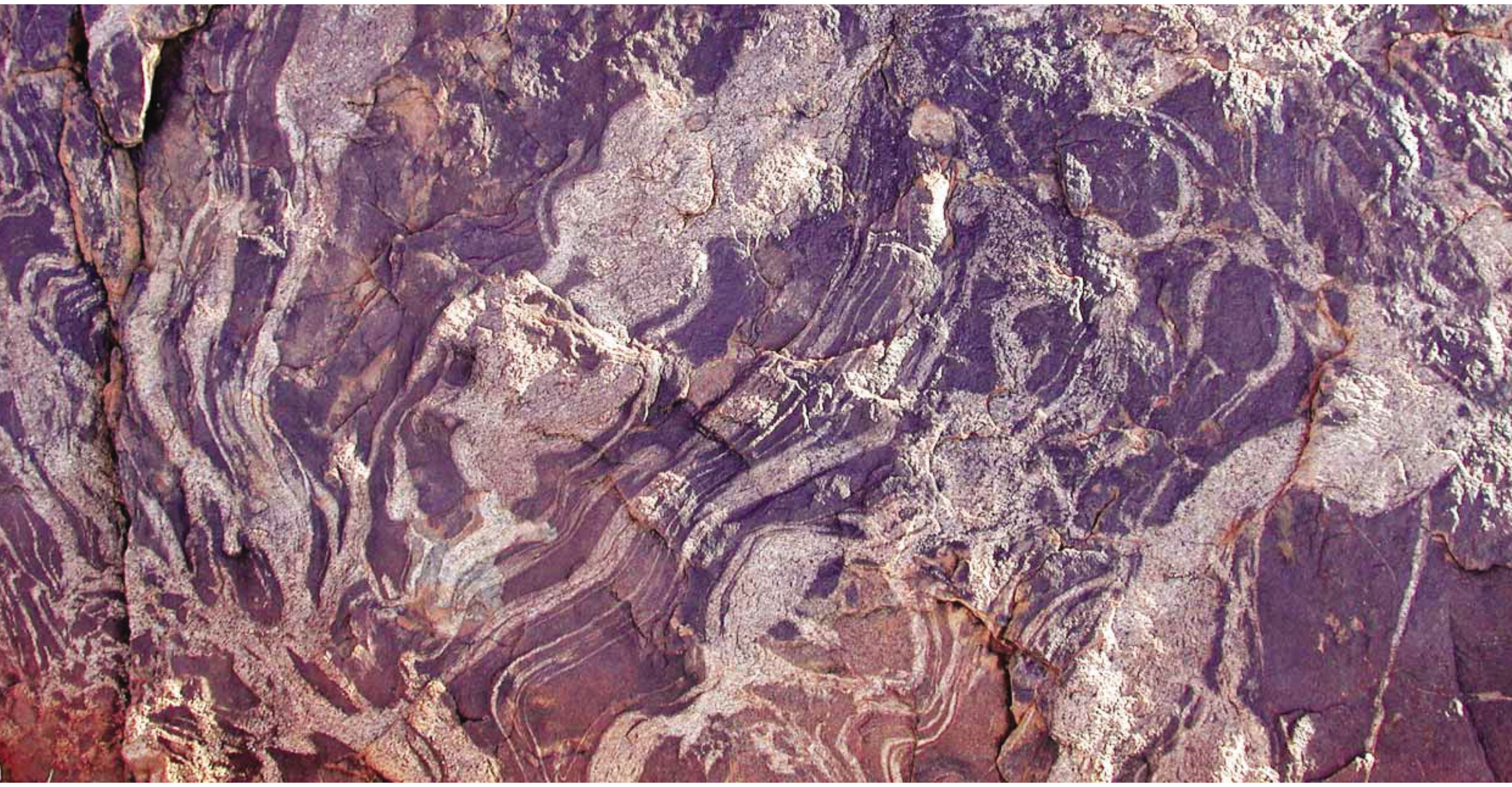
Government of Western Australia
Department of Mines and Petroleum

EXPLANATORY NOTES FOR THE WEST MUSGRAVE PROVINCE

by HM Howard, RH Smithies, PM Evins, CL Kirkland, M Werner, MTD Wingate, and F Pirajno



NGAANYATJARRA COUNCIL (Aboriginal Corporation)

Geological Survey of Western Australia

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HM Howard, RH Smithies, PM Evins[1], CL Kirkland, M Werner[2], MTD Wingate, and F Pirajno

[1] URS Nordic AB, Hannebergsgatan 33, 17168 Solna, Sweden
[2] Geological Survey of South Australia, PIRSA — Minerals and Energy Resources, GPO Box 1671, Adelaide, 5001, South Australia

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Cover photograph:
ductile deformation associated with the intrusion of partially to largely solidified gabbro by leucogranite, within the greater massive gabbro and leucogranite intrusions (G2) of the Warakurna Supersuite (northern Bell Rock).

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Explanatory Notes for the west Musgrave Province

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Abstract

The Musgrave Province, in central Australia, is a west-northwest trending Mesoproterozoic belt of high-grade metamorphic rocks, intruded and overlain by voluminous mafic to felsic igneous rocks of late Mesoproterozoic age, and structurally bound by Neoproterozoic to Phanerozoic sedimentary basins. The province represents the least studied of Australia's exposed Proterozoic terranes. The portion that lies within Western Australia — the west Musgrave Province — can be divided into three lithotectonic zones based on the age of granites and detrital age patterns in paragneisses. To the northeast, the Walpa Pulka Zone is a deep crustal domain dominated by high-K granites related to the 1220–1150 Ma Musgrave Orogeny. To the southwest, the Mamutjarra Zone is dominated by calc-alkaline granites of the older (1345–1293 Ma) Mount West Orogeny. Between these lies the Tjuni Purlka Tectonic Zone, a west-northwesterly trending zone of multigenerational shearing, the boundaries of which formed the focus for mafic and felsic intrusions during the younger (1085–1040 Ma) Giles Event. To the west and southwest, the west Musgrave Province is unconformably overlain by mafic to felsic volcanic and volcaniclastic rocks, and clastic rocks, of the Bentley Supergroup.

Locally exposed basement rocks in the eastern part of the Musgrave Province, in South Australia, are possibly as old as c. 1600 Ma, but the oldest exposed rocks in the west Musgrave Province are extremely rare calc-alkaline orthogneisses dated at c. 1400 Ma. The next oldest crustal component includes gneisses of sedimentary, volcaniclastic, and volcanic origin, with maximum depositional ages of between c. 1340 and c. 1300 Ma. These form the redefined Wirku Metamorphics, which, together with volcanic rocks deposited during the Mount West Orogeny, represent the newly defined Ramarama Basin.

Granites with crystallization ages between c. 1345 and c. 1293 Ma are the most voluminous felsic component in the southwestern part of the west Musgrave Province. They belong to the Wankanki Supersuite and are a product of the Mount West Orogeny. Volcanic equivalents are present, and detritus of this age contributed to units within the Wirku Metamorphics. The Wankanki Supersuite comprises calc-alkaline, I-type granites, and differs in this respect from all other granites in the west Musgrave region.

The Musgrave Orogeny, between 1220 and 1150 Ma, involved intense deformation and widespread high-grade crustal reworking that included the production of the voluminous ferroan (A-type) granites, including rapakivi granites, of the Pitjantjatjara Supersuite. The distribution of these granites and those of the Wankanki Supersuite is essentially antithetic — granites of the Pitjantjatjara Supersuite are most abundant in the northeast of the west Musgrave Province, but occur only as small plutons and dykes in the Mumutjarra Zone to the southwest. The Musgrave Orogeny itself records a ~100 m.y. history of ultrahigh-temperature metamorphism.

Following the Musgrave Orogeny, renewed magmatism in the west Musgrave region is documented by intrusive and extrusive igneous rocks related to the c. 1085–1040 Ma Giles Event, grouped into the Warakurna Supersuite. This younger phase of magmatism was associated with regional-scale crustal extension and subsidence, leading to the formation of the Bentley Basin, in which the volcano-sedimentary successions of the Bentley Supergroup were deposited.

The layered mafic–ultramafic intrusions that form the west-northwest spine of the west Musgrave region are likely to have intruded within a narrow period between c. 1078 and c. 1075 Ma. Unlayered gabbro intrudes the layered intrusions, forming a regionally extensive feature that is offset by sinistral movement along late, west-trending faults. Coeval leucogranite (c. 1078 and c. 1074 Ma) corresponds to a period of mafic and felsic magmatism, upright folding, and northwesterly to north-northwesterly trending shearing. Like the Pitjantjatjara Supersuite, the granites formed during the Giles Event show strongly developed ferroan (A-type) compositional characteristics. A suite of late and highly evolved Fe-rich gabbros, dated at c. 1067 Ma, directly relates to orthomagmatic Ni–Cu mineralization and is part of the Alcurra Dolerite (suite).

The Bentley Supergroup was deposited within an extensive, probably intracontinental, rift basin — the Ngaanyatjarra Rift — that was much larger than the present outcrop extent. Rocks of the Bentley Supergroup outcrop in two main areas within the west Musgrave region. In the smaller Blackstone area (Blackstone Sub-basin), the

Bentley Supergroup is represented by the Kunmarnara and Tollu Groups, consisting of a succession of coarse siliciclastic rocks and amygdaloidal basalts (Kunmarnara Group) overlain by felsic and then mafic to felsic lavas. To the southeast of Blackstone, at Skirmish Hill, this basal sequence is locally dominated by felsic volcanic rocks. In the larger area between Warburton and Jameson (Talbot Sub-basin), the Bentley Supergroup is represented by the south-dipping and south-younging succession of the Pussy Cat, Cassidy, and Mission Groups. The lower part of this succession is dominated by extrusive felsic and mafic igneous rocks, such as rhyolitic to dacitic lava flows and ignimbrite sheets, as well as basaltic to andesitic lavas and continental volcaniclastic rocks. The higher part of this succession is characterized by fluvio-lacustrine to deeper water, possibly marine, siliciclastic, and calcareous rocks, as well as thick and extensive piles of stacked mafic lava flows. In addition to sequences within the Blackstone and Talbot Sub-basins, isolated outcrops of siliciclastic rock and amygdaloidal basalt overlie gneiss throughout the Tjuni Purlka Tectonic Zone and Mamutjarra Zone, and are correlated with the Kunmarnara Group at the base of the Bentley Supergroup.

In the early Neoproterozoic, large parts of the Musgrave region were likely to have been covered by sediments thought to represent the basal deposits of the Centralian Superbasin (Townsend, Heavitree, and Dean Quartzites). Early uplift in the Musgrave region occurred during the c. 700 Ma Areyonga Movement, indicated by the significant detrital zircon component with an age compatible with the Musgrave Orogeny in the c. 660 Ma Aralka Formation of the Amadeus Basin. Transpressional deformation during the c. 550 Ma Petermann Orogeny resulted in significant uplift and exhumation of the Musgrave Province from beneath the Centralian Superbasin, resulting in the formation of a narrow foreland basin in the southwestern part of the Amadeus Basin.

KEYWORDS: Musgrave Province, Mesoproterozoic, Mount West Orogeny, Musgrave Orogeny, Giles Event, Ngaanyatjarra Rift,Warakurna Large Igneous Province, Wirku Metamorphics, Wankanki Supersuite, Pitjantjatjara Supersuite, Bentley Supergroup, granitic rocks, felsic volcanic rocks, mafic rocks, layered intrusions, tectonics, crustal evolution, mineralization, nickel, gold, PGE

Introduction

The Musgrave Province straddles the borders between the Northern Territory, Western Australia, and South Australia (Fig. 1). Although it probably represents the least studied of Australia's exposed Proterozoic terranes, it lies at the nexus of three Proterozoic structural trends formed by the amalgamation of the North, West, and South Australian Cratons (Fig. 1), and is accordingly one of the most important regions in terms of the geological evolution of Proterozoic central Australia. Rocks within this region have a long and very complex geological history. They have recently been the site of significant economic mineral discoveries, the most notable being the orthomagmatic nickel – copper – platinum group elements (PGE) deposit at Nebo–Babel, south of Jameson, and the Handpump gold discovery (e.g. Tan, 2010) to the southwest of Jameson. The remote location and historical problems regarding access to this culturally sensitive region have meant that it remains a major target for greenfields exploration.

The west Musgrave Province mapping project: scope, collaborative work, and progress

Geological investigations of the portion of the Musgrave Province lying within Western Australia form the basis of the **west Musgrave Province mapping project**, which commenced in 2004. The objectives of the project are to increase the geological knowledge of the Musgrave Province (and the rocks intruding and overlying it), and to provide comprehensive pre-competitive geoscience datasets to assist and encourage a range of land use activities within the region. This involves the collection, synthesis, and dissemination of geological information and interpretations, particularly through the production of systematic regional 1:100 000 scale geological maps and supporting geophysical, geochronological, geochemical, and structural data.

The **west Musgrave Province mapping project** has been strongly supported and facilitated by local Traditional Owners and the Ngaanyatjarra Council, and continues to operate under a formal agreement as a joint Geological Survey of Western Australia (GSWA) – Ngaanyatjarra Council project. The project also enjoys ongoing collaboration with research staff from the Tectonics, Resources and Exploration (TRaX) Centre at the University of Adelaide, and this has so far resulted in the publication of six BSc Honours theses that cover various aspects of the area's geology (Belperio, 2009; Walker-Hallam, 2009; Raimondo, 2009; King, 2009; Coleman, 2009; Sen, 2009). More recently, an Australian Research Council Linkage proposal (LP100200127), submitted by TRaX, has successfully gained funding for three years (from mid-2010), enabling a collaborative study between TRaX, GSWA, and Curtin University, aimed at 'constraining conditions and timing of orogeny and reworking in the west Musgrave Province'. In addition to these studies, GSWA is currently providing logistical support for two PhD studies from Monash University, Melbourne, concerned with physical volcanological aspects of the Bentley Supergroup, and petrogenetic aspects of the layered mafic–ultramafic Giles intrusions of the Warakurna Supersuite.

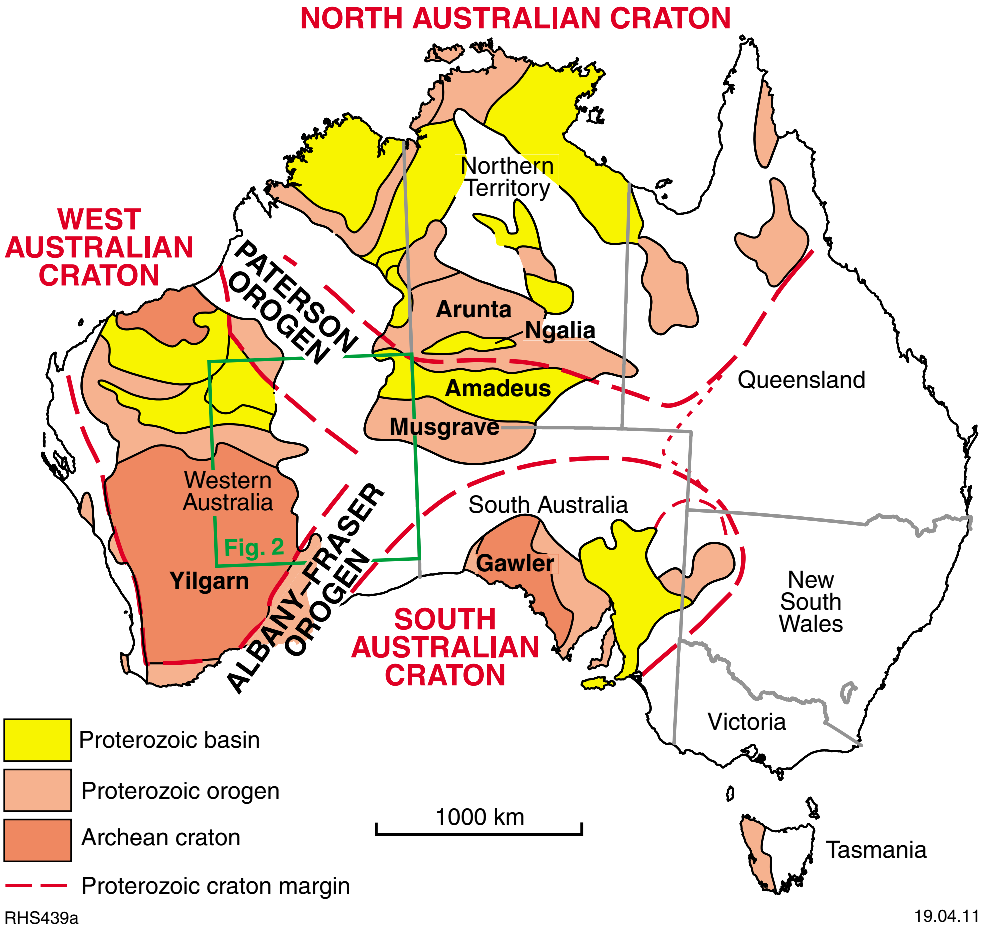


Figure 1. Location of the Musgrave Province with respect to the North, South, and West Australian Cratons (modified from Myers et al., 1996)

As part of the Exploration Incentive Scheme (EIS), GSWA has also contracted the Centre for Exploration Targeting (CET), at the University of Western Australia, to collect and interpret magnetotelluric data along two traverses (Fig. 2). These data were collected during the 2010 field season. The magnetotelluric data will be combined with a range of pre-existing geophysical and geological datasets to produce three-dimensional models of the west Musgrave Province crust, as well as a minerals system and exploration targeting analysis.

As part of a National Geoscience Agreement between GSWA and Geoscience Australia, the first half of 2011 saw the acquisition of seismic reflection, refraction, gravity, and additional magnetotelluric data along a traverse that originates in the eastern part of the Archean Yilgarn Craton and traverses both the Neoproterozoic–Paleozoic Officer Basin and the west Musgrave Province (Fig. 2). Interpretation of these datasets will take place in late 2012.

At the end of 2010, fieldwork had been completed on seven 1:100 000 Geological Series map sheets (Bates, Bell Rock, Blackstone, Holt, Finlayson, Cooper, and Mount Eveline; Fig. 3), with map compilation complete on all except Mount Eveline. Regional geophysical datasets now include complete airborne aeromagnetic and radiometric coverage (flown at 400 m line spacing), and regional gravity (collected on a 2.5 km grid). Geochronology (mostly by secondary ionization mass spectrometry (SIMS) U–Pb zircon analyses on a sensitive high-resolution ion microprobe (SHRIMP)) has been collected on about 100 samples, and major- and trace-element geochemistry has been determined on more than 1200 samples.

These Explanatory Notes describe the various tectonic units and events recognized within the region, and summarize the current state of understanding of the geology of the west Musgrave Province and the Mesoproterozoic rocks that have intruded or overlie it, based on the area mapped so far (Fig. 3). The publication is divided into two parts. The first part gives an overview of the major tectonic units and events, and the geology, of the region. The second part, Explanatory Notes, gives detailed descriptions of each lithological unit, although only for the first four published maps — Bates, Bell Rock, Blackstone, and Holt (Fig. 3).

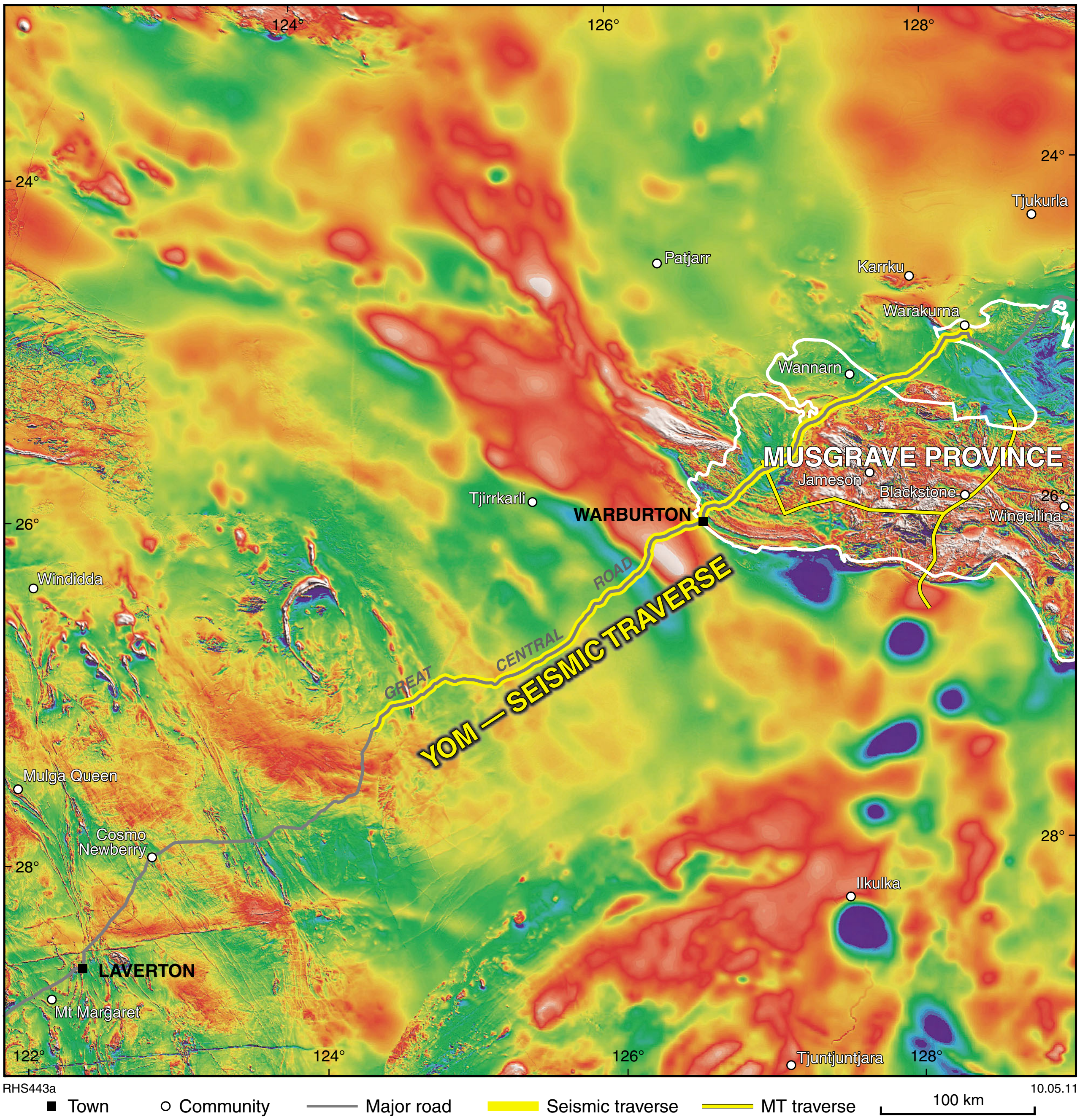


Figure 2. State Total Magnetic Intensity image, showing the location of the 2010 magnetotelluric (MT) traverses, and of the Yilgarn Craton – Officer Basin – Musgrave Province (YOM) seismic traverse

The introductory part of the publication is divided into two sections. Section 1 outlines the nomenclature adopted here, and defines and briefly describes the various major tectonic units and events. Section 2 decribes in detail the geology and geological history of the west Musgrave Province and integrates this with interpreted tectonic models. Note that parts of the geology described in Section 2 do not appear on map sheets Bates, Bell Rock, Blackstone or Holt, and the corresponding units are not described in the detailed Explanatory Notes. This section is an update and expansion of GSWA Record 2008/19 (Smithies et al., 2009).

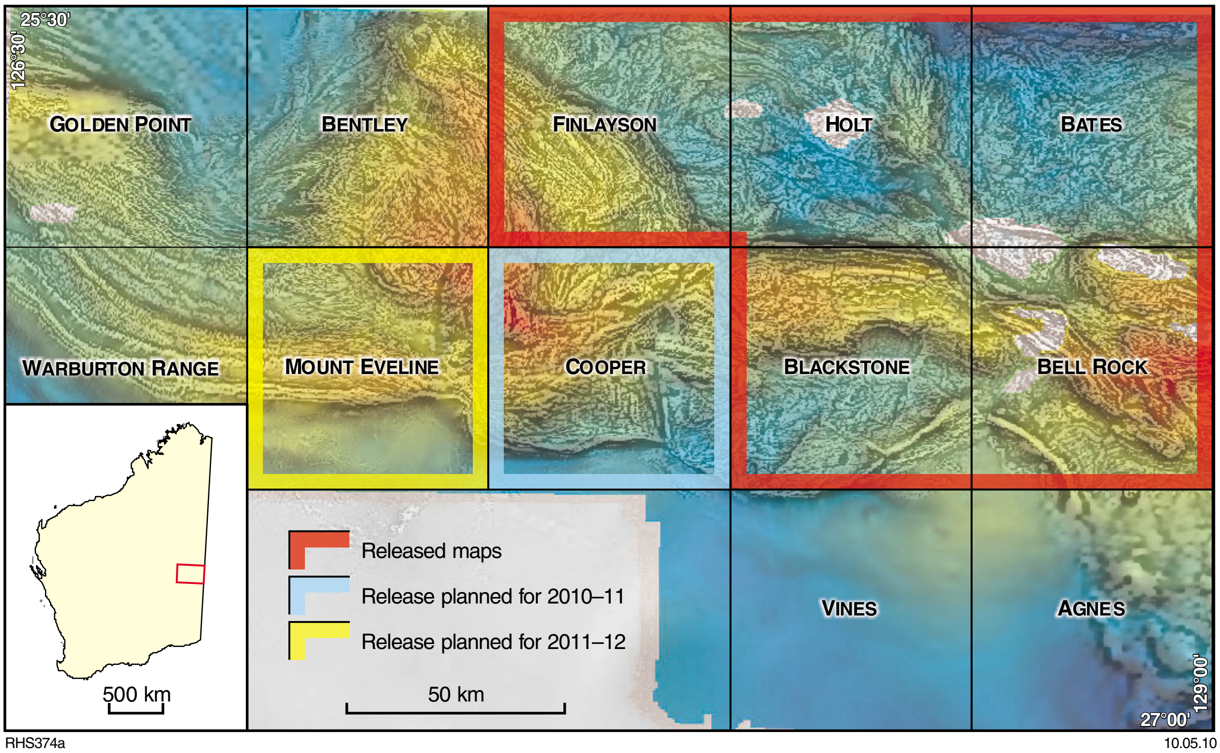


Figure 3. Map showing the location of the project area within Western Australia (inset), a combined gravity and TMI (total magnetic intensity — grey scale) image of the project area, and the location of individual 1:100 000 map sheets

Section 1: Nomenclature and definition

Musgrave region

The term Musgrave region is used in a purely geographical sense to denote the general area in which the Mesoproterozoic rocks of the Musgrave Province outcrop.

Musgrave Province

The Musgrave Province is a Mesoproterozoic belt bounded by Neoproterozoic to Paleozoic basins. It is expressed on geophysical images as a series of east-trending anomalies, covering an area up to 800 km long and 350 km wide, that straddles the borders between the Northern Territory, Western Australia, and South Australia (Figs 1–3).

A ‘Province’ was defined in GSWA Memoir 2 as ‘An area of the earth’s crust in which the rocks have some geological character, or combination of characters, in common; these are usually either age, metamorphic grade, structural style, or type of mineralization’ (Trendall, 1975, p. 30). As discussed by Sheppard et al. (2010), the term ‘province’ was abandoned in GSWA Memoir 3, as it was felt that this two-dimensional term was inappropriate for what are three-dimensional objects. The term ‘complex’ was applied ‘…to the main metamorphic and igneous components of all the orogens. [Thus] within the Paterson Orogeny, the Wingelina Complex and Rudall Complex’ were identified (Trendall, 1990, p. 197). However, the Wingelina Complex (later renamed the Musgrave Complex; Myers et al., 1996) also included the lithostratigraphic ‘Musgrave–Mann Complex’ and ‘Giles Complex’. To avoid confusion between lithostratigraphic and tectonic units, the terms ‘Wingelina Complex’ and ‘Musgrave Complex’ are discontinued, and the term ‘Musgrave Province’ is used instead.

The term ‘Musgrave Province’ is used here to refer to all the high-grade metamorphic rocks affected by the Mesoproterozoic Musgrave Orogeny, located at the southeastern end of the Paterson Orogen, in central Australia. The component of the Musgrave Province lying within the state of Western Australia is referred to here as the **west Musgrave Province**. During the 1085 to 1040 Ma Giles Event, rocks of the Musgrave Province were intruded by rocks of the Warakurna Supersuite, and unconformably overlain by rocks of the Bentley Supergroup. The exposed and near-surface extent of the Musgrave Province is defined by the surrounding younger sedimentary basins (e.g. Edgoose et al., 2004) — namely, the Amadeus Basin to the north, and Officer Basin to the south (Fig. 4). These boundaries are tectonic and reflect movements during the c. 580 to 530 Ma Petermann Orogeny (e.g. Camacho, 1997; Flöttmann and Hand, 1999; Edgoose et al., 2004).

Tectonic subdivisions of the west Musgrave Province

The Musgrave Province was previously divided into zones with different structural and metamorphic characteristics, separated by major westerly and west-northwesterly trending faults that were last active during the c. 580 to 530 Ma Petermann Orogeny (Camacho, 1989). In the north, the south-dipping Woodroffe Thrust (Fig. 4) separates the northern amphibolite-facies Mulga Park Zone from the southern granulite-facies Fregon Zone. Geochemical and geochronological similarities between these zones indicate similar tectonic histories (Camacho and Fanning, 1995).

Mesoproterozoic rocks to the north of the west-trending Mann Fault (Fig. 4) have been multiply metamorphosed at granulite facies, and most have been deformed within the anastomosing westerly to west-northwesterly trending and shallow-dipping network of Petermann Orogeny aged mylonites that cut this part of the Musgrave Province. In the eastern part of the west Musgrave Province, the Fregon Zone shows a marked north to south change in the pressure of granulite-facies metamorphism. To the north, high-pressure (10 to 14 kbar; Scrimgeour and Close, 1999) metamorphism during the Petermann Orogeny has masked the effects of Mesoproterozoic metamorphism (Scrimgeour and Close, 1999). To the south, where metamorphic overprints of Petermann Orogeny age are not as marked, evidence for Mesoproterozoic high-temperature metamorphism, at much lower pressures, is preserved (Clarke et al., 1995a). In the west Musgrave Province, the boundary separating these two metamorphic styles lies close to the west-trending and near vertical Mann Fault. Edgoose et al. (2004) speculated that this fault may further subdivide the Fregon Zone.

Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, and Mamutjarra Zone

Outcrop of the west Musgrave Province consists almost entirely of the Fregon Zone. Based on changes in the age and distribution of various rock types, and on the intensity and style of deformation, this part of the Fregon Zone has now been subdivided (Figs 5 and 6) into the Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, and Mamutjarra Zone (from northeast to southwest; Smithies et al., 2009, 2010). The most notable changes are in the distribution of granites of the two voluminous Mesoproterozoic supersuites — the Wankanki and Pitjantjatjara Supersuites (Fig. 6) — and in detrital age distribution patterns in Mesoproterozoic paragneisses (Fig. 7).

The **Tjuni Purlka Tectonic Zone** is a broad northwest-trending zone (Fig. 5) of multigenerational (c. 1220, 1075, and 550 Ma) shearing. The extent and intensity of northwest-trending shearing in this zone exceeds that of neighbouring zones, and the observation that a compositionally unique suite of schlieric leucogranites (the Tjuni Purlka suite of the Pitjantjatjara Supersuite; Smithies et al., 2010) related to the Musgrave Orogeny is totally restricted to this zone, suggests that this narrow zone was a broad synmagmatic zone of deformation throughout that period. The boundaries of the Tjuni Purlka Tectonic Zone were also the locus for mafic and felsic magmatism during the 1085–1040 Ma Giles Event (Figs 5 and 6). During the early stages of the Giles Event, giant layered troctolite–gabbronorite–gabbro intrusions (Giles intrusions) were emplaced along the southwestern edge of the zone. A thick zone of syntectonic and co-mingled gabbro and granite follows the northeastern edge of the Tjuni Purlka Tectonic Zone (Figs 5 and 6). The effects of the Petermann Orogeny in this zone are most intense to the northeast, near the contact with the Walpa Pulka Zone, and decrease towards the southwest.

The **Walpa Pulka Zone** to the north (Fig. 5) is a deep-crustal domain dominated by 1220–1150 Ma high-potassium granite plutons of the Pitjantjatjara Supersuite, emplaced during the Musgrave Orogeny. It contains high-pressure metamorphic assemblages preserved by rapid exhumation along easterly and northwesterly trending mylonites and migmatitic shear zones related to the Petermann Orogeny (Scrimgeour and Close, 1999; Camacho et al., 1997; Raimondo et al., 2009, 2010).

The **Mamutjarra Zone**, south of the Tjuni Purlka Tectonic Zone (Fig. 5), is dominated by c. 1345 to 1293 Ma calc-alkaline granites of the Wankanki Supersuite, formed during the Mount West Orogeny (Figs 5 and 6). The effects of the Petermann Orogeny in this zone are minimal.

Basement to the Musgrave Province

Clear evidence for exposed crust formed before c. 1400 Ma is yet to be found in the west Musgrave Province. In the South Australian section of the Musgrave Province, all rocks metamorphosed during the Musgrave Orogeny, including the Mesoproterozoic granite suites and the basement through which they intruded, were initially grouped into the Birksgate Complex (Major and Conor, 1993). The basement component was thought to have included orthogneisses as well as banded paragneiss derived mainly from volcanic, volcaniclastic, and sedimentary rocks, all formed or deposited between c. 1550 and 1600 Ma (Gray, 1971, 1978; Gray and Compston, 1978; Maboko et al., 1991; Major and Conor, 1993; Camacho and Fanning, 1995; Edgoose et al., 2004). However, recent work has shown that much of what was previously regarded as exposed basement in the west Musgrave Province actually comprises supracrustal packages (now mainly paragneiss) deposited between c. 1340 and 1270 Ma (Evins et al., 2011). These are referred to as the Wirku Metamorphics (Howard et al., 2007a; Smithies et al., 2009; Evins et al., 2009).

Recent SHRIMP U–Pb zircon dating from an area between the communities of Blackstone and Jameson, has suggested the presence of isolated remnants of c. 1400 Ma crust (Kirkland et al., in prep.). The original extent of this crust cannot be inferred from the isolated outcrops that remain, but the rocks are referred to here as the Papulankutja Supersuite.

Unexposed basement in the west Musgrave area can only be studied through the provenance of the sedimentary components of the supracrustal gneisses, whole-rock Sm–Nd isotopic data, and zircon xenocrysts. According to Smithies et al. (2010), the basement consists of several components, including at least one aged between c. 1650 and c. 1400 Ma, and another of Archean age.

