally continuous, graded graywacke and siltstone, indicating deposition in a probable deeper marine environment. In comparison, the Century Formation, cross-bedded coarse sandstone and pebble conglomerate overlain by planar siltstone and lithic sandstone, indicates deposition in an initially moderate energy environment, rapidly quietening to a lower energy environment. This suggests either deposition on a rapidly submerging shore, or fluvial and lacustrine deposition.

Although stratigraphic relationships between the units of the Ware Group are not observed, geochronology has allowed some inferences to be made. The oldest unit is the submarine Mount Winnecke Formation, which is overlain by the subaerial Nanny Goat Volcanics. These volcanic rocks may have been eroded while deposition of the Wilson and Century Formations took place.

Mount Charles Formation

The Mount Charles Formation is a succession of intercalated basalt and fine- to coarse-grained clastic sedimentary rocks that host significant gold mineralization in the Tanami mine corridor. The unit was previously mapped as part of the Mount Charles beds (Blake et al. 1972) and the informal Black Peak formation by Tunks (1996). It crops out poorly as low rounded hills with minor silicified outcrop and sub-crop east of the Tanami Range on the northwestern margin of the Frankenia granite complex. It is well exposed in open pits northeast and southwest of the Tanami mine treatment plant, and in Jim's Find pit 40 km to the south. Near Mount Charles, it is faulted against Dead Bullock Formation to the west. To the east, it has small garnet porphyroblasts in fine-grained sandstone and siltstone that are interpreted to have resulted from contact metamorphism due to intrusion of Grimwade-suite granite.

Southwest of the Coomarie granite complex, gold in the Mt. Charles Formation was extracted from open pits sited along the east side of the Bluebush Fault. This ferricrete covered region, informally known as the "Flores complex," is characterized by high magnetic and gravity response (Slater 2000a). In general, the Mount Charles Formation is highly to intensely magnetic and has an associated high Bouguer gravity response (Figs. 3 and 4).

An unconformity between the underlying Dead Bullock Formation and basal thinly bedded pebbly lithic sandstone of the Mount Charles Formation is exposed 400 m west of Jim's Find open cut. The top of the Mount Charles Formation is not exposed.

Mount Charles Formation comprises intercalated extrusive basalt, basaltic breccia, fine- to coarse-grained turbiditic sedimentary rock, and basal quartz sandstone. Geological cross-sections combined with interpretation and modeling of magnetic and gravity data suggests that the formation has a thickness of between 1,750 and 2,100 m (Vandenberg and Meixner 2003, 2004). A stratigraphy within the Mount Charles Formation is described in detail by Tunks (1996) and Tunks and Cooke (2006) from their work at the Tanami mine. Four sedimentary and three basaltic lithofacies have been identified within the Mount Charles Formation at the Tanami mine, comprising sandstone (graywacke), mudstone, carbonaceous mudstone, intraclast conglomerate, massive basalt, brecciated basalt, and pillow basalt (Tunks and Cooke 2006). Gold mineralization is not concentrated at any particular unit or stratigraphic level, although the uppermost "hanging wall sediment" is relatively poorly mineralized. Deposits in the southwest of the corridor tend to contain mineralization in the lower units of Mount Charles Formation.

Obtaining reliable geochronological constraints on the age of the Mount Charles Formation has proven to be problematic. Five samples containing detrital zircon returned maximum depositional ages around 1905–1920 (Cross and Crispe 2006; Ozchron database, Geoscience Australia), which is approximately 100 Ma older than field relationships indicate. Structural and stratigraphic relationships indicate deposition of the Mount Charles Formation postdates the early regional deformational events observed in the Tanami Group (Vandenberg et al. 2001a–c: see below), and aplite dike intrusion and local contact metamorphism indicate that some magmatism postdated deposition. Using the results of geochronological studies on granitic intrusives in the region (see below), a tentative depositional age of around 1,800 Ma can be inferred.

The association of pillow basalt and sedimentary rocks indicates that the Mount Charles Formation was deposited in a subaqueous environment. Tunks (1996) proposed local shallowing of water depth due to the influx of thick basalt flows to account for carbonaceous shale in the succession. Geochemistry indicates the basalt is low-K, high-Fe tholeiite (Tunks 1996), consistent with deposition of the Mount Charles Formation in a continental rift environment.

Mafic intrusive rocks

Mafic intrusive rocks occur as dolerite dikes and sills in the Tanami Group, as well as isolated stocks that typically do not crop out, but are locally encountered in drill core (e.g., within the Frankenia and Coomarie granite complexes:

Blake 1974). A thick, foliated dolerite sill forms the host to the Groundrush deposit (Crispe and Vandenberg 2004; Huston et al. 2006), and this example highlights the economic potential of mafic rocks in the Tanami Region. Most mafic rocks are interpreted to have intruded before or during regional deformation and metamorphism (Dean 2001).

Multiple generations of dolerite sills intrude the Tanami Group, and have been described by Dean (2001). At Dead Bullock Soak, the locally named Coora dolerite and End It All dolerite (Smith et al. 1998) are up to 200 m thick and are affected by the main deformation and metamorphic events that affect the Tanami Group. The Coora dolerite has pepperitic textures at its lower contact with the Dead Bullock Formation, indicating that it intruded into soft sediment. At Bunkers Hill pit at The Granites goldfield, dolerite dikes crosscut major fold structures but are deformed by later shearing and faulting. The dolerites have a dominantly tholeiitic geochemical character (Garnaut 1995).

The informally named "Borefield road intrusion," a circular composite intrusion around 6 km in diameter, 4 km northeast of The Granites (Dean 2001), has been encountered in drill core and can be discerned in regional magnetic and gravity data (Slater 2000b). It includes pyroxenite, augite norite, diorite/gabbro, tonalite, and granodiorite and displays medium- to coarse-grained, cumulate and sub-ophitic textures (Dean 2001).

Granites

The Tanami Region is dominated by the Frankenia, Coomarie, and Browns Range granite complexes (Fig. 2). These are located in a central corridor between the major Tanami-Bluebush and Supplejack Faults and have low magnetic intensities coincident with low Bouguer gravity anomalies (Figs. 3 and 4). Within each granitic complex there are domains of contrasting magnetic intensity, consistent with multiple intrusive phases. The central corridor also contains small, circular to ovoid, weakly to strongly magnetic features interpreted to be granite plutons (Slater 2000a,b). Northeast of the Supplejack Fault, magnetic granophyre extends south from the Winnecke Range (north of the area depicted on Fig. 2). Inversion modeling of magnetic and gravity data from the Tanami Region suggests that while surface exposures of granitic rocks are rare, a large proportion (up to half) of the upper 15 km of the Paleoproterozoic Tanami basement may be composed of granite (Meixner and Lane 2005).

Most felsic magmatic rocks in the Tanami Region have interpreted U-Pb zircon ages of between 1,825 to 1,791 Ma (Smith 2001). These ages do not show any consistent variation either spatially or between different suites. Most granitic bodies in the Tanami Region intruded Tanami and Ware Group sedimentary rocks, and their emplacement was broadly coincident with protracted regional deformation (see below). The Mount Charles Formation was deposited before local granite intrusion, as it is cut by felsic dikes and affected by contact metamorphism related to emplacement of granites that comprise the Frankenia granite complex (Tunks 1996). There are no granitic intrusions in the Pargee Sandstone or Birrindudu Group.

The Tanami granites typically have 65 to 77 wt% SiO_2 contents and are generally peraluminous (apatite corrected; Zen 1986). This is consistent with biotite being the dominant accessory mineral, with hornblende and muscovite only present in the metaluminous and strongly peraluminous samples, respectively. Major element variation diagrams define broad linear trends and are most consistent with preservation of magmatic abundances (Green, in Crispe and Vandenberg, in preparation). Hence, alteration has had minimal affect at the whole-rock scale. A review of Paleoproterozoic granites from the North Australian Craton (NAC), including some from the Tanami Region, found them to be compositionally uniform over large areas (Wyborn 1988). Nevertheless, granites in the Tanami Region differ from most in the NAC by being more aluminous, and have lower K_2O and higher CaO abundances (Green, in Crispe and Vandenberg, in preparation).

Dean (2001) provided a detailed description of igneous rocks of the Tanami Region, including outcrop descriptions and geochemical interpretation. This geochemical interpretation has been revised by Green (in Crispe and Vandenberg, in preparation) who has divided the granites of the Tanami Region into three suites, using the suite classification of White et al. (2001) as outlined below. Green (in Crispe and Vandenberg, in preparation) proposed that granites in the Tanami Region were derived from partial melting of late Archean gneiss with minor assimilation of Tanami Group sediments.

Birthday Suite

The Birthday Suite (Winnecke Suite of Dean 2001) is restricted to the northeastern Tanami Region and includes the formally named Winnecke Granophyre (Blake et al. 1976) and volcanic rocks of the Mount Winnecke Formation. It correlates with a highly magnetic domain and comprises intimately related intrusive and extrusive rocks with interpreted igneous crystallisation ages between 1,825 and 1,810 Ma. The Winnecke Granophyre is commonly porphyritic and biotite-bearing and also includes medium- to coarse-grained monzogranite and granodiorite, commonly with micrographic and myrmekitic textures (Blake et al. 1979). The least SiO_2-rich granite in the suite, and by inference the least fractionated, contains minor green hornblende intergrown with brown biotite. In places, K-feldspar and plagioclase are concentrically zoned. The Birthday Suite is strongly potassic with very high SiO_2 abundances (>70.7 wt%), and all but one analyzed sample is peraluminous. Extrapolation from these high silica abundances defines the Birthday Suite as alkali-calcic, and thus are the most alkali-rich granites of the Tanami Region.

Frederick Suite

The Frederick Suite includes the magnetic parts of the Browns Range and Coomarie granite complexes and, apart from the Birthday Suite, other discrete plutons with high magnetic response (Figs. 2 and 3). Frederick Suite granites have interpreted SHRIMP U-Pb zircon igneous crystallization ages in the range 1,815±4 to 1,801±4 Ma, and contain abundant older inherited zircon (Smith 2001). Rocks from the Frederick Suite are typically medium- to fine-grained equigranular biotite monzogranite to syenogranite. Hornblende is common in the least SiO_2-rich samples. Accessory minerals include titanite, magnetite, pyrite, apatite, and zircon. Plagioclase is commonly concentrically zoned and often displays cores clouded by fine-grained sericite. The Frederick Suite is generally peraluminous and is defined as calc-alkaline.

Grimwade Suite

The weak to non-magnetic Grimwade Suite (Coomarie Supersuite of Dean 2001) is widely distributed and includes The Granites, Slatey Creek, and Lewis Granites of Blake et al. (1979), parts of the Browns Range and Frankenia granite complexes and granite south of Dead Bullock Soak and The Granites goldfields. The Grimwade Suite extends southeast into the adjacent Aileron Province, and it has interpreted igneous crystallization ages between 1,821±4 and 1,791±4 Ma (Smith 2001). Green (Crispe and Vandenberg, in preparation) divides the Grimwade Suite into five sub-groups based on trace element compositions. The Grimwade Suite comprises texturally diverse monzogranite to syenogranite and includes coarse to fine and porphyritic to non-porphyritic varieties. The suite also includes The Granites Granite, which prominently crops out south of The Granites gold mine and predominantly comprises medium-grained biotite monzogranite, with lesser-foliated to massive leucocratic monzogranite and biotite granodiorite. The least SiO_2-rich samples of the Grimwade Suite contain hornblende; otherwise, biotite is the main mafic mineral. Accessory minerals include zircon, apatite, tourmaline, and titanite. The Grimwade Suite has the broadest range of SiO_2 abundances of the three suites, and most samples are peraluminous. The suite is defined as calcic, and thus is the least alkali-rich of the Tanami granites (Green in Crispe and Vandenberg, in preparation).

Pargee Sandstone

The Pargee Sandstone (Blake et al. 1972) is a thick succession of interbedded conglomerate, pebbly sandstone, quartz arenite and minor siltstone. It is exposed discontinuously along a narrow north-trending zone up to 24 km wide and 70 km long on the western side of the Coomarie granite complex, including the Pargee Range. The Pargee Sandstone unconformably overlies cleaved siltstone of Killi Killi Formation, and is unconformably overlain by the Gardiner Sandstone, the basal unit of the Birrindudu Group (Blake et al. 1975, 1979). The folded, unconformable contact is well exposed. Regionally, the angular difference between the Pargee Sandstone and Gardiner Sandstone is small (<10°), although locally it can be in the order of 30°. The unit attains a maximum thickness of 1,300 m, although this may be complicated by repetition or loss of section due to faulting. The Pargee Sandstone has a maximum deposition age of 1,768±14 Ma (Cross and Crispe 2006).

The Pargee Sandstone is dominated by thick-bedded quartz arenite, lithic arenite, and conglomerate. Pebbly sandstone and conglomerate are prominent throughout the formation. Individual beds are up to 1 m thick and cross-bedding is commonly observed. Most clasts are sub-angular to sub-rounded and comprise vein quartz, graywacke, jasper chert (derived from the underlying Tanami Group), and rare rounded basalt clasts that were probably derived from Mount Charles Formation. In comparison to Gardiner Sandstone, Pargee Sandstone can be distinguished due to the more angular nature of its clasts, the presence of jasper chert as a significant lithic component, and poorer sorting. The Pargee Sandstone often has a reddish appearance, while Gardiner Sandstone is mostly pink or gray. Sandstone cobbles, which are plentiful in Gardiner Sandstone, are rare in Pargee Sandstone.

The Pargee Sandstone is interpreted to have been rapidly deposited in a shallow marine environment under high-energy conditions (Hendrickx et al. 2000a; Crispe and Vandenberg, in preparation). Some of the upper parts of the formation may be fluvial. The succession broadly coarsens upward, possibly reflecting a transition to fluvial conditions. The formation is inferred to represent a restricted molasse type basin that formed in response to significant uplift in the source area.

Birrindudu Group

The Birrindudu Group (Blake et al. 1975) consists of three units comprising, from the base, Gardiner Sandstone, the fine-grained and calcareous Talbot Well Formation, and Coomarie Sandstone. Based on lithological and structural similarities to Gardiner Sandstone, the Supplejack Downs Sandstone (Blake et al. 1975) is now included in the group.

Birrindudu Group is observed to rest unconformably on all older units of the Tanami Region. Blake et al. (1975) indicated a maximum thickness of 6,000 m for the group east of Gardiner Range in Western Australia. Outcrops south of Browns Range granite complex show duplication of stratigraphy due to shallow dipping thrust faults, which appear to be rooted in Talbot Well Formation or involve a major basement detachment, which has propagated through the succession. Duplication of stratigraphy is inferred to be a common feature of the group. A structurally simple and continuous section on the northern margin of the Coomarie granite complex has a total thickness of approximately 1,900 m, comprising 1,000 m of Gardiner Sandstone, 500 m of Talbot Well Formation, and 400 m of Coomarie Sandstone.

The Birrindudu Group outcrop dominates the landscape of the Tanami but is of little economic interest with respect to gold; it has been omitted from Fig. 2 for clarity. For the distribution of Birrindudu Group units, the reader is directed to the surface geology maps of The Granites and Tanami 1:250,000 map sheets (Crispe 2006,Vandenberg and Crispe, in preparation).

Age and regional correlations of the Birrindudu Group

As the Gardiner Sandstone unconformably overlies the Pargee Sandstone, which has a maximum age of 1,768± 14 Ma, this figure provides an older age constraint on the Birrindudu Group also. Rocks in drill holes interpreted to belong to Birrindudu Group to the north are overlain by the Limbunya Group (Cutovinos et al. 2002), which was deposited at 1,640–1,635 Ma (SHRIMP U-Pb zircon dating of tuffaceous horizons, Smith 2001). We conclude that deposition of the Birrindudu Group is likely to have occurred in the interval 1,735–1,640 Ma. Birrindudu Group is a correlative of the Tolmer Group, which unconformably overlies the western Pine Creek Orogen.