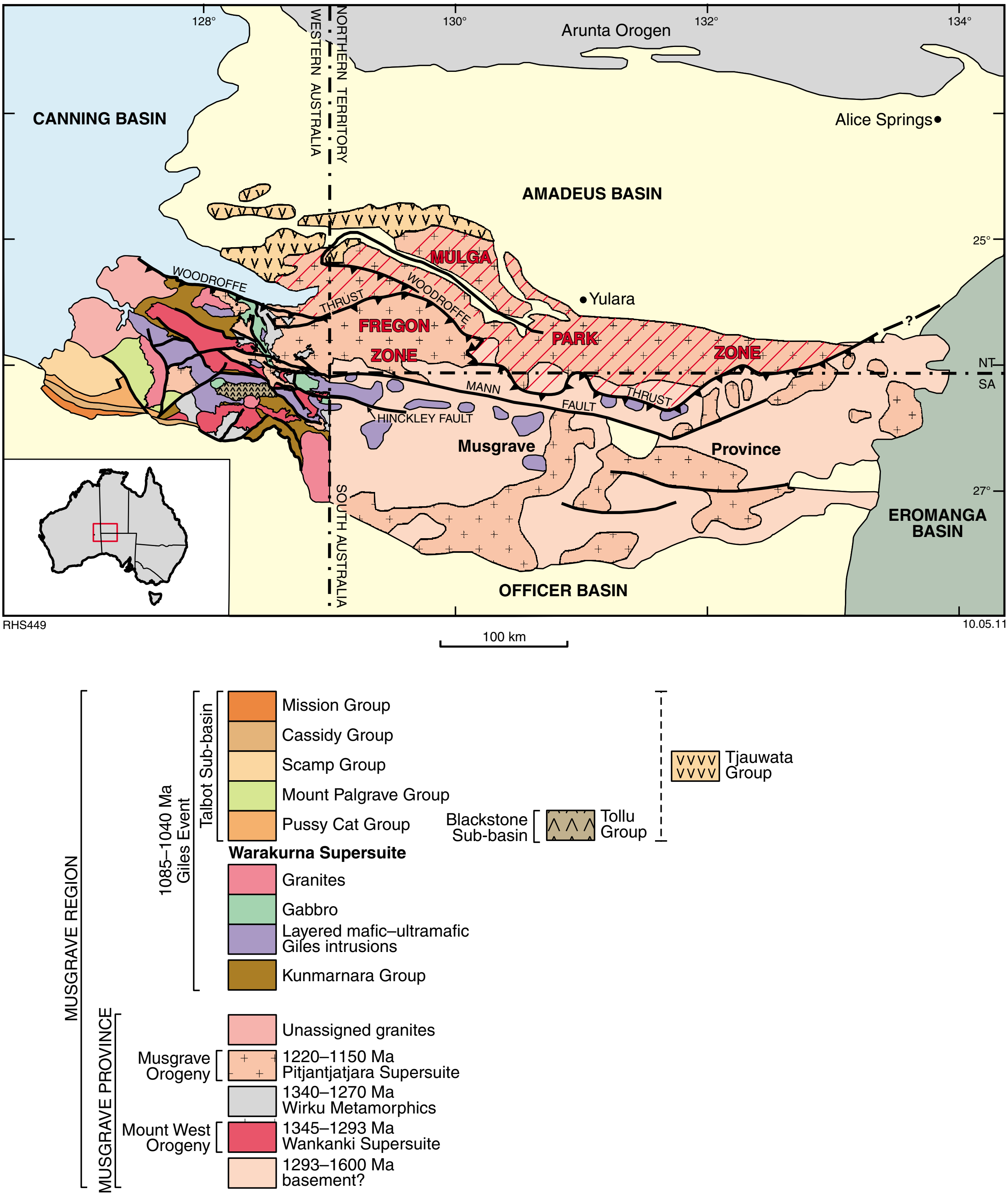
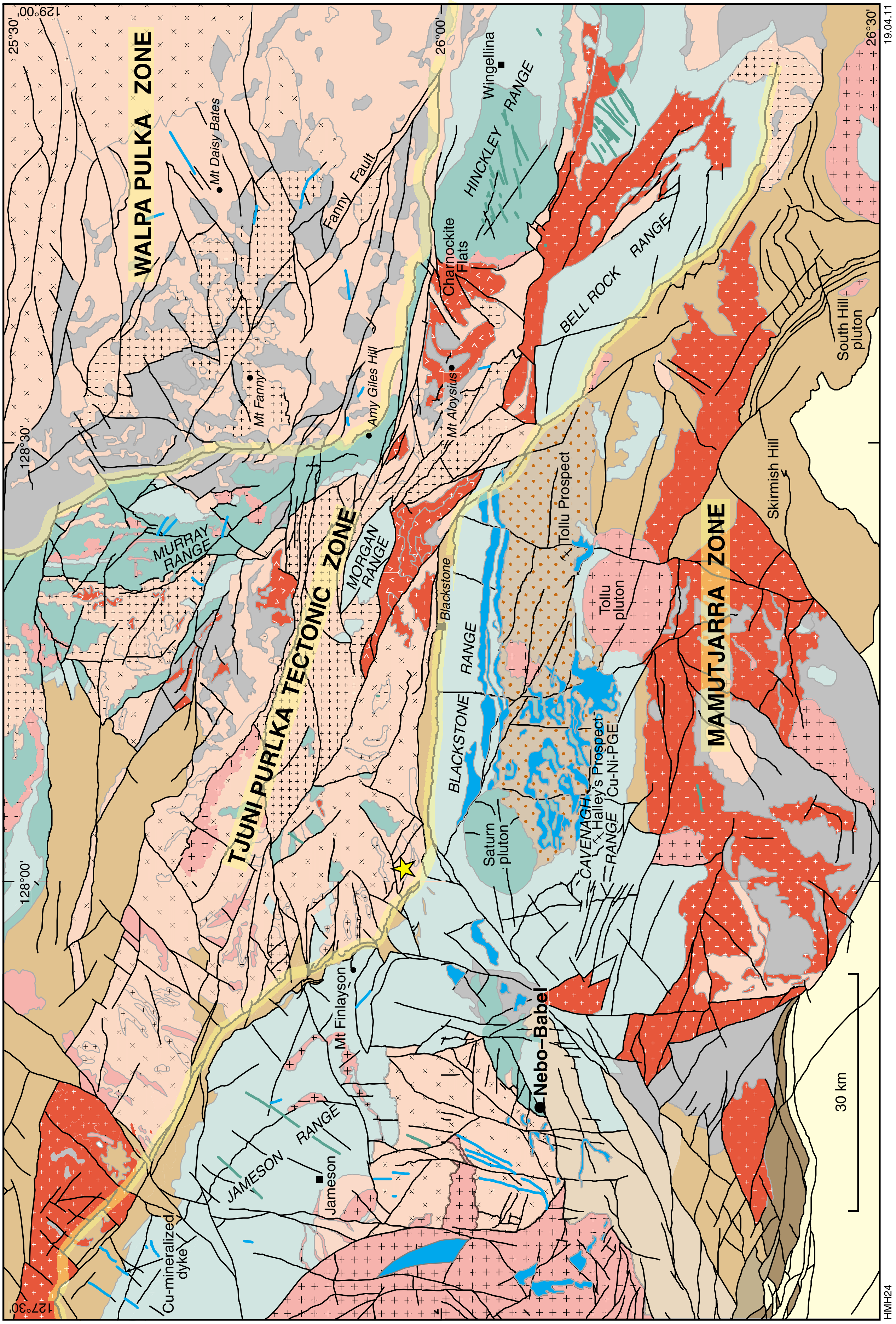


Figure 4. Regional geological sketch of the Musgrove Province (modified from Glikson et al., 1996; Edgoose et al., 2004)


WALPA PULKA ZONE
TJUNI PURLKA TECTONIC ZONE
MAMUTJARRA ZONE
Mt Daisy Bates
Fanny Fault
Mt Fanny
Amy Giles Hill
MURRAY RANGE
MORGAN RANGE
Blackstone
BLACKSTONE RANGE
Mt Aloysius
Charnockite Flats
HINCKLEY RANGE
Wingellina
BELL ROCK RANGE
South Hill pluton
Skirmish Hill
Tollu Prospect
Tollu pluton
Halley's Prospect
Cu-Ni-PGE
CAVENAGH RANGE
Saturn pluton
Mt Finlayson
Nebo–Babel
JAMESON RANGE
Jameson
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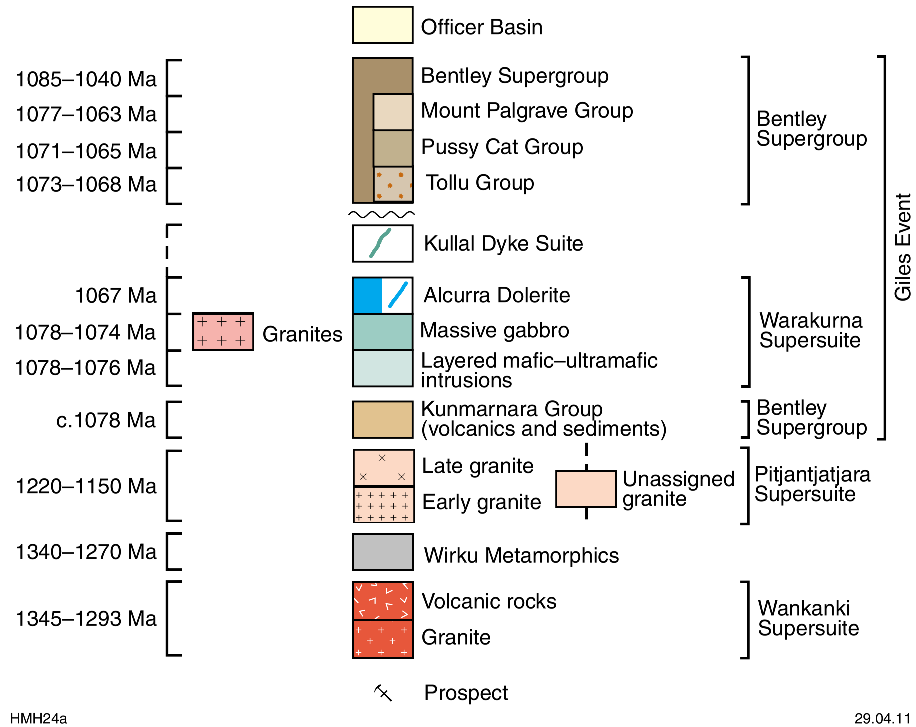

Figure 5. Interpreted bedrock geology map of the eastern portion of the west Musgrave Province. Star to the west of Blackstone Community shows the location of outcrops of the Papulankutja Supersuite.

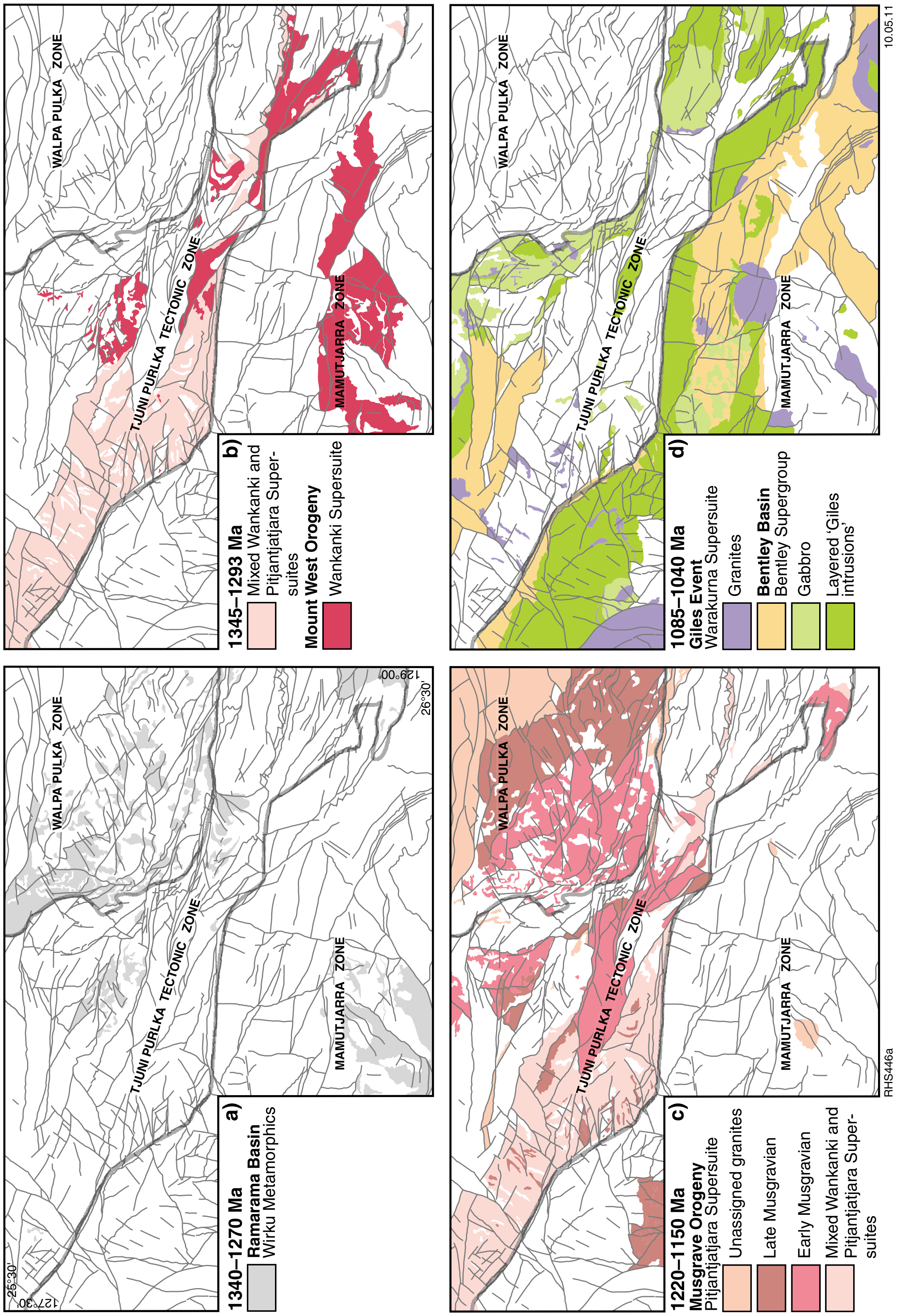

Figure 6. Interpreted bedrock geology maps of the eastern portion of the west Musgrave Province, showing outcrop distribution for rocks of specific age groups

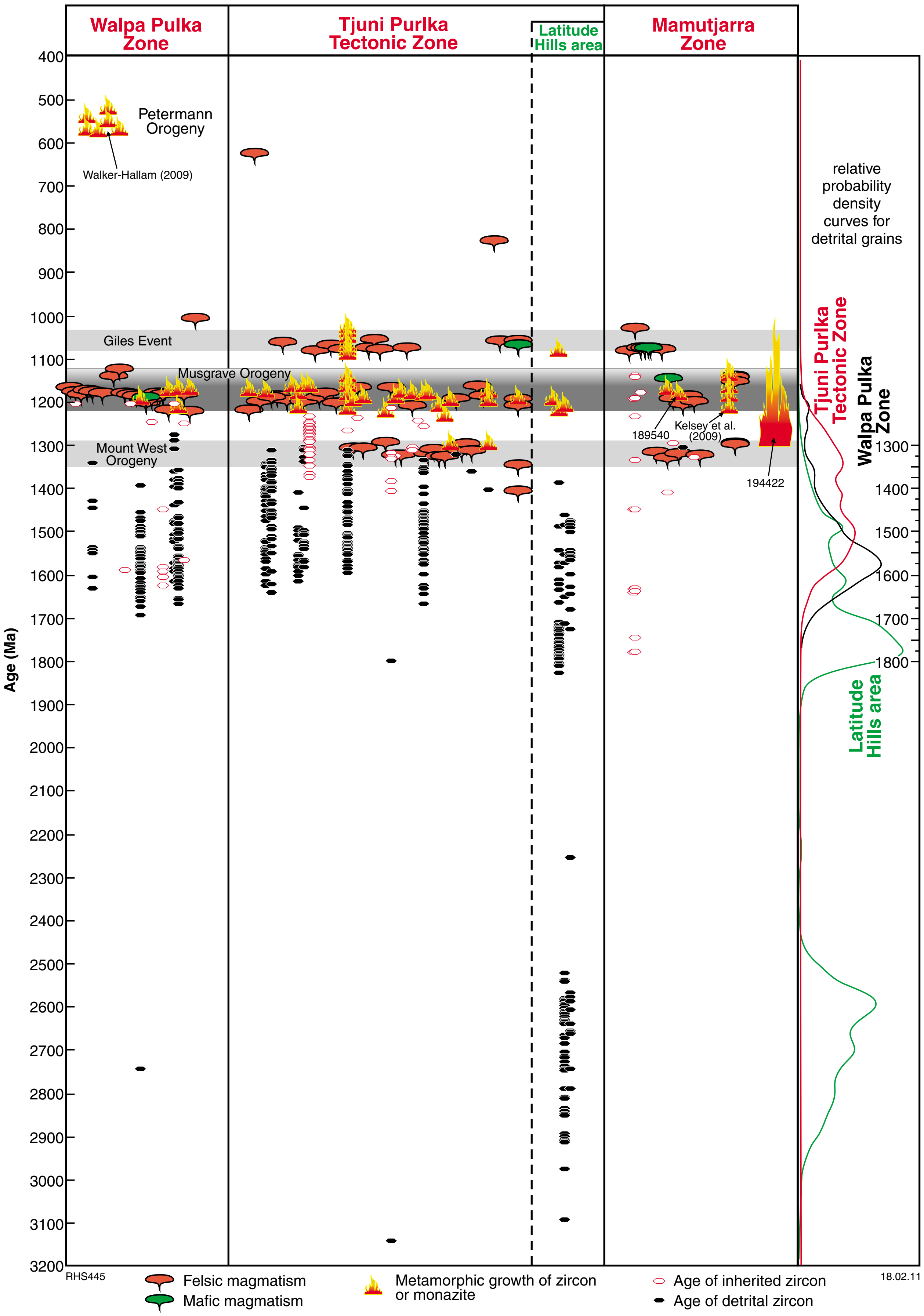

Figure 7. Time–space plot of SHRIMP U–Pb zircon ages obtained from the west Musgrave Province (data from GSWA's online geochronology database, <http://www.dmp.wa.gov.au/geochron>)

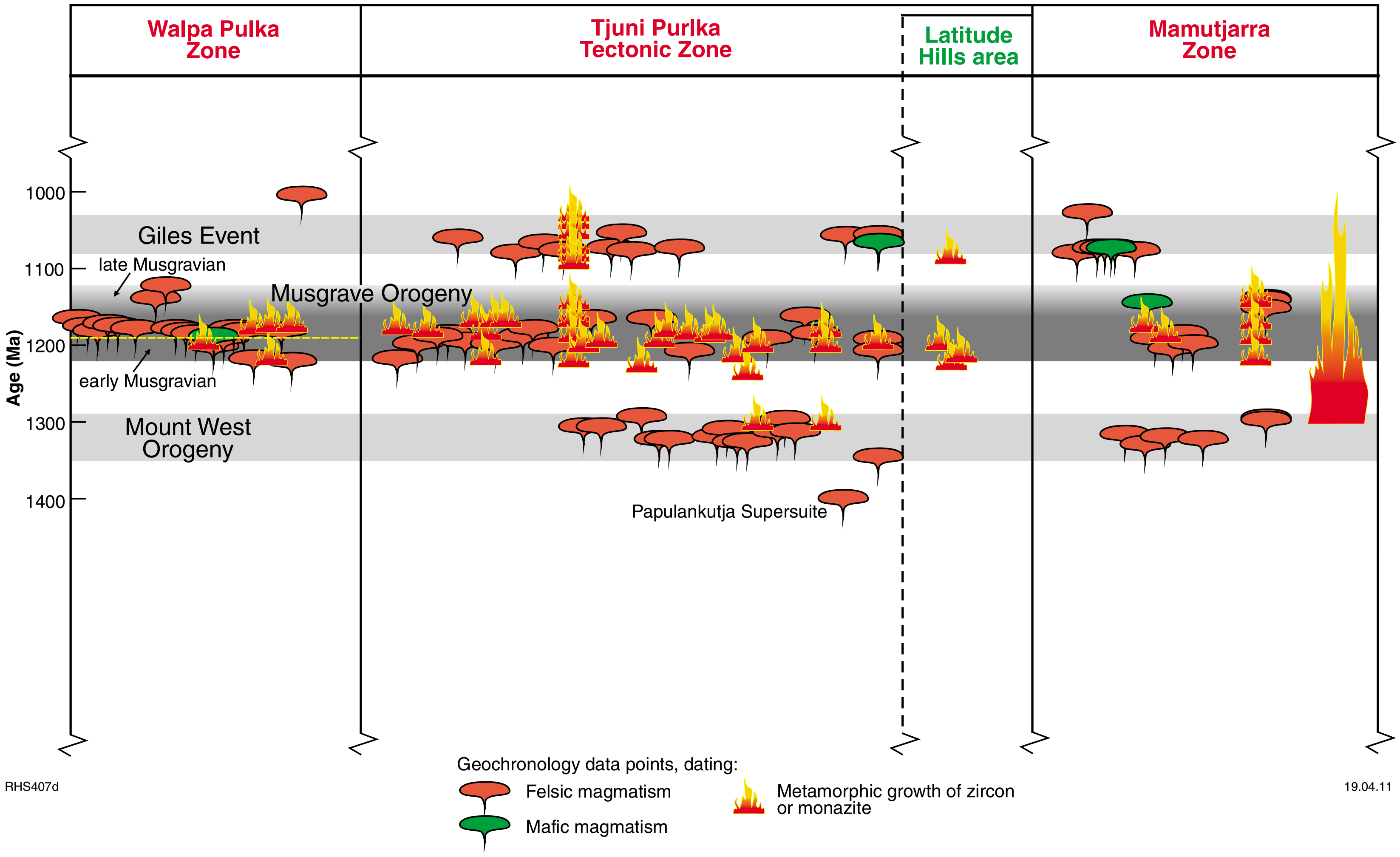

Figure 8. Detailed time–space plot of SHRIMP U–Pb zircon ages from the west Musgrave region, covering the period between c. 1400 Ma and 1000 Ma (data from GSWA's online geochronology database, <http://www.dmp.wa.gov.au/geochron>).

Magmatism and supersuites

Musgrave Province

All Mesoproterozoic metagranitic components of the west Musgrave Province are now assigned to three supersuites, largely on the basis of SHRIMP U–Pb zircon geochronology. These supersuites are the c. 1400 Ma Papulankutja Supersuite, the 1345 to 1293 Ma Wankanki Supersuite, and the 1220 to 1150 Ma Pitjantjatjara Supersuite. In the Walpa Pulka Zone, the combined age populations for rocks of the Pitjantjatjara Supersuite can be divided into two broad but distinct groups: an older group reflecting magmatism and metamorphism between c. 1220 and 1200 Ma, and a younger group reflecting magmatism and metamorphism between c. 1190 and 1155 Ma (Fig. 8). These two groups bracket events referred to as 'early Musgravian' and 'late Musgravian', respectively (Smithies et al., 2009). However, it is important to note that on the more regional scale of the entire west Musgrave Province, the combined age population for rocks of the Pitjantjatjara Supersuite show that magmatism was continuous throughout the period from 1220 to 1150 Ma.

Rocks of the Papulankutja Supersuite are confined to the Tjuni Purlka Tectonic Zone, where they are known only from a small region near Mount Scott, west of the Blackstone Community. Rocks of the Wankanki Supersuite form a significant component within the Tjuni Purlka Tectonic Zone, and represent the most voluminous pre-c. 1100 Ma magmatic component in the Mamutjarra Zone (Figs 5 and 6), but are not known from the Walpa Pulka Zone. There is a clear antithetic relationship in the relative geographical distribution of granites of the Pitjantjatjara and Wankanki Supersuites (Fig. 6), with rocks of the Pitjantjatjara Supersuite dominating in the northeast (to the total exclusion of the Wankanki Supersuite in the Walpa Pulka Zone) and rocks of the Wankanki Supersuite dominating in the southwest.

Warakurna Supersuite

All igneous rocks assigned to the Warakurna Supersuite relate to the 1085 to 1040 Ma Giles Event. The supersuite outcrops across approximately 1.5 million km^2 of central and western Australia (Fig. 9), forming the Warakurna Large Igneous Province (Wingate et al., 2004; Morris and Pirajno, 2005). In the west Musgrave region, the Giles Event and Warakurna Supersuite encompass voluminous mafic to felsic magmas that were intruded through, and onto, the Musgrave Province from c. 1085 to c. 1040 Ma. These include the giant layered mafic–ultramafic 'Giles intrusions', massive gabbros mixed and mingled with granite, the Alcurra Dolerite (suite), and granite plutons, as well as mafic and felsic lavas.

In the Walpa Pulka Zone, rocks of the Warakurna Supersuite are restricted to minor northeast-trending dolerite dykes of the Alcurra Dolerite. Rocks of the Warakurna Supersuite are abundant throughout the Tjuni Purlka Tectonic Zone, where they typically occur as tectonically dismembered intrusions of layered mafic–ultramafic 'Giles intrusions', massive gabbro, and granite. The margins of the Tjuni Purlka Tectonic Zone, in particular, have formed the focus for felsic and mafic magmas of the Warakurna Supersuite (Fig. 5). These tectonic boundaries were synmagmatic shear zones active throughout much of the Giles Event.

Basins, groups, and supergroups

Ramarama Basin, Wirku Metamorphics

During the early stages of the west Musgrave Province mapping project, supracrustal gneisses were mapped as two separate sequences — the Piti Palya Metamorphics in the Mamutjarra Zone and Tjuni Purlka Tectonic Zone, and the Wirku Metamorphics in the Tjuni Purlka Tectonic Zone and Walpa Pulka Zone — and they are displayed as such on the first edition BATES, BELL ROCK, BLACKSTONE, and HOLT geological maps. However, subsequent work did not support this division, and all of these rocks are now grouped into the Wirku Metamorphics. Hence, in general discussion the unit 'Wirku Metamorphics' refers to the combined Wirku and Piti Palya Metamorphics. Rocks of the Wirku Metamorphics are found in all lithotectonic zones in the west Musgrave Province.

The basin into which the Wirku Metamorphics protoliths were deposited is referred to as the Ramarama Basin (Fig. 6; Evins et al., 2011). As the sedimentary protoliths to the Wirku Metamorphics were intruded by Mesoproterozoic granites of the Wankanki Supersuite, the depositional age range for the sedimentary protoliths to the Wirku Metamorphics can be constrained between the minimum age range of the Wankanki Supersuite and the age of the youngest detrital zircon component within the paragneisses, and lies between 1340 and 1293 Ma (Smithies et al., 2009; Evins et al., 2011).

Bentley Basin, Bentley Supergroup

Volcanic components of the Warakurna Supersuite are grouped into the Bentley Supergroup, which also includes volcaniclastic and sedimentary rocks. The outcrop extent of the Bentley Supergroup defines the preserved extent of the Bentley Basin (Figs 4 and 10). In Western Australia, this basin can be subdivided into at least two sub-basins — the Talbot Sub-basin, in the area west of the Jameson Community, and the smaller Blackstone Sub-basin, in the area south of the Blackstone Community. An episode of syn- to post-depositional folding deformed the rocks of the Blackstone Sub-Basin, with a fold axis of the large-scale syncline more or less parallel with the axis of the basin. Hence, the depositional Blackstone Sub-basin and the structural Blackstone syncline are effectively synonymous.

The lithological range, lithological associations, and distribution of the Warakurna Supersuite and Bentley Supergroup, and their geological history, is consistent with a long-lived intracontinental rift setting, referred to as the Ngaanyatjarra Rift.

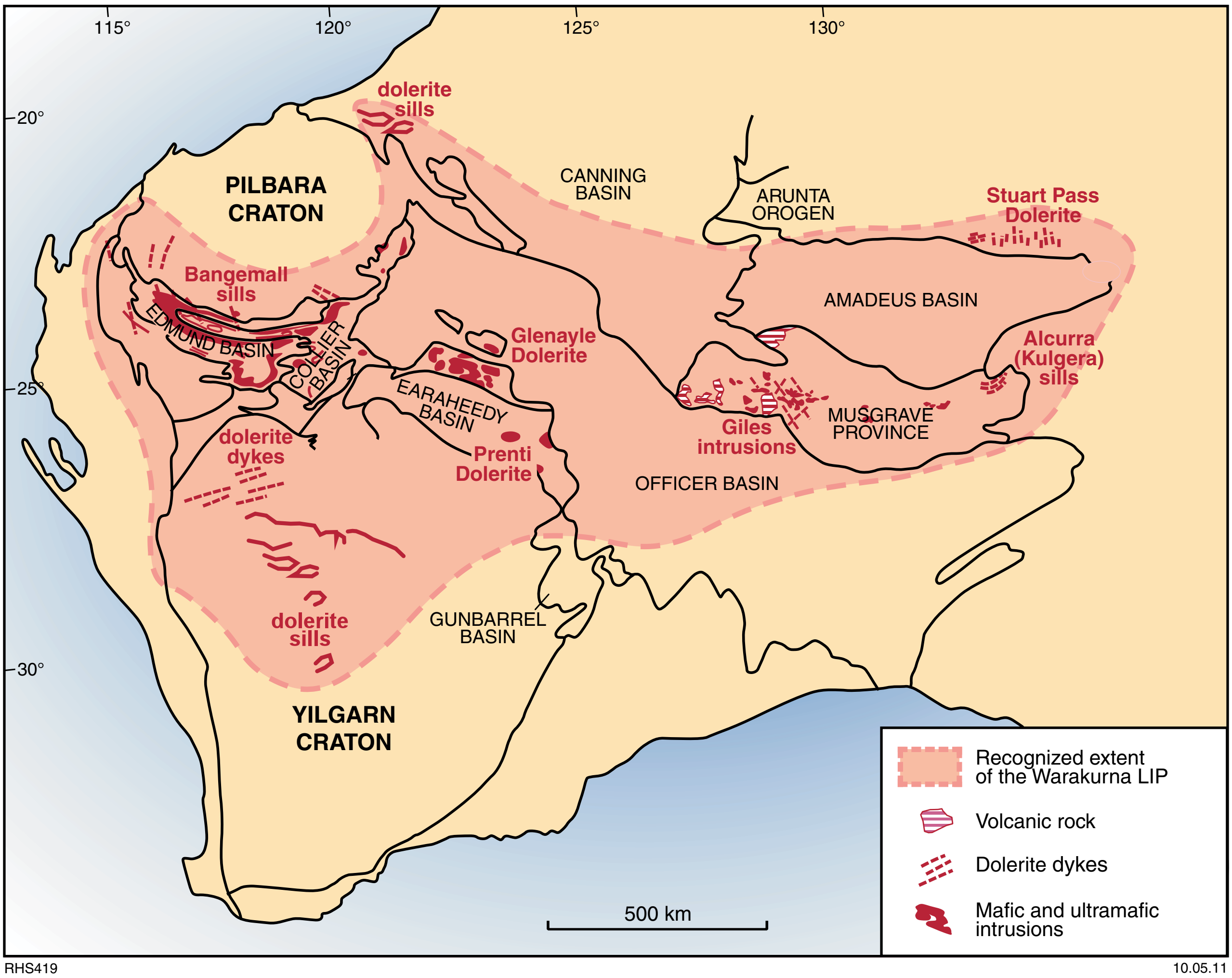

Figure 9. Map of central and Western Australia, showing the regional extent of extrusive and intrusive rocks attributed to the Warakurna Large Igneous Province (modified from Wingate et al., 2004).

Main tectonomagmatic events

Very little information is available about the basement upon which the exposed rocks of the west Musgrave Province lie, or about the nature of the events through which the remnants of 1400 Ma crust were derived. Nevertheless, SHRIMP U–Pb geochronological studies identify at least four main orogenic events (the Mount West Orogeny, the Musgrave Orogeny, the Giles Event, and the Petermann Orogeny) that shaped the region after c. 1400 Ma.

Unnamed and undated events

In addition to the four main orogenic events described below, there are several other deformational events that remain unnamed and are only loosely constrained through their relationship to dated events. These unnamed events are described in more detail in a later section (‘**Detailed geology and geological history of the west Musgrave Province**’) and include:

- the formation of a deformational fabric after intrusion of the Papulankutja Supersuite but before the Mount West Orogeny
- large-scale northwest–southeast compression, followed by crustal thinning between the end of the Mount West Orogeny and the beginning of the Musgrave Orogeny
- at least two phases of folding, which occurred before the intrusion of granites related to the early stages of the Musgrave Orogeny.

Other, mostly younger, events are indicated through the presence of regional dolerite dyke suites (at c. 1000 Ma, c. 825 Ma, and c. 750 Ma) and low-volume felsic magmatism (at c. 995 Ma and c. 625 Ma). However, the regional effects of these events were either not significant, or were masked within crust already subjected to several phases of granulite-facies metamorphism.

Mount West Orogeny

Prior to the current GSWA mapping program, magmatic ages between c. 1330 and 1293 Ma were identified by Gray (1971), Sun et al. (1996), White (1997), and White et al. (1999). Subsequent regional mapping of the west Musgrave Province (Howard et al., 2007a; Smithies et al., 2009; Evins et al., 2009) and geochronological data (Figs 7 and 8) show that igneous rocks of this age form a significant component within the west Musgrave Province. Howard et al. (2007a) grouped these rocks into the Wankanki Supersuite, and termed the crustal event that produced them the Mount West Orogeny. The crystallization age range of these rocks is from c. 1345 to c. 1293 Ma (White et al., 1999; Kirkland et al., 2008a, 2010a), with most ages lying within a narrow period between c. 1326 and 1312 Ma (Figs 7 and 8); their tectonic setting is possibly that of a continental arc (Giles et al., 2004; Betts and Giles, 2006; Smithies et al., 2009, 2010; Evins et al., 2011).

Musgrave Orogeny

The Musgrave Orogeny is the oldest orogenic event to have clearly affected all areas of the Musgrave Province. It involved intense deformation and widespread amphibolite- to granulite-facies crustal reworking. Enormous amounts of granitic magma were generated during the Musgrave Orogeny. These granites have been grouped into the Pitjantjatjara Supersuite (Edgoose et al., 2004), which covers roughly half of the entire Musgrave Province (Figs 4 and 5). Edgoose et al. (2004) placed the orogeny between c. 1200 and 1160 Ma, and formation of the Pitjantjatjara Supersuite between 1190 and 1130 Ma. Recent dating from the west Musgrave Province (Bodorkos et al., 2008a–e; Bodorkos and Wingate, 2008; Kirkland et al., 2008b–d; Howard et al., 2006, 2007a; summarized in Smithies et al., 2010) requires minor modifications to these age brackets. In this region, magmatism related to the Pitjantjatjara Supersuite extends in age from c. 1220 to c. 1150 Ma. There is also evidence that high-grade metamorphism related to the Musgrave Orogeny continued to as late as 1119 ± 7 Ma (Figs 7 and 8; Kirkland et al., 2010a; Smithies et al., 2010). The orogeny represented an unusually long period (c. 100 Ma) of ultrahigh-temperature (>900ºC) metamorphism (Kelsey et al., 2009; Smithies et al., 2010), most likely in an intracontinental setting (Wade et al., 2008; Smithies et al., 2010).

Giles Event

Voluminous mafic to felsic magmas were intruded into, and extruded onto, the west Musgrave Province during the 1085 to 1040 Ma Giles Event (Figs 4 and 7), and include the Giles layered mafic–ultramafic intrusions (Figs 4 and 5). The age of this event broadly coincides with the assembly of Rodinia (e.g. Cawood, 2005). The Giles Event has been interpreted as the result of a mantle plume (Wingate et al., 2004; Morris and Pirajno, 2005); however, more or less continuous mafic magmatism for at least 20 m.y., and felsic magmatism for as much as 45 m.y., suggests the event reflects a more protracted and complex geodynamic setting inconsistent with a simple plume model (Smithies et al., 2009; Evins et al., 2010). In the west Musgrave region, the Giles Event was responsible for the formation of a long-lived, but failed, intracontinental rift called the Ngaanyatjarra Rift (Evins et al., 2010), which is almost entirely contained within Western Australia.