Depositional environment

Sedimentary structures and the presence of stromatolites and dolostone in the Talbot Well Formation are consistent with deposition of the Birrindudu Group in shallow marine conditions. The extent of the group suggests deposition in a large, shallow marine shelf. The low proportion of dolostone in the succession supports a moderate rate of sediment supply in relatively high-energy conditions.

Structure

Detailed mapping and structural analysis indicate a complex and protracted structural evolution for the Tanami Region. Structural investigations in the region include studies of the Tanami mine area (Nicholson 1990; Tunks 1996; Tunks and Cooke 2006), Dead Bullock Soak (Lovett et al. 1993; Smith et al. 1998) and The Granites (Ireland and Mayer 1984; Mayer 1990; Scott 1993; Valenta and Wall 1996; Adams et al. 2006). More regional structural interpretations are presented in Blake et al. (1979), Ding and Giles (1993), Cooper and Ding (1997), Vandenberg et al. (2001a–c, 2002), Vandenberg (2002), and Vandenberg and Meixner (2003, 2004).

Pre D_1-M_1

Archean basement in the Tanami Region has a gneissic foliation that is interpreted to predate deposition of the Tanami Group (Page et al. 1995). This event is recognized in the Archean Billabong complex (Page et al. 1995), where a penetrative, steep, NW-dipping gneissosity is overprinted by NNE-dipping shear bands with left-lateral displacement (Vandenberg et al. 2002). In the Browns Range Metamorphics at the southern margin of Browns Range granite complex, Page et al. (1995) identified metamorphic zircon growth dated at 1,882±14 Ma, although re-examination of these zircon mounts led Cross and Crispe (2006) to conclude they are inherited grains and are not evidence of an earlier metamorphism.

Tanami Event (D_1-M_1)

The first tectonothermal event to affect sedimentary rocks of the Tanami Group is the Tanami Event (D_1-M_1; previously named the Tanami Orogenic Event by Hendrickx et al. 2000a). Meso- and macroscopic D_1 structures within the Tanami Group comprise tight-to-isoclinal disharmonic F_1 folds that in general plunge moderate-to-steep ESE and NNW (Fig. 7). F_1 fold axial traces trend to the southeast in the northwest Tanami Region, trend east in the central Tanami Region (Dead Bullock Soak), and trend to the southeast in the east Tanami Region (east of The Granites). The change in plunge direction, together with a regional variation in the strike of F_1 structures, has been attributed to the affects of later deformation (Vandenberg et al. 2001b,c; Vandenberg 2002). In F_1 hinge regions greenschist facies micaceous rock-types have an axial planar S_1 slaty cleavage. More siliceous low-grade lithologies have a weak anastomosing spaced cleavage. Within and to the east of The Granites goldfield area, tight to isoclinal F_1 folds in metasediment of the Dead Bullock Formation and Killi Killi Formation (Fig. 8) possess axial-planar cleavages defined by greenschist to amphibolite facies minerals (M_1 white mica ± biotite ± andalusite). F_1 structures are crosscut by Grimwade-suite granite, and contact metamorphic minerals overprint F_1 fabric (Vandenberg 2002).

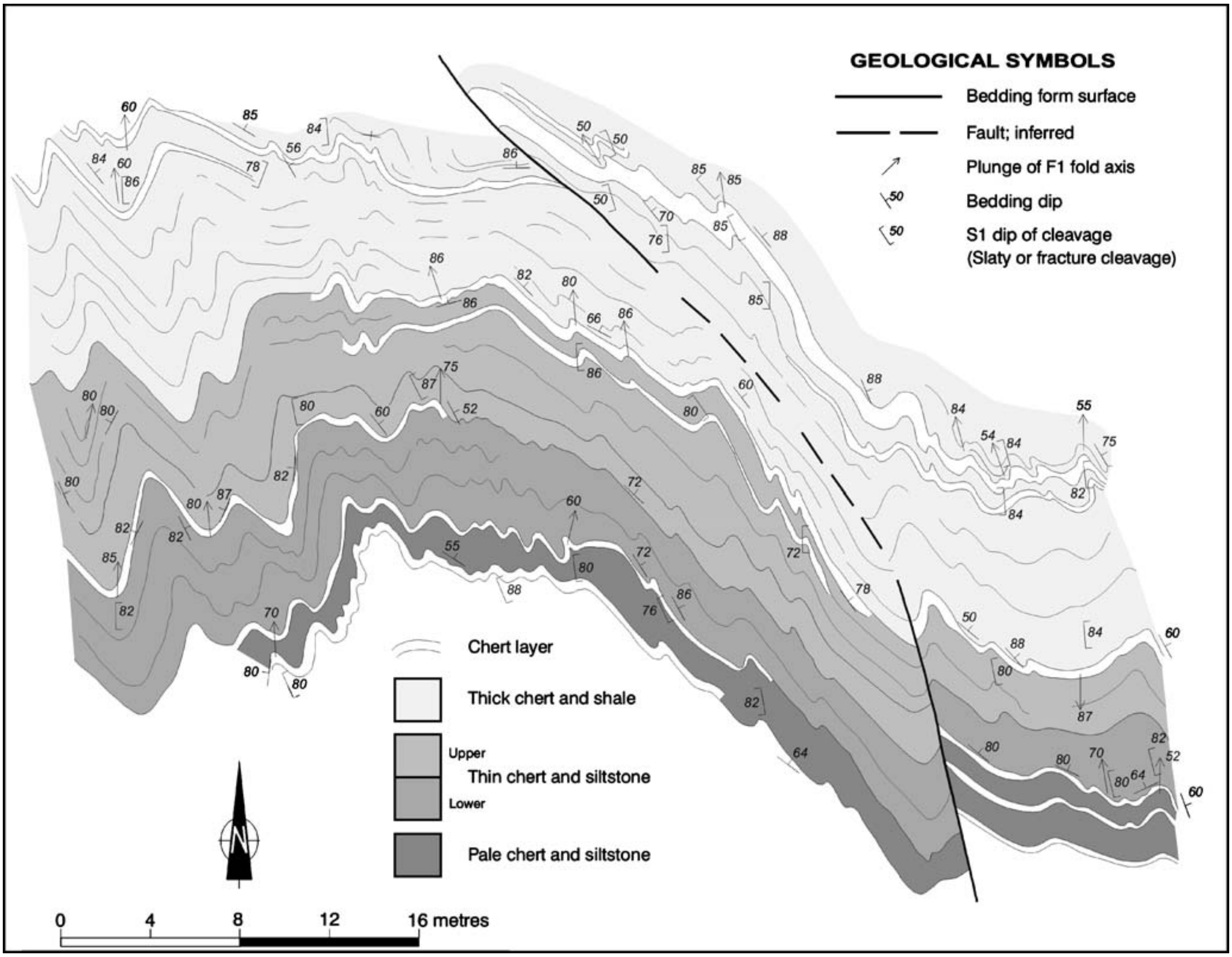


Fig. 7 Simplified geology of Dead Bullock Formation interbedded silt, shale and chert from Black Hills illustrating form and orientation of the F_1 folding and S_1 fabric. (GDA94, Zone 52, 588550 mE 7798060 mN)

Fig. 8 Dead Bullock Formation, Quorn pit, the Granites goldfield: steep SW plunging isoclinal F_1 folds in biotite–andalusite schist, thin calc-silicate, laminated chert and nodular chert bands

The earliest structures observed in the 1,825–1,810 Ma Ware Group are NNE trending structures attributed to later D_2 deformation (see below). Since the Tanami Event has affected the underlying Tanami Group (maximum deposition age circa 1,840 Ma), the D_1-M_1 Tanami Event is constrained within the interval 1,840–1,825 Ma. This period is much younger than the Barramundi Orogeny with which it has been previously correlated (Scrimgeour and Sandiford 1993). The Tanami Event may be a distal expression of the collision between the Kimberley and North Australian Cratons in the Halls Creek Orogen, at around 1,835–1,805 Ma (Myers et al. 1996; Sheppard et al. 1999; Bodorkos et al. 2002).

D_2 -D_3 folding

D_2 structures in the Tanami Group are local open, angular NE to NNE striking F_2 folds due to NW–SE to WNW–ESE directed regional shortening. In F_2 hinge regions the axial-planar S_2 fabric crenulates S_1 fabric and is spaced between 0.1–1 cm. S_2 mineralogically differentiated crenulation cleavage is not generally observed; however, D_1-M_1 minerals such as biotite are often bent by S_2 crenulation.

The earliest structures within the sedimentary rocks of the Ware Group (Wilson Formation) are NE-trending open folds (Fig. 9). These folds contain a weakly developed axial-planar slaty cleavage in fine-grained units, and are interpreted to be equivalent to the regional D_2-F_2 structures identified in the underlying Tanami Group.

D_3 structures in the Tanami Group are open, angular NW to N–S striking F_3 folds due to to NE–SW to E–W directed regional shortening (Fig. 9). Locally developed S_3 crenulation of S_1 fabric is generally only developed in F_3 hinge regions and is spaced between 0.1 and 1 cm. In rocks with well-developed D_1-M_1 fabric, S_3 is commonly a spaced crenulation cleavage and minerals such as biotite are often bent. Rare oblique F_1- and F_3-fold interference structures have been observed and regional F_1 and F_3 interference structures have been interpreted from combined outcrop and aeromagnetic data in the southeast margin of the Frankenia granite complex. At The Granites goldfield, F_3 structures are intruded by leucogranitic bodies with a magmatic age of 1,791±4 Ma (Smith 2001), providing a minimum age constraint for D_3.

The most dominant structures within the sedimentary rocks of the Ware Group (adjacent to the Supplejack Fault Zone and to the west in the Wilson Formation) are N–S to NNW trending open to tight, angular, upright folds. These folds display an axial-planar fabric that crenulates locally developed S_1 slaty cleavage (regional S_2 fabric) in fine-grained lithologies, but elsewhere is expressed as a strong, fine, penetrative fabric that resembles a slaty cleavage. These folds are interpreted to be equivalent to the regional D_3-F_3 structures identified in the underlying Tanami Group. As the interpreted depositional age for the Ware Group spans 1,825–1,810 Ma, it is possible that the regional D_2 and D_3 deformations may be related to the 1,815–1,800 Ma Stafford Event in the Arunta Region (Collins and Shaw 1995; Scrimgeour 2003).

Post-D_3 rifting

Detailed work within pits in the Tanami mine corridor shows that the Mount Charles Formation does not display fold structures attributed to the D_1, D_2, or D_3 deformation events. Four hundred meters west of Jim's Find pit, small outcrops of sandstone overlying cleaved siltstone are interpreted to represent basal Mount Charles Formation unconformably overlying Dead Bullock Formation, which is supported by interpretation of drilling results combined with detailed aeromagnetic data. The Mount Charles Formation is, therefore, interpreted to have been deposited after D_3. The lithostratigraphy and basalt geochemistry of the Mount Charles Formation is consistent with a continental rift setting (Tunks 1996). While large scale structures related to the deposition of the Mount Charles Formation are yet to be identified, small-scale syn-depositional extensional growth faults have been identified at the Tanami mine (Tunks and Cooke 2006). It is, therefore, suggested that localized post-D_3 extension probably led to the extrusion and deposition of the Mount Charles Formation (D_4 of Vandenberg et al. 2001a–c). The Mount Charles Formation has also been intruded by aplite and contact metamorphosed by granitic intrusions of the Frankenia granite complex, which has phases returning ages of 1,805±6 and 1,815±5 Ma (Smith 2001). From the relationships outlined above, this localized extension is interpreted to have occurred some time in the period 1,810–1,790 Ma, after D_3 and the deposition of the Ware Group.

D_4 south- to southeast-directed shortening

Structures resulting from D_4 SSE-directed shortening are seen as ENE to E- to W- trending F_4-fold structures (D_3 structures of Vandenberg et al. 2001a–c). F_4-fold structures are generally characterized by ENE trending, steeply SSE dipping angular chevron folds, crenulations and kink-bands within the Tanami and Ware Groups. Within micaceous greenschist facies slate and metasiltstone, F_4 axial planes are characterized by S_4 crenulations of earlier fabrics and structures. Mineralogically differentiated S_4 crenulation cleavage is rare. Within siliceous units, the S_4 fabric is a fracture or dissolution-style cleavage.

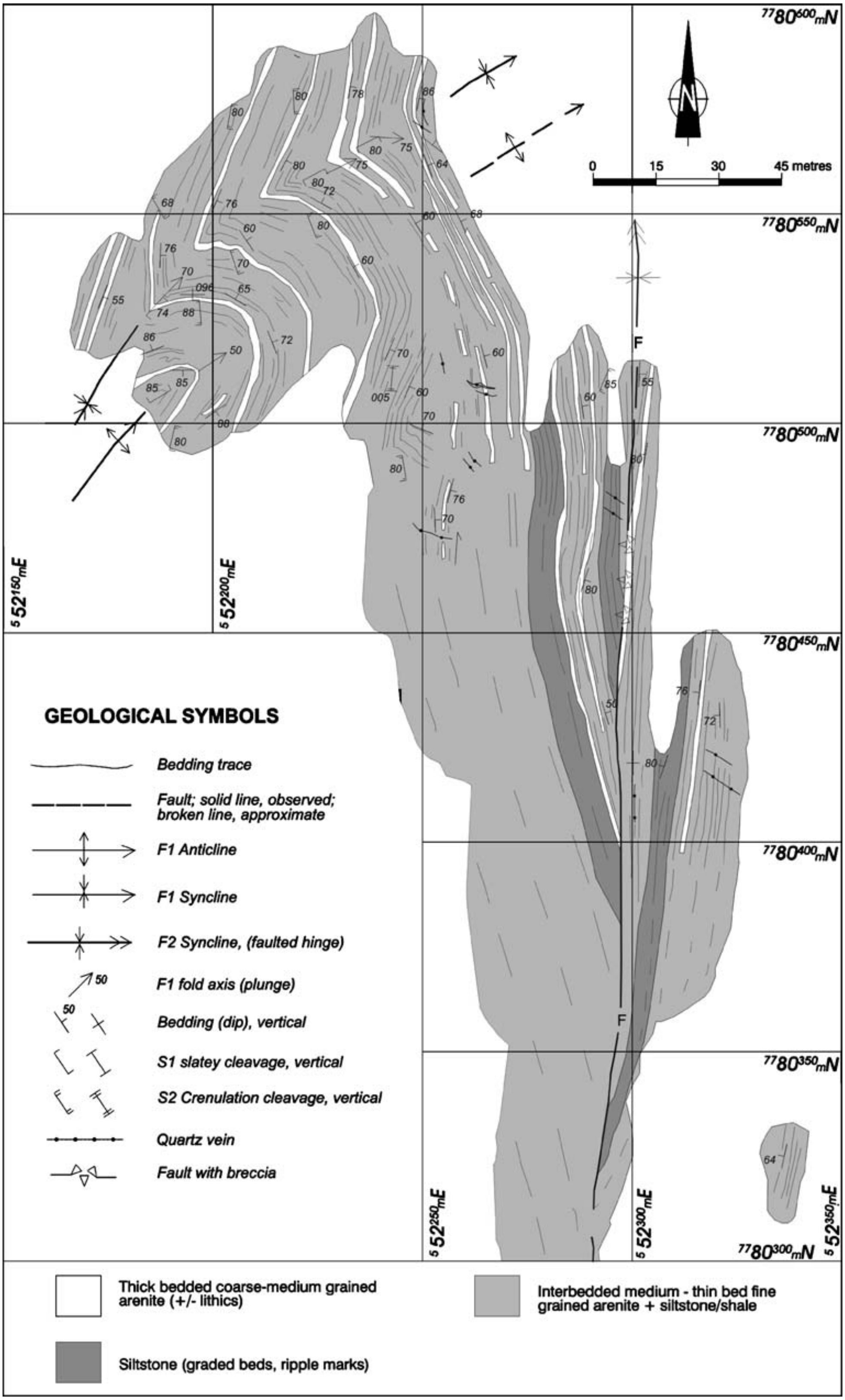
Whereas outcrop is very limited, regional mapping indicates that D_4-fold structures tend to be developed (or best preserved) around the margins of several granitic intrusions. Limited overprinting evidence with respect to contact metamorphic minerals and D_4 folding also indicates that SSE-directed D_4 shortening may have closely followed the emplacement of many of the granitoids (circa 1,800 Ma) in the Tanami Region.