Petermann Orogeny

The exposed and near-surface extent of the Musgrave Province is defined by the surrounding, younger sedimentary basins (e.g. Edgoose et al., 2004) — the Amadeus Basin to the north, and the Officer Basin to the south (Fig. 4). These boundaries are tectonic, and reflect movements during the c. 580 to 530 Ma Petermann Orogeny (e.g. Camacho, 1997; Flöttmann and Hand, 1999; Edgoose et al., 2004), although deformation along the northern margin of the Officer Basin has also been attributed to the c. 450 to 300 Ma Alice Springs Orogeny (Drexel et al., 1993). The Musgrave Province, and the rocks of the Bentley Supergroup and Warakurna Supersuite, were also locally strongly deformed during the Petermann Orogeny, which coincides with the global Pan-African period of plate reorganization that marks the assembly of Gondwana.

The Petermann Orogeny appears to have been essentially intracratonic, with very little production of new crust. Granulites and high-grade gneisses of the Musgrave Province were thrust northwards, over or into (interleaved with) rocks of the Neoproterozoic basins (Camacho, 1997; Flöttmann and Hand, 1999; Edgoose et al., 2004), in a process that may have involved intracontinental channel flow (Raimondo et al., 2009, 2010). At some stage during this orogeny, significant vertical displacements juxtaposed lower-crustal near-eclogite facies rocks against amphibolite-facies rocks along the westerly to west-northwesterly trending Mann Fault in the south, and the Woodroffe Thrust in the north of the province (Fig. 4; Camacho et al., 1997).

Alice Springs Orogeny

The Alice Springs Orogeny was a major intraplate event, or series of events, that affected much of central Australia from c. 450 to 300 Ma (Collins and Teyssier, 1989; Haines et al., 2001). Although deformation along the northern margin of the Officer Basin has been attributed to the Alice Springs Orogeny (Drexel et al., 1993), there is no firm evidence that the orogeny had any significant effect on the Musgrave region. North-trending brittle fractures are developed throughout rocks of the west Musgrave Province and appear to cut mylonites attributed to the Petermann Orogeny. However, these appear inconsistent with deformation associated with the Alice Springs Orogeny, which primarily involved north–south shortening (e.g. Flöttmann and Hand, 1999).

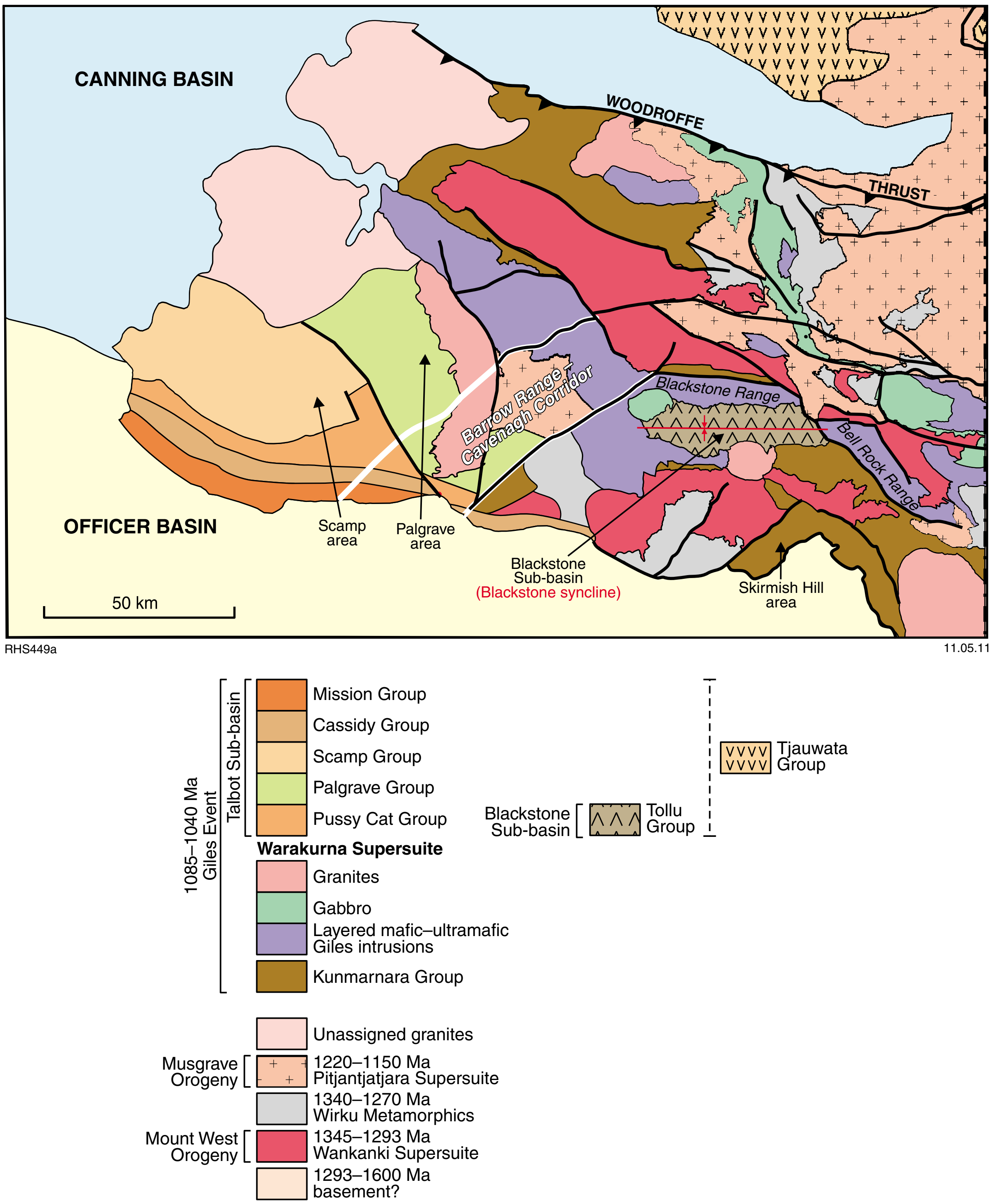

Figure 10. Regional sketch of the west Musgrave Province and Bentley Basin

Section 2: Detailed geology and geological history of the west Musgrave Province

In the context of the Proterozoic geological evolution of central and southern Australia, the nature and tectonic setting of the Mesoproterozoic events in the Musgrave Province are very poorly constrained. A coincidence of intrusive and metamorphic ages provides a late Mesoproterozoic link between this province and the Albany–Fraser Orogen, which lies along the southern and southeastern margin of the West Australian Craton (e.g. Myers et al., 1996; White et al., 1999; Fitzsimons, 2003; Spaggiari et al., 2009). At some stage in its evolution, the Musgrave Province also likely formed the southeastern part of the Paterson Orogen (Fig. 1), a 2000 km long Paleoproterozoic to Neoproterozoic belt in western to central Australia that connects to the Musgrave Province under Phanerozoic cover, via a prominent gravity-high known as the Anketell Regional Gravity Ridge (Fraser, 1976).

Regional surveys of the Musgrave Province have established a broad lithological framework (Daniels, 1974; Glikson et al., 1996; Edgoose et al., 2004). However, insight into the wider evolutionary context has hinged on only a few studies (e.g. Gray, 1971; Maboko, 1988; Camacho, 1997; White, 1997; Scrimgeour and Close, 1999; Scrimgeour et al., 2005; Wade et al., 2006, 2008; Aitken and Betts, 2008; Aitken et al., 2009). The following section expands on earlier work and documents many of the new insights into the geological evolution of the west Musgrave Province that have resulted through the west Musgrave Province mapping project. Our current understanding of the geological evolution of the west Musgrave region is summarized as a time–space plot in Figure 11.

Basement rocks

Gneissic rocks metamorphosed during the Musgrave Orogeny (the Birksgate Complex of Major and Conor, 1993) form a major component of the west Musgrave Province (Stewart, 1995; Edgoose et al., 2004; Howard et al., 2006, 2007a). Gray (1971, 1978), and Gray and Compston (1978) recognized a package of banded composite gneiss at Mount Aloysius (on the northwestern part of Bell Rock) and in the Mann Ranges (on the Northern Territory – South Australia border, approximately 20 km east of the border with Western Australia) with a Rb–Sr isotopic age of c. 1550 Ma. According to these authors, protoliths to the gneisses were supracrustal rocks dominated by volcanic material deposited at c. 1550 Ma, and were strongly metamorphosed at c. 1200 Ma. Maboko et al. (1991), Camacho and Fanning (1995), and Edgoose et al. (2004) also identified c. 1600 to 1540 Ma U–Pb ages in zircons from gneissic rocks in the eastern part of the Musgrave Province. Again, these gneisses were thought to be dominated by supracrustal material derived from volcanic, volcaniclastic, and clastic protoliths (Major and Conor, 1993; Edgoose et al., 2004).

However, in reviewing the geochronological data used to infer pre- c. 1345 Ma ages throughout the Musgrave Province, Evins et al. (2011) found many of these older ages could be interpreted as reflecting either detrital or xenocrystic zircons, derived from sedimentary, volcaniclastic, and volcanic units of the Wirku Metamorphics. Such units, along with very rare and isolated outcrop of rocks as old as c. 1400 Ma (see below), form the oldest exposed crust in the west Musgrave Province.

Nevertheless, the neodymium- and hafnium-isotopic evolution of nearly all rocks in the Musgrave Province necessitates the presence of an early Mesoproterozoic (c. 1650 and c. 1400 Ma) juvenile basement, along with a minor Archean component probably concealed below the current exposure level (Smithies et al., 2010). Rare exposures of c. 1550 Ma orthogneiss elsewhere in the province (in South Australia and the Northern Territory; e.g. Edgoose et al., 2004) confirm the presence of basement of this age. However, the extent and tectonic setting of this basement is very poorly constrained. Based on juvenile incompatible trace-element compositions and radiogenic neodymium isotopic compositions, Wade et al. (2006) suggested an arc setting for the protolith to the orthogneiss (or, in the case of the Wirku Metamorphics, for the igneous hinterland to the old detrital component in those paragneisses).

The c. 1400 Ma Papulankutja Supersuite

In a small region to the south of Mount Scott, in the southwestern part of Holt (Tjuni Purlka Tectonic Zone; Fig. 5), recent geochronological studies on a small outcrop of felsic gneiss have identified an orthogneiss with protolith ages significantly older than the maximum depositional age of protoliths to the Wirku Metamorphics. One sample from this region — a moderately foliated, K-feldspar porphyritic, orthopyroxene–clinopyroxene–biotite granodiorite to monzogranite, metamorphosed at or near granulite-facies conditions (GSWA 194764) — contains a population of 19 (out of 20) euhedral oscillatory zoned zircons that yielded a date of 1402 ± 4 Ma (Fig. 12; Kirkland et al., 2011b). A single zircon rim yielded a date of 1316 ± 8 Ma (1σ), equivalent to the crystallization age of the Wankanki Supersuite of the Mount West Orogeny.

The mineralogy and geochemistry seen in the limited samples of the granodiorites and monzogranites from this area are indistinguishable from that of the calc-alkaline granites belonging to the Wankanki Supersuite. Dated samples of the Wankanki Supersuite typically do not contain significant proportions of inherited zircon, and much of the recorded inheritance is of zircon with crystallization ages that fall within the period of the Mount West Orogeny itself (Evins et al., 2011). This presumably indicates that the final emplacement for most intrusions of the Wankanki Supersuite was within only slightly older rocks of the same supersuite. The granodiorites and monzogranites from the area south of Mount Scott have intruded paragneisses with a dominant

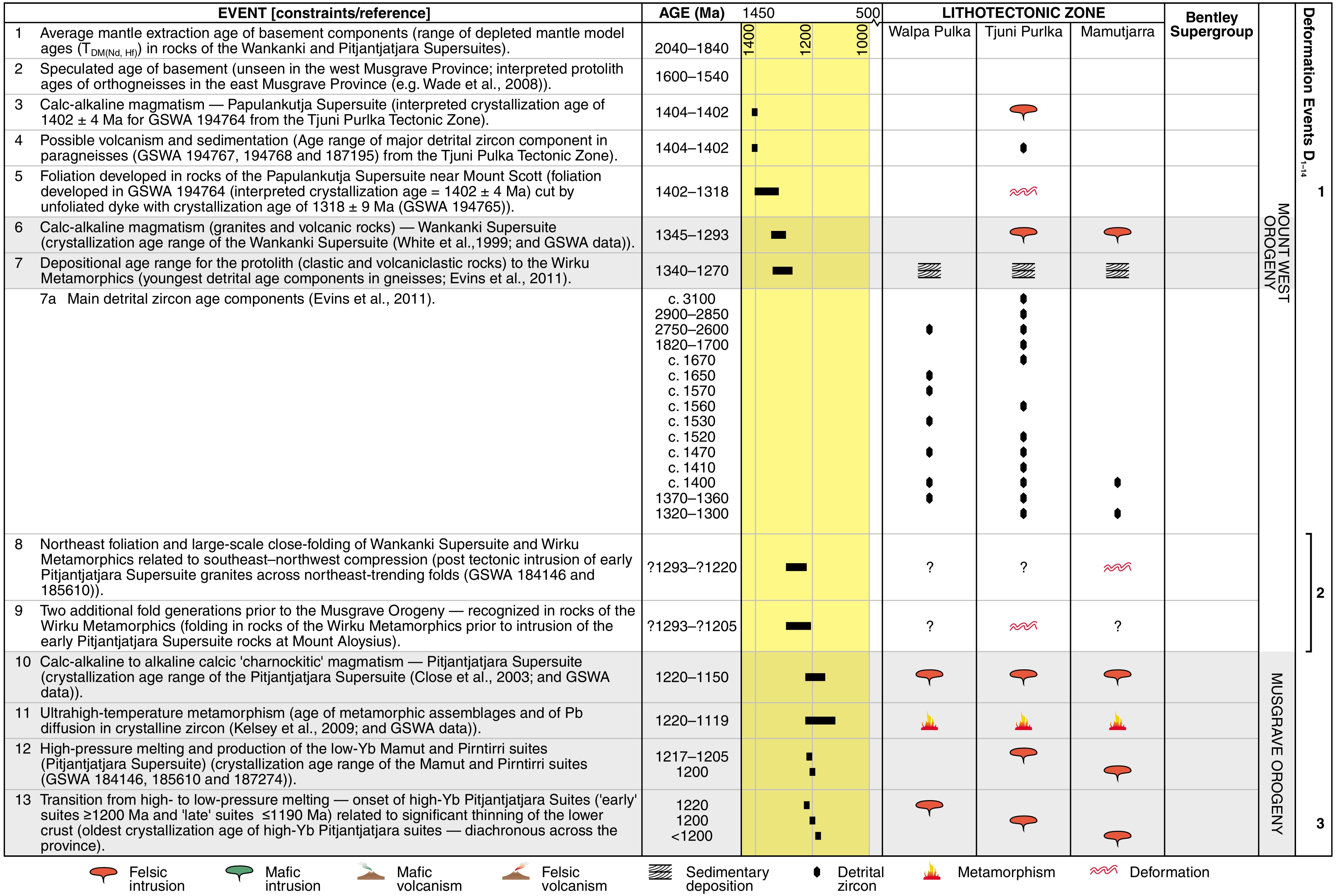

Figure 11. Detailed events–time–space chart for the west Musgrave Province.

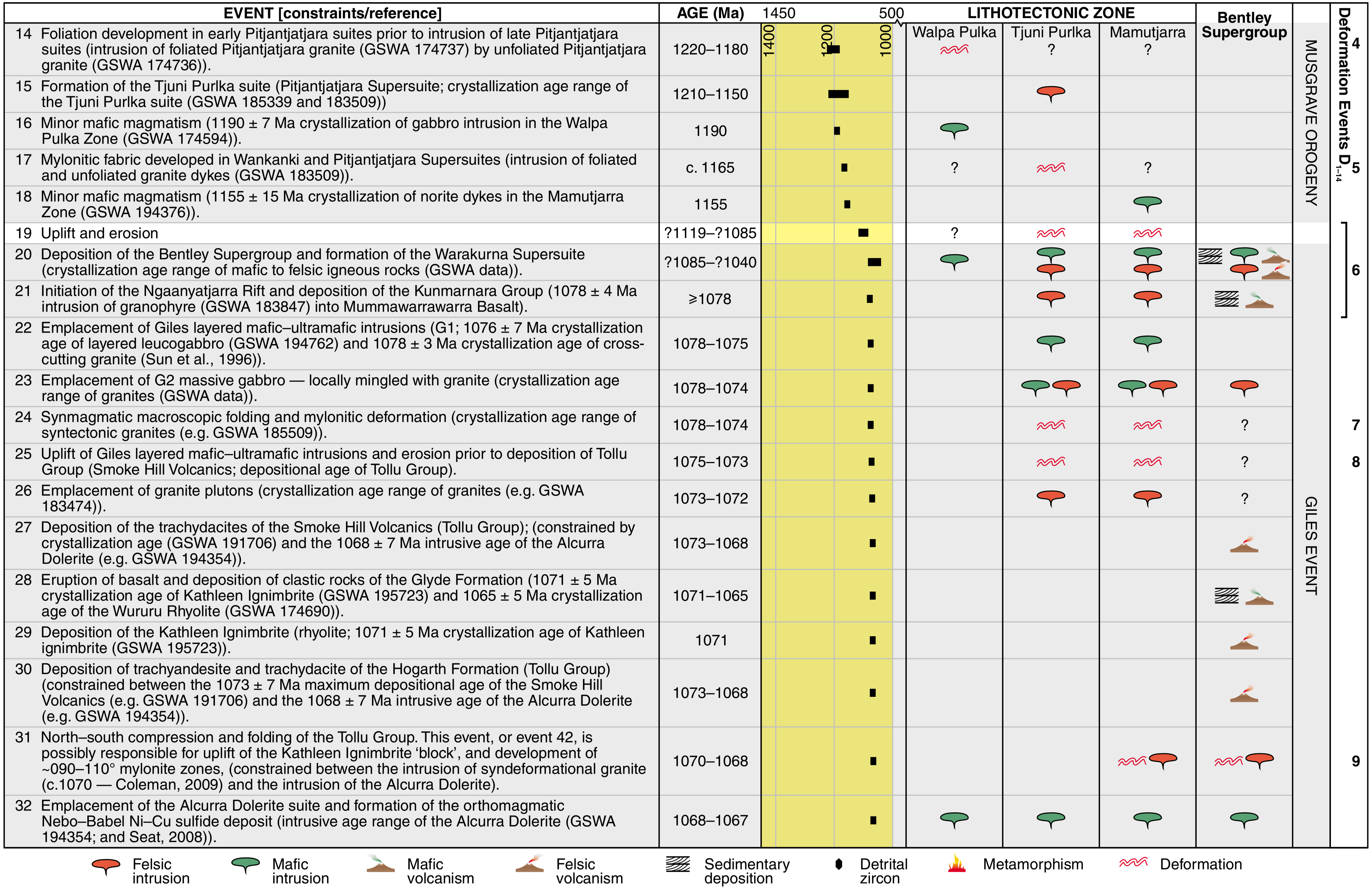

Figure 11. (continued)

	EVENT [constraints/reference]	AGE (Ma)	Walpa Pulka	Tjuni Purlka	Mamutjarra	Bentley Supergroup	Deformation Events D_{1-14}
33	Emplacement of minor granite plutons (crystallization age of granites (e.g. GSWA 187256 and 194554)).	1066–1062		Felsic intrusion	Felsic intrusion	Felsic intrusion	
34	Deposition of spherulitic and perlitic trachyrhyolites and rhyolites and minor basalts and clastic rocks of the lower part of the Palgrave Group (Palgrave area; constrained between the 1077 ± 6 Ma crystallization age of the Mount Eliza granophyre (GSWA 174662) and 1064 ± 7 Ma post depositional porphyry intrusion (GSWA 194637)).	1077–1064				Felsic volcanism	
35	Deposition of rhyolite in the Scamp area (1064 ± 5 Ma, GSWA 195678), deposition of the felsic volcanics, pyroclastic and siliciclastic rocks of the upper part of the Palgrave Group (1063 ± 8 Ma, GSWA 189580), and eruption of the Wururu Rhyolite (1065 ± 5 Ma, GSWA 174690).	c. 1064				Felsic volcanism; Felsic intrusion; Sedimentary deposition	
36	Deformation, uplift, erosion, and deposition of diamictite at the base of the upper part of the Palgrave Group.	1065–1063				Deformation; Sedimentary deposition	
37	High-level block-faulting (caldera-subsidence) and intrusion of porphyritic microgranite (Mount Eveline microgranite and 'Pigs Head porphyry'), equivalent in composition to the Wururu Rhyolite, into faults (age range based on compositional similarities with Wururu Rhyolite).	1065–1063				Deformation; Felsic intrusion	
38	Extrusion of the Gurgadi Basalt (constrained between depositional age of 1065 ± 5 Ma Wururu Rhyolite (GSWA 174690) and the 1057 ± 6 Ma Thomas Rhyolite (GSWA 174691)).	1065–1057				Mafic volcanism	
39	Intrusion of subvolcanic protolith of the 'Scamp granofels' (1059 ± 6 Ma crystallization age (GSWA 195673)).	1059				Felsic volcanism; Felsic intrusion	
40	Eruption of the Thomas Rhyolite (1057 ± 6 Ma depositional age (GSWA 174691)).	1057				Felsic volcanism	
41	Deposition and eruption of the remaining upper part of the Bentley Supergroup (maximum age constrained by age of Thomas Rhyolite).	<1057				Mafic volcanism; Felsic volcanism; Sedimentary deposition; Mafic intrusion	
42	North–south compression, forming large-scale east-trending, open- to close- folds along the eastern Palgrave margin, possibly accompanied by subvolcanic magmatic doming of the Winburn Granite. Intrusion of quartz-diorite dykes into east-trending axial plane (locally intense ~090-110°cleavage) possibly related to this event. This event, or event 31, is possibly responsible for uplift of the Kathleen Ignimbrite 'block' (1055 ± 10 Ma crystallization age of quartz diorite (GSWA 187054)).	1055 ± 10				Felsic intrusion; Deformation	10
43	Northwest-trending faulting, including reactivation of earlier subvolcanic block-faults in the area between Mount Squires and Mount Weir juxtaposing diamictite of the basal upper Palgrave Group against Glyde Formation (maximum age constrained by age of quartz diorite (GSWA 187054)).	<1055 ± 10				Deformation	10
44	Subvolcanic trachydacite sills emplaced near the base of the Smoke Hill Volcanics (Tollu Group; 1026 ± 26 Ma crystallization age of trachydacite (GSWA 187177)).	1026 ± 26				Felsic volcanism	
45	Kullal Dyke Suite (constrained between minimum age of massive Giles gabbro (G2) and the 824 ± 4 Ma emplacement age of the Gairdner Dyke Swarm (Glikson et al., 1996)).	?1074–?825		Mafic intrusion	Mafic intrusion	?	11
46	Emplacement of minor leucogranitic dykes (1004 ± 8 Ma crystallization age (GSWA 183597)).	1004 ± 8	Felsic intrusion				11
47	Gairdner Dyke Swarm (824 ± 4 Ma emplacement age (Glikson et al., 1996)).	824 ± 4		Mafic intrusion			12
48	LREE-depleted dolerite dykes (constrained by a 3 point Sm–Nd errorchron yielding an age of 747 ± 48 Ma (GSWA unpublished data)).	c. 750	Mafic intrusion				
49	Emplacement of minor tourmaline–muscovite-bearing pegmatite dykes (625 ± 11 Ma crystallization age (GSWA 187175))	625 ± 11		Felsic intrusion			13
50	Petermann Orogeny (e.g. Scrimgeour et al., 1999 and Raimondo et al., 2009).	580–530	Deformation	Deformation	Deformation	Deformation	14

LITHOTECTONIC ZONE: Walpa Pulka, Tjuni Purlka, Mamutjarra. Detrital zircon age axis: 1450–500 (1400, 1200, 1000). GILES EVENT (events 33–44); PETERMANN OROGENY.

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Legend: Felsic intrusion; Mafic intrusion; Mafic volcanism; Felsic volcanism; Sedimentary deposition; Detrital zircon; Metamorphism; Deformation

Figure 11. (continued)

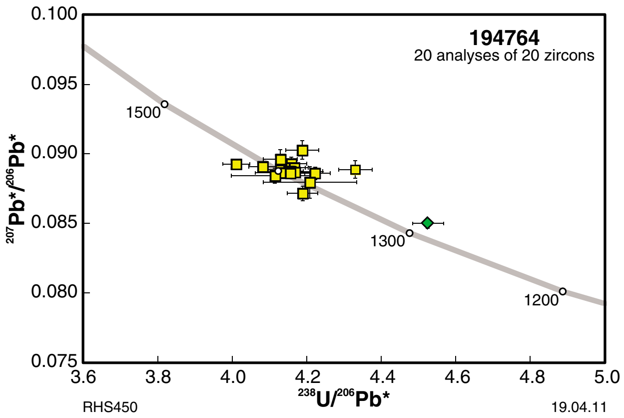

Figure 12. U–Pb analytical data for zircons from sample GSWA 194764.

detrital component of c. 1400 Ma zircons, but including detrital age components as old as c. 1550 Ma (GSWA 187195, Kirkland et al., 2010b). If these metagranites belong to the geochemically similar Wankanki Supersuite, they must have selectively inherited only the c. 1400 Ma detrital component from the country rock. A more likely explanation is that the c. 1400 Ma zircon population reflects the true crystallization age of the granodiorites and monzogranites. If this interpretation is correct, then this metagranite sample represents outcrop of hitherto unrecognized igneous basement rocks significantly older than the Wankanki Supersuite of the 1345–1293 Ma Mount West Orogeny. Therefore, we have tentatively assigned the granodiorites and monzogranites from the area south of Mount Scott to the Papulankutja Supersuite (a new name derived from the Aboriginal name for the nearby Blackstone Community).

Volcanosedimentary rocks possibly associated with the Papulankutja Supersuite

A garnetiferous diatexite, locally with rafts of psammitic gneiss, outcrops approximately 10 km to the north of Mount Scott. During initial mapping of Holt, the diatexite was assigned to the Pitjantjatjara Supersuite, whereas the psammitic rocks were thought to belong to the Wirku Metamorphics. Subsequent dating of the psammitic gneiss (GSWA 194767, Kirkland et al., in prep.) yielded a major detrital zircon age component dated at 1404 ± 15 Ma. Likewise, two samples of the host diatexite (GSWA 187195, Kirkland et al., 2010b; GSWA 194768, Kirkland et al., in prep.) yielded dominant zircon age components of c. 1409 Ma and c. 1402 Ma respectively. In all three cases, a significantly smaller population of younger zircons (mainly rims), dated at 1313 ± 15 Ma (GSWA 194767), 1298 ± 26 Ma (GSWA 187195, one zircon), and 1311 ± 21 Ma (GSWA 194768), can either be interpreted as a detrital component that constrains a maximum depositional age of the protolith, or as a result of local partial melting (incipient migmatization) during the Mount West Orogeny. If the former alternative is correct, the psammite and diatexite belong to the Wirku Metamorphics, the sedimentary protoliths for which were deposited between c. 1340 and 1270 Ma (Evins et al., 2011). However, rocks of the Wirku Metamorphics do not typically contain a significant detrital age component dated at c. 1400 Ma. Because zircons of this age overwhelmingly dominate the samples from near Mount Scott, the alternative suggestion — that the protoliths to these rocks contain a major volcanic component deposited at c. 1400 Ma, likely related to the Papulankutja Supersuite — is favoured here. The c. 1300 Ma age component in these rocks is then attributed to metamorphic regrowth of zircon during the Mount West Orogeny.

Unnamed and undated deformation event

To the south of Mount Scott, in the southwestern part of Holt (Tjuni Purlka Tectonic Zone), a fine-grained, unfoliated, leucogranitic dyke cuts foliated granodiorites and monzogranites of the c. 1400 Ma Papulankutja Supersuite (Fig. 13). The leucogranitic dyke has an igneous crystallization age of 1318 ± 9 Ma (GSWA 194765, Kirkland et al., in prep.) and belongs to the Wankanki Supersuite. The c. 1318 Ma date also represents the minimum age of deformation of the host granodiorites and monzogranite, whereas the c. 1400 Ma zircon age population from the Papulankutja Supersuite represents a maximum age constraint on that deformation, irrespective of how that date is interpreted. This represents the first clear temporal constraint on deformation events either associated with, or older than, the Mount West Orogeny — at some time between c. 1400 and 1318 Ma.

Figure 13. Outcrop photograph showing the contact between a foliated granite of the Papulankutja Supersuite and an unfoliated leucogranite of the Wankanki Supersuite (southwestern Holt).

The 1345–1293 Ma Mount West Orogeny

Migmatitic gneisses with protolith ages between c. 1330 and 1300 Ma were identified by Gray (1971), who also noted that these rocks appeared to be restricted to the south of the Mann and Hinckley Faults. Gray (1978) further suggested that the gneissic rocks were metamorphosed volcanic rocks; however, gradational contacts with foliated porphyritic monzogranites of equivalent age (Sun et al., 1996; White, 1997; White et al., 1999; Howard et al., 2007a) suggest that many of these rocks were intrusive. The results of subsequent regional mapping in the west Musgrave Province (Howard et al., 2007a; Smithies et al., 2009; Evins et al., 2009) and of geochronological data (Figs 7 and 8) show that intrusive igneous rocks of this age form a significant component within the Tjuni Purlka Tectonic Zone, and represent the most voluminous pre- c. 1100 Ma magmatic component to the Mamutjarra Zone (Figs 5 and 6). Howard et al. (2007a) grouped these rocks into the Wankanki Supersuite and termed the crustal event that produced them the Mount West Orogeny. The crystallization age range of the supersuite is from c. 1345 to c. 1293 Ma (White et al., 1999; Kirkland et al., 2008a; GSWA 194393, Kirkland et al., 2010a), with most ages lying within a narrow period between c. 1326 and 1312 Ma (Figs 7 and 8).

Wirku Metamorphics (includes Piti Palya Metamorphics) and the Ramarama Basin

Banded gneiss, mainly preserved as rafts in granite, occurs in all three zones of the west Musgrave Province and is assigned to the Wirku Metamorphics (Figs 4 and 6). Based on locally continuous layering, the presence of pelitic, arkosic, and near-orthoquartzitic interlayers (Fig. 14), and on complex zircon age spectra, this gneiss is interpreted to have protoliths of sedimentary and lesser volcaniclastic and volcanic origin (e.g. Evins et al., 2011). Detailed analysis of detrital zircon age patterns from a large number of samples of the Wirku Metamorphics, collected throughout the west Musgrave Province (Evins et al., 2011), indicates that the protoliths to these supracrustal rocks were deposited between c. 1340 and 1270 Ma. Since sedimentary deposition overlapped in space and time with magmatism related to the c. 1345 to c. 1293 Ma Wankanki Supersuite, the Wirku Metamorphics can also be regarded as a supracrustal (depositional) component of the Mount West Orogeny. Volcanic units of the Wankanki Supersuite (see below) are interlayered with, contributed detritus to, and are thus a component of, the Wirku Metamorphics in both the Mamutjarra Zone and the Tjuni Purlka Tectonic Zone. However, no volcanic or intrusive rocks of this age are known from the Walpa Pulka Zone (Bates). The basin into which the protoliths to the Wirku Metamorphics were deposited is referred to as the Ramarama Basin (Fig. 6; Evins et al., 2011).

Detrital zircon age spectra from the Wirku Metamorphics reveal distinct age trends for the Walpa Pulka, Tjuni Purlka Tectonic, and Mamutjarra Zones. Wirku Metamorphics of the Walpa Pulka Zone contain a main 1650 to 1530 Ma detrital zircon age component dominated by c. 1570 Ma zircon. More varied and slightly more pelitic lithologies in the Tjuni Purlka Tectonic Zone contain a main 1580 to 1450 Ma detrital zircon age component dominated by c. 1520 Ma zircon, and with significant c. 1370 and c. 1320 Ma age components sourced from the Wankanki Supersuite. In the western portion of the Tjuni Purlka Tectonic Zone (Prostenthera Hill – Mount Scott area of Holt), the Wirku Metamorphics are possibly exposed at a higher stratigraphic level, and are dominated by c. 1500 to 1400 Ma detrital zircon. Samples from the Mamutjarra Zone are characterized by zircon derived from younger c. 1345 to 1293 Ma Wankanki Supersuite magmatism, and by zircon with ages older than c. 1410 Ma. Wirku Metamorphics from the Latitude Hills area in the southeast part of the Tjuni Purlka Tectonic Zone (Bell Rock) yield unique detrital spectra with two main Proterozoic detrital zircon populations at c. 1560 to 1400 Ma and c. 1820 to 1700 Ma, as well as an Archean component as old as c. 3200 Ma. Zircon in the Wirku Metamorphics of the Cohn Hill – Mount Blythe area (Cooper) in the far southwest of the Mamutjarra Zone are variably to completely reset by later high-grade metamorphism and deformation, and yield no detrital zircon ages (Evins et al., 2011).

In the Mamutjarra Zone, rare, laminated, orthopyroxene-bearing granulites to the south of the Cavenagh Range are geochemically similar to granites of the Wankanki Supersuite, and are interpreted as representing the volcanic or volcaniclastic equivalents of these granites (Smithies et al., 2009). These units with magmatic protoliths belong to the Wankanki Supersuite. They are also interleaved (?interbedded) with minor garnet and garnet–hercynite pelitic gneiss, and are a component of the Wirku Metamorphics, and hence of the Ramarama Basin. Geochemically similar sequences of laminated, fine to medium grained, orthopyroxene-bearing felsic granulites also occur in the Tjuni Purlka Tectonic Zone (on Holt) to the north of the Blackstone Range, where they are also interlayered with other clastic paragneisses of the Wirku Metamorphics, including pelitic units. Dating of zircons from these orthopyroxene-bearing felsic granulites gives a maximum depositional age of 1319 ± 7 Ma (GSWA 180867, Kirkland et al., 2009a) in the Tjuni Purlka Tectonic Zone north of the Blackstone Range, and 1317 ± 9 Ma (GSWA 184150, Kirkland et al., 2011c) in the Mamutjarra Zone.