D_5 faulting and mineralization

A network of N- to NW-striking D_5 faults, several of which are interpreted as oblique thrusts with a component of left lateral movement, indicates a period of D_5 convergence during WSW- to ENE- to E- to W-directed shortening. Notably, D_5 structures are important controls on gold mineralization throughout the Tanami Region. Although their main features are covered briefly below, they are discussed in more detail in Wygralak et al. (2005).

As described in Vandenberg (2002), a steep N to NE dipping brittle-ductile shear zone with left-lateral reverse sense movement (oblique thrust) follows the northern

Fig. 9 Simplified geology of Wilson Formation, Ware Group. Medium-and thick-bedded, purple and gray interbedded graywacke and siltstone shows F_1 folding (regional F_2) overprinted by penetrative S_2 fabric (regional S_3 fabric)



margin of an 1,815±4 Ma Grimwade-suite granite and cuts F_3-fold structures. This mineralized brittle-ductile shear zone has been subsequently crosscut by a 1,791±4 Ma granite. We relate the formation of this shear zone to the D_5 event (i.e., at some stage between 1815 and 1791).

At the Dead Bullock Soak goldfield, mineralization is associated with WNW-trending stratabound, bedding-parallel faults, and shears localized along the limbs of regional isoclinal F_1 folds, together with an E- to W-trending corridor of steeply SE dipping, sheeted, dilatant quartz veins that crosscut F_1-fold closures (as in the Villa and Callie pits). Dead Bullock Soak mineralized structures are consistent with formation during overall left-lateral, brittle-ductile shearing (Vandenberg 2002; Williams 2002). Although F_2 and F_3 structures are not clearly expressed, the mineralizing event was probably related to regional D_5 WSW-directed shortening and the formation of left-lateral brittle-ductile shear zones and related faults.

Within the mine pits of the Tanami mine corridor, numerous small-scale D_5 thrusts occur in the Mount Charles Formation (Vandenberg et al. 2001b; Vandenberg 2002). Mineralization is controlled by the intersection of 350–000°, 20–40°, and 60–70° orientations, generally E- to SE-dipping thrust and wrench faults with chemically favorable NW dipping stratigraphy (Nicholson 1990; Tunks and Marsh 1998). For example, in the Hurricane-Repulse pit north-plunging lensoidal ore zones are controlled by the intersection of ESE-dipping D_5 thrust-related structures with chemically favorable NW- dipping lithostratigraphy. These structures and associated mineralization do not affect the overlying Birrindudu Group (S. Henderson 2002, personal communication).

A network of large scale N to NE striking faults through the Tanami mine corridor can also be interpreted from regional magnetic data. Although apparent two-dimensional right- and left-lateral displacements can be interpreted, little is known about the nature of, and displacements along, these larger controlling faults in three dimensions. Most mined deposits are on the smaller subsidiary structures.

Geophysical modeling suggests that the Black Peak Fault bounds the Mount Charles Formation to the west, and dips moderately W to NW (Vandenberg and Meixner 2003). This is in contrast to the mainly E to SE dips indicated for most of the fault structures in the Tanami mine corridor. The large Frankenia granite complex effectively acted as a buttress during WSW-directed D_5 shortening.

As outlined above, some indication as to the timing of D_5 structures can be gained from the relationships described from The Granites goldfield (between 1,815–1,791 Ma), and the Tanami mine corridor where it occurred after deposition of the Mount Charles Formation (approximately 1,800 Ma) and before deposition of the Birrindudu Group (1,768±14 Ma maximum). In addition, SHRIMP dating of xenotime from auriferous quartz veins interpreted to have been emplaced during D_5 returned ages of 1,803±19 Ma (Cross et al. 2005) for the Callie deposit and 1,791±8 Ma (Bagas et al. 2006) for the Coyote deposit (in Western Australia). Overall, these relationships suggest that D_5 faulting and gold mineralization occurred around 1,800–1,790 Ma.

D_{6+} faulting

Numerous late thrust faults, oblique slip faults and normal faults cut all earlier structures and are collectively designated D_{6+} (Vandenberg et al. 2001a–c, 2002; Vandenberg 2002). Many are likely to postdate ~1,700 Ma, and some may be related to the Paleozoic King Leopold and Alice Springs Orogenies. D_{6+} faults affect the Birrindudu Group and are responsible for fault-propagated folding and displacement of this cover sequence. Displacement along regional D_{6+} structures range from several hundred meters to several kilometers. Northeast to southeast striking D_{6+} normal faults postdate mineralization within the Tanami mine goldfield and have displacements of up to several metres. In The Granites and Dead Bullock Soak goldfields, D_{6+} thrusts with calcite-quartz infill postdate mineralization, dip east to southeast and have vertical displacements of tens to hundreds of meters.

Metamorphism

The metamorphic grade of metasedimentary rocks in the Tanami Group is most commonly greenschist facies. Across most of the Tanami Region, pelitic rocks are fine-grained phyllites, with mineral assemblages including quartz-sericite and quartz-biotite-muscovite. Localized contact metamorphism has resulted in growth of andalusite and less common garnet and/or cordierite porphyroblasts around some granitic intrusions, typically overgrowing the regional D_1-M_1 fabric (Scrimgeour and Sandiford 1993; Scott 1993; Valenta and Wall 1996; Vandenberg 2002). Contact metamorphism up to mid-amphibolite facies (with growth of fibrolitic sillimanite) has also been recorded around the Lewis Granite in adjacent regions of Western Australia (Blake et al. 1979).

Metamorphic grade of the Tanami and Ware Groups is lowest in the northeast where they are metamorphosed to lower-greenschist facies. The Mount Charles Formation at the Tanami mine is less metamorphosed than the Tanami and Ware Groups, with actinolite, epidote, and chlorite alteration indicating at most lower-greenschist facies metamorphism (Tunks 1996). The formation has also undergone contact metamorphism in the Black Hills area. Contact metamorphic affects typically extend only a few hundred meters from intrusive margins into the surrounding country rock, indicative of intrusion into relatively high levels of the crust.

Higher regional metamorphic grades (mid-amphibolite facies) occur in the southeast in the vicinity of The Granites goldfield. Work by Scrimgeour and Sandiford (1993) in this area indicates that peak M_1 conditions of 600°C and 3.5 kbar were followed by near-isobaric cooling. Mineral assemblages in pelitic rocks at The Granites contain cordierite-garnet-biotite ± andalusite ± gedrite, with local development of late fibrolitic sillimanite as well as cummingtonite-rich schist that developed due to metasomatism accompanying mineralization. M_1 garnet, cordierite and andalusite porphyroblasts grew during D_1 with overprinting gedrite and second generation cordierite forming post-D_1, suggesting peak temperatures were attained near the end of deformation. Scrimgeour and Sandiford (1993) also suggest that the P-T path described by these metamorphic textures is consistent with the involvement of a magmatic heat source.

In the Fiddlers Lake area, 50 km south-southeast of The Granites, sedimentary rocks subjected to high-grade metamorphism and partial melting were included in the Arunta Province by Blake et al. (1979). The metasediments include psammite with biotite–garnet assemblages, and andalusite ± cordierite migmatitic pelite. The foliation defined by these high-grade mineral assemblages is the earliest recognizable fabric and is crosscut by thin pegmatite dikes, overprinted by a coarse pervasive crenulation, and cut by a late ESE-striking shear zone (Vandenberg et al. 2001b). A maximum igneous crystallisation age of 1,731±31 Ma was returned from an S-type granite 9 km to the southeast (Sample #2000082026, Ozchron database, Geoscience Australia). A 1,710–1,735 Ma $^{40}Ar/^{39}Ar$ age from biotite from the Callie deposit indicates lower temperature effects of the Strangways Orogeny extended into the southern Tanami Region.