The indication that the Wirku Metamorphics and Wankanki Supersuite, in both the Tjuni Purlka Tectonic Zone north of the Blackstone Range and in the southwestern part of the Mamutjarra Zone, contain rocks of volcanic origin, suggests that these areas represent a slightly higher crustal level than in the Tjuni Purlka Tectonic Zone to the north of the Latitude Hills area (Bell Rock), where only the intrusive rocks of the Wankanki Supersuite are exposed. Some samples of the Wirku Metamorphics from the Walpa Pulka Zone (Bates) show detrital zircon age patterns that reflect a very minor

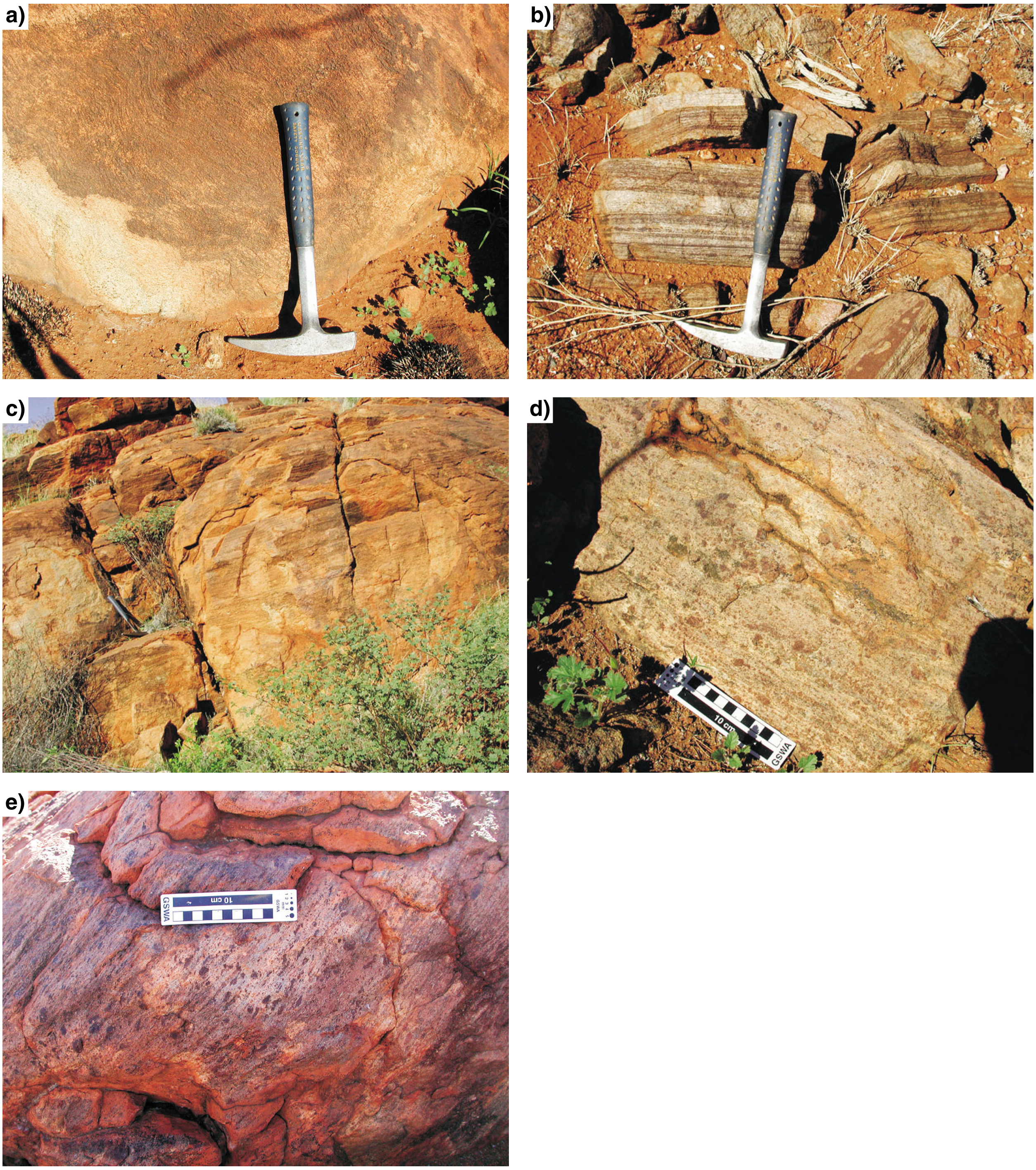

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Figure 14. Outcrop photographs of the Wirku Metamorphics: a) thinly bedded arkosic metasandstone (Latitude Hills area — Bell Rock); b) thinly interlayered arkosic metasandstone (Latitude Hills area — Bell Rock); c) laminated arkosic metasandstone (southern Holt); d, e) pelitic (garnet–sillimanite–hercynite–cordierite) gneiss (Latitude Hills area — Bell Rock).

contribution from sources equivalent in age to rocks of the Wankanki Supersuite (Smithies et al., 2009; Evins et al., 2011), and may reflect a sporadic volcanosedimentary contribution from distal Wankanki Supersuite felsic volcanism.

The dominance of medium-grained and quartz-rich lithologies, the absence of abundant pelitic units, and the distribution of the Wirku Metamorphics, together suggest that the protoliths to these rocks were deposited in the proximal regions of submarine fans (Evins et al., 2011).

The Wankanki Supersuite

Granites of the Wankanki Supersuite are typically strongly deformed and have been metamorphosed up to granulite facies (Fig. 15). Migmatization in the most leucocratic granites of the Wankanki Supersuite is locally conspicuous (Fig. 15). In lower strain zones, the granites are typically porphyritic granodiorites and monzogranites, containing up to 15% (?primary) clinopyroxene and orthopyroxene, and late (?retrograde) hornblende.

Xenoliths and rafts of the Wirku Metamorphics locally occur within granites of the Wankanki Supersuite, but the granites rarely contain zircon xenocrysts derived from those metasedimentary rocks. This is consistent with neodymium-isotopic data (Smithies et al., 2009) that indicate negligible contamination of the magmas by strongly non-radiogenic rocks of the Wirku Metamorphics.

Rocks of the Wankanki Supersuite show a large range in SiO_2 from 58.95 to 76.76 wt%, although there is a gap from 60.33 to 65.79 wt%, which separates rare tonalites and granodiorites from more abundant monzogranites and syenogranites. The granites and associated volcanic units are metaluminous (ASI = 0.85 – 1.02), calc-alkaline, I-type rocks. On tectonic discrimination diagrams (e.g. Pearce et al., 1984), they consistently fall within the field for volcanic-arc granites, and in this respect they differ from all other granites in the west Musgrave Province (Fig. 16). For both neodymium- and hafnium-isotopic data, calculated T_{DM} model ages for the Wankanki Supersuite lie between c. 2000 and c. 1900 Ma, up to 700 m.y. older than the crystallization age (Fig. 17; Smithies et al., 2010). This suggests a source component with considerable (>700 m.y.) crustal residence time. If these rocks are indeed arc related, then these isotopic data suggest a continental-, rather than oceanic- or island-arc.

The Wankanki Supersuite may reflect the final stage in the Proterozoic amalgamation (at least by lateral accretion) of central Australia (Giles et al., 2004; Betts and Giles, 2006; Smithies et al., 2010), ending before the main onset of the Musgrave Orogeny, with a collisional event that produced regional northeast-trending folds. Several studies suggest that the evolution of the Albany–Fraser Orogen to the southwest involved the convergence, collision, and suturing of the West Australian Craton with the southern Mawson Craton, along a south-dipping subduction zone between c. 1345 and 1290 Ma (e.g. Clark

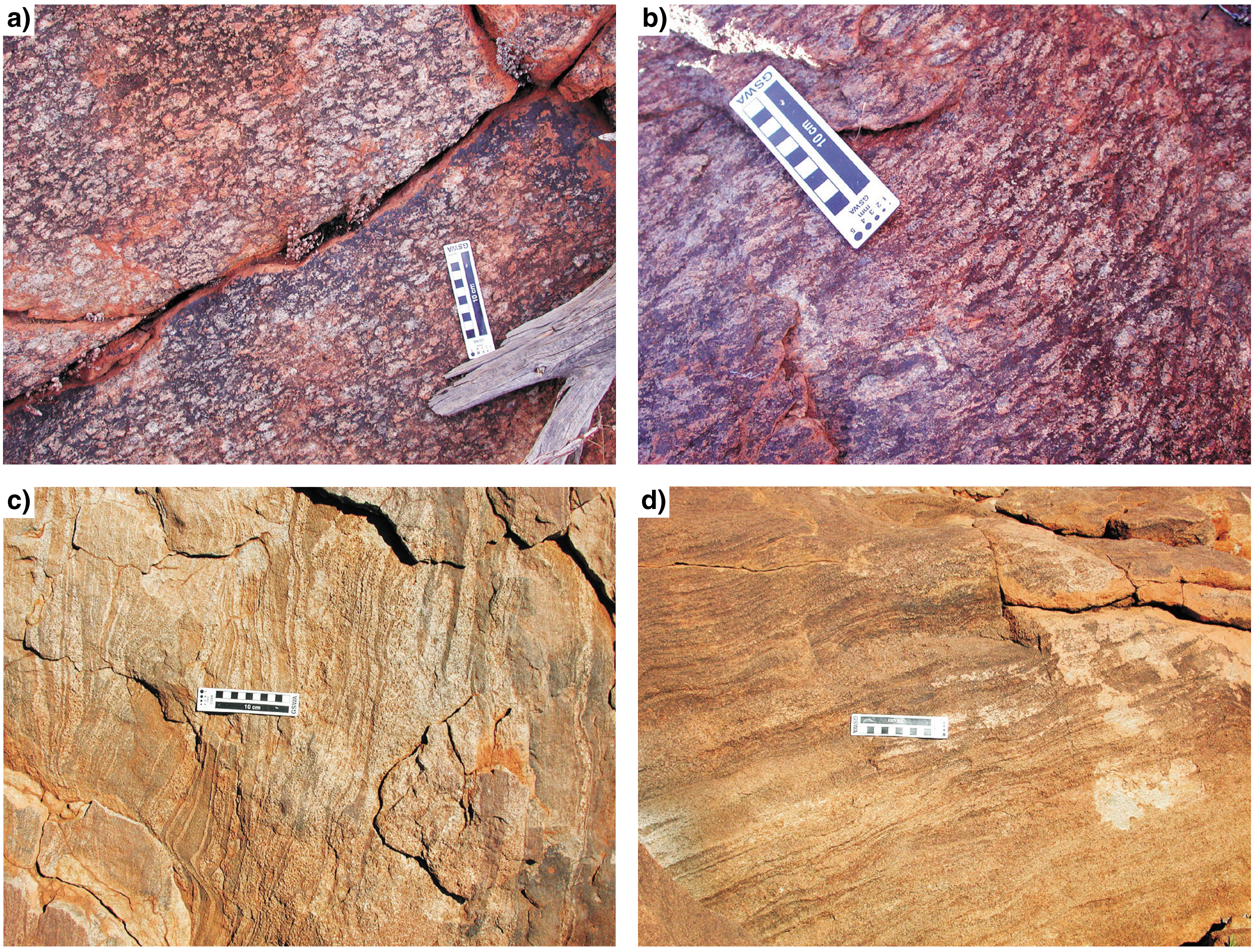

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Figure 15. Outcrop photographs of granites and gneisses of the Wankanki Supersuite (Mount West area — Bell Rock): a) weakly foliated porphyritic monzogranite; b) strongly foliated porphyritic monzogranite; c, d) leucosome-rich gneiss.

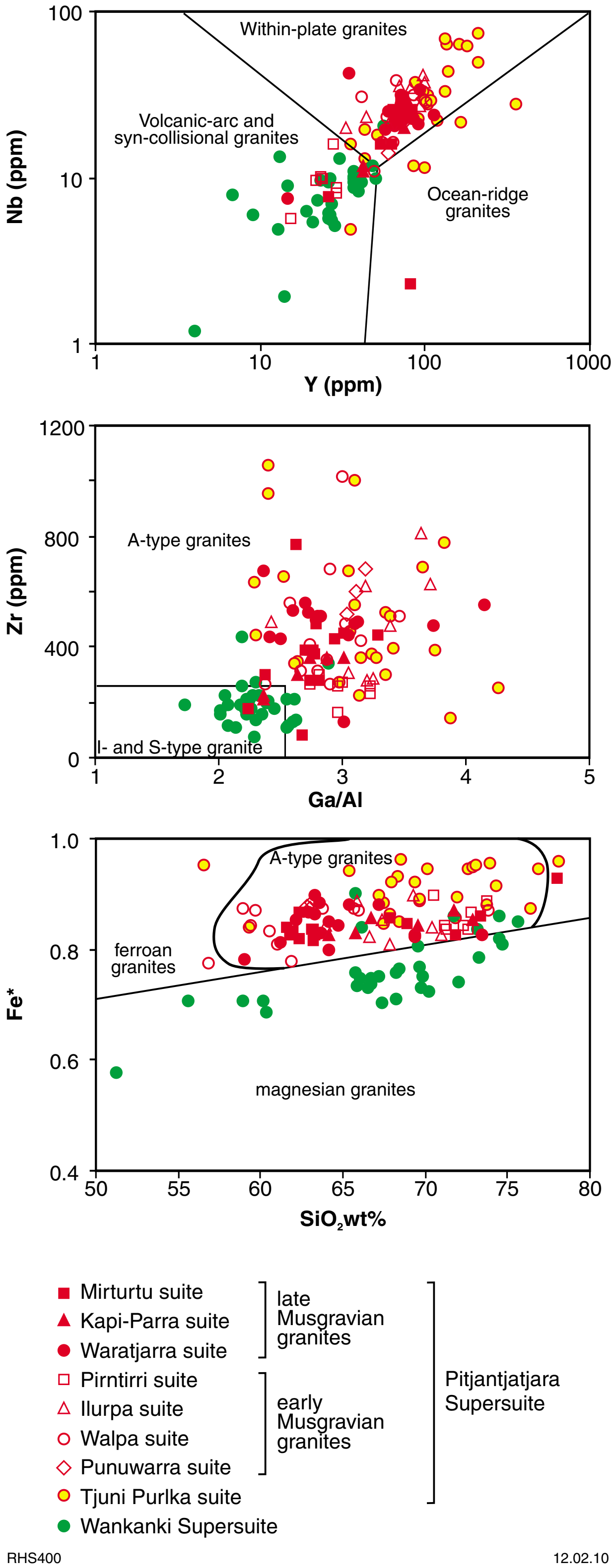

Figure 16. Tectonic and composition discrimination diagrams for granites of the Pitjantjatjara and Wankanki Supersuites (after Pearce et al., 1984; Whalen et al., 1987; Frost et al., 2001).

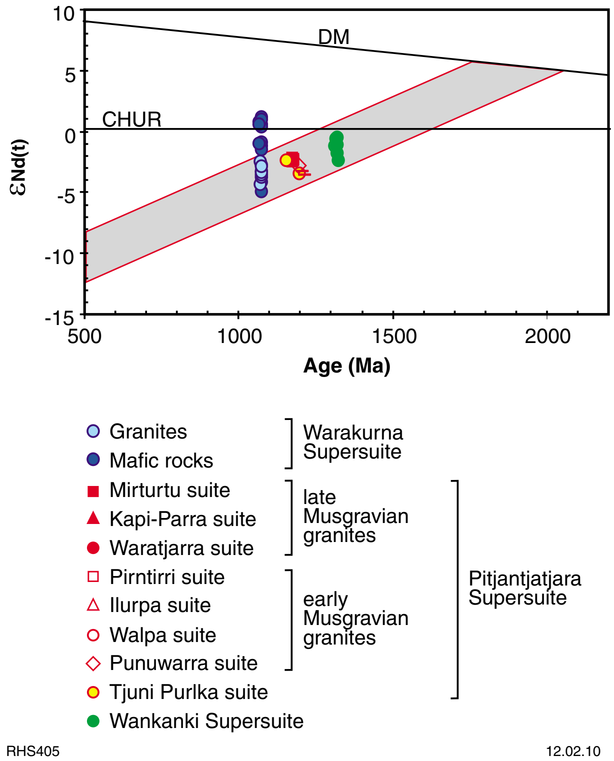

Figure 17. ε_{Nd} evolution diagram for rocks of the Wankanki, Pitjantjatjara, and Warakurna Supersuites.

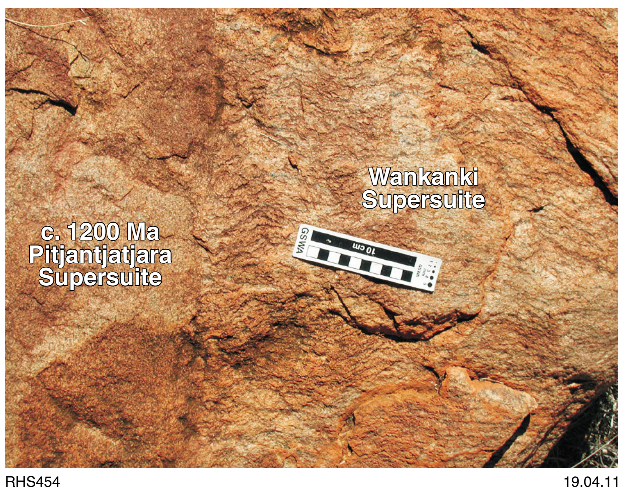

Figure 18. Outcrop photograph of the contact between an unfoliated northeast-trending granite dyke of the Pitjantjatjara Supersuite, and a strongly foliated gneissic granite of the Wankanki Supersuite (southwestern Blackstone).

et al., 2000; Bodorkos and Clark, 2004; Cawood and Korsch, 2008). For the Wankanki Supersuite, subduction-like geochemistry and moderately juvenile isotopic compositions (Figs 16 and 17) favour a subduction setting. However, a southerly dipping slab, as proposed for the Albany–Fraser Orogen, is difficult to accommodate with the Mount West Orogeny if, as suggested by neodymium- and hafnium-isotopic compositions, granites in both the Wankanki Supersuite and the Pitjantjatjara Supersuite share a common crustal source component (Smithies et al., 2010, 2011). If the Wankanki granites are arc related, then a north-dipping slab is required. In this scenario, the Tjuni Purlka Tectonic Zone may have been initiated during the Mount West Orogeny as an incipient back-arc rift. Indeed, a recent reinterpretation of the tectonic evolution of the Albany–Fraser Orogen also favours subduction, with a north-dipping slab, during the event (Stage 1) temporally equivalent to the Mount West Orogeny (Kirkland et al., 2011a).

Unnamed and undated deformation events

In the southwestern part of the Mamutjarra Zone (BLACKSTONE and COOPER), in the area around, and immediately east and southeast of, Borrows Hill, the gneissosity developed in rocks of the Wirku Metamorphics and the Wankanki Supersuite is folded about kilometre-scale folds with a northeast-trending axial plane. Granite of the Pitjantjatjara Supersuite locally forms thin, northeast-trending dykes (mostly too small to show at map scale), axial planar to these large-scale folds, and which cut the gneissosity (Fig. 18). Two of these granites have been dated: GSWA 184146, with a crystallization age of 1201 ± 6 Ma (Kirkland et al., 2009b), and GSWA 185610, with a crystallization age of 1199 ± 5 Ma (Kirkland et al., 2009c). These are the oldest manifestation of the Pitjantjatjara Supersuite in this region. Granite in the dykes does not show an axial-planar fabric, suggesting that the folding pre-dates intrusion of granites into axial planar fractures, and is thus pre- c. 1201 Ma. These granites (Mamut suite of Smithies et al., 2010) have compositions that are very highly depleted in ytterbium (Fig. 19) and other heavy rare-earth elements compared with all other granites of the Pitjantjatjara Supersuite. An exception is the granites of the Pirntirri suite, from the Tjuni Purlka Tectonic Zone (Smithies et al., 2010; Fig. 19), which, like those of the Mamut suite, are the oldest local manifestation of the Pitjantjatjara Supersuite. Two samples from the Pirntirri suite have yielded crystallization ages of 1217 ± 12 Ma (GSWA 187166, Kirkland et al., in prep.) and 1205 ± 6 Ma (GSWA 187274, Kirkland et al., 2009g).

In both regions, all younger granites of the Pitjantjatjara Supersuite are ytterbium-enriched, and Smithies et al. (2010, 2011) relates this to a change from a garnet-present to a garnet-free crustal source region, most likely reflecting removal, or significant thinning, of the lower crust from c. 1220 Ma (beneath the Walpa Pulka Zone) to

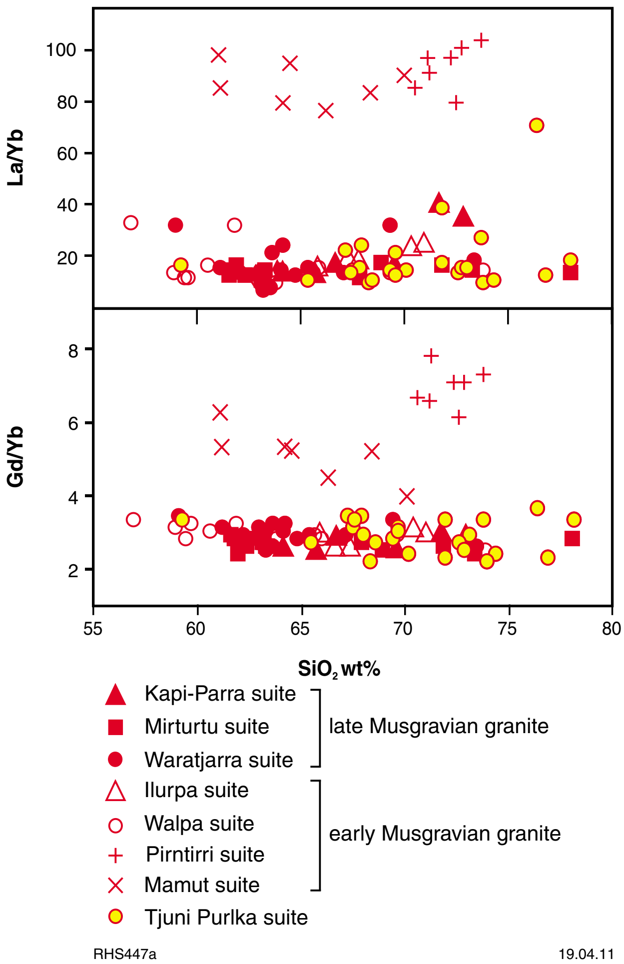

Figure 19. Plot of La/Yb and Gd/Yb vs SiO_2, distinguishing the ytterbium-depleted granites of the Mamut and Pirntirri suites from the other geochemical suites of granites belonging to the Pitjantjatjara Supersuite.

c. 1200 Ma (beneath the Mamutjarra Zone). The presence of unfoliated ytterbium-depleted granites cutting regional folds indicates that the crustal thinning event beneath the Mamutjarra Zone was either synchronous with the latest stages of, or post-dated, the pre- c. 1201 Ma compressional deformation described above. However, the timing of the pre- c. 1201 Ma compressional deformation with respect to the thinning event beneath the Walpa Pulka Zone remains unclear. The interpretation preferred here is that this sequence of events reflects large-scale northwest–southeast compression followed by crustal thinning, between the end of the Mount West Orogeny and the beginning of the Musgrave Orogeny. Even if this is the case, it is highly likely that this is an oversimplification of pre- Musgrave Orogeny events. In the Mount Aloysius region (BELL ROCK) for example, layering within rocks of the Wirku Metamorphics shows evidence for at least two phases of folding before the intrusion of granites related to the early stages of the Musgrave Orogeny.

The 1220–1150 Ma Musgrave Orogeny and the Pitjantjatjara Supersuite

The dominant northwest structural trend of the west Musgrave Province reflects a crustal architecture that was established during or before the Musgrave Orogeny, and was subsequently locally modified and reactivated during the Musgrave Orogeny, Giles Event, and Petermann Orogeny. The Musgrave Orogeny is the oldest orogenic event to have clearly affected all areas of the west Musgrave Province, and this involved intense deformation and widespread granulite-facies crustal reworking. Edgoose et al. (2004) placed the orogeny between c. 1200 and 1160 Ma, and grouped syn- to post-tectonic granite magmas into the Pitjantjatjara Supersuite. Geochronological studies during the west Musgrave Province mapping project have extended this range from c. 1220 to 1120 Ma (Figs 7 and 8; e.g. Kirkland et al., 2010a).

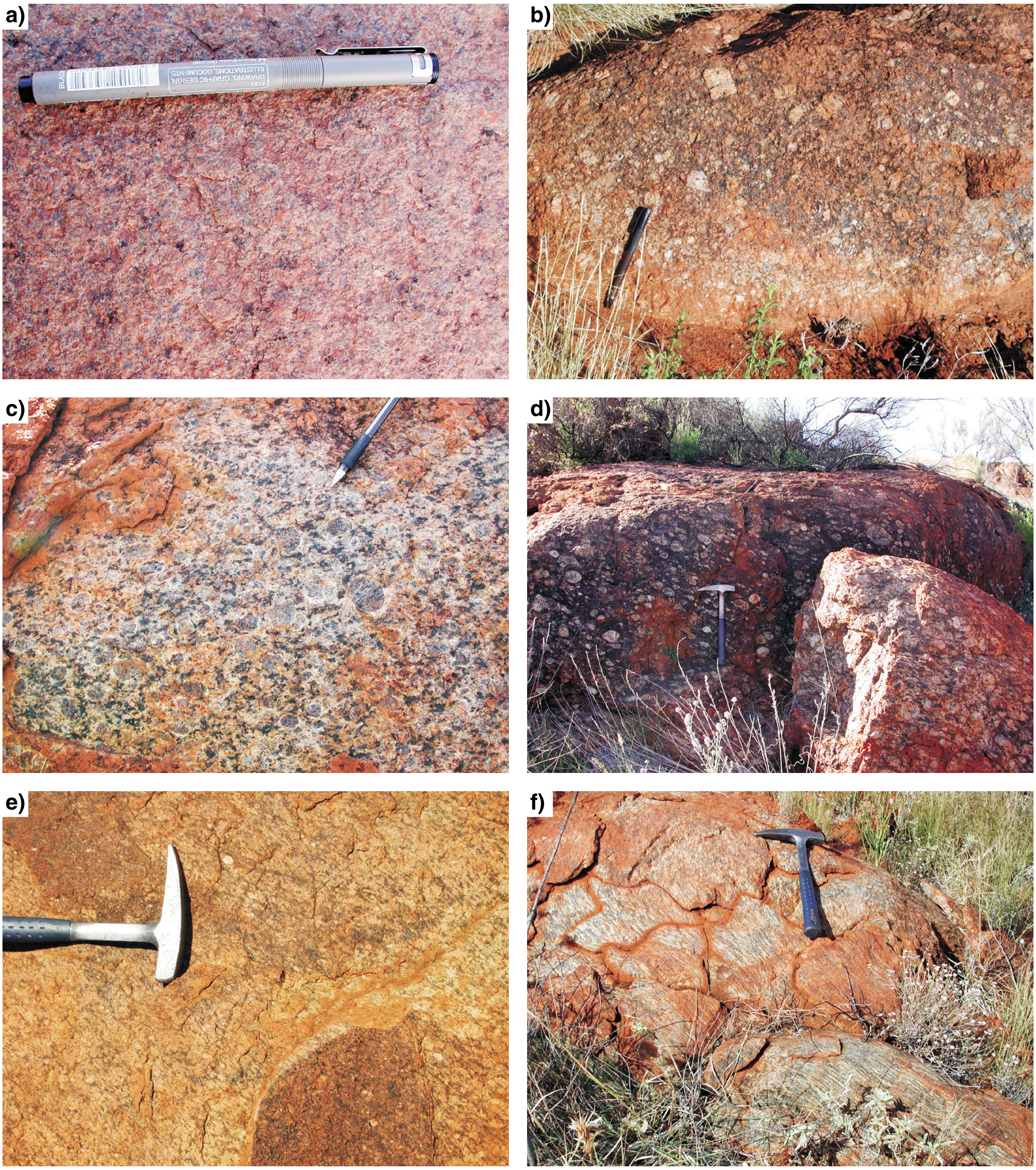

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Figure 20. Various textural manifestations of the Pitjantjatjara Supersuite (Bates): a) massive and equigranular; b) massive and seriate textured; c) massive, with large rapakivi-textured feldspars; d) weakly foliated, with large rapakivi-textured feldspars; e) foliated; f) mylonitic.

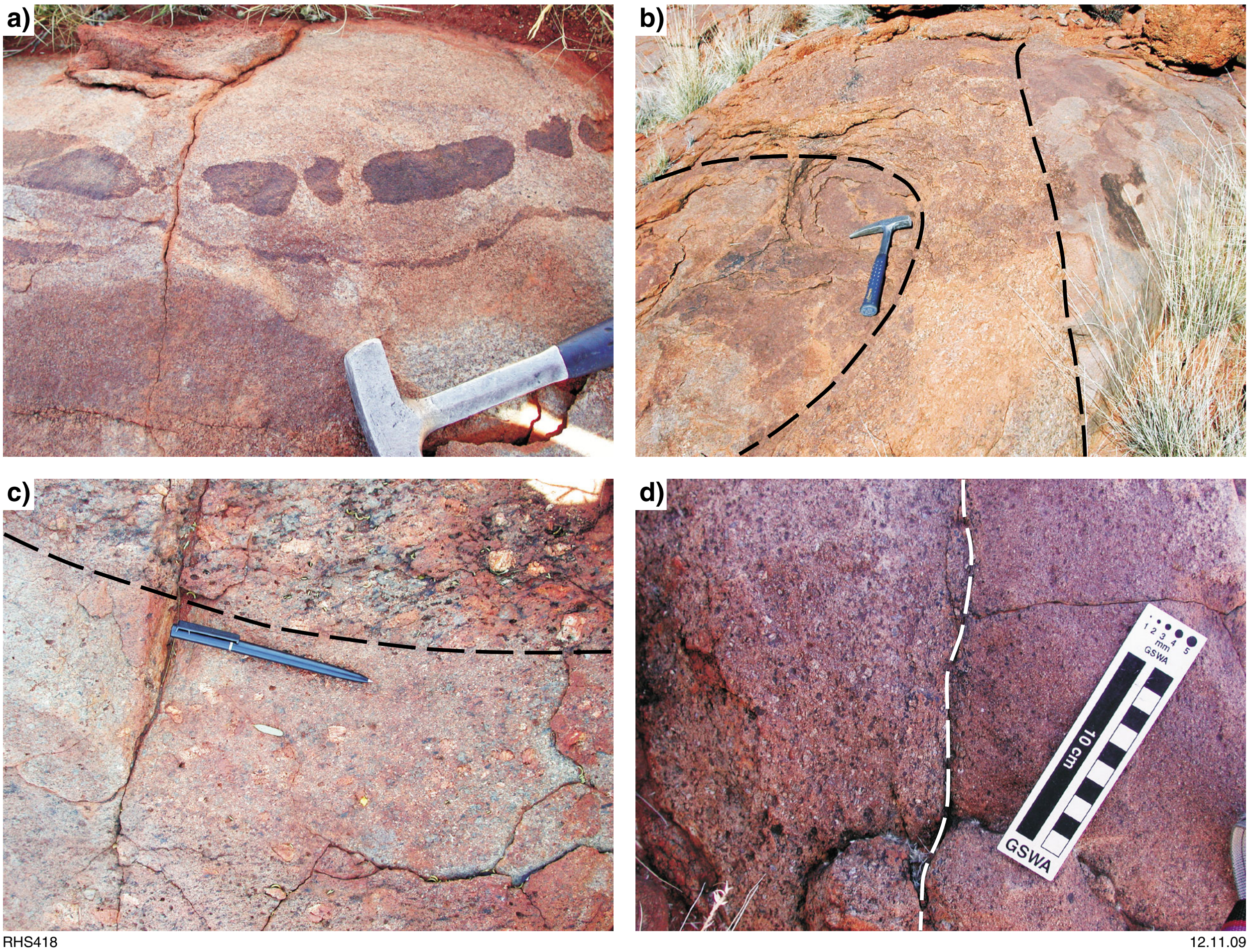

Figure 21. Various large-scale textural features of the Pitjantjatjara Supersuite (Bates): a) disrupted synmagmatic dioritic dyke; b–d) various internal intrusive contacts (marked with dashed line) between texturally different intrusive phases, demonstrating the composite nature of the granite bodies.

In the eastern part of the Musgrave Province (in South Australia), Aitken and Betts (2008) combined structural mapping with a regional aeromagnetic interpretation to identify an early northeasterly structural trend. Although poorly constrained by isotopic age dating, the trend was attributed to compression during the Musgrave Orogeny. However, recently acquired seismic reflection data (reported in Korsch and Kositcin, 2010) show this region to be characterized by horizontal reflectors consistent with extension, or at least with horizontal flow, rather than by major compressional deformation. In addition, firm constraints on the timing of deformation and on the presence and extent of various granite age groups in the west Musgrave Province (see above) suggest that early northeasterly structural trends in that area reflect pre-, or at least very early, Musgrave Orogeny events. Thus, there is no clear evidence for significant compressional deformation associated with the prolonged Musgrave Orogeny.

Most rocks of the Pitjantjatjara Supersuite have been metamorphosed under granulite-facies conditions, in some cases as a result of thermal peaks late in the Musgrave Orogeny, but also during the 1085–1040 Ma Giles Event (Clarke et al., 1995b). In addition, parts of the region were deeply buried beneath Neoproterozoic sedimentary basins, and rapid, differential uplift of the Walpa Pulka Zone during the c. 580 to 530 Ma Petermann Orogeny has exposed metamorphic assemblages reflecting pressures as high as 10 to 14 kbar (Scrimgeour and Close, 1999). The metamorphosed granites of the Pitjantjatjara Supersuite range from statically recrystallized and unfoliated, to strongly foliated and mylonitized (Fig. 20). Whereas the primary mineralogy of these granites was essentially anhydrous (quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, biotite), retrograde recrystallization is locally directly associated with foliation development, resulting in partial to near-complete alteration of pyroxene to hornblende, actinolite, and biotite.