The timing of regional metamorphism in the Tanami Region remains poorly constrained, with no published absolute ages of metamorphism. Using structural criteria we assign regional greenschist facies metamorphism, including amphibolite facies metamorphism in the southeast Tanami Region, to the (D_1-M_1) Tanami Event, which occurred around 1,835–1,825 Ma (Crispe and Vandenberg 2006). In contrast to Scrimgeour and Sandiford (1993), we note that there is overprinting evidence indicating that early structures and associated metamorphic fabric were subjected to later granitic (and mafic) intrusion in an event circa 1,825–1,790 Ma. The later regional intrusive event is probably related to the Stafford Event in the Arunta Region at around 1,815–1,800 Ma, which involved widespread high-temperature, low-pressure metamorphism (Scrimgeour 2003, 2004).

Discussion

Is there a boundary between the Tanami and Arunta?

Although the Tanami Region is a world-class Paleoproterozoic gold province, the adjacent Aileron province of the Arunta Region, which has a similar geological evolution, has relatively little known economic gold mineralization. Our studies in the Tanami and northern Arunta Regions appear to confirm the proposition that no fundamental boundary between them exists, and they both form part of the same geological province (Green 2004). Similar sedimentology and detrital zircon populations in the Killi Killi Formation of the Tanami Region and in the Lander Rock Beds of the Arunta Region (Ozchron database, Geoscience Australia) indicate they were probably deposited in the same basin and sourced similar areas. Furthermore, granites that are geochemically indistinguishable from 1,820–1,790 Ma Grimwade Suite granites in the Tanami Region extend into large areas of the northern Arunta Region, intruding both the Killi Killi Formation and the Lander Rock Beds.

The differing gold endowment of the two regions can either be due to processes taking place after the deposition of gold, or pre-existing differences in the (potential) hosts. The Arunta Region has experienced numerous metamorphic events from ~1,790 Ma, which had only minor effects on the majority of the Tanami Region. The Yambah Event, Strangways Orogeny, Chewings Orogeny, and Teapot Event had a minor influence on the Tanami Region (Fraser 2003), but contributed to considerable reworking of the Arunta. Some difference in the properties of the pre-1,880 Ma basement to the Tanami Group may exist to prevent tectonic reworking and, therefore, preserve gold accumulations.

The presence of the Callie Member of the Dead Bullock Formation in the Tanami Region is an important factor in gold deposition, as it contains an abundance of reactive rock types such as graphitic shale, iron-rich siltstone, and mafic rocks. Its distribution was probably determined by two main factors: basin architecture and deformation. The basin architecture of the lower Tanami Group is postulated to be controlled, in part, by the activity of the Supplejack Fault, a major north-trending structure that curves east at its southern extent (Vandenberg and Meixner 2004). Granitic detritus, forming arkose of the Ferdies Member at nearby Groundrush, may have been shed from uplifted gneissic basement on the eastern block during pre-Tanami Group extension. Distal, finer-grained sediment would deposit to the west and south. At the cessation of tectonism, the ensuing sediment-starved, deep-water environment would have resulted in deposition of the fine-grained Callie Member.

It is suggested that post-Tanami Group deformation has resulted in basin inversion on the Supplejack Fault to give present outcrop distribution (Crispe and Vandenberg 2004). Deformation may also have been responsible for curtailing Callie Member preservation to the south, where a network of steep south-dipping thrusts and normal faults, identified through combined mapping and geophysical modeling, have exposed domains of deeper crustal rocks of similar age to the Tanami Group but of higher metamorphic grade (Vandenberg and Meixner 2004; Meixner and Vandenberg, in preparation). The easternmost extent of outcropping Callie Member is in the DeBavay Hills, 70 km east of The Granites. The Dead Bullock Formation provides a stratigraphic marker, valuable for orienting local stratigraphy characteristic to the Tanami Region. This does not imply, however, that gold mineralization is restricted to the Tanami Region, as it may extend into the adjacent parts of the Arunta Region.

Geological history, regional correlations, and tectonic framework of the Tanami Region

Most of the geological history of the Tanami Region appears to have taken place in an intraplate setting within the North Australian Craton (NAC), although tectonic events in the region are likely to have occurred as a distal response to processes acting at plate margins. The localized exposure of 2,520–2,500 Ma basement and inheritance of zircon of this age in most Paleoproterozoic sedimentary and granitic units indicates the presence of widespread Neoarchean crust, which is likely to have formed an extensive platform that formed the basement to the region. This implies that the continental crust in the Tanami Region was formed by 2,500 Ma and since then has largely remained intact. Deformational events in the Tanami Region are significantly younger than the Barramundi Orogeny in much of northern Australia (1,860–1,850 Ma; Lally and Worden 2004). The ~1,880 Ma age of metamorphism at Browns Range granite complex (Page et al. 1995) has been re-interpreted as representing inheritance from a sedimentary protolith (Cross and Crispe 2006).

The basal succession of the Tanami Group, comprising arkose, and fine-grained deep water sedimentary rocks of the Dead Bullock Formation was deposited at 1,880–1,840 Ma (Cross and Crispe 2006). This formation is a deepening-upward sediment package that was deposited in a deep marine setting with a progressively reduced clastic input. The overlying Killi Killi Formation reflects a deep-water setting with an increased clastic input, with the deposition of turbiditic rocks. The Killi Killi Formation forms part of a regionally extensive turbiditic package that was deposited across the Tanami and northern Arunta Regions at ~1,840 Ma, which includes the Lander Rock Beds. It is a time equivalent of the lower Ooradidgee Group in the Tennant Region (Claoué-Long et al. 2005) and the upper Olympio Formation in the Halls Creek Orogen (Blake et al. 2000). Deposition of the Killi Killi Formation was terminated by regional deformation during the Tanami Event, which occurred in the interval 1,840–1,825 Ma.

In the Halls Creek Orogen to the northwest, plate margin processes have been invoked to account for Paleoproterozoic tectonism (Myers et al. 1996; Sheppard et al. 1997, 1999). The collision of the Kimberley Craton (KC) and North Australian Craton (NAC) is believed to have commenced at around 1,835 Ma, and was completed by 1,805 Ma (Myers et al. 1996; Sheppard et al. 1997,1999; Bodorkos et al. 2002). Widespread turbiditic successions, including the Killi Killi Formation, may have been sourced from uplift produced by the early stages of this event. Deformation associated with the Tanami Event is interpreted to be an intraplate response to the KC–NAC collision, and was followed by a period of prolonged post-collisional 1,825–1,790 Ma felsic magmatism, accompanied by deformation and localized volcanism and sedimentation. Volcanic and clastic sedimentary rocks of the 1,825–1,810 Ma Ware Group form part of a more regionally widespread episode of volcanism and clastic sedimentation that is represented by upper Ooradidgee Group and lower Wauchope Subgroup in the Tennant Region (Donnellan et al. 2001), the El Sherana and Edith River Groups in the Pine Creek Orogen (Lally and Worden 2004 and references therein), and the lower parts of the Strangways Metamorphic Complex in the Arunta Region (Scrimgeour 2003, 2004).

Nd T_{DM} model ages between 2,516 and 3,297 Ma (Page et al. 1995) indicate granites in the Tanami Region are likely to have been derived from partial melting of Neoarchean felsic gneisses. Deformation associated with $D_{2–5}$ in the Tanami Group postdated deposition of the Ware Group, and is likely to correspond with the Stafford Event in the Arunta Region (Scrimgeour 2003, 2004) and the Murchison Event in the Tennant Region (Donnellan et al. 2001). In light of the numerous granitic bodies in the Tanami Region, any proposed tectonic setting would require a sufficient heat source to melt the basement and form felsic magmas. To explain the tectonothermal evolution of the Tanami Region, Scrimgeour and Sandiford (1993) proposed crustal thickening accompanied by thinning of the lithospheric mantle, which resulted in melting of the lower crust and advection of heat by magma transfer into the upper crust. Alternatively, intrusion of mafic rock into the crust in a possible extensional setting may be invoked as a mechanism for introducing heat, particularly given the suggestion that post-D_3 extension may have been synchronous with ongoing felsic magmatism.