Based on intrusive field relationships, outcrop patterns, and rock textures, granites of the Pitjantjatjara Supersuite can be broadly subdivided into three lithological groups. The first and most voluminous group typically ranges from granodiorite to syenogranite (although the full range is from monzodiorite to alkali-feldspar granite). Where primary igneous textures are preserved, they include

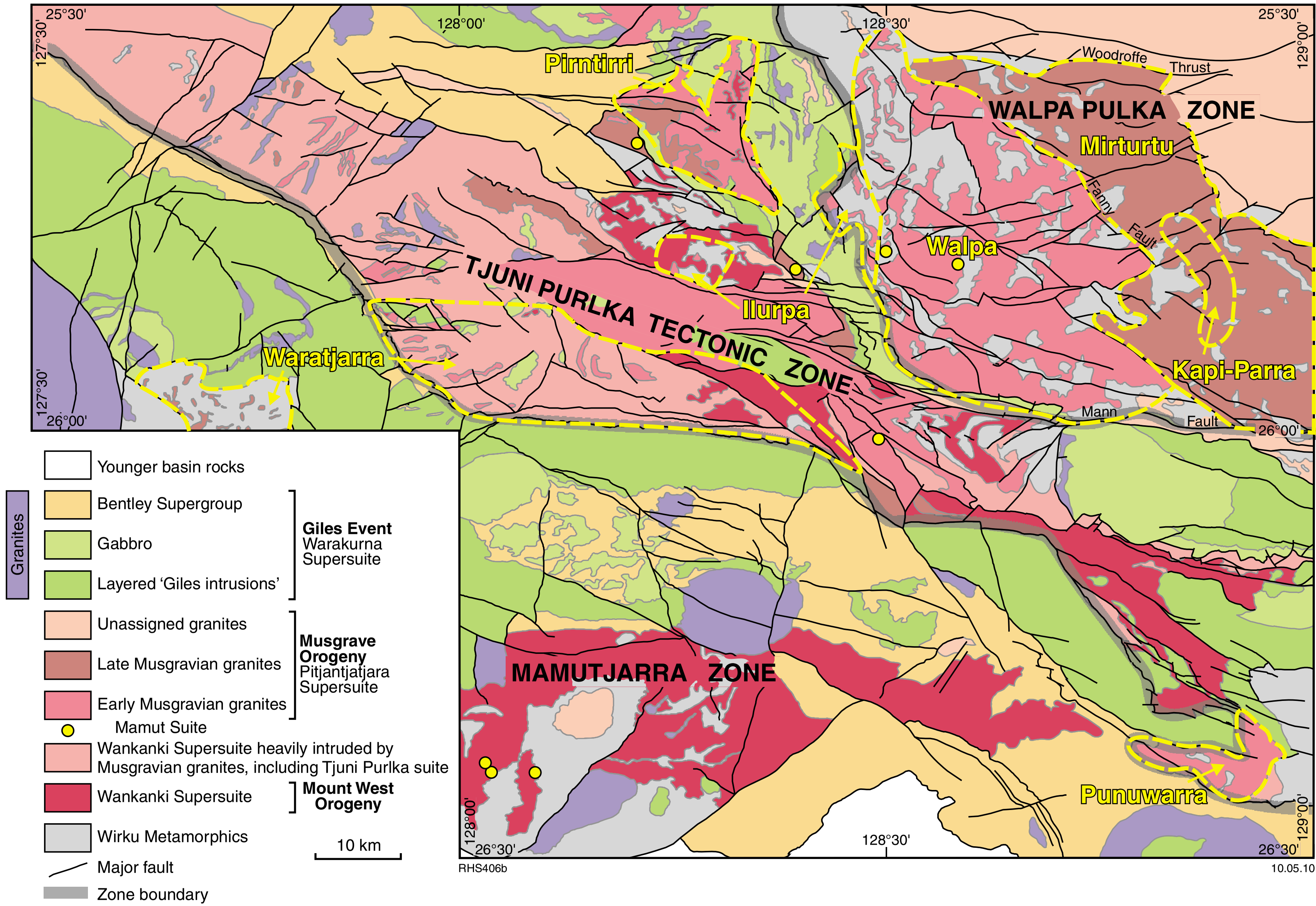

Figure 22. Simplified geological map of the eastern portion of the west Musgrave Province, showing the location of various geochemically and geochronologically constrained granite suites within the Pitjantjatjara Supersuite.

rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of primary orthopyroxene-bearing mineralogy. The porphyritic granodiorite–syenogranite group dominates outcrop in the Walpa Pulka Zone (Figs 5 and 6) as large composite plutonic bodies, and forms smaller plutons and dykes in the Tjuni Purlka Tectonic Zone. These rocks are mostly restricted to dykes and minor intrusions within the Mamutjarra Zone, although they form a widespread but non-continuous collection of small intrusions in the northwest of that zone.

This first group of Pitjantjatjara Supersuite granites typically do not contain abundant enclaves, and although other evidence for mixing or mingling (e.g. dykes terminating in chains of lobate inclusions) is locally present, there is little field evidence for significant physical interaction between individual granite intrusions. Several broad styles of intrusion are identified. Most exposures show significant variation in texture (from seriate to porphyritic to megacrystic), and in grain size on a scale of a metre to many tens of metres (Fig. 21), suggesting that larger bodies are typically composite intrusions of numerous individual dykes and sills. Geochemical data show that individual intrusions, or collections of intrusions, are: i) compositionally heterogeneous throughout; ii) show a systematic compositional variation that parallels the northwest trend of major shear zones; or iii) are compositionally homogeneous (Smithies et al., 2010). Slight variations in geochemistry allow the identification of eight individual suites belonging to this first group of Pitjantjatjara Supersuite granites (Fig. 22; Smithies et al., 2010, 2011).

The second group of Pitjantjatjara Supersuite granites is entirely restricted to the Tjuni Purlka Tectonic Zone, and comprises locally schlieric biotite–orthopyroxene leucogranites typically in the monzogranite to syenogranite compositional range. These form veins and sheets that cut and engulf earlier rocks of the Wirku Metamorphics and Wankanki Supersuite. The restriction of this unit to the Tjuni Purlka Tectonic Zone provides evidence that the zone was an active magma conduit during the Musgrave Orogeny.

The third group of Pitjantjatjara Supersuite granites are locally derived anatectic melts that formed highly leucocratic sheets and veins, typically with granofelsic textures. These engulf all earlier lithologies (Fig. 23), throughout the entire duration of the Musgrave Orogeny.

Igneous events and geographic trends

A compilation of new U–Pb (SHRIMP) dates on zircons from >100 samples (see Smithies et al., 2010) includes ages interpreted to reflect crystallization of the granite magma, as well as ages interpreted to reflect growth during metamorphism. In the Walpa Pulka Zone, the combined age populations can be divided into two broad but distinct groups: an older group reflecting magmatism and metamorphism between c. 1220 and 1200 Ma, and a younger group reflecting magmatism and metamorphism between c. 1190 and 1155 Ma (Fig. 8). These two groups bracket events referred to as 'early Musgravian' and 'late

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Figure 23. Angular inclusions of c. 1220 Ma Pitjantjatjara Supersuite swamped by younger granofelsic-textured leucogranitic anatectic melts (Bates)

Musgravian' respectively (Smithies et al., 2009). However, it is important to note that on a regional scale, intrusion of granites of the Pitjantjatjara Supersuite occurred more or less continuously throughout the Musgrave Orogeny.

The oldest early Musgravian granite identified so far is dated at 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008d), and was foliated before or during the intrusion of, and metamorphism by, late Musgravian anatectic melt veins at 1180 ± 6 Ma (GSWA 174736, Bodorkos et al., 2008c). The youngest late Musgravian granite from the Walpa Pulka Zone has been dated at 1157 ± 9 Ma (GSWA 189254, Kirkland et al., in prep.), and is an unfoliated granite dyke that cuts an early Musgravian foliation. Zircons from early Musgravian granites commonly have rims with ages reflecting growth (or regrowth) during late Musgravian events.

Based on the crystallization ages of granites, the Walpa Pulka Zone can be broadly divided into two areas separated by the northwest-trending Fanny Fault (Figs 5 and 6). Early Musgravian granites are restricted to the western area, and range in composition from quartz monzodiorite and granodiorite to monzogranite. Late Musgravian granites form the eastern area, and range in composition from monzogranite to syenogranite.

Most granites of the Pitjantjatjara Supersuite in the Mamutjarra Zone have late Musgravian intrusive ages between 1189 ± 11 Ma (GSWA 184147, Kirkland et al., 2009d) and 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.).

The northeastern part of the Tjuni Purlka Tectonic Zone contains deformed plutons of granites with early Musgravian ages similar to those in the western part of the adjacent Walpa Pulka Zone. In the southwest, the Tjuni Purlka Tectonic Zone contains late Musgravian granites similar to those in the adjacent part of the Mamutjarra Zone. Apart from these, Pitjantjatjara Supersuite granites in the Tjuni Purlka Tectonic Zone are schlieric biotite–orthopyroxene leucogranites intruded throughout the Musgrave Orogeny, with dates ranging from 1210 ± 10 Ma (GSWA 185339, Kirkland et al., 2009e) to 1165 ± 10 Ma (GSWA 183509, Kirkland et al., 2008c).

Based on the current level of exposure, it appears that mafic magmatism did not form a significant component of the Musgrave Orogeny. Mafic dykes of this age are extremely rare, and the granites themselves do not typically contain abundant mafic enclaves. Nevertheless, rare leucogabbro intruded into the Walpa Pulka Zone at 1190 ± 7 Ma (GSWA 174594, Bodorkos and Wingate, 2008), and rare norite dykes intruded the Mamutjarra Zone at 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010c).

There is a broad northeast to southwest trend in the crystallization ages of Pitjantjatjara Supersuite granites, including the schlieric biotite–orthopyroxene leucogranites of the Tjuni Purlka Tectonic Zone. However, only late Musgravian granites occur to the northeast of the Fanny Fault. To the southwest of the Fanny Fault, crystallization ages decrease from c. 1220 Ma in the northeast to c. 1155 Ma in the southwest (Mamutjarra Zone). This trend in crystallization age reflects a migration of the locus of melting, the locus of intrusion, or both.

There is also a clear antithetic relationship in the relative geographical distribution of granites of the Pitjantjatjara and Wankanki Supersuites (Fig. 6), with granites of the Pitjantjatjara Supersuite dominating in the northeast (to the total exclusion of granites of the Wankanki Supersuite in the Walpa Pulka Zone) and granites of the Wankanki Supersuite dominating in the southwest.

Metamorphic conditions during the Musgrave Orogeny

In the Walpa Pulka Zone, metamorphic assemblages in the pelitic gneisses intruded by granites of the Pitjantjatjara Supersuite have been overprinted by high-pressure granulite assemblages that formed during burial beneath Neoproterozoic basins and were exhumed during the Petermann Orogeny. However, pelitic rocks located far enough south of areas significantly affected by Petermann Orogeny metamorphism (e.g. Mamutjarra Zone and much of the southwestern portion of the Tjuni Purlka Tectonic Zone) preserve mineral assemblages that reflect pressure–temperature (*P–T*) conditions achieved during the Musgrave Orogeny (e.g. King, 2009; Kelsey et al., 2009). In the southeastern parts of the Tjuni Purlka Tectonic Zone and west of the Mamutjarra Zone, King (2009) and Kelsey et al. (2009; also D. Kelsey, written comm., 2010) established that metapelites with the coarse-grained peak mineral assemblage of garnet–sillimanite–spinel–quartz equilibrated at conditions of ≥1000°C and 7–8 kbars at several stages between 1220 and 1150 Ma. Such conditions reflect ultrahigh-temperature (UHT) metamorphism, the most thermally extreme type of crustal metamorphism, characterized by temperatures >900°C (Harley, 1998; Kelsey et al., 2004; Kelsey, 2008) and a geothermal gradient >>20°C/km (Brown, 2007). In the case of the west Musgrave Province, the *P–T* estimates define an apparent geothermal gradient of >40°C/km.

Patterns of lead diffusion in dated zircon crystals also indicate that UHT metamorphic conditions occurred at the present level of exposure during several events throughout the Musgrave Orogeny, at least until c. 1119 ± 7 Ma (Kirkland et al., 2010d; Kelsey et al., 2009; Smithies et al., 2010).

The Pitjantjatjara Supersuite granites (or their protoliths) are compositionally and mineralogically equivalent to a series of anhydrous, titanium- and phosphorus-rich charnockitic intrusive and extrusive rocks described by Kilpatrick and Ellis (1992) from a range of Paleozoic to Proterozoic terranes (Fig. 24). In unmetamorphosed

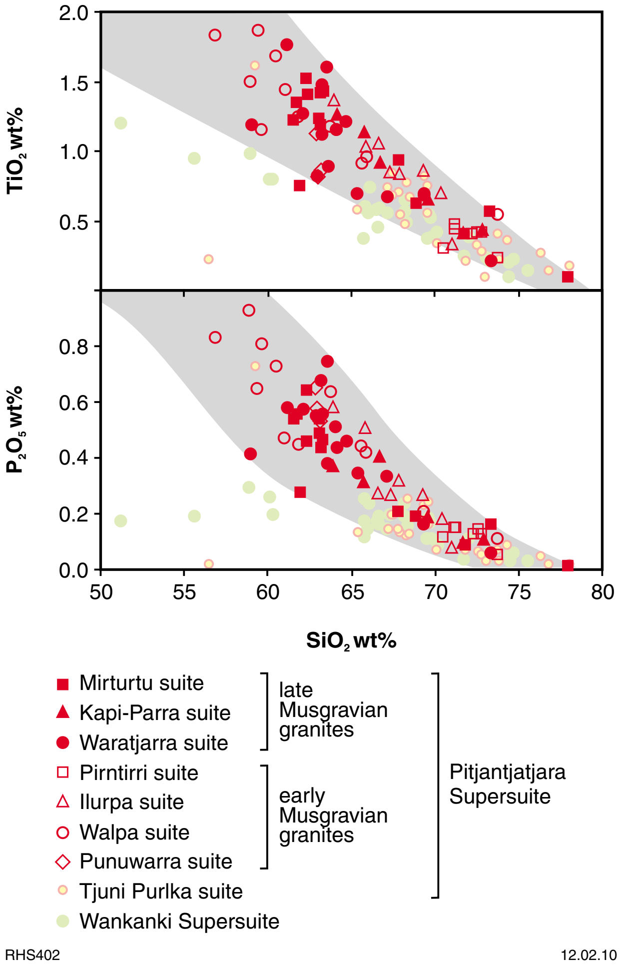

Figure 24. Plot comparing the composition of the Pitjantjatjara Supersuite with high-temperature charnockite-series granites (grey field — from Kilpatrick and Ellis, 1992).

examples of these 'charnockite series' granites and volcanic rocks, the presence of inverted pigeonite and the application of two-pyroxene thermometry confirm extremely high crystallization temperatures, in some cases greater than 1100˚C (e.g. Garland et al., 1995; Ewart et al., 2004a). Thus, the composition of the Pitjantjatjara Supersuite granites themselves certainly reflect UHT conditions at the source, and given the large volumes of magma involved, almost certainly at the presently exposed level of emplacement as well. Since voluminous Pitjantjatjara magmatism was more or less continuous throughout the c. 1220 to 1150 Ma time span of the Musgrave Orogeny, it appears likely that UHT conditions also persisted more or less continuously at that crustal level throughout the ~70 m.y. period of the orogeny and continued to c. 1120 Ma.

Nevertheless, although the spread of ages attributable to UHT events (1220–1120 Ma) is interpreted to reflect sustained ultrahigh temperatures throughout the Musgrave Orogeny, the preservation of planar internal contact relationships within intrusions of the Pitjantjatjara Supersuite indicate that temperatures periodically fluctuated below the liquidus temperatures. Irrespective of this, a ~100 m.y. history, dominated by episodes (pulses) of UHT metamorphism, including more or less continuous high-temperature charnockitic magmatism, chronicles an extremely unusual tectonothermal regime, almost certainly involving extensive crust–mantle interaction.

Other deformation events during the Musgrave Orogeny

The UHT events described above are typically associated with the development of a penetrative fabric, and direct dating (U–Pb SHIMP dating of monazite and zircon) of these fabrics (King, 2009; Kelsey et al., 2009; D. Kelsey, written comm., 2010) indicates at least three main events at c. 1220 Ma, 1180 Ma, and 1150 Ma. In the Walpa Pulka Zone, a foliation developed in a granite intruded during the early stages of the Musgrave Orogeny (GSWA 174737 with a crystallization age of 1219 ± 12 Ma, Bodorkos et al., 2008d), has been cut by a granite with a crystallization age of 1180 ± 7 Ma (GSWA 174736, Bodorkos et al., 2008c). In the eastern part of the Tjuni Purlka Tectonic Zone, intrusion of leucogranite dykes at 1165 ± 10 Ma (e.g. GSWA 183509, Kirkland et al., 2008c) was also synchronous with the development of a strong west-northeasterly trending mylonitic fabric. The prevailing stress regime during these events is unclear, although it clearly involved a strong element of simple shearing.

Tectonic setting of the Musgrave Orogeny

The time by which the amalgamation of the North, South, and West Australian Cratons was complete is debated (e.g. Li, 2000; Giles et al., 2004; Betts and Giles, 2006; Wade et al., 2006, 2008; Cawood and Korsch, 2008), although most models of Australian continental amalgamation have the major cratonic components in place by at least c. 1290 Ma (e.g. see Cawood and Korsch, 2008). This means that during the Musgrave Orogeny, a large portion (possibly as much as 60 000 km^2) of central Australia, overlying the point where the cratonic elements of the continent join, was subjected to unusually high heat flow for up to 100 million years.

Taylor et al. (2010) reviewed various models proposed to explain regional episodes of low- to medium-pressure, high-temperature metamorphism, typically with isobaric cooling paths, similar to the Musgrave Orogeny. Common to these models is a substantial amount of advective mantle heat, and significant crustal thinning and extension. Currie and Hyndmann (2006) and Kelsey (2008) suggest that one possible setting for UHT metamorphism is in the thin, weak crust of back-arc basins, and Brown (2006) notes that many Ediacaran–Cambrian aged UHT belts resemble inverted and thickened back-arc basins.

Whereas a compressional regime may have existed locally, or at some stages, during the Musgrave Orogeny (e.g. Aitken and Betts, 2008), the evidence from the west Musgrave Province is that the major northeasterly folding pre-dates the main stage of the Musgrave Orogeny, that the onset of UHT metamorphism coincided with significant thinning of the lower crust, and that this thin crust was sustained throughout the orogeny. The Musgrave Orogeny appears more compatible with an intracratonic extensional regime (e.g. Wade et al., 2006, 2008), in terms of both sustained UHT conditions and granite geochemistry (Fig. 16). Mahoney et al. (2008) point out that in many zones of intracontinental bimodal magmatism, a dominance of felsic magmatism over mafic magmatism typically reflects slow rates of extension, and a relatively low flux of mantle-derived magmatism. This might appear to apply to the Musgrave Orogeny because of the lack of evidence, at the present surface, for mafic magmas. However, the geochemical and isotopic composition of the Pitjantjatjara Supersuite and the evidence for protracted UHT conditions require that the source of the Pitjantjatjara Supersuite was dominated (>50%) by juvenile mantle material, and in this sense, the supersuite represents significant crustal growth (Smithies et al., 2010, 2011). A ductile middle crust, at UHT conditions, probably prevented accumulating mafic magmas from rising to higher crustal levels.

The onset of the Musgrave Orogeny and UHT metamorphism was also synchronous with emplacement of the craton-scale Marnda Moorn Large Igneous Province, thought to be a response to a regional tectonothermal feature such as a plume (Wingate et al., 2005). Active continental rifting is commonly ascribed to mantle plumes impinging on the base of the lithosphere; for example, the Early Cretaceous break-up of Gondwana, attributed to the effects of several plumes (e.g. Pankhurst et al., 2000; Riley et al., 2001; Ewart et al., 2004b). However, magmatism related to the break-up of Gondwana covered periods of only a few millions of years (for most of the basaltic volcanism; Duncan et al., 1997) to 30 m.y. (Chon Aike; Pankhurst et al., 2000). Whereas the duration of magmatism attributed to a single plume can be arguably stretched to about 50 m.y. (e.g. Ernst and Buchan, 2001), the ~100 m.y. duration of the Musgrave Orogeny certainly does not favour a simple, single, mantle plume.

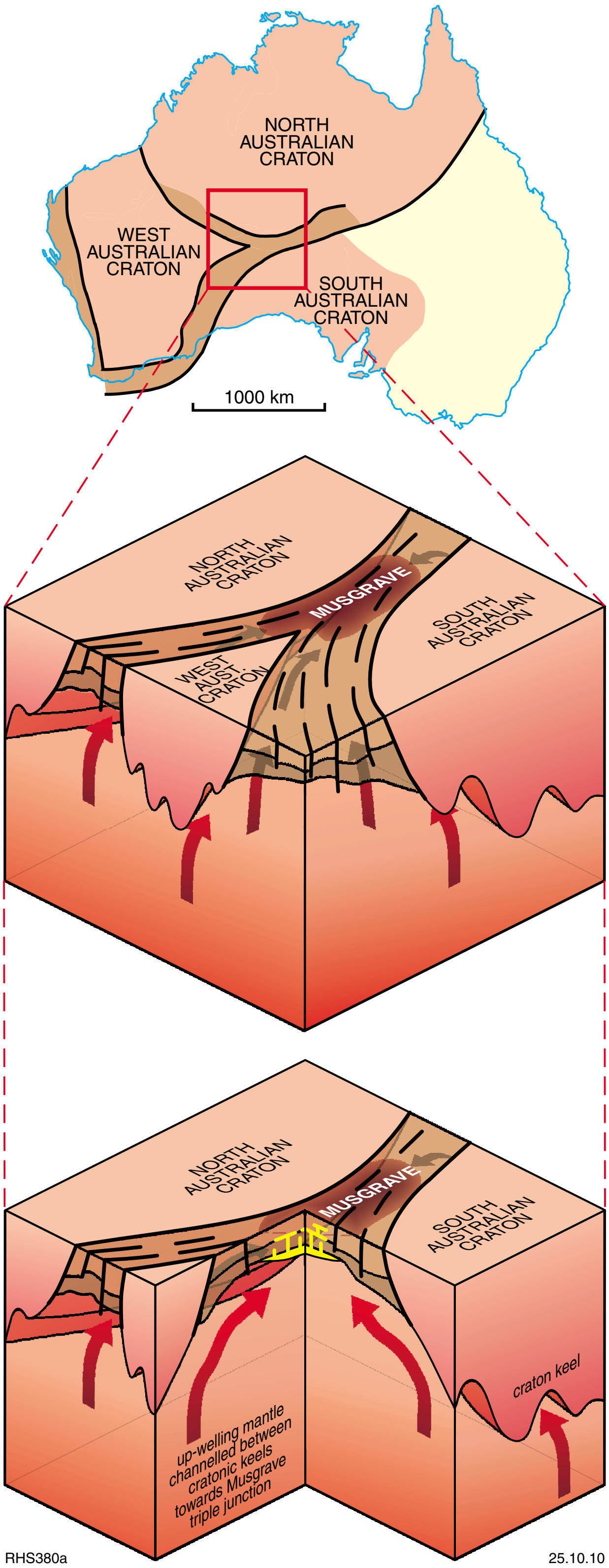

Figure 25. Block diagram showing the influence of crustal blocks on tectonothermal evolution during the Musgrave Orogeny (see text for details)

The position of the Musgrave Province over the join of three main cratonic elements may have provided a significant control on the thermal history of the Musgrave Orogeny. The boundaries of ancient crustal blocks remain fundamental features of lithospheric structural architecture (e.g. Begg et al., 2009), and correspondingly can remain the sites of geological activity for long periods after collisional orogeny. According to Begg et al. (2009), the lithospheric architecture of the African continent comprises a number of cratonic blocks with deep, rigid, and steep-sided sub-continental lithospheric mantle roots. The orogenic boundaries of these blocks eventually form thinner lithospheric regimes that provide pathways for heat, either through the direct focusing of ascending magmas, or by channelling convecting mantle into where decompression melting becomes possible. Thus, the sub-lithospheric architecture (not the location, or even the existence, of mantle plumes) might provide a significant control on the regional distribution of mantle-derived melts. We suggest that it was the location of the Musgrave Province — fixed throughout the Proterozoic above a regional low-pressure melt-trap, at the join between three older cratonic blocks (Fig. 25) — that charted the thermal history of the orogeny, although the far-field effects of accretionary–extensional margin processes or short duration thermal events, such as plumes, might individually have had a lesser role.

The 1085–1040 Ma Giles Event and the Warakurna Supersuite

Overview

All igneous rocks related to the Giles Event are grouped into the Warakurna Supersuite. The supersuite outcrops across approximately 1.5 million km^2 of central and western Australia (Fig. 9), forming the Warakurna Large Igneous Province (Wingate et al., 2004; Morris and Pirajno, 2005). In the Musgrave region, the Giles Event and the Warakurna Supersuite encompass the intrusion and extrusion of voluminous mafic to felsic magmas from 1085 to 1040 Ma. These include the giant, layered mafic–ultramafic 'Giles intrusions', massive gabbros mixed and mingled with granite, Alcurra Dolerite (suite), and granite plutons. Volcanic components of the Warakurna Supersuite, such as mafic and felsic lavas, are grouped into the Bentley Supergroup, which also includes volcaniclastic, siliciclastic, and minor calcareous sediments.

The giant, layered mafic–ultramafic Giles intrusions have attracted particular attention due to their large size and inferred economic potential for nickel–copper and PGE mineralization (see below and 'Mineralization in the west Musgrave Province'). Past studies have focused on the geology, petrography, and mineral chemistry of the Kalka and Ewararra mafic–ultramafic layered intrusions in South Australia (Goode, 1970, 1976, 1977, 1978; Goode and Krieg, 1967; Goode and Moore, 1975; Gray and Goode, 1981, 1989). Glikson (1995) and Glikson et al. (1996) summarized results from an Australian Geological Survey Organisation (AGSO — now Geoscience Australia) mapping program focused on the Giles intrusions. Temporally associated felsic magmatism and extrusive packages have mostly been discussed within the context of regional mapping projects in Western Australia by Daniels (1974) and in the Northern Territory by Close et al. (2003). Gray (1971, 1978) investigated relationships between the intrusions and the volcanic rocks, and Giles (1981) studied the geochemistry of volcanic rocks. Smaller nickel–copper mineralized dykes and intrusions have recently been the focus of detailed studies by Seat (2008) and Howard et al. (2009).

The outcrop extent of the Bentley Supergroup defines the preserved extent of the Bentley Basin. In Western Australia, this basin can be subdivided into at least two sub-basins: the Talbot Sub-basin, in the area west of the Jameson Community, and the smaller Blackstone Sub-basin, in the area south of the Blackstone Community (Fig. 10). An episode of syn- to post-depositional folding deformed the rocks of the Blackstone Sub-basin, with a fold axis more or less parallel with the axis of the basin. Hence, the depositional Blackstone Sub-basin and the structural Blackstone syncline are effectively synonymous.

In the Talbot Sub-basin, rocks of the Bentley Supergroup were deposited in several, spatially closely associated, semi-connected, and fault-bounded depositional areas, each of them characterized by a specific stratigraphy, structural style, and diagenetic–metamorphic history. Recent geochronological studies show that volcanicity and sedimentation in the individual depositional areas clearly overlap in time. This indicates that, during some stages of the Giles Event, the west Musgrave region was structurally compartmentalized by syndepositional tectonics, likely involving caldera subsidence, subvolcanic doming, and possibly compressional deformation.

Previous dating of the Bentley Supergroup has led to the suggestion that these rocks were co-magmatic with the granites and the layered mafic–ultramafic Giles intrusions (e.g. Compston and Nesbitt, 1967; Daniels, 1974; Glikson, 1995; Glikson et al., 1996), although such a relationship was disputed by Gray (1971), who considered the mafic rocks of the Giles intrusions to be significantly older than those of the Tollu Group. The results of our geochronological work appear to support the view of Gray (1971) — the Giles intrusions were emplaced into the Kunmarnara Group before deposition of the Tollu Group.

The Giles Event has been interpreted as the result of a mantle plume (Wingate et al., 2004; Morris and Pirajno, 2005), but sporadic continuation of igneous activity to c. 1040 Ma suggests the event reflects a more complex geodynamic setting. The time scale for the Bentley Supergroup, or the Giles Event, brackets the emplacement of more than six phases of mafic to felsic magmas that include emplacement of the Giles intrusions, and a 1075 Ma crustal-scale mafic magmatic shear zone. The event reflects a highly unstable geological environment. One interpretation is that this may reflect the formation of a long-lived, failed intracontinental rift called the Ngaanyatjarra Rift (Evins et al., 2010). The main aspects of the formation of the Ngaanyatjarra Rift are summarized below and in Figure 11.

Description of major lithological units

Layered mafic–ultramafic Giles intrusions (G1)

In the west Musgrave Province, a clear distinction needs to be made between the layered mafic–ultramafic 'Giles intrusions' (denoted P_WKg1-… on Plate 1; Fig. 26), and the massive gabbro and gabbro/granite hybrid intrusions (denoted P_WKg2-… on Plate 1; Fig. 27). Where contacts are preserved, the former always pre-dates the latter.

The petrography of some layered Giles intrusions has been studied in detail by Daniels (1974) and Glikson et al. (1996). These intrusions can be subdivided into those that are either broadly troctolitic (e.g. Bell Rock, Blackstone), peridotitic (e.g. Wingellina), or gabbroic (e.g. Michael Hills). The layered bodies reach a maximum cumulative thickness of ~10 km in the Jameson area, and the present outcrop extent clearly understates the original size of some of the intrusions. The Blackstone intrusion, for example, is interpreted to be the exposed northern limb of an upright west-trending structural syncline (Blackstone syncline), with relics of the southern limb sporadically exposed approximately 20 km to the south, immediately north of the Cavenagh intrusion. It is also very likely that the troctolitic Bell Rock, Blackstone, and Jameson–Finlay intrusions are tectonically dislocated parts of a single intrusion. If this is the case, then this intrusion could have originally been greater than 170 km long, 25 km wide, and up to 10 km thick.

The age of the layered Giles intrusions emplaced within the west Musgrave Province is now constrained, by several dates, to between c. 1078 and c. 1075 Ma. Sun et al. (1996) obtained a U–Pb zircon age of 1078 ± 3 Ma from a granophyric leucogranite thought to form part of the layering in the Bell Rock intrusion. However, this date is within error of the c. 1075 Ma crystallization age of locally common felsic dykes that elsewhere clearly truncate the layering and were co-magmatic with massive gabbros that also engulf the layered intrusions. We identified no granitic or pegmatitic granophyric rocks within the Bell Rock Range, and no sample taken from there had zirconium concentrations greater than 50 ppm; therefore, the likelihood of finding zircon in the rock is minimal. It is suggested that the leucogranite from the Bell Rock intrusion is a localized sill. A felsic granophyre is interlayered with the Mummawarrawarra Basalt near Skirmish Hill, and has a crystallization age of 1078 ± 4 Ma (GSWA 183847, Kirkland et al., in prep.). This date provides the only direct age constraint on deposition of the Kunmarnara Group, and is a maximum constraint on emplacement of the Giles intrusions, which locally contain xenoliths of the Kunmarnara Group. More recently, a sample of a layered gabbro (GSWA 194762) interpreted to form a component of the Giles intrusions gave a crystallization age of 1076 ± 4 Ma (Kirkland et al., 2011d).

Massive gabbro and leucogranite (G2)

Large bodies of massive, unlayered, gabbro emplaced at c. 1075 Ma form a near-continuous feature focused along syn-magmatic shear zones that mark the northeastern boundary of the Tjuni Purlka Tectonic Zone. These gabbro bodies locally intrude and engulf the layered intrusions

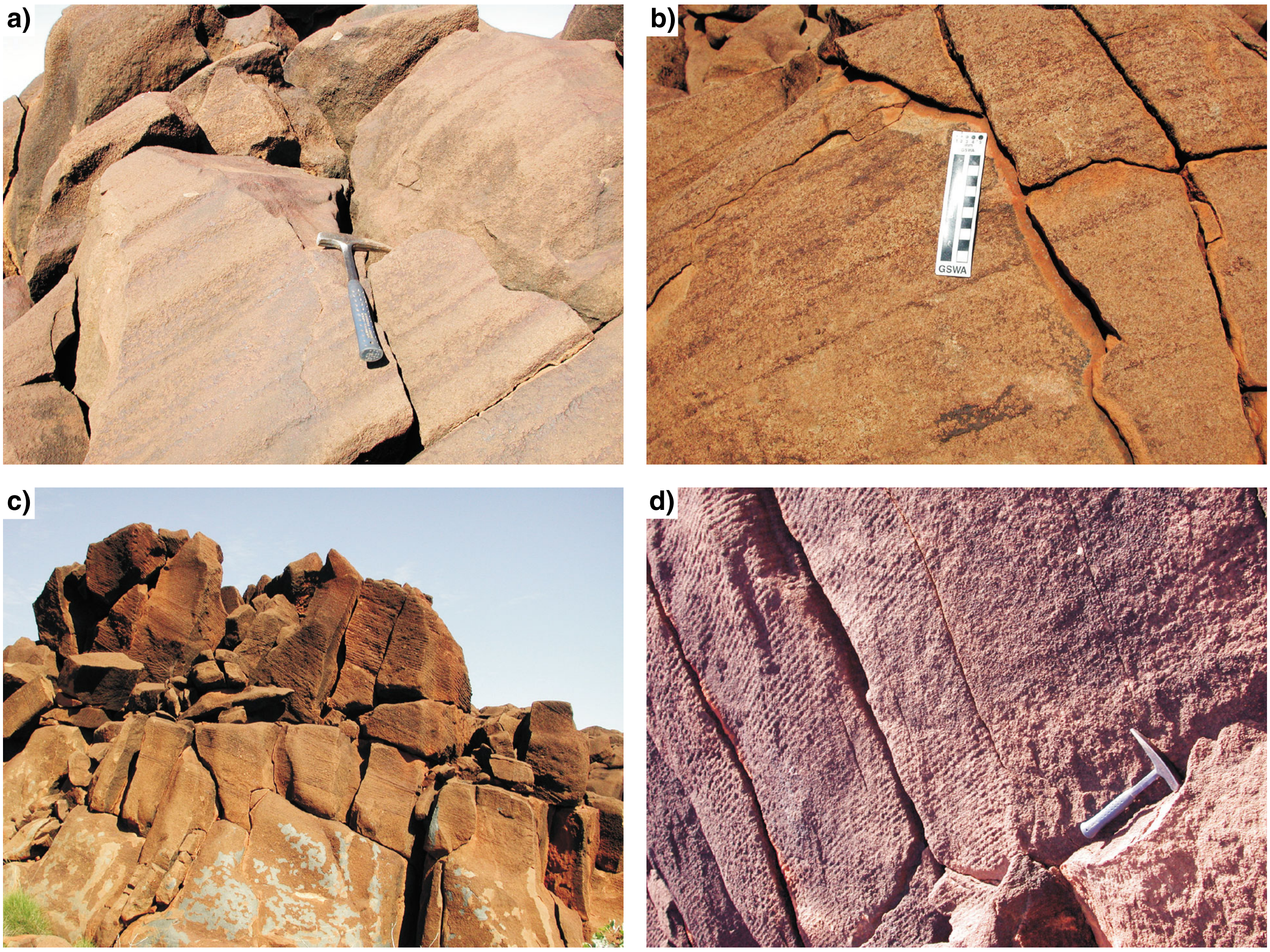

Figure 26. Outcrop photographs showing various types of compositional and mineralogical layering within the Giles intrusions (G1): a) weakly layered leucogabbronorite (northeast HOLT); b) distinct mineralogical banding in gabbronorite (BELL ROCK intrusion — BELL ROCK); c) fine-scale banding overlying more massive layers in olivine gabbronorite (northeast HOLT): d) close-up of fine-scale banding in olivine gabbronorite (northeast HOLT); e) irregular mineralogical layering in olivine gabbronorite (Cavenagh intrusion — BLACKSTONE).

and are particularly well exposed in the Murray Range, the West Hinckley Range, and immediately northeast of the Michael Hills intrusion. Leucogranite intrudes as dykes and also forms larger pluton-scale bodies such as the Tollu pluton, a circular intrusion to the south of the Blackstone Range, which is ~12 km in diameter (Fig. 5). The granites are typically hornblende-, clinopyroxene- and biotite-bearing, equigranular to porphyritic quartz syenites, syenogranites, and lesser monzogranites, and locally show well-developed rapakivi textures (Fig. 27a). Abundant leucogranite veins and dykes are spatially and temporally associated with the massive gabbros, and typically show well-developed mingling and mixing textures (Fig. 27b).