After 1,800 Ma, the Tanami Region was influenced by tectonic activity that was occurring on the southern margin of the NAC, with geochronological evidence for structural, thermal and/or exhumation events that correspond to tectonic events in the Arunta Region. In particular, $^{40}Ar/^{39}Ar$ thermo-geochronology suggests that there was a thermal and fluid flow event in the southeast of the Tanami Region that may correspond to the 1,730–1,700 Ma Strangways Orogeny (Fraser 2002). The Pargee Sandstone, with a maximum deposition age of around 1,760 Ma, may have been sourced from the Arunta Region during this event. The age of the overlying Birrindudu Group is not well constrained. Rocks in drill core that are interpreted to belong to the Birrindudu Group north of the Tanami Region are overlain by the Limbunya Group, which was deposited at 1,640–1,635 Ma (Cutovinos et al. 2002). Therefore, deposition of the Birrindudu Group is likely to have occurred in the interval 1,760–1,640 Ma.

The Birrindudu Group is interpreted to have been deposited in an extensive, shallow marine shelf setting and is a correlative of the Tolmer Group, which unconformably overlies the western Pine Creek Orogen. A thermal overprint or exhumation event also occurred associated with the Chewings Orogeny (1,590–1,570 Ma), which involved north–south shortening in the Arunta Region and forms part of a more widespread event that affected most Paleoproterozoic terranes of northern Australia. The influence of the Chewings Orogeny is yet to be distinguished in the Tanami Region. A final stage of intraplate reactivation of structures in the Tanami Region is likely to have taken place during the Paleozoic Alice Springs Orogeny.

Acknowledgements The authors acknowledge the major contributions of Marc Hendrickx, Kerry Slater, and Alison Dean in the development of the stratigraphic framework, geophysical interpretation, and geological models presented in this report. Interpretation of granite geochemistry was undertaken by Mike Green. High-quality geochronology and scientific input was provided by Andrew Cross, Julie Smith, and Jon Claoue-Long of Geoscience Australia. The authors thank David Huston of Geoscience Australia (North Australian Project co-coordinator) for his significant geological input, numerous discussions and reviews. Tony Meixner of Geoscience Australia is also thanked for his significant input into developing our understanding of three-dimensional geological relationships in the Tanami. Constructive reviews by Ian Tyler and David H Blake are gratefully acknowledged, and we also wish to thank past and present geologists from Newmont Australia, Anglogold, and Otter Gold NL for their cooperation and significant geological input during the course of this project.

References

Adams GJ (1997) Structural evolution and ore genesis of The Granites gold deposits, Northern Territory. Unpublished PhD thesis, University of Adelaide, Australia

Adams GJ, Both RA, James P (2006) The Granites gold deposits, Northern Territory, Australia: evidence for an early syn-tectonic ore genesis. Miner Deposita (in press). doi: 10.1007/s00126-006-0110-6

Bagas L, Huston DL, Anderson J (2006) Gold deposits in the Paleoproterozoic Tanami Group, Western Australia. Miner Deposita (in press)

Blake DH (1974) Shallow stratigraphic drilling in The Granites-Tanami Region, Northern Territory and Western Australia, 1971–1973. Bureau of Mineral Resources, Australia, Canberra, Record 1974/104

Blake DH, Hodgson IM, Smith PA (1972) Geology of the Birrindudu and Tanami 1:250 000 sheet areas, Northern Territory. Report on the 1971 field season. Bureau of Mineral Resources, Australia, Canberra, Record 1972/92

Blake DH, Hodgson IM, Muhling PC (1973) Geology of The Granites and Precambrian parts of Billiluna, Lucas And Stansmore 1:250 000 sheet areas, Northern Territory and Western Australia. Bureau of Mineral Resources, Australia, Canberra, Record 1973/171

Blake DH, Hodgson IM, Smith PA (1975) Geology of the Birrindudu and Tanami 1:250 0000 Sheet Areas, Northern Territory. Bureau of Mineral Resources, Australia, Canberra, Report 174

Blake DH, Hodgson, IM, Walton DG, Muhling PC (1976) The Granites, Northern Territory (First Edition). Australia 1:250 000 Geological series, SF52-03. Bureau of Mineral Resources, Australia, Canberra

Blake DH, Hodgson IM, Muhling PC (1979) Geology of The Granites-Tanami Region. Bureau of Mineral Resources, Australia, Canberra, Bulletin 197

Blake DH, Tyler IM, Warren RG (2000) Gordon Downs (Second edition) 1:250 000 geological series, explanatory notes. Australian Geological Survey Organisation, Canberra and Geological Survey of Western Australia, Perth (National Geoscience Mapping Accord)

Bodorkos S, Sandiford M, Oliver NHS, Cawood PA (2002) High-T, low-P metamorphism in the Palaeoproterozoic Halls Creek Orogen, northern Australia: the middle crustal response to a mantle-related transient thermal pulse. J Metamorph Geol 20:217–237

Claoué-Long J, Cross AJ, Smith J (2001) NTGS-AGSO Geochronology Project, Report 4. AGSO Record 2001/06

Claoué-Long J, Fraser G, Huston D, Neumann N, Worden K (2005) Towards a correlation of the earliest Proterozoic evolution in central Australia. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2005-001

Collins WJ, Shaw RD (1995) Geochronological constraints on orogenic events in the Arunta Inlier, a review. Precambrian Res 71:315–346

Cooper JA, Ding PQ (1997) Zircon ages constrain the timing of deformation events in the The Granites-Tanami region, northwest Australia. Aust J Earth Sci 44:777–787

Crispe AJ (2006) The Granites, Northern Territory (Second Edition), 1:250 000 scale geological map, SF52-03. Northern Territory Geological Survey, Darwin (in press)

Crispe AJ, Vandenberg LC (2004) Northern Tanami: findings from reconnaissance mapping 2003. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2004-001

Cross AJ, Crispe AJ (2006) SHRIMP U-Pb analyses of detrital zircon: a window to understanding the early Palaeoproterozoic development of the Tanami Basin, Northern Australia. Miner Deposita (in press). doi: 10.1007/s00126-102-6

Cross AJ, Fletcher IR, Crispe AJ, Huston DL, Williams N (2005) New constraints on the timing of deposition and mineralization in the Tanami Group. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2005-001

Cutovinos A, Beier PR, Kruse PD, Abbott ST, Dunster JN, Brescianini RF (2002) Limbunya, Northern Territory (2nd edn). 1:250 000 geological map series explanatory notes, SE 52-07. Northern Territory Geological Survey, Darwin

Dean AA (2001) Igneous rocks of the Tanami Region. Northern Territory Geological Survey Record 2001-003

Ding PQ, Giles CW (1993) Geological setting of gold mineralization in the Tanami Region, Northern Territory, Australia. In: Proceedings of the International symposium of gold mining technology, Beijing, June 1993, pp 15–17

Donnellan N, Hussey KJ, Morrison RS (2001) Short Range, Northern Territory. 1:100 000 geological map series explanatory notes, 5659. Northern Territory Geological Survey, Darwin

Fraser G (2002) Timing of regional tectonism and Au-mineralization in the Tanami Region: ^{40}Ar/^{39}Ar geochronological constraints. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2002-003

Fraser G (2003) Geological relationships between the Tanami and Northern Arunta Regions: evidence from ^{40}Ar/^{39}Ar geochronology. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2003-001

Garnaut K (1995) Geochemical classification of the mafics in The Granites-Tanami Inlier and their implication for the region's evolution. B.Sc.(Hons) thesis (unpublished), University of Adelaide, Australia

Green MH (2004) Gold Prospectivity in the Northern Arunta Region: extrapolating from the Tanami Deposits. Annual Geoscience Exploration Seminar (AGES 2004) Record of abstracts, Northern Territory Geological Survey Record 2004-001

Griffin TJ, Page RW, Sheppard S, Tyler IM (2000) Tectonic implications of Palaeoproterozoic post-collisional, high-K felsic igneous rocks from the Kimberley region of northwestern Australia. Precambrian Res 101:1–23

Hendrickx MA, Slater KR, Crispe AJ, Dean AA, Vandenberg LC, Smith JB (2000a) Palaeoproterozoic stratigraphy of the Tanami Region: regional correlations and relation to mineralization—preliminary results. Northern Territory Geological Survey Record 2000-13

Hendrickx MA, Vandenberg LC, Crispe AJ, Dean AA (2000b) McFarlane (First Edition) 1:100 000 Surface geology map, 4757. Northern Territory Geological Survey, Darwin, Australia