Sun et al. (1996) obtained a U–Pb zircon age of 1078 ± 3 Ma from a granophyric leucogranite intruding the BELL ROCK intrusion (Giles intrusion). A leucogranite at Amy Giles Hill showing well-developed mixing and co-mingling textures with gabbro (Howard et al., 2007b) has been dated at 1074 ± 3 Ma (Bodorkos and Wingate, 2008). In the West Hinckley Range, locally mingled gabbro forms a kilometre-scale

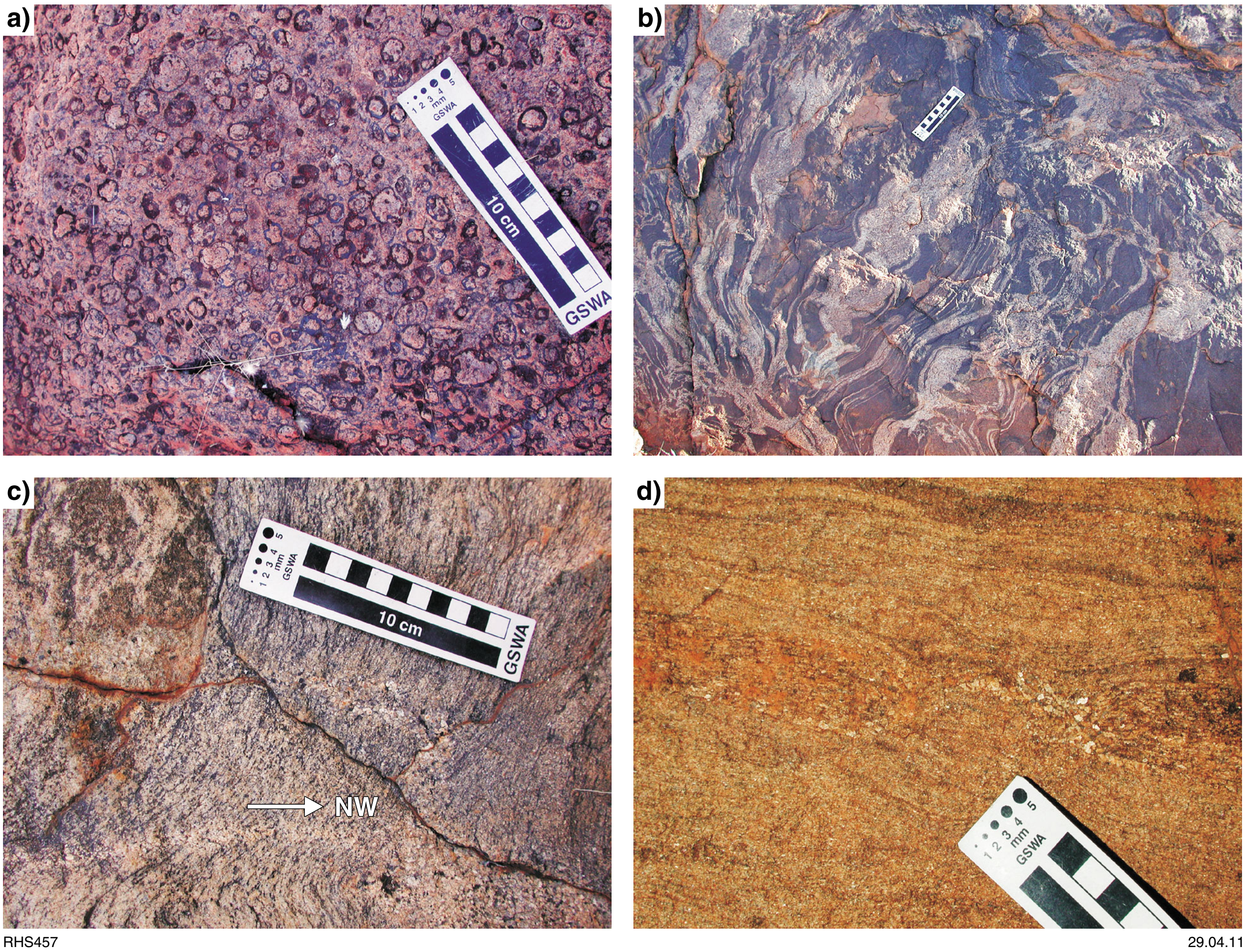

Figure 27. Outcrop photographs showing general features associated with massive gabbro and leucogranite intrusions (G2) of the Warakurna Supersuite: a) rapakivi-textured leucogranite (northeast Holt); b) ductile deformation associated with intrusion of partially to largely solidified gabbro by leucogranite magma (northern Bell Rock); c) strongly foliated leucogranite cut by veins of leucogranite in fractures that are axial planar to northwest-trending folds. U–Pb SHRIMP dates on zircons from both generations of leucogranites (younger generation sampled elsewhere, where it forms larger discrete dykes less likely to be contaminated with zircon from the host) are within analytical error at c. 1075 Ma (northern Bell Rock); d) 1075 ± 2 Ma leucogranite migrated into boudin necks during synmagmatic deformation (northern Bell Rock).

fold with a steep northwest-trending axial plane, intruded by syndeformational leucogranite (including synmagmatic mylonites; Howard et al., 2007b) dated at 1075 ± 7 Ma (Kirkland et al., 2008e; Fig. 27c). Synmylonitic leucogranite, pooled into boudin necks (Fig. 27d) in a northwest-trending mylonite immediately south of Charnockite Flats, has been dated at 1075 ± 2 Ma (Kirkland et al., 2008f). These data effectively define a very narrow period of intrusion of massive gabbro, multiphase intrusion of leucogranites, northwest-trending folding, and northwest-trending shearing, and confirm earlier suggestions by Clarke et al. (1995b) that substantial deformation occurred in the west Musgrave Province during the Giles Event. As mentioned above, where temporal field relationships can be established, these gabbros and gabbro/granite hybrids (i.e. the massive gabbro and leucogranite) are always younger than the layered Giles intrusions, although the actual emplacement age brackets are very similar (c. 1078 to 1075 Ma for the Giles intrusions, vs c. 1078 to 1074 Ma for the massive gabbro and leucogranite).

Late iron-rich gabbro, norite, and diorite — part of the Alcurra Dolerite

A series of c. 1070 Ma dykes in Western Australia are contemporaneous with the Alcurra Dolerite and Stuart Pass Dolerite in the Northern Territory, also showing geochemical similarities with the former. They have been attributed to the c. 1075 Ma Giles Event and the Warakurna Large Igneous Province (Wingate et al., 2004). In the Musgrave Province, they intrude felsic rocks of the Pitjantjatjara Supersuite, but typically have mylonitic contacts. To the north of the Mann Fault in Western Australia, these dykes have a distinctive ophitic texture with pyroxene oikocrysts several centimetres in diameter, and are commonly oriented east-southeast with a 40–60º dip to the south. In the Jameson area, they form northeast-trending plagioclase-phyric dykes. They have MgO contents of 5.2 to 6.8 wt%, and have higher TiO_2 and P_2O_5, and lower SiO_2, than mafic dykes from other dyke suites within the Musgrave region. They are light rare earth element (LREE)-enriched

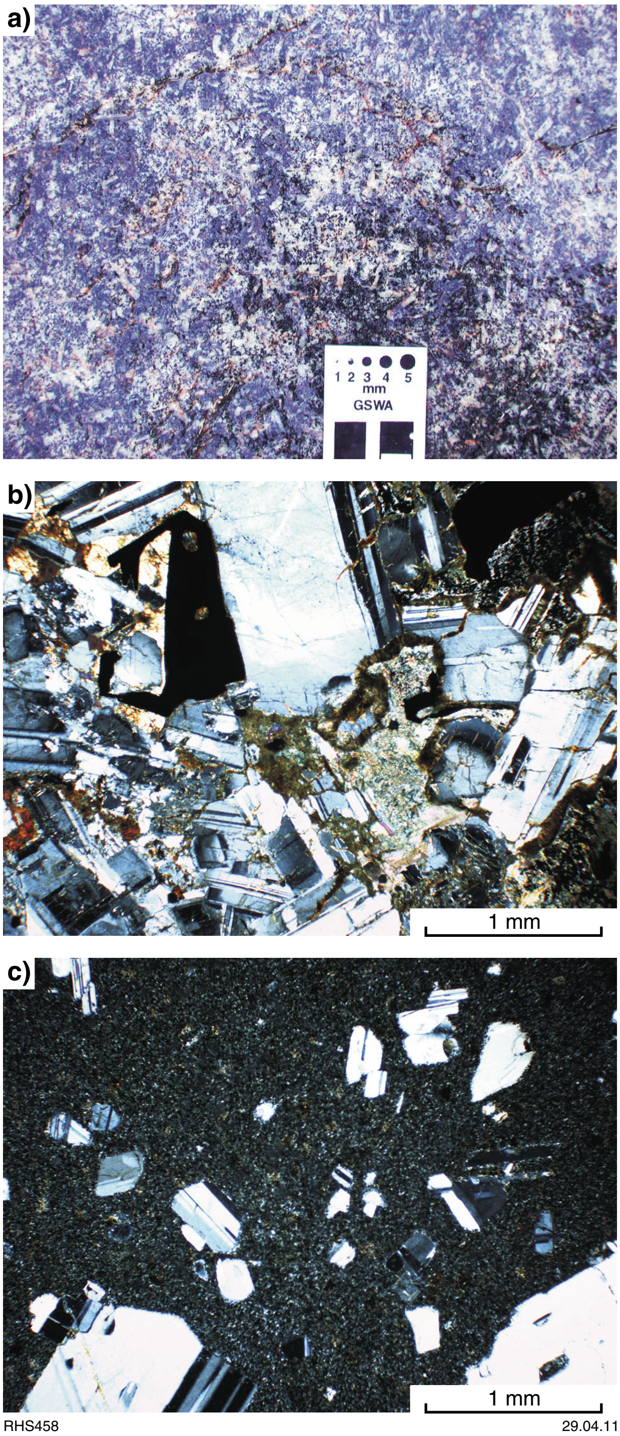

Figure 28. a) Outcrop photograph showing the 'dual-texture' typical of ferronorite and ferrogabbro of the Alcurra Dolerite (suite); b, c) photomicrographs comparing textures in a medium-grained ferronorite (b), and in a spatially associated fine-grained plagioclase-phyric basaltic rock (c) — both of the Alcurra Dolerite. These two rocks essentially represent end-members in a mix of (framework) plagioclase crystals and fine-grained groundmass.

$(La/Sm_{(PM)}$ = 2.6 to 3.3, $Gd/Yb_{(PM)}$ = 1.5 to 2.0) with slight negative niobium anomalies. ε_{Nd} values range from +0.89 to -0.92 (calculated at t = 1075 Ma), and are inside the range of +0.1 to -1.3 obtained for Alcurra dykes in the Northern Territory (Scrimgeour et al., 1999).

Iron-rich olivine gabbros, olivine norites, ferronorites, and ferrodiorites have intruded the Smoke Hill Volcanics (Tollu Group) in the western part of the Blackstone Sub-basin (Blackstone syncline). They also form the host to orthomagmatic nickel–copper mineralization at Nebo–Babel, approximately 30 km to the west (on Cooper), and form copper-mineralized dykes intruding the earlier layered mafic Giles intrusion (Finlay intrusion) that forms the Jameson and Finlay Range, approximately 60 km to the northwest (on Finlayson). Many of these rocks are characterized by a 'dual texture' (Fig. 28a) comprising a framework of coarse-grained crystals (mainly euhedral plagioclase) enclosing a mineralogically identical (except for the presence of accessory quartz in granophyric intergrowths) and locally granophyric-textured fine-grained assemblage in interstitial pockets and veins (Howard et al., 2009). In places, fine-grained rocks containing euhedral plagioclase phenocrysts are also found, and these represent interstitial mineral components freed from the coarse-grained crystal framework (Fig. 28b).

The gabbro at Nebo–Babel has been dated at 1068 ± 4 Ma (Seat, 2008), and the dykes in the Finlay intrusion have an age of 1067 ± 8 Ma (GSWA 194354, Kirkland et al., 2009f), indicating they were synchronous with the c. 1070 Ma intrusion of the Alcurra Dolerite. Howard et al. (2009) also showed that the iron-rich olivine gabbros, olivine norites, ferronorites, and ferrodiorites are also compositionally equivalent to the Alcurra Dolerite. These authors accordingly grouped all of these rocks into a single suite (the Alcurra Dolerite — denoted P_WKA-…. on Plate 1) of highly evolved iron-rich tholeiitic intrusions that intruded at a relatively late stage in the Giles Event (certainly the last stage of major mafic intrusion), at c. 1067 Ma. At least locally, these rocks are directly related to orthomagmatic nickel–copper mineralization (Howard et al., 2009).

Granites

Granites intruded at several stages within the Giles Event (Fig. 11). These granites, including those temporally associated with the massive gabbros, show strongly developed A-type compositional characteristics (Sheraton and Sun, 1995; Smithies et al., 2010), similar in most respects to the leucogranites that formed during the Musgrave Orogeny within the Tjuni Purlka Tectonic Zone. They are ferroan and alkali-calcic, and fall into the 'within-plate granite' field on the tectonic discrimination diagrams of Pearce et al. (1984), and the A-type fields of Whalen et al. (1987) and Frost et al. (2001). Like the leucogranites formed during the Musgrave Orogeny, the Giles Event granites are significantly enriched in rare earth elements (REE) and high field strength elements (HFSE) compared to most of the Pitjantjatjara Supersuite magmas at similar silica values.

Table1. Stratigraphy of the Bentley Supergroup

Age (Ma)	Bentley Supergroup							Warakurna Supersuite		
	Talbot Sub-basin					Blackstone Sub-basin				
	Upper Bentley area		Scamp area	Palgrave area						
		Townsend Quartzite								
		Milesia Formation								
	Mission Group	Lilian Formation								
		Frank Scott Formation								
		Gamminah Conglomerate								
		Miller Basalt								
		Hilda Rhyolite								
		Warubuyu Basalt								
1055					quartz diorite					
1057		Thomas Rhyolite								
	Cassidy Group	Gurgadi Basalt								
		Gombugurra Rhyolite								
		Wururu Rhyolite								
1063					rhyolite					granite
			Scamp dolerite	U Mount Palgrave Group						
1064			Scamp rhyolite		microgranite					
1065		Wururu Rhyolite	Mount Eveline granite	L Mount Palgrave Group						
		Glyde Formation					? Hogarth Formation			
1067	Pussy Cat Group								Alcurra Dolerite	
1071		Kathleen Ignimbrite				Tollu Group				
1076–1075								Giles Suite	Massive gabbro and granite	
1078–1075									Layered mafic–ultramafic intrusions	
1077							Smoke Hill Volcanics			
1078						Kunmamara Group	Mummawarrawarra Basalt			
							MacDougall Formation			

Bentley Supergroup

Felsic and mafic volcanic and volcaniclastic rocks, and interlayered sedimentary rocks, form the regionally extensive Bentley Supergroup (Daniels, 1974). The stratigraphy of this supergroup is summarized in Table 1. In the southeastern to central part of the west Musgrave region, the Bentley Supergroup is represented by the Kunmarnara Group (Fig. 10), a succession of pebbly sandstones (MacDougall Formation), basalts (Mummawarrawarra Basalt), and minor felsic volcanic rocks that form the base of the supergroup. These have been interpreted to represent the basal succession to the Ngaanyatjarra Rift (Evins et al., 2010). The layered mafic–ultramafic Giles intrusions of the Jameson, Cavenagh, and BELL ROCK ranges were emplaced into the Kunmarnara Group, and outcrop of the group parallels the west- to northwest-trend of those intrusions. Pebbly sandstone and basalt correlated with the Kunmarnara Group unconformably overlies much of the northern part of the Tjuni Purlka Tectonic Zone (Fig. 10). In the fault-bounded Skirmish Hill area (southeast corner of BLACKSTONE), rhyolitic to dacitic volcanic rocks (Skirmish Hill volcanic association of Daniels, 1974) are interlayered with the geochemically distinctive rocks of the Mummawarrawarra Basalt (Fig. 29), indicating that this volcanic succession also belongs to the Kunmarnara Group.

The Kunmarnara Group is unconformably overlain by the Blackstone Sub-basin, which incorporates the rocks of the Tollu Group. These comprise felsic and mafic volcanic units, including the Smoke Hill Volcanics and the Hogarth Formation. The present-day distribution of the Tollu Group is restricted to the central part of the Blackstone Sub-Basin, immediately to the south of the Blackstone Range.

The Palgrave area (Fig. 10), a north-trending region approximately 70 km long and up to 35 km wide, lies to the west of the Blackstone Sub-basin, forming the eastern part of the Talbot Sub-basin. The Palgrave area is separated from outcrops of the layered ultramafic–mafic Jameson intrusion and the Kunmarnara Group by a fault or fault zone. Within this area, various phases of the Winburn Granite either intrude, or are overlain by, generally north-trending and west- to southwest-younging dacitic to rhyolitic volcanic and pyroclastic rocks, with minor intercalations of basalt and sedimentary rocks belonging to the Mount Palgrave Group (Palgrave volcanic association of Daniels, 1974; Fig. 30). The northwestern preserved portion of the Talbot Sub-basin includes the Scamp area, an oval-shaped region at least 75 km long in an east–west direction and up to 40 km wide, which is dominated by extrusive rhyolitic volcanic rocks (the Scamp volcanic association of Daniels, 1974) and intrusive granitic rocks (Fig. 30). These are informally referred to here as the Scamp rhyolite. Significant similarities in age and composition with rocks of the Mount Palgrave Group (Howard et al., 2011) suggest that the Scamp rhyolite might form a component of that group. The southern part of the Talbot Sub-basin includes the south-dipping and

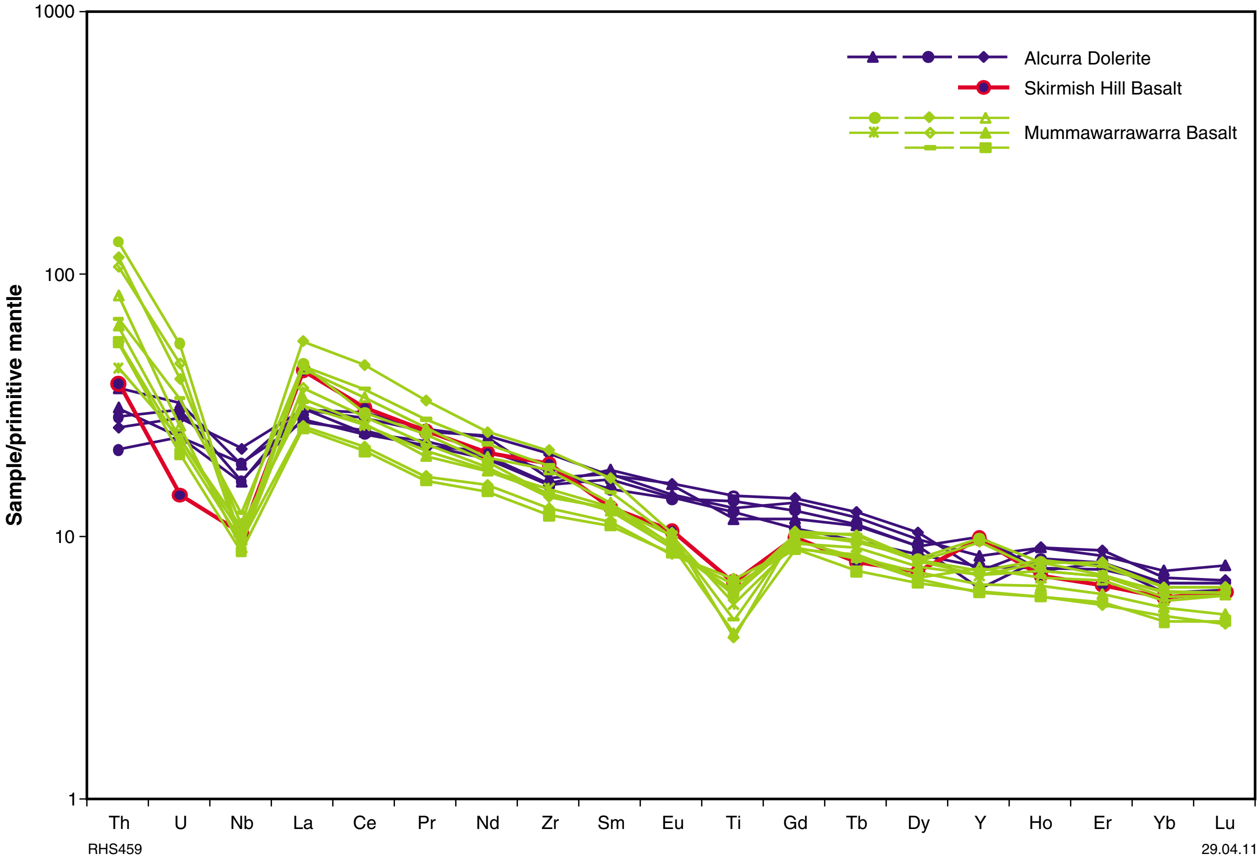

Figure 29. Primitive-mantle normalized incompatible trace-element spidergram, showing the close compositional affinity of basalt from the Skirmish Hill area with the Mummawarrawarra Basalt. Samples of the Alcurra Dolerite are also shown for comparison (normalization after Sun and McDonough, 1989).

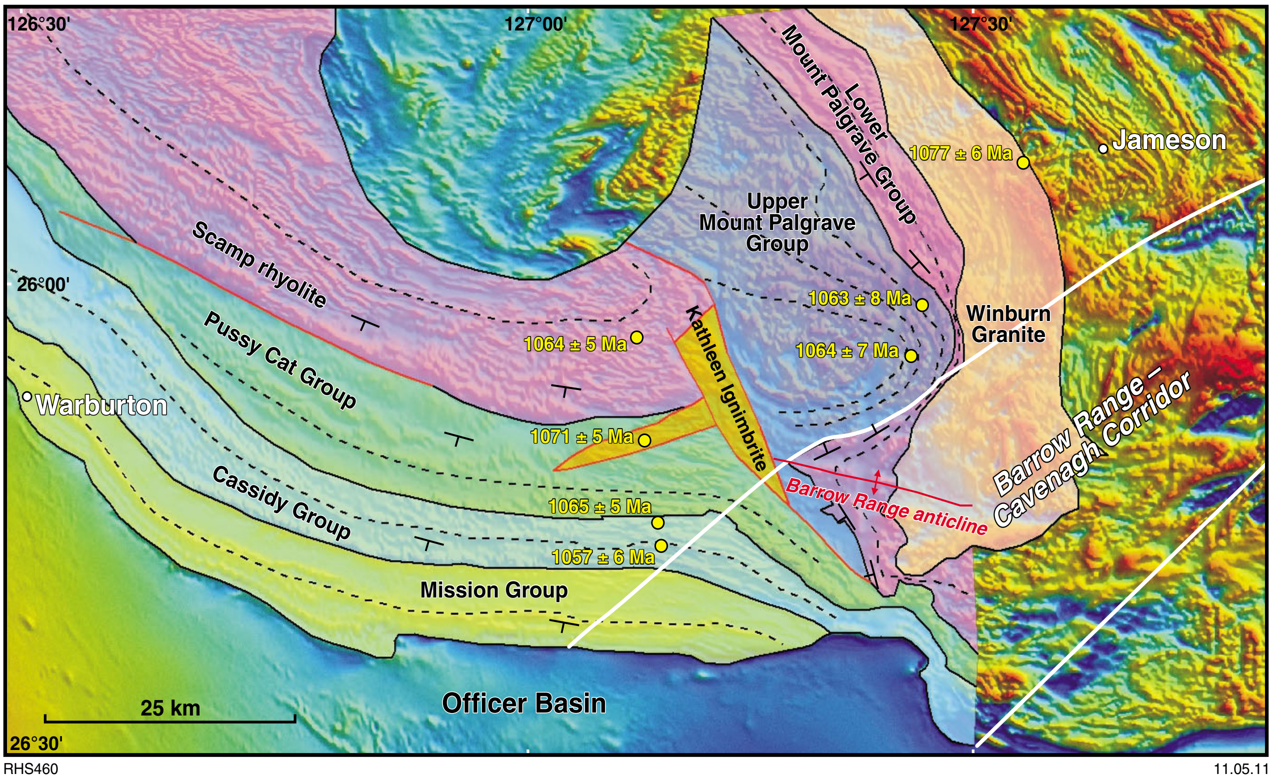

Figure 30. Schematic interpretive bedrock geological map (overlain on a TMI image) of the area between Jameson and Warburton, showing the main lithostratigraphic units of the Bentley Supergroup. Also shown are geochronology sample locations and results (see text for discussion). Solid black lines are lithological boundaries, solid red lines are faults, and dashed black lines mark the trend of bedding/layering. Note bedding symbols; all beds are right way up.

younging volcanosedimentary succession of the Pussy Cat, Cassidy, and Mission Groups (Fig. 30; note that detailed unit by unit descriptions of these groups are not included in Part 2). This succession has a cumulative thickness of several kilometres, and forms a stratigraphically continuous, arcuate, southeast- to east-trending outcrop belt. The Palgrave, Scamp, and Skirmish Hill areas were initially interpreted as fault-bounded successions reflecting volcanic calderas (Daniels, 1974). Although we recognized several features (structures, facies, lithologies) likely to be directly related to syn-magmatic faulting and/or doming or caldera formation or collapse, current interpretations do not support the idea that these three identified areas necessarily reflect three discrete calderas.

Basis for recognition of the Kunmarnara Group

The stratigraphy of the Tollu Group, as originally defined and described by Daniels (1974), included basal sandstones, pebbly sandstones, and conglomerates of the MacDougall Formation, overlain by amygdaloidal basalts of the Mummawarrawarra Basalt. The basalts were in turn overlain by felsic lavas of the Smoke Hill Volcanics, and then by basic to intermediate volcanic rocks of the Hogarth Formation. The Smoke Hill Volcanics and the Hogarth Formation only outcrop south of the Blackstone intrusion, within the core of the west-trending Blackstone syncline, of which the Blackstone intrusion forms the northern limb. The MacDougall Formation and the Mummawarrawarra Basalt are mainly restricted to outcrops south of the poorly exposed southern limb of that syncline (Fig. 10). However, as noted by Daniels (1974), xenoliths of Mummawarrawarra Basalt occur in the northern (basal) portions of the Blackstone and Jameson intrusions and to the north of the Hinckley intrusion, and indicate that the layered mafic–ultramafic intrusions were actually emplaced within, or at the top of, the Mummawarrawarra Basalt.

Volcanic rocks of the Smoke Hill Volcanics directly overlie the Blackstone intrusion, and depositional layering in the volcanic rocks parallels igneous layering in the intrusion. There is no evidence for a faulted contact between the intrusion and the volcanic rocks. Hence, deposition of the Mummawarrawarra Basalt and of the overlying felsic volcanic rocks must be separated by a significant time gap. During that time gap, the layered mafic–ultramafic intrusions were emplaced within the Mummawarrawarra Basalt, and the whole package was uplifted, eroded, and possibly folded, before deposition of the Smoke Hill Volcanics and the Hogarth Formation. We have accordingly split the previously defined 'Tollu Group' into the Kunmarnara Group (MacDougall Formation and Mummawarrawarra Basalt) and the overlying redefined Tollu Group (Smoke Hill Volcanics and Hogarth Formation; Smithies et al., 2010).

Kunmarnara Group

The maximum age of the Kunmarnara Group is poorly constrained. However, the rocks are not cut by granites related to the Musgrave Orogeny, and typically preserve a much lower (greenschist facies) metamorphic grade. They must be younger than the youngest detrital zircon age grouping of c. 1172 Ma from the group's clastic rocks (Evins et al., 2010) and the youngest record of high-grade metamorphism in the rocks of the underlying Musgrave Province (i.e. c. 1120 Ma; GSWA 194422, Kirkland et al., 2010d). Notably, since the layered mafic–ultramafic Giles intrusions were emplaced into the Kunmarnara Group, the low metamorphic grade of this group also constrains the emplacement depth, at the base of the intrusions, to less than ~15 km.

As previously noted, the minimum age of the Kunmarnara Group is constrained by the 1078–1075 Ma age of the Giles intrusions emplaced within the group. This is directly supported by dating of rocks in the Skirmish Hill area, to the southeast of the Blackstone syncline. The Skirmish Hill area represents a now fault-bounded depocentre, filled with mainly rhyolitic–dacitic volcanic and volcaniclastic rocks. However, these felsic rocks are locally interlayered with amygdaloidal andesitic volcanic rocks that have compositions identical to the geochemically distinct Mummawarrawarra Basalt, and on that basis can be confidently assigned to the Kunmarnara Group. Associated with these volcanic rocks are subvolcanic quartz–feldspar granophyres, which have been dated at 1078 ± 4 Ma (GSWA 183847, Kirkland et al., in prep.). It is very likely that this minimum age for deposition of the Mummawarrawarra Basalt lies very close to the actual depositional age.

Tollu Group

Age constraints on the Smoke Hill Volcanics (and the Tollu Group in general) have hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop previously mapped as rhyolite (Daniels, 1974). Re-examination of that outcrop (in 2008) indicated that the rock is in fact a fine- to medium-grained leucogranite, petrographically and texturally identical to c. 1075 Ma leucogranites described above. Two rhyolite samples recently taken from around Mount Jane, in the east of the Blackstone syncline, have given crystallization ages of 1071 ± 8 Ma (GSWA 191728, Coleman, 2009) and 1073 ± 7 Ma (GSWA 191706, Coleman, 2009). A sample taken from the southwestern part of the Blackstone syncline, approximately 10 km west of Naries Hill, gave a crystallization age of 1073 ± 8 Ma (GSWA 189561, Kirkland et al., in prep.). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites of the geochemically distinctive c. 1067 Ma Alcurra Dolerite (Seat, 2008; Howard et al., 2009) have intruded the Smoke Hill Volcanics in the western part of the Blackstone syncline. In addition, a monzogranite pluton clearly intruded into rocks of the Smoke Hill Volcanics, and possibly also into rocks of the overlying Hogarth Formation, at Barnard Rocks in the central part of the Blackstone syncline. This monzogranite pluton has a crystallization age of 1065 ± 9 Ma (GSWA 189563, Kirkland et al., in prep.). Rocks of the Tollu Group are locally folded about an east-trending axis that parallels the axis of the Blackstone syncline, and Coleman (2009) established that mylonite zones that are either syn- or post-folding developed by 1071 ± 8 Ma. This date most likely represents an effective minimum age of deposition of the Smoke Hill Volcanics (and possibly also the Hogarth Formation), which likely evolved within a narrow period between c. 1075 and c. 1070 Ma. It is interesting to note that development of an east-trending fracture cleavage in the Palgrave region to the west (Fig. 10), is constrained between 1064 ± 7 Ma (the youngest depositional age of the volcanic rocks of that region; GSWA 194637, Kirkland et al., 2011e) and 1055 ± 8 Ma (the age of diorite intrusions into ~100° trending fractures; GSWA 187054, Kirkland et al., in prep.).

A vitric dacite sampled to the south of the Blackstone Range and north of Smoke Hill gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010e), which was interpreted as the age of igneous crystallization of lavas or a subvolcanic sill in the upper part of the Smoke Hill Volcanics (Smithies et al., 2009). The older (1075–1070 Ma) rhyolites and younger (1026 ± 26 Ma) dacites are clearly distinct from each other in other respects. In particular, the younger dacites contain a significant population of old (>1550 Ma) inherited zircon crystals and contain garnet xenocrysts — suggesting that these lavas flowed over, or at least interacted with, basement paragneiss (i.e. Wirku Metamorphics) and that the older rhyolite did not. Accordingly, it is likely that:

- the Smoke Hill Volcanics should be subdivided into a lower unit deposited at c. 1073 Ma, and a younger package deposited at 1026 ± 26 Ma
- or that the 1026 ± 26 Ma age relates to a subvolcanic sill of the Hogarth Formation, and that the Smoke Hill Volcanics and the Hogarth Formation should be assigned to separate lithostratigraphic groups
- or, most likely, that the 1026 ± 26 Ma age relates to a subvolcanic sill that intrudes the combined Smoke Hill Volcanics and the Hogarth Formation.

A sequence of supracrustal rocks with a similar lithological range to the Kunmarnara and Tollu Groups forms the Tjauwata Group, which straddles the Western Australian and Northern Territory border to the north, and lies unconformably beneath the basal sedimentary rocks of the Amadeus Basin. Close et al. (2003) pointed out some stratigraphic, geochemical, and geochronological similarities between the Tjauwata Group and the combined Kunmarnara and Tollu Groups (i.e. the previously defined Tollu Group).

Talbot Sub-basin

Winburn Granite — Barrow Range anticline

Along the eastern margin of the Palgrave area, rocks of the Winburn Granite have intruded into, and form the base of, the thick succession of volcanic, volcaniclastic, and minor

Figure 31. **Outcrop photograph showing intense, ~100° trending, slaty cleavage developed in vitric rhyolites of the lower Mount Palgrave Group (eastern MOUNT EVELINE)**

sedimentary rocks that form the Mount Palgrave Group. The Winburn Granite comprises rocks that range from fine to medium grained, from equigranular to porphyritic (and typically rapakivi-textured), and from monzogranitic to alkali-feldspar granite and quartz alkali feldspar syenite, and have a mafic mineralogy including variable proportions of biotite, blue-green amphibole, and clinopyroxene. The crystallization age range for various phases of the Winburn Granite appears to vary considerably. A sample from Eliza Rocks, approximately 11 km west of Jameson Community, gave a crystallization age of 1077 ± 6 Ma (GSWA 174662, Kirkland et al., 2010f), and contained inclusions of an older granite phase. Several porphyritic microgranite dykes intrude the lower stratigraphic levels of the Mount Palgrave Group, adjacent to the contact with the Winburn Granite, and have given younger crystallization ages of 1064 ± 7 Ma (GSWA 194637, Kirkland et al., 2011e) and 1055 ± 10 Ma (GSWA 187054, Kirkland et al., in prep.).

The evolution of some magmatic units of the Winburn Granite is almost certainly genetically linked with the volcanogenic evolution of the Talbot Sub-basin. In the area around Barrow Range, on the eastern central edge of MOUNT EVELINE, a large west-trending (west closing) anticline is developed (Barrow Range anticline), with volcanic units of the Mount Palgrave Group younging away from a core of Winburn Granite (Fig. 30). An intense west-trending (080–110º) fracture cleavage is locally developed throughout this region (Fig. 31), and both the Winburn Granite and the volcanic rocks are cut by large west-trending quartz veins and quartz stockwork vein systems. In the vicinity of Mount Florrie (and the Beadell Resources gold-bearing Handpump Prospect; Tan, 2010), earlier tectonic or autoclastic breccias have been overprinted by hydraulic fracturing and hydrothermal alteration (Fig. 32), possibly related to the development of the anticlinal structure.

Although there is likely a tectonic component to the development of the Barrow Range anticline, it is also possible that synmagmatic doming played a role. Approximately 6 km to the north of Mount Florrie, porphyritic microgranite with a crystallization age of 1055 ± 10 Ma (GSWA 187054, Kirkland et al., in prep.) has intruded along a west-trending fracture, and possibly places a minimum age on the development of fractures related to the anticline. Constraints on the depositional age of the lower part of the Mount Palgrave Group lie between the 1077 ± 6 Ma (GSWA 174662, Kirkland et al., 2010f) age on the older phase of the Winburn Granite and a 1064 ± 7 Ma (GSWA 194637, Kirkland et al., 2011e) age on a microgranite that cuts the volcanic rocks. Thus, if the west-trending fractures north of Mount Florrie are related to the development of the Barrow Range anticline, then doming or folding is potentially synvolcanic, or immediately post-volcanic. This is consistent with the observation that the volcanic rocks in the Mount Florrie region appear to contain a higher proportion of stratigraphically constrained tectonic breccia (rather than autoclastic breccia) than is typical elsewhere in the Mount Palgrave Group, and may have been deposited on the flanks of an active volcanic dome.

However, the steeply dipping northeast-trending limb of the Barrow Range anticline lies along the northeastern margin of a ~30 km wide northwest-trending fault zone, referred to here as the Barrow Range – Cavenagh corridor (Figs 10 and 30). Thus, development of the anticline can also be attributed to dextral and south-side-up movement

Figure 32. **Outcrop photographs showing an autoclastic breccia within vitric rhyolites of the lower Mount Palgrave Group, which has undergone secondary hydrothermal brecciation and hydraulic fracturing (near Beadell Resources' Handpump Prospect; eastern MOUNT EVELINE).**

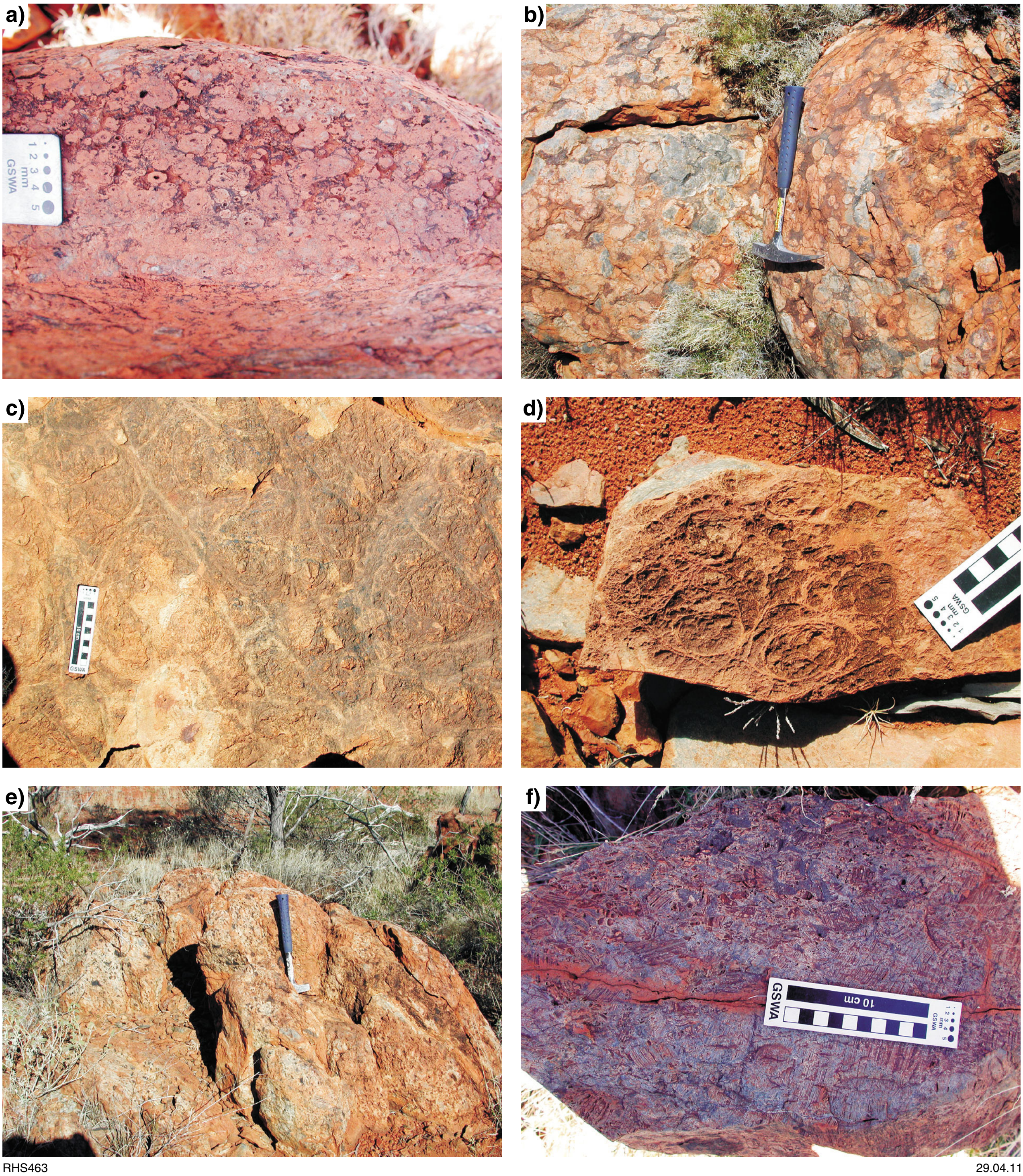

Figure 33. Outcrop photographs showing lithologies characteristic of the lower Mount Palgrave Group: a, b) spherulites developed in rhyolitic ignimbrite; c, d) perlitic cracks developed in rhyolitic ignimbrite; e) non-rheomorphic and weakly welded ignimbrite (note dark fiamme); f) autoclastic breccia developed in finely flow-laminated rhyolitic ignimbrite (eastern Mount Eveline).

along the northwestern margin of this structural corridor. The timing of faulting has not been established; however, whereas units in the upper stratigraphic parts of the Bentley Supersuite (Glyde Formation and above) in the southwestern extension of the Barrow Range – Cavenagh corridor may also have been displaced, they do not appear to have been affected to the same extent as the rocks in the Barrow Range anticline. On this basis, we suggest that at least a component of deformation within the structural corridor occurred before 1065 ± 5 Ma, the age of the Wururu Rhyolite in the lower part of the Cassidy Group (GSWA 174690, Kirkland et al., 2011f). This age is within analytical error of the depositional age of the Mount Palgrave Group (see below), possibly suggesting that magmatic components of the Winburn Granite and the Mount Palgrave Group and stages in the development of the Barrow Range – Cavenagh corridor were synchronous.

Mount Palgrave Group

The Mount Palgrave Group reflects a series of extremely violent, high-energy eruptions of compositionally evolved rhyolitic magmas and less voluminous tholeiitic mafic magmas. Recent mapping has enabled subdivision of the group into a number of depositional packages. The lowermost units overlying the Winburn Granite consist of aphyric to sparsely feldspar-phyric, highly vitric, rhyolites. These include locally voluminous and laterally continuous massive, perlitic and spherulitic ignimbrites, flow banded feldspar-phyric flows (primary lavas or rheomorphic ignimbrites), fiamme-textured ignimbrites (rheomorphic and non-rheomorphic), and, in the upper parts of the succession, units of stratified pyroclastic rocks and autoclastic breccia (Fig. 33). Basalt and basaltic andesite flow units, and siliciclastic conglomerates, sandstones, and mudstones rich in volcanogenic detritus, form minor intercalations. The basal rhyolite units, in proximity to intrusive contacts with the Winburn Granite, often have a slightly coarser, crystalline appearance due to the thermal overprint, and spherulitic units in particular take on a fragmental or brecciated appearance through a combination of compaction and differential recrystallization of spherulites and inter-spherulitic domains.

The lower rhyolitic ignimbrite package of the Mount Palgrave Group is overlain by a coarse clastic diamictite (Fig. 34), locally with deep erosive scours into the rhyolitic ignimbrite package. This significant change in the deposition pattern is probably connected to a hiatus in volcanic deposition, deformation, uplift, and erosion, possibly related to doming in the Barrow Range anticline.

The diamictite is overlain by a depositional package (‘upper Mount Palgrave Group’) that is characterized by massive to flow-banded, feldspar(–quartz)-phyric rhyolite, and lesser trachyte and dacite with locally significant intercalations of crystal-rich ignimbrite and siliciclastic rocks, the latter locally including interbeds containing microbial laminites (Fig. 35). The flow-banded rhyolite, trachyte, and dacite have the appearance of coherent volcanic units, and some examples may represent either

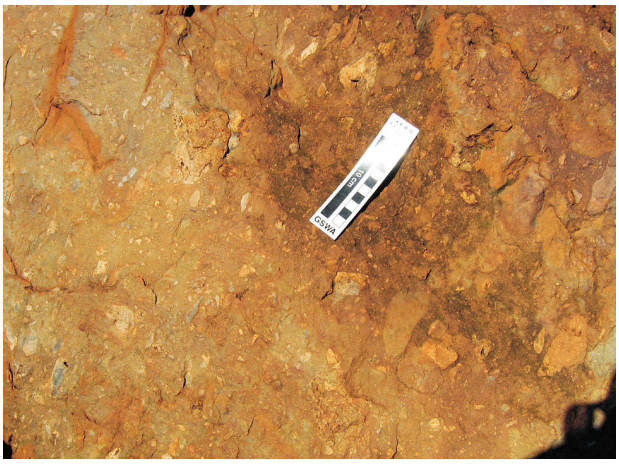

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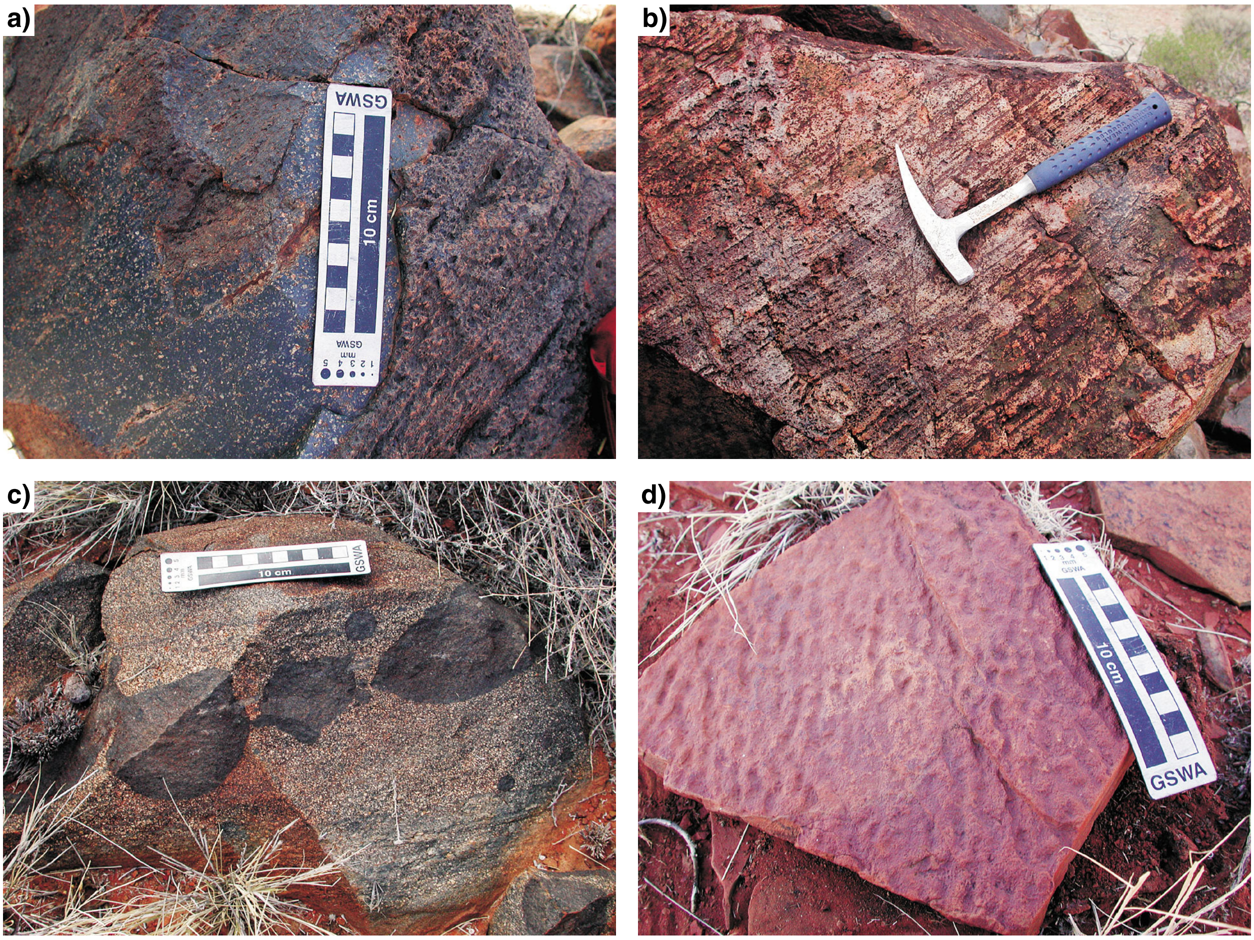
Figure 34. Outcrop photographs showing the diamictite unit that separates the lower and upper Mount Palgrave Group (eastern Mount Eveline)

lavas or subvolcanic sills. However, the abundance and size of phenocrysts in these rocks are typically quite variable, and the spatial phenocryst distribution is locally fairly heterogeneous. These observations point to a pyroclastic origin. Flow banding indicates that these pyroclastic rocks underwent intensive welding and experienced rheomorphic flow.

A porphyritic dacite to rhyolite horizon also divides the upper Mount Palgrave Group into two subunits. This marker horizon can be traced from the mid-central part of the Palgrave area into its northern part for at least 30 km. This marker horizon is composed of a distinctly quartz- and feldspar-porphyritic dacitic and rhyolitic rock, with slightly larger phenocrysts and a coarser crystalline (microgranitic) groundmass than the over- and underlying rhyolites. A large portion of this rock appears massive, and could be misinterpreted as intrusive in origin. However, in places this rock clearly shows well-preserved relicts of densely packed, centimetre-sized spherulites, demonstrating its former vitric character. Furthermore, this marker horizon is locally composed of stacked layers characterized by a decrease in size and abundance of quartz and feldspar phenocrysts in an upward direction, and has sharp basal contacts (fining-upward sequences), implying a pyroclastic depositional origin. The microgranitic character of these rocks is attributed to later heating and recrystallization of the originally spherulitic groundmass. A sample of a massive feldspar-phyric rhyolite positioned above the porphyritic marker horizon yielded a U–Pb SHRIMP age of 1063 ± 8 Ma (GSWA 189580, Kirkland et al., 2011g).

Higher in the stratigraphy, the pyroclastic character of the feldspar(–quartz)-phyric rhyolites of the upper Mount Palgrave Group package is more apparent. The volcaniclastic portion of the uppermost part of the Mount Palgrave Group consists of interbedded, massive to vaguely stratified crystal-ash tuffs, graded or layered crystal tuffs, fiamme-textured ignimbrites, flow banded



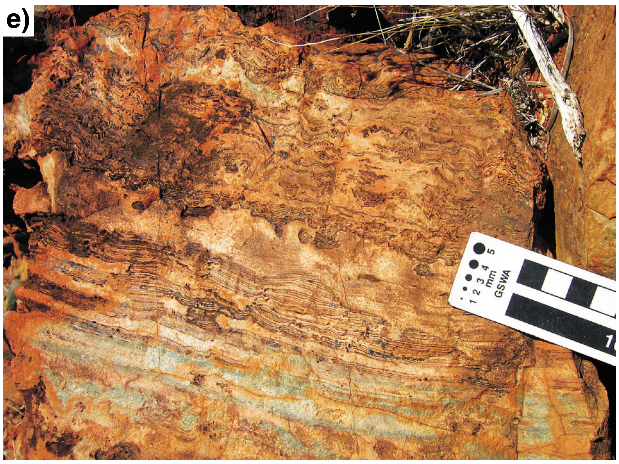


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Figure 35. Outcrop photographs showing lithologies characteristic of the upper Mount Palgrave Group: a,b) flow-banded to laminated feldspar-phyric rhyolite. Locally developed eutaxitic textures show such rocks to be rheomorphic ignimbrites; c) banded to layered crystal-rich tuff. Dislocation of a vitric feldspar-phyric rhyolite layer (dark layer) probably reflects rheomorphic flow of the deposit; d) ripples in a volcaniclastic siltstone; e) microbial laminae in volcaniclastic siltstone.

rhyolites, and siliciclastic sedimentary horizons. Some outcrop areas are also characterized by rhyolitic breccias of mainly autoclastic and minor gravitational origin (e.g. volcaniclastic talus and debris avalanche deposits). At one locality in the uppermost part of the Mount Palgrave Group, a crystal tuff contains rare, dark-grey, concentrically laminated, accretionary lapilli.

The sedimentary part of the upper Mount Palgrave Group package consists of dark-coloured mudstones, sandstones, conglomerates, and diamictites. Bedding surfaces of sandstones show wave ripples at a number of localities. These sedimentary rocks are probably composed almost entirely of locally derived, mixed felsic–mafic volcanogenic detritus, including reworked pyroclastic material. The boundaries between larger sedimentary horizons and overlying dacitic volcanic/pyroclastic intervals are often gradational, and are characterized by the lenticular geometries of depositional bodies; e.g. dacite intercalations several metres thick and tens of metres long in mudstone-dominated sedimentary rocks.

Intrusive rocks within the Mount Palgrave Group comprise dykes, sills, and irregular small bodies of feldspar-and quartz–feldspar-phyric rhyolitic microgranites, quartz diorites, as well as dolerites. The rhyolitic microgranites preferentially intrude into mudstone-dominated intercalations, and thus commonly carry abundant mudstone xenoliths of various sizes. Feldspar-phyric microgranite, intrusive into crystal tuffs of the upper part of the Mount Palgrave Group, was dated at 1064 ± 7 Ma (GSWA 194637, Kirkland et al., 2011e). A quartz diorite intruded into an east-trending fracture zone within the upper part of the Mount Palgrave Group in the central part of the Palgrave area yielded an age of 1055 ± 10 Ma (GSWA 187054, Kirkland et al., in prep.).

Scamp area — Scamp rhyolite and Mount Waugh rhyolite

Outcrop of the Bentley Supergroup in the Scamp area extends in a westerly direction for about 75 km (Fig. 30). The nature of the contact between the Scamp rhyolite and rocks of the Mount Palgrave Group to the east is unclear, but is likely to be faulted, based on aeromagnetic trends and on a notable change in metamorphic grade (higher grade in the Scamp area) across that contact. The western outcrop margin of the Scamp area lies north of Warburton, where the Scamp rhyolite extends under a cover of Cenozoic sediments farther west. Daniels (1974) inferred the existence of a northern and southern boundary fault for the Scamp area, and interpreted the area as a volcanic caldera. The southern margin of the currently defined Scamp area is apparently the faulted southern margin of a rhyolite unit, of which Mount Waugh forms a prominent exposure. This rhyolite unit is informally called the Mount Waugh rhyolite, and is composed of flow banded, sparsely quartz- and feldspar-phyric rhyolite. In its eastern parts, the Mount Waugh rhyolite includes alteration areas in which the original rhyolite is transformed to a schistose quartz- and muscovite-rich assemblage that locally contains veins, stringers, and pods of nodular, granoblastic, aluminosilicate minerals, including kyanite and andalusite. Although Daniels (1974) interpreted these alteration zones as places of former fumarolic activity, their texture is mylonitic and they appear to coincide with the intersections of northeast- and northwest-trending faults. The Mount Waugh rhyolite is fringed to the north and south by outcrops of dark-coloured, micaceous metasedimentary rocks comprising mudstones, sandstones, conglomerates, and diamictites. These rocks are very similar to the sedimentary rocks in the Mount Palgrave Group to the east, and in the Pussy Cat Group to the south.

To the north of the Mount Waugh rhyolite are outcrops of the Scamp rhyolite, including leucocratic rhyolitic rocks with a slightly coarser crystalline groundmass. These rocks were described by Daniels (1974) as ‘felsites’ to distinguish them from rhyolites with a microcrystalline groundmass. The majority of these ‘felsites’ are either aphyric or microphenocrystic. Relicts of flow banding and spherulites can be observed in a number of places. At this stage, it is difficult to say if these ‘felsites’ were originally deposited as effusive rhyolite flows or as rhyolitic pyroclastic rocks. Relicts of possible fiamme have been observed only at one or two localities. Some of the ‘felsites’, containing slightly larger feldspar phenocrysts and appearing to have a slightly coarser grained groundmass, may have been emplaced as shallow subvolcanic cryptodomes. One peculiar feature of the Scamp ‘felsites’ is that they are commonly garnet bearing; these garnets vary in colour from pale pinkish, to yellowish, to dirty olive-greenish. Their shapes are also highly variable, ranging from idioblastic hexagonal ?porphyroblasts to roundish xenoblastic inclusion-rich (‘spongy’) poikiloblasts. Many garnets show signs of corrosion, resorption, and degradation, including non-isotropic optical behaviour. One sample of these garnet-bearing Scamp ‘felsites’ was dated at 1064 ± 5 Ma (GSWA 195678, Kirkland et al., in prep.). Towards the north and northwest, the Scamp ‘felsites’ are underlain and intruded by a large belt of equigranular to porphyritic, felsic, granofelsic-textured rocks. A sample from the southeastern margin of this belt yielded a U–Pb SHRIMP age of 1059 ± 6 Ma (GSWA 195673, Kirkland et al., in prep.). Felsic intrusions were also emplaced as smaller dykes and plugs within the Scamp ‘felsites’ outcrop area. One ~200 m wide dyke composed of porphyritic microgranite also contains locally millimetre-sized orange- to pinkish-coloured garnets.

Mafic volcanic rocks in the Scamp area seem to be restricted to dolerite dykes — no mafic extrusive rocks have been found. The dolerite dykes can locally be up to 400 m wide, but good outcrops with fresh material are commonly restricted to metre-sized boulders. With the exception of one locality where a strongly deformed (sheared) metaconglomerate outcrops at a microgranite contact, no rocks of sedimentary origin have been observed so far within the Scamp area.

Pussy Cat Group

The Pussy Cat Group represents the oldest part of the southeast- to east-trending, south-dipping and south-younging volcanosedimentary succession in the southwestern part of the Talbot Sub-basin. To the north and east, outcrops of the Pussy Cat Group are fault-bounded against rocks of the Scamp and Palgrave areas, respectively. There are no known exposures of the base of the Pussy Cat Group. The top of the Pussy Cat Group and base of the overlying Cassidy Group are defined by the first occurrence of a rhyolitic unit — the Wururu Rhyolite. As this rhyolite appears to be laterally discontinuous, the boundary between the Pussy Cat Group and the Cassidy Group is locally irregular and less well defined. An unconformable contact between these two groups, as inferred by Daniels (1974), cannot be confirmed. Local strike divergences between rocks of these groups are subtle and may be related to intrusions of large quartz- and feldspar-phyric rhyolitic microgranite bodies (e.g. at Mount Shaw), or could be caused by localized deformation during the Petermann Orogeny. In addition, a distinct difference in metamorphic grade between the Pussy Cat Group and the Cassidy Group could not be verified. A gradational decrease of metamorphic grade may be present in the Pussy Cat Group from north to south (in upward stratigraphic direction). However, both the metabasalts and intercalated metasedimentary rocks in the upper part of the Pussy Cat Group, and comparable rocks in the overlying lower part of the Cassidy Group, show a similar low to very low metamorphic grade. We therefore infer a largely conformable contact between these groups.

In its eastern outcrop area, the Pussy Cat Group is represented by the Glyde Formation and intercalated Kathleen Ignimbrite (cf. Daniels, 1974). The Glyde Formation is here composed mainly of low-grade metamorphic, volcaniclastic sedimentary rocks in its lower part, and of amygdaloidal metabasaltic lavas in its upper part, with the intercalated Kathleen Ignimbrite marking approximately the stratigraphic position of this lithofacies change within the Glyde Formation.

Glyde Formation

The lower volcaniclastic metasedimentary rocks of the Glyde Formation comprise dark-coloured, massive to laminated mudstones, siltstones, and shales; planar-bedded as well as ripple- and trough cross-bedded, well to poorly sorted, partly arkosic or calcareous sandstones; conglomerates; and very poorly sorted, matrix-supported diamictites (Fig. 36a). The clastic components of these rocks are mainly composed of volcanogenic detritus, representing reworked pyroclastic rocks and erosion products of volcanic extrusive rocks. Some of the finely laminated mudstones may represent subaqueously deposited ash-fall tuffs. Mafic source components commonly dominate over felsic components in the finer-grained fraction of the volcaniclastic, metasedimentary Glyde Formation rocks, giving the rocks their typical dark-coloured, 'mafic' appearance. Minor lithofacies components, important for paleoenvironmental reconstructions, include dolomitic marbles (Fig. 36b) and associated calc-silicate rocks, relict evaporite horizons, and siliciclastic microbialites (stromatolites; Fig. 36c). The volcaniclastic metasedimentary rocks of the lower Glyde Formation were deposited in a volcanically active alluvial to fluviolacustrine environment. Deposition of coarser clastic rocks in the lower parts of the volcaniclastic succession occurred as episodic high energy events (flash-flood mud- and debris-flows, lahars), whereas finer grained rocks were deposited in small lakes and ponds of an alluvial plain. Desiccation cracks on mudstone bedding surfaces indicate that some of these shallow water bodies dried quickly. Outcrops of trough cross-bedded fluvial sandstones are comparatively rare, and this may indicate that the paleoenvironment during deposition of the lower Glyde Formation lacked well-established river systems. Higher in the metasedimentary succession, very well sorted, slightly calcareous, planar-bedded to climbing-ripple cross-laminated and hummocky cross-bedded sandstones, outcropping below the base of the Kathleen Ignimbrite, indicate deposition in a more extensive, deeper, and more permanent water body. Gypsum crystal moulds within mudstones, and structures that look like enterolithic folds of former gypsum layers, associated with siliciclastic microbialites and dolomitic metalimestones, indicate intermittent evaporitic or hypersaline conditions.

The upper part of the Glyde Formation is dominated by extrusive metabasaltic lavas, some of which are massive, but more commonly are highly amygdaloidal (Fig. 37). Most of these metabasalts are aphyric, but plagioclase-phyric varieties do occur. In rare cases, ropy lava surfaces can be observed. Intercalated in these lavas are thin horizons of metasedimentary rocks, including epidotitic–cherty metapelites, quartzites, and siliceous microbialites (stromatolites). These intercalations indicate the presence of running and standing water during the deposition of the basaltic lavas. No pillow lavas have

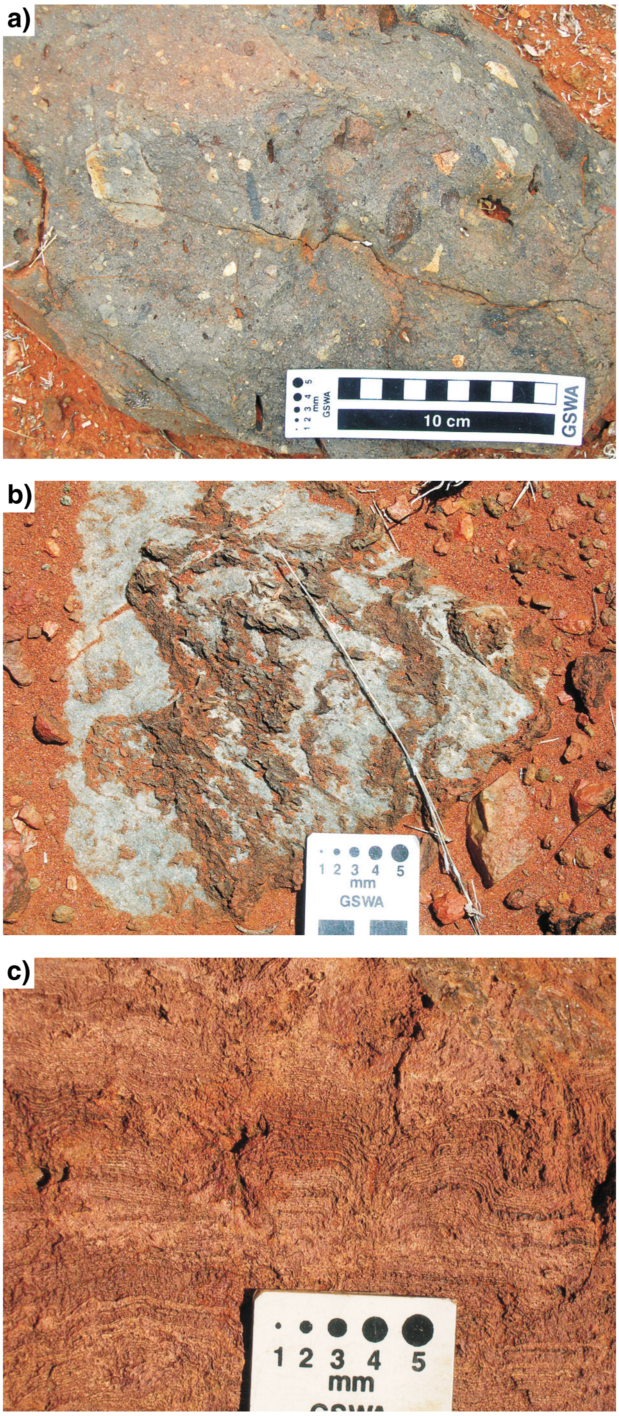

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Figure 36. Outcrop photographs showing lithologies characteristic of the Glyde Formation (Pussy Cat Group): a) diamictite; b) dolomitic marble; c) stromatolites (central MOUNT EVELINE).

been found, and autoclastic metabasalt breccias are fairly rare in the Glyde Formation. East of Mount Shaw, possible hyaloclastite breccias occur in association with amygdaloidal metabasalt, quartzite, and microbialite mudstone. Therefore, it appears that the majority of the Glyde Formation lavas were erupted and deposited subaerially, but entered small water bodies locally to form occurrences of peperites and hyaloclastites.

Rocks of the Glyde Formation were affected by moderate-temperature, low-pressure metamorphism. Some of the muddy to sandy, fine grained, volcaniclastic sediments were transformed into dark-grey to blackish, biotite-rich, epidotitic, quartz–feldspar microgranofelses, some of which are also strongly amphibole-porphyroblastic. Other volcaniclastic mudstones were altered and deformed to dark bluish-green to olive-green, epidotitic–actinolitic, slatey to crudely schistose rocks. The mafic volcanic lavas were metamorphosed to epidotitic–actinolitic metabasalts.

Kathleen Ignimbrite

The Kathleen Ignimbrite is a mappable unit within the Glyde Formation, and forms a prominent range of hills. It has a maximum thickness of over 500 m, and is mainly composed of a flow-banded and lava-like rhyolite, which Daniels (1974) interpreted as a densely welded and rheomorphic, originally pyroclastic, deposit (rheoignimbrite). The Kathleen Ignimbrite is thickest in its eastern outcrop area, and shows a diverse range of lithofacies, including parts that are very rich in quartz and feldspar phenocrysts. Towards the west, the thickness and phenocryst content decreases and the rock grades into a massive to flow-banded, aphyric, more homogenous rhyolite, indicating that it was probably erupted from a volcanic source to the east. Observations supporting a pyroclastic origin are best developed in its eastern part, and include the irregular and patchy distribution of quartz and feldspar phenocrysts and crystal fragments, the presence of cognate quartz- and feldspar-phyric rhyolite or microgranite clasts as lithic fragments, and alternating felsic and mafic ash layers in its basal part. Higher up, the Kathleen Ignimbrite grades from a strongly flow-banded rock into a eutaxitic, fiamme-textured rock (Fig. 38a) that is overlain by a stratified succession of fine to coarse grained, commonly crystal-rich, rhyolitic lapilli-ash tuffs (Fig. 38b), including relicts of glass shards near the top. At its base, the Kathleen Ignimbrite also contains upwardly intruded clastic dykes of Glyde Formation material, indicating that the ignimbrite was deposited rapidly onto semi-consolidated, water-bearing, volcaniclastic sediments. Finely laminated siliceous ash tuffs in the upper, well-stratified, part of the Kathleen Ignimbrite contain flame structures that strongly resemble sedimentary structures normally seen in subaqueous settings. In view of the apparently subaqueous setting of hummocky cross-bedded and climbing-ripple cross-laminated Glyde Formation sandstones that underlie the Kathleen Ignimbrite, it can be speculated that the Kathleen Ignimbrite was also deposited in a larger water body.

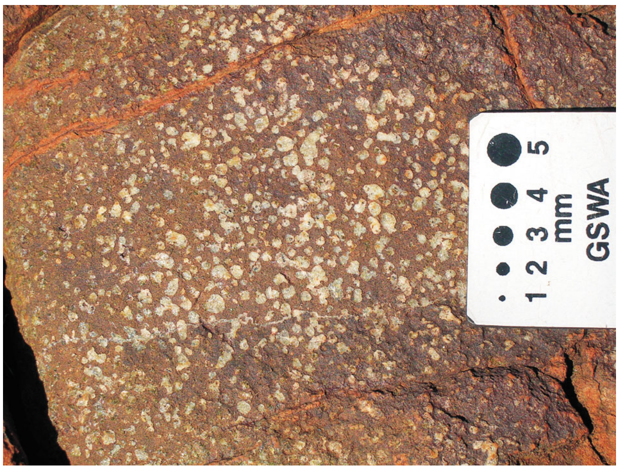

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Figure 37. Outcrop photograph showing an amygdaloidal basalt from the Glyde Formation of the Pussy Cat Group (central Mount Eveline).

The outcropping part of the Pussy Cat Group, as defined by Daniels (1974), is up to about 3000 m thick. However, the entire thickness of this group is unknown as its base is not exposed. Further complications arise because the exact location of the boundary fault against rocks of the Scamp area is uncertain. Daniels (1974) placed the fault at the southern margin of a rhyolite unit of which Mount Esme, Flower Hill, and Mount Waugh are prominent landmarks. This rhyolite unit is informally referred to here as the Mount Waugh rhyolite, and it lies less than 1 km north of the Kathleen Ignimbrite on the Mount Eveline 1:100 000 map sheet. Dark, volcaniclastic metasedimentary rocks that are very similar to the Glyde Formation lithofacies elsewhere are exposed on both the northern and southern margins of the Mount Waugh rhyolite. It is therefore possible that all of these rocks (rhyolite and metasedimentary rocks) are still part of the Glyde Formation (Pussy Cat Group), and that the fault boundary to the Scamp area lies farther north, possibly at the southern margin of the more strongly recrystallized and slightly granular rhyolites that Daniels (1974) termed ‘felsites’.

Age constraints for the Pussy Cat Group derive from a 1071 ± 5 Ma date on the Kathleen Ignimbrite (GSWA 195723, Kirkland et al., 2011h), which is interpreted to be the age of igneous crystallization (and of pyroclastic deposition). A minimum age constraint comes from a sample of the Wururu Rhyolite, which lies at the base of the overlying Cassidy Group. This sample yielded an age of 1065 ± 5 Ma (GSWA 174690, Kirkland et al., 2011f), which is interpreted to be the age of igneous crystallization.