Hodgson IM (1976) The Granites 1:250 000 Geological series—explanatory notes. Bureau of Mineral Resources, Australia, Canberra

Huston DL, Vandenberg L, Wygralak A, Mernagh T, Bagas L, Crispe A, Lambeck L, Cross A, Fraser G, Williams N, Worden K, Meixner T, Goleby B, Jones L, Lyons P, Maidment D (2006) Lode-gold mineralization in the Tanami Region, northern Australia. Miner Deposita (in press). doi: 10.1007/s00126-006-0106-2

Ireland TJ, Mayer TE (1984) The geology and mineralization of the Granites gold deposits, Northern Territory. In: Darwin Conference, Australasian Institute of Mining and Metallurgy, Darwin pp 397–406

Lally J, Worden K (2004) Geochronology in the Pine Creek Orogen—new results from NTGS. Annual Geoscience Exploration Seminar (AGES 2004) Record of Abstracts, Northern Territory Geological Survey Record 2004-001

Lambeck A (2004) Sequence stratigraphy interpretation at Callie Mine, Tanami Desert, Northern Territory. Geoscience Australia Professional Opinion 2004/03, pp 23

Lovett DR, Giles CW, Edmonds W, Gum JC, Webb RJ (1993) The geology and exploration of the Dead Bullock Soak gold deposits, The Granites-Tanami Goldfield NT. In: Proceedings of AusIMM centenary conference, The Australian Institute of Mining and Metallurgy, Melbourne, 1993, pp 73–80

Mayer TE (1990) The Granites gold field. In: Hughes FE (ed) Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy, Melbourne, pp 719–724

Meixner T, Lane R (2005) 3D inversion of gravity and magnetic data for the Tanami region. Annual Geoscience Exploration Seminar (AGES 2005) Record of abstracts, Northern Territory Geological Survey Record 2005-001

Myers JS, Shaw RD, Tyler IM (1996) Tectonic evolution of Proterozoic Australia. Tectonics 15:1431–1446

Nicholson PM (1990) Tanami gold deposit. In: Hughes FE (ed) Geology of the mineral deposits of Australia and Papua New Guinea. The Australasian Institute of Mining and Metallurgy, Melbourne, pp 719–724

Page R, Sun S-s, Blake DH (1995) Geochronology of an exposed late Archaean basement terrane in The Granite-Tanami Region. AGSO Res Newsl 22:19–20

Scott J (1993) The structural setting of the Proterozoic gold mineralization at Bunkers Hill open cut mine, The Granites, Northern Territory. BSc (Hons) thesis, University of Adelaide

Scrimgeour IR (2003) Developing a revised framework for the Arunta Region. Annual Geoscience Exploration Seminar (AGES 2003) Record of abstracts, Northern Territory Geological Survey Record 2003-001

Scrimgeour IR (2004) A revised province definition and Palaeoproterozoic framework for the Arunta Region, central Australia. Geological Society of Australia, Abstract, 73:185

Scrimgeour IR, Sandiford M (1993) Early Proterozoic metamorphism at The Granites gold mine, Northern Territory: implications for the timing of fluid production in high-temperature, low-pressure terranes. Econ Geol 88:1099–1113

Sheppard S, Griffin TJ, Tyler IM (1997) Compilation of whole-rock geochemical data for the King Leopold and Halls Creek Orogens. Geological Survey of Western Australia Record 1997/4

Sheppard S, Tyler IM, Griffin TJ, Taylor WR (1999) Palaeoproterozoic subduction-related and passive margin basalts in the Halls Creek Orogen, northwest Australia. Aust J Earth Sci 46: 679–690

Slater KR (2000a) Tanami SE 52-15 1:250 000 Integrated interpretation of geophysics and geology. Northern Territory Geological Survey, Darwin, Australia

Slater KR (2000b) THE GRANITES SF 52-3 1:250 000 Integrated interpretation of geophysics and geology. Northern Territory Geological Survey, Darwin, Australia

Smith JB (2001) Summary of results. Joint NTGS-AGSO age determination program 1999-2001. Northern Territory Geological Survey Record 2001-007

Smith MEH, Lovett DR, Pring PI, Sando BG (1998) Dead Bullock Soak gold deposits. In: Berkman DA, Mackenzie DH (eds) Geology of Australian and Papua New Guinean mineral deposits. The Australasian Institute of Mining and Metallurgy, Melbourne, pp 449–460

Traves DM (1955) The geology of the Ord-Victoria region, northern Australia. Bureau of Mineral Resources, Australia, Bulletin 27

Tunks AJ (1996) Structure and origin of gold mineralization, Tanami Mine, Northern Territory. PhD thesis, University of Tasmania, Hobart

Tunks AJ, Cooke D (2006) Geology and structural controls on mineralization at the Tanami Gold Mine. Miner Deposita (in press). doi: 10.1007/s00126-006-0097-z

Tunks AJ, Marsh S (1998) Gold deposits of the Tanami corridor. In: Berkman DA, Mackenzie DH (eds) Geology of Australian and Papua New Guinean mineral deposits. The Australasian Institute of Mining and Metallurgy, Melbourne, pp 443–448

Valenta R, Wall V (1996) Controls on gold mineralization at The Granites, Tanami Desert, Northern Territory. Geol Soc Aust 41:451 (abstract)

Vandenberg LC (2002) Tanami Uncovered: structure of gold deposits in the Tanami- North Arunta Region. In: Applied structural geology for mineral exploration and mining international symposium (Kalgoorlie, Western Australia) Abstract volume. Australian Institute of Geoscientists, Bulletin 36:223–225

Vandenberg LC, Meixner T (2003) The Tanami in 3D. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey, Record 2003-001

Vandenberg LC, Meixner T (2004) The Tanami 3D model—2004 update. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey, Record 2004-001

Vandenberg LC, Crispe AJ, Hendrickx MH, Dean AA, Slater KR (2001a) Geology and mineralization of the Tanami Gold Region. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2001-006

Vandenberg LC, Hendrickx MH, Crispe AJ (2001b) Structural geology of the Tanami Region. Northern Territory Geological Survey Record 2001-004

Vandenberg LC, Hendrickx MA, Crispe AJ, Slater KR, Dean AA (2001c) Unraveling polydeformed Palaeoproterozoic basement structure of the Tanami gold province, NT: 5% outcrop, 100% geophysics. Geological Society of Australia, Conference Abstracts 64:189

Vandenberg LC, Crispe AJ, Green MG, Johnstone A (2002) Mount Solitaire: Establishing Tanami-Tennant Links. Annual Geoscience Exploration Seminar (AGES) Record of abstracts, Northern Territory Geological Survey Record 2002-0003

Vandenberg LC, Johnstone A, Donnellan N, Green MG, Crispe AJ (2004) Northern Arunta Region Geophysical Interpretation, Northern Territory (First edition) 1:500 000-scale map. Northern Territory Geological Survey, Alice Springs

Waddell DP (1999) Quarterly report for the period ending 30 September, 1999. Tanami Gold N.L. Subiaco, Western Australia

White AJR, Allen CM, Beams SD, Carr PF, Champion DC, Chappell BW, Wyborn D, Wyborn LAI (2001) Granite suites and supersuites of eastern Australia. Aust J Earth Sci 48:515–530

Williams NC (2002) Controls on mineralization at the Callie lode gold deposit, Tanami Desert, Northern Territory. Geoscience Australia Professional Opinion 2002/09, p 41

Williams NC (2006) Controls on mineralization at the world-class Callie gold deposit, Tanami desert, Northern Territory, Australia. Miner Deposita (in press)

Wyborn LAI (1988) Petrology, geochemistry and origin of a major Australian 1,880–1,840 Ma felsic volcano-plutonic suite: a model for intracontinental felsic magma generation. Precambrian Res 40/41:37–60

Wygralak AS, Mernagh TP, Huston DL, Ahmad M (2005) Gold mineral system of the Tanami Region. Northern Territory Geological Survey, Report 18

Zen E-A (1986) Aluminium enrichment in silicate melts by fractional crystallisation: some mineralogic and petrographic constraints. J Petrol 27:1095–1117