Cassidy Group

The contact between the Cassidy Group and the underlying Pussy Cat Group is most likely conformable, and represents a succession of alternating units of rhyolitic (Wururu, Gombugurra, Thomas, and Hilda Rhyolites) and basaltic (Gurgadi, Warubuyu, and Miller Basalts)

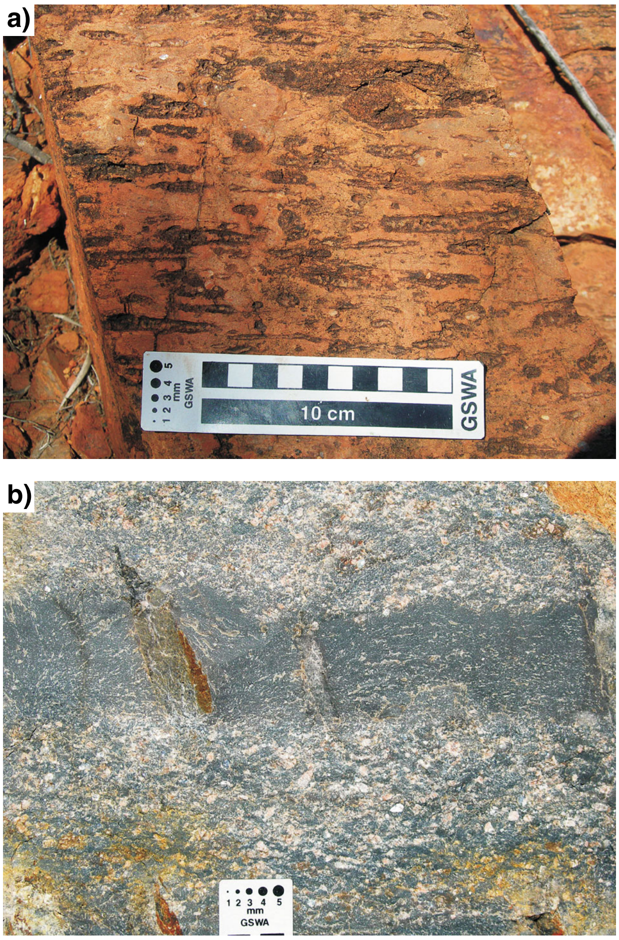

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Figure 38. Outcrop photographs of the Kathleen Ignimbrite: a) eutaxitic facies; b) crystal-rich lapilli-ash tuff (central-northern Mount Eveline).

lava flows, with minor intercalations of sedimentary rocks. The base of the Cassidy Group is defined by the first occurrence of the Wururu Rhyolite. However, in some places, where the Wururu Rhyolite is not present, amygdaloidal basalts of the Glyde Formation (upper Pussy Cat Group) are in contact with amygdaloidal basalts of the Gurgadi Basalt (lower Cassidy Group), making a distinction between the two groups difficult. The top of the Cassidy Group is defined as the boundary between the rocks of the Miller Basalt and the overlying conglomeratic or sandy siliciclastic rocks of the lower part of the Mission Group. Daniels (1974) reported a total thickness for the Cassidy Group of slightly over 3000 m.

The rhyolitic units are very similar in their lithological appearance. They are all dark-grey, feldspar-phyric rhyolites with a very fine grained groundmass, and all can be massive, flow banded, or spherulitic (Fig. 39). According to Daniels (1974), the thickness of the individual rhyolite units ranges from about 260 to 550 m. The individual rhyolites do not form laterally continuous units over the entire outcrop extent of the Cassidy Group. The Wururu Rhyolite is laterally continuous in its western and eastern parts, but appears to be locally absent in the area south of Mount Shaw. The stratigraphically higher Gombugurra Rhyolite is only present in the area of the Warburton Range 1:100 000 map sheet, and thins to the east in the Mount Hilda area. The Thomas Rhyolite is the most laterally continuous rhyolite unit, and can be traced over the entire extent of the Cassidy Group outcrop area. The stratigraphically highest Hilda Rhyolite can be traced from the Warburton area eastward as a continuous unit, but thins out to the east, north of Frank Scott Hill. Nevertheless, these rhyolite flows have remarkable lateral extent and show only very minor development of autoclastic brecciation, indicating low flow viscosities.

Between the Wururu Rhyolite and the Gombugurra Rhyolite lies an approximately 50 m thick unnamed unit of sedimentary rocks, mainly composed of fine-grained siltstones with some sandstone and conglomerate layers and very minor basalt. In the western half of the Cassidy Group outcrop area, the Gombugurra Rhyolite is overlain by fine-grained siltstones with minor sandstones, which are in turn followed by the amygdaloidal Gurgadi Basalt. In the eastern Cassidy Group outcrop area, the Gurgadi Basalt directly overlies the Wururu Rhyolite, and is in turn overlain by the Thomas Rhyolite. Here, the Gurgadi Basalt represents a succession of amygdaloidal basaltic lavas, which contain numerous, but thin and laterally discontinuous, layers, and small successions of volcaniclastic sedimentary rocks comprising cherty–epidotitic mudstones, siltstones, sandstones, and conglomerates. The thickness of the Gurgadi Basalt (including sedimentary rocks) is approximately 500–600 m.

The stratigraphic interval between the Thomas Rhyolite and the Hilda Rhyolite is also characterized by sedimentary rocks and basaltic lavas. At the western margin of the Mount Eveline map sheet, this stratigraphic interval can be subdivided, over about 3 km along strike, into a siliciclastic sedimentary lower part, and a basaltic volcanic upper part (Warubuyu Basalt). This subdivision is not possible further to the east where the sedimentary siliciclastic lower part is not present. However, in the

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Figure 39. Outcrop photograph showing a spherulitic facies of the Hilda Rhyolite (Cassidy Group; central Mount Eveline).

eastern area, the dominantly basaltic pile is intercalated with siliciclastic rocks, and since these sedimentary horizons can be found throughout the whole stratigraphic interval, the sequence would be better termed 'Warubuyu Formation'. The thickness of this basaltic–sedimentary interval is around 250 m. Sedimentary rocks include cherty–epidotitic mudstones, light bluish-grey shales, brownish volcaniclastic siltstones, ripple cross-laminated sandstones, and minor conglomerates. A light-greenish, cherty–epidotitic, laminated microbialite horizon forms a conspicuous marker horizon within this stratigraphic interval, and can be traced for more than 5 km laterally along strike. Basaltic volcanic rocks shallowly intruded into (and possibly extruded onto) this microbialite horizon, causing disruption, tilting, and soft-sediment deformation (faulting, folding, and slumping) of the cohesive sedimentary deposits (Fig. 40a). Partial extrusion and shallow intrusion of basalts into subaqueously deposited sediments also led to the formation of extensive hyaloclastite breccias (Fig. 40b) and peperites. These observations point to a subaqueous emplacement of basalts, but true pillow structures are not observed. Similarly, the immediately overlying Hilda Rhyolite is locally under- and overlain by sedimentary rocks including finely laminated 'paper' shales, and fine-grained volcaniclastic siltstones and sandstones, which strongly suggest a low-energy, subaqueous (marine or continental) depositional environment. Strangely, the Hilda Rhyolite does not have a hyaloclastite breccia carapace.

The Miller Basalt overlies the Hilda Rhyolite, but is commonly separated from it by a thin succession of fine-grained sedimentary rocks. The Miller Basalt represents, for the most part, a repetitive succession of lava flows characterized by 10–20 m thick basal sequences of massive basalts that grade upward into progressively stronger vesicular and amygdaloidal basalts. In places, intensively silicified or brecciated basalts occur at the top of such sequences, marking the tops of lava flows. The Miller Basalt is not an entirely volcanic unit because it also contains a substantial amount of sedimentary interlayers and horizons. Near the base, a number of conspicuous, resistant, orange-weathering, 1–2 m thick, cherty to quartzitic mudstone–sandstone layers (containing redistributed rhyolitic ash?) form a laterally traceable marker interval within the Miller Basalt (Fig. 41a). Higher up, approximately in the middle of the Miller Basalt, a mappable, ~200–250 m wide zone is characterized by several conspicuous, coarsening-upward successions of volcaniclastic conglomerates (Fig. 41b) and sandstones, intercalated within the basaltic rocks. Laterally restricted sedimentary intercalations are also common in the remaining upper part of the Miller Basalt. They comprise cherty–epidotitic mudstones, fine-grained cherty microbialites, siltstones, sandstones, and minor conglomerates, often located at the top of lava flows. Laminated to thinly bedded, muddy to sandy, quartz granule bearing sedimentary rock is very common, and is intensively disrupted by a network of vertical fluid or mud escape structures (Fig. 41c). The whole Miller Basalt succession has a thickness of about 750 m. The age of the basalt is constrained between the crystallization ages determined for the underlying Wururu Rhyolite (1065 ± 5 Ma: GSWA 174690, Kirkland et al., 2011f), and for the overlying Thomas Rhyolite (Cassidy Group; 1057 ± 6 Ma: GSWA 174691, Kirkland et al., in prep.).

Mission Group

The Mission Group conformably overlies the Cassidy Group and represents the youngest stratigraphic interval of the Bentley Supergroup. It can be subdivided into a sedimentary lower part (Gamminah Conglomerate, Frank Scott Formation, and Lilian Formation), and an upper basalt-dominated part (Milesia Formation). No evidence of felsic volcanism has yet been found. The Mission Group is conformably to unconformably overlain by the Townsend Quartzite. Daniels (1974) reported a total thickness for the Mission Group of about 4000 m.

The Miller Basalt, as the top unit of the Cassidy Group, is overlain by siliciclastic and calcareous rocks of the Frank Scott Formation. In the Warburton Range area, the transition is characterized by 'interbanded thin basalt flows, and thin silts and dolomites' (Daniels, 1974, p. 78).

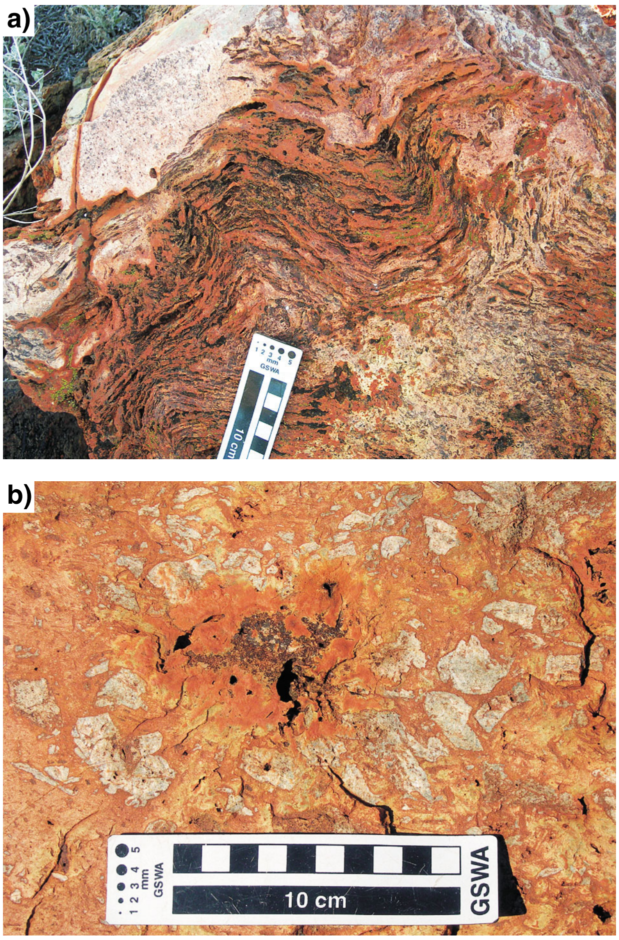

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Figure 40. Outcrop photographs of the Cassidy Group showing: a) soft-sediment deformation in fine-grained sedimentary rocks (microbial laminite) associated with the Warubuyu Basalt; b) hyaloclastite brecciation of the Warubuyu Basalt (central Mount Eveline).

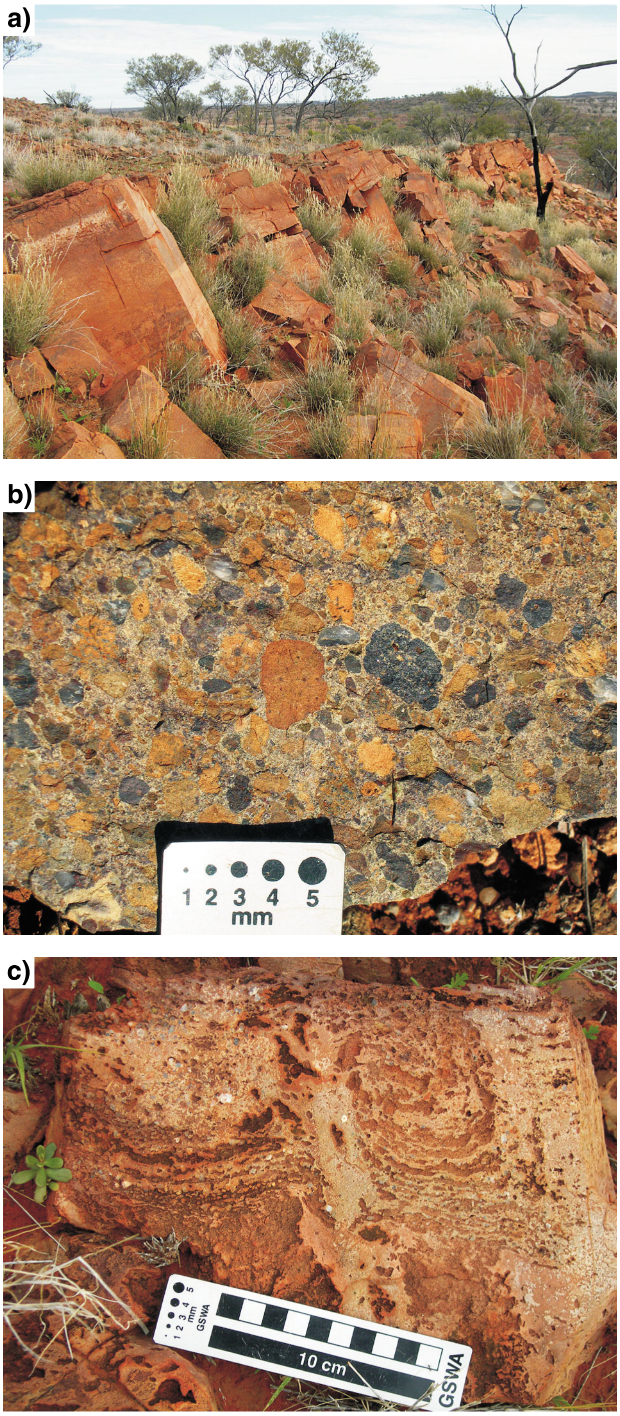

Figure 41. Outcrop photographs of the Cassidy Group showing: a) a cherty to quartzitic mudstone–sandstone layer within the Miller Basalt; b) volcaniclastic conglomerate within the Miller Basalt; c) fluid escape structures in fine-grained sedimentary rocks within the Miller Basalt (central MOUNT EVELINE).

In that area, the Frank Scott Formation lithologies include finely laminated siltstones, dolomitic siltstones, shales, and dolomites, as well as minor sandstones and cherts (Daniels, 1974). In the adjacent MOUNT EVENLINE area, the Miller Basalt is, in contrast, overlain by coarse clastic sedimentary rocks of the Gamminah Conglomerate, a locally restricted basal member of the Frank Scott Formation. In this area, the succession from the Gamminah Conglomerate, to the overlying finer-grained siliciclastic and calcareous rocks of the Frank Scott Formation, and up into the overlying shale-dominated Lilian Formation, forms a distinct fining- and deepening-upward sedimentary succession.

The Gamminah Conglomerate (Fig. 42a) is a moderately coarse-grained rock containing subrounded to well-rounded pebbles and cobbles up to about 20 cm in diameter. These clasts are mainly composed of amygdaloidal basalt, felsic porphyritic volcanic rock, and milky quartz. The boundary to the Miller Basalt can be sharp or transitional. Sedimentary structures are predominantly crude planar-bedding, but cross-bedding also occurs. Intercalated within the conglomerates are thin sandstone layers. Towards the top, the conglomerates become finer-grained and eventually grade into the sandstone–shale succession of the lower Frank Scott Formation. The sandstones are predominantly fine-grained quartzites, which weather to reddish-brown colours, but fresh surfaces show a dark bluish-greenish-grey colour, indicating the abundance of altered volcanic detritus in these rocks. The sandstone layers characteristically show parallel lamination grading into ripple cross-lamination (Fig. 42b). Low-angle, swaley trough cross-bedding also occurs. Trough cross-bedding typical of fluvial origin is virtually absent, and the depositional environment of these quartzites is interpreted as marine or lacustrine. The sandstones most probably represent tempestites or turbidites with their tops locally modified by wave- or storm-current action. The thickness of individual sandstone layers ranges from a few centimetres to about 2 m.

The shales in which the sandstones are intercalated are light bluish-grey, to olive-green, to bluish-green, and represent suspension settling of mud in an offshore, low-energy, sub-wavebase setting within a larger water body. Higher in the Frank Scott Formation, the number of sandstone layers decreases, and limestone layers (of comparable thickness) appear as intercalations within the shales. Some of the limestones show cross-bedding, are rich in intraclasts, or appear to be oolitic. North of Frank Scott Hill, a number of limestones contain metre-sized, pillow-shaped stromatolites. These are commonly internally laminated, and locally show small domal structures (Fig. 42c). Higher up in the stratigraphy follows a shale-dominated interval, which contains minor intercalations of fine-grained quartzitic sandstones, dolomitic limestones, and siliceous mudstones or cherts. Daniels (1974) also reported polymict conglomerate layers. Some of the more siliceous and less altered mudstones are black in colour, and are probably rich in organic carbon (black shales; Fig. 42d). This part of the stratigraphy is transitional to the overlying Lilian Formation, which on MOUNT EVELINE consists almost entirely of reddish to olive-green weathering shales. The sedimentary rocks of the Frank Scott and Lilian Formations were laid down in a deeper, fairly extensive water body that existed for a substantial period of time. It is not known whether this water body represented a large lake or lake system, or was connected to the marine realm. The combined thickness of the two formations is probably in the order of 1200–1500 m.

North of the large dolerite intrusion at Frank Scott Hill, the limestone–shale succession of the upper Frank Scott Formation contains a thin, laterally traceable sheet of basalt that is slightly vesicular at its top. Also south of Frank Scott Hill, the shale-dominated outcrops contain a number of fine-grained basaltic intercalations. These volcanic rocks lack intense vesiculation, do not contain autoclastic breccias, and do not form peperites with the shaly host rock. Therefore, we interpret these basaltic intercalations as shallow intrusive sills rather than extrusive lavas.

The Milesia Formation consists predominantly of basaltic volcanic rock and has a minimum thickness of about 300 m. In the lower part, these basalts are commonly highly altered (epidotitic or hematitic), strongly amygdaloidal, or strongly quartz-mottled. Basalt breccias are also observed, some of which appear autoclastic, whereas others are clearly peperitic in origin, with fine-grained sandstone filling the space between basalt clasts (Fig. 43a). The whole succession essentially represents a pile of basaltic lava flows. These lava flows contain a number of sedimentary intercalations consisting of pinkish, quartzitic sandstones, and conglomerates. Some of these interlayers are laterally continuous and traceable over about 5–6 km, whereas others are lenticular and only 5–10 m wide along strike. The thickness of these interlayers is commonly 1–5 m. About 5 km south of Frank Scott Hill, the basalts close to the southern outcrop margin of the Milesia Formation contain a laterally traceable horizon of chocolate-brown, ferruginous, fine to coarse grained, and possibly subarkosic, sandstones (Fig. 43b). This is the first occurrence of continental redbed-type sedimentary rocks in the Mission Group. The uppermost part of the Milesia Formation (and the Mission Group), which directly underlies the Townsend Quartzite, is covered by a thick wedge of eolian sand and other unconsolidated Cenozoic sediments. Two recent stratigraphic drillholes partly penetrated this stratigraphic interval (Eaton, 2010). In both wells, the upper portion of the drilled cores contains a thick interbedded sandstone–shale redbed sequence overlying extrusive basaltic rocks. One drillhole also contained an additional lower interval of redbed-type siliciclastic rocks sandwiched between basaltic intervals.

The continental redbed-type sedimentary rocks at the top of the Milesia Formation appear to provide a depositional link between the Bentley Supergroup and the Townsend Quartzite (~260 m maximum exposed thickness). Although not exposed, the boundary between the Mission Group and the Townsend Quartzite seems to be largely conformable in

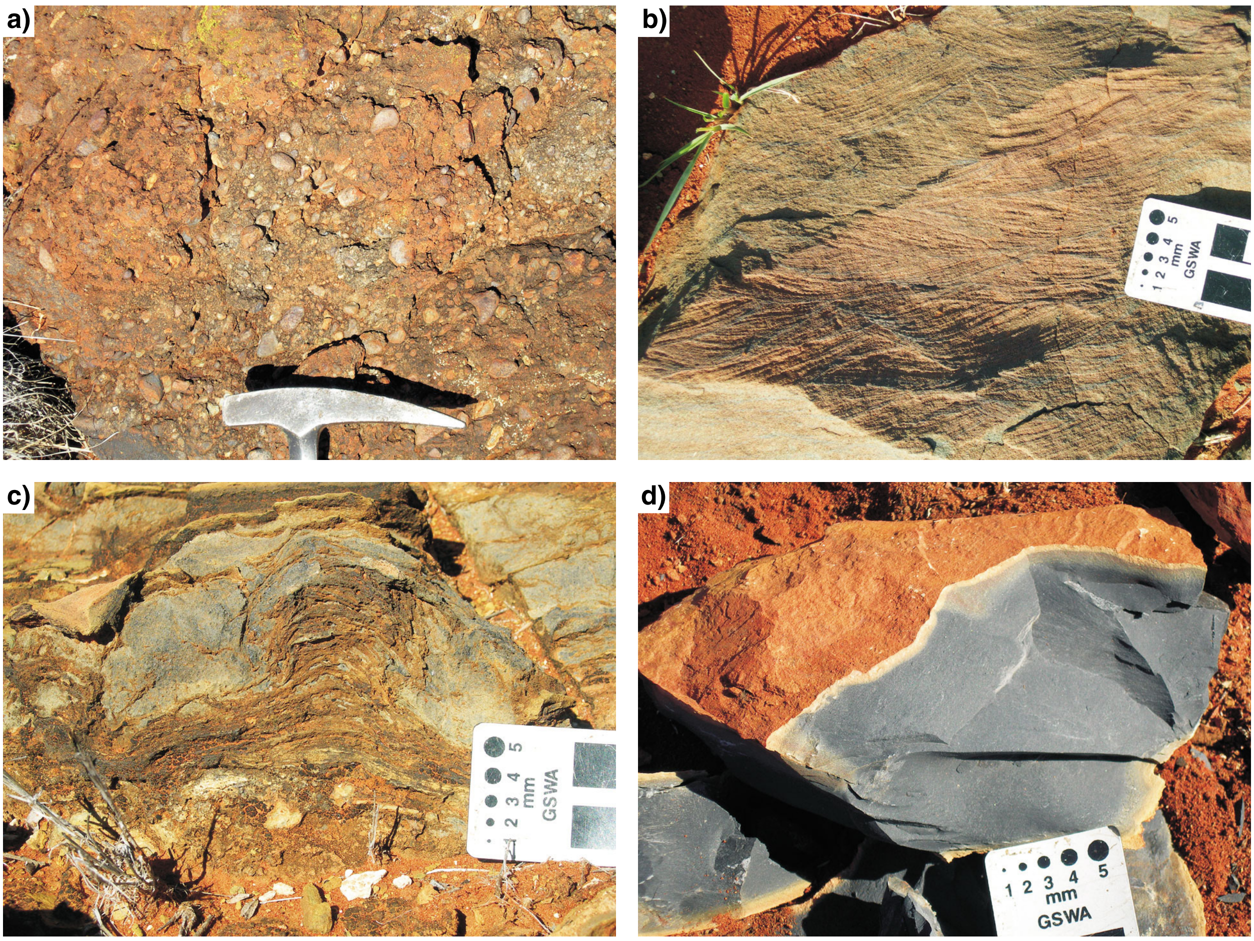

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Figure 42. Outcrop photographs of the Cassidy Group showing: a) Gamminah Conglomerate; b) ripple cross-laminated sandstone in the lower part of the Frank Scott Formation; c) stromatolites from the Frank Scott Formation; d) black shales in the Frank Scott Formation (central Mount Eveline).

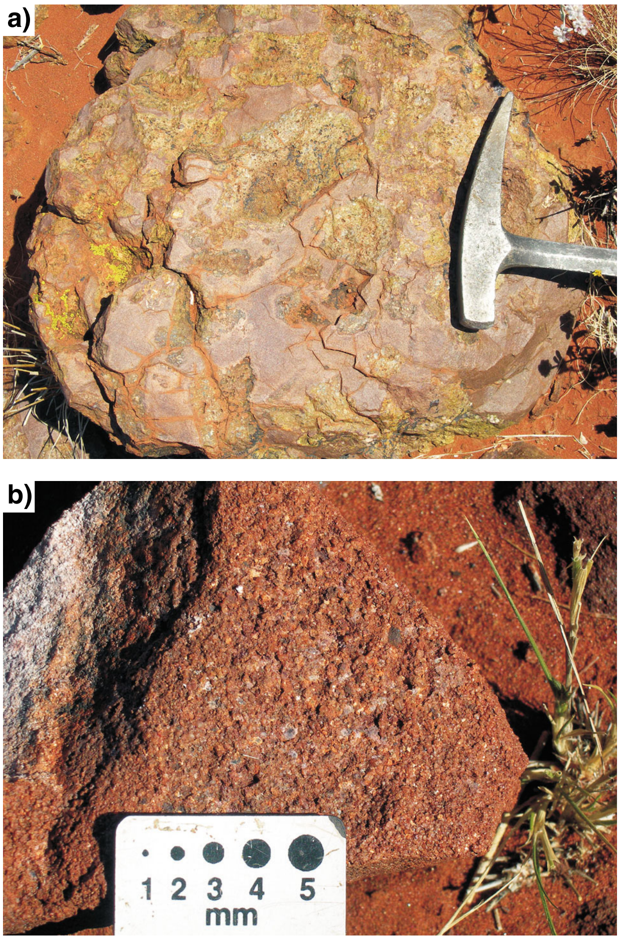

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Figure 43. Outcrop photographs of the Cassidy Group showing: a) peperite associated with basalts of the Milesia Formation; b) redbed-type sandstone in the Milesia Formation (central MOUNT EVELINE).

the western part of the Talbot Sub-basin, but is apparently unconformable in the area between Ranford Hill and Barrow Hill. However, it is still unclear if this apparently unconformable contact is a true erosional unconformity caused by uplift and erosion between deposition of the Milesia Formation and the Townsend Quartzite, or if the apparently unconformable contact is caused by younger (post-Townsend Quartzite deposition) tectonism that caused local detachment of the more rigid Townsend Quartzite from the underlying softer sandstone–shale sequence at the top of the Milesia Formation. It is also possible that this unconformable contact locally has both an erosional and a structural component.

Constraints on the depositional age of the Milesia Formation and the Townsend Quartzite are derived from the crystallization age of the underlying Thomas Rhyolite (of the Cassidy Group: 1057 ± 6 Ma; GSWA 174691, Kirkland et al., in prep.), and from the 825–800 Ma depositional age for the Bitter Springs Formation (Maidment et al., 2007), which overlies equivalents of the Townsend Quartzite in the Amadeus Basin.

The Ngaanyatjarra Rift

Summary

An intracontinental setting is indicated for the Musgrave Province for at least 150 m.y. before the Giles Event, and this is a setting in which the rocks have remained until the present day (Smithies et al., 2009; Evins et al., 2010). The sequence of events encompassed by the Giles Event describes a long-lived, failed intracontinental rift, which we refer to as the Ngaanyatjarra Rift. Rifting began with deposition of the Kunmarnara Group — a typical intracontinental rift sequence of basal conglomerates and sandstones, followed by basalt flows (the Mummawarrawarra Basalt). The Kunmarnara Group traces the rift-basin boundaries. The rift basin widens to 70 km to the west, where the Kunmarnara Group splits into a northern arm that trends northwest across the FINLAYSON map sheet, and a southern arm that trends southwest across the COOPER sheet (Fig. 10). The northern basin margin is defined by a major set of faults that can be traced west from the Blackstone Community, then northwest for a distance of over 100 km (Fig. 10). The southern basin margin follows the southern limb of the regional Blackstone syncline, and continues southwest to Mount Blyth where its basal contact is undeformed and well exposed.

Following deposition of the Kunmarnara Group, giant, layered mafic–ultramafic Giles intrusions were emplaced into the Mummawarrawarra Basalt. Emplacement of these sills represents an addition of ~10 km of dense material to the upper crust. Because of the lack of high-pressure and high-temperature assemblages at the bottom of these sills, their emplacement was likely accommodated by inflation and roof uplift. These events occurred sometime between c. 1078 and c. 1075 Ma; however, mutual contacts invariably show that the c. 1075 Ma massive gabbro and co-mingled leucogranite intruded fully crystallized Giles intrusions (Smithies et al., 2009). Therefore, immediately after emplacement of layered mafic–ultramafic Giles intrusions, c. 1075 Ma magmatism in the west Musgrave Province may have been characterized by mafic and felsic magmas focused along coeval, linear, shear zones (parallel to the Tjuni Purlka Tectonic Zone and the northern rift boundary). This magmatism was concomitant with macroscopic, upright folding in a transpressional setting — events indicative of basin inversion (Evins et al., 2010).

According to Evins et al. (2010), deformation ceased abruptly after intrusion of the massive gabbro and co-mingled leucogranite. Magmatic activity in the rift was sporadic thereafter, with at least four pulses of dominantly felsic magmatism alternating with ~10 m.y. long quiescent periods until approximately 1040 Ma.

Analogues

The Ngaanyatjarra Rift is similar in many respects to the Mid-Continental Rift in North America (Evins et al., 2010). Both rifts were distant from continental margins during their lifetime and failed to open into an ocean basin. Both have an episodic and complicated magmatic history that begins with basalt flows (1109–1107 Ma for the Mid-Continental Rift), followed by emplacement of large, layered mafic–ultramafic intrusions (the 1102–1094 Ma Duluth, Sonju Lake, and other intrusions in the Mid-Continental Rift), and a period of waning volcanism (1094–1086 Ma for the Mid-Continental Rift; Hanson et al., 2004). The first two stages in the Mid-Continental Rift were accompanied by voluminous felsic volcanism (Green and Fitz, 1993; Vervoort et al., 2007), producing similar lithologies to those found in the Ngaanyatjarra Rift. However, the Mid-Continental Rift differs from the Ngaanyatjarra Rift in several ways. Firstly, major magmatism in the Mid-Continental Rift spans about 25 m.y. as opposed to greater than 40 m.y. for the Ngaanyatjarra Rift. Secondly, the Mid-Continental Rift is dominated by mafic volcanic flows (flood basalts) rather than the intrusions seen in the west Musgrave Province. This may simply be the result of a deeper exposure level in the Ngaanyatjarra Rift. Thirdly, the main stage of felsic magmatism occurs much later in the evolution of the Ngaanyatjarra Rift than in the Mid-Continental Rift. Finally, in the Mid-Continental Rift, there is no evidence of a major synmagmatic deformation event.

Possible tectonic setting for the Ngaanyatjarra Rift

Several characteristics of the Ngaanyatjarra Rift can be used to exclude hypothetical mechanisms for the formation of the rift (Evins et al., 2010). The earliest sedimentary package (Kunmarnara Group) is relatively thin, with no evidence of rapid regional uplift. This excludes lithospheric delamination (Elkins-Tanton, 2005) as a cause of rifting. There was no thick sedimentary cover preceding initiation of the Ngaanyatjarra Rift, which also rules out a thermal blanket scenario (Sandiford and Hand, 1998) for rift initiation. Distance from, and orientation to, coeval plate boundaries preclude the Ngaanyatjarra Rift from being a back-arc. This leaves plume-related (active) or far-field extensional or transtensional (passive) settings the most likely setting for this type of rift.

Recent dating now indicates that the giant Giles intrusions, and voluminous massive gabbros and co-mingled leucogranites, are constrained within a narrow time span from c. 1078 Ma to 1074 Ma. This represents a large volume of magma emplaced over a short time period coeval with the c. 1075 Ma Warakurna Large Igneous Province. A mantle plume could be the heat source for such magmatism.

Alternatively, a local, transtensional setting might be more appropriate for the formation of the east–west trending Ngaanyatjarra Rift (Evins et al., 2010). This local, transtensional setting may have been a far-field effect from an overall, regional east–west compressional stress field formed due to the collision of India ~1000 km to the west during the c. 1080 Ma Pinjarra Orogeny (Wilde, 1999; Fitzsimons, 2003). Zhao (2009) suggests that the extension in some intracontinental rifts, such as the Baikal Rift, may be due to far-field slab-pull stresses along a subduction zone parallel to the rift margin. For the Ngaanyatjarra Rift to form by this mechanism, a hitherto unknown subduction zone in the Mawson Craton to the south is required. Furthermore, the Ngaanyatjarra Rift is a larger and much more magmatically complex rift than the Baikal Rift. A comparable scenario may have been the setting for the Mid-Continental Rift of North America (Van Schmus and Hinze, 1985; Ojakangas et al., 2001) and for the emplacement of the Bushveld Complex in southern Africa (Clarke et al., 2009).

Smithies et al. (2010) have shown that thermal events related to the Musgrave Orogeny span a ~100 m.y. period to a minimum age of 1119 ± 7 Ma. Accordingly, it might be fair to regard the Giles Event as a late component of the Musgrave Orogeny: a combined high-temperature metamorphic and magmatic period spanning about 200 m.y. between c. 1220 and 1020 Ma. Smithies et al. (2010) proposed that these circumstances came about because the pre- Musgrave Orogeny crustal architecture was characterized by the relatively thin crust of the Musgrave Province lying between thicker, Archean-cored West Australian, North Australian, and South Australian Cratons (Fig. 25). This region of thinner crust could either channel upwelling asthenosphere in an active plume scenario, or, as a relatively weak zone, become the locus of extension or transtension due to far-field (passive) stresses from plate boundary interactions.

Mafic dykes younger than the Giles Event

Kullal Dyke Suite (c. 1000 Ma)

Dykes belonging to the Kullal Dyke Suite (c. 1000 Ma) are fine-grained olivine and plagioclase porphyritic dolerites. They are mostly northeast-trending, and are most common in the Michael Hills and Hinckley Range regions. They crosscut the igneous layering of the ≥1078 Ma Giles intrusions, and are crosscut by the c. 825 Ma Gairdner Dolerite. A poorly constrained Sm–Nd mineral isochron age of 1000 Ma was obtained for one of the dykes (S-S. Sun, unpublished data; Glikson et al., 1996). The dykes are chemically more primitive than many of the other suites, with high MgO (mostly 9 to 13 wt%), and Ni (132–291 ppm) reflecting their high olivine content. Nevertheless, they have LREE-enriched profiles ($La/Sm_{(PM)}$ = mostly 2.8 to 3.5 (slightly lower than that of the Alcurra Dolerite)), high $Gd/Yb_{(PM)}$ ratios (1.6 – 2.0), but at significantly lower REE abundances than the Alcurra Dolerite. They have a slightly negative niobium anomaly, suggesting limited crustal contamination. ε_{Nd} values of the olivine dolerite dykes range from 0.65 to -2.84, when calculated at t = 1000 Ma.

An unnamed plagioclase-rich suite of dykes clearly post-dates the ≥1078 Ma layered Giles intrusions, but their relationship with younger mafic dyke suites is uncertain. They are northwesterly to north-northwesterly trending, subophitic to ophitic dolerite dykes with 60–65% plagioclase. The dykes have flat, unfractionated,

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Figure 44. Outcrop photographs of a tourmaline-bearing pegmatite from the Murray Range (eastern HOLT).

primitive mantle-normalized trace element patterns with generally slight negative niobium anomalies. ε_{Nd} values of two dykes are 0.58 and -2.06, calculated at t = 1075 Ma (the maximum age of the unnamed plagioclase-rich dolerites).

Gairdner Dolerite (c. 825 Ma)

Intrusions related to the Gairdner Dolerite are mostly northwest- to north-trending and extend from the Gawler and Stuart Shelf to the Musgrave Province. One dyke in Western Australia yielded a zircon U–Pb age of 824 ± 4 Ma (Glikson et al., 1996), similar to the baddeleyite U–Pb age of 827 ± 6 Ma for a Gairdner dyke on the Stuart Shelf (Wingate et al., 1998). Amata Dolerite dykes, which are confined to the east Musgrave Province, have been linked to the Gairdner Dolerite on the basis of similar chemistry and age (Glikson et al., 1996) — one Amata Dolerite dyke sample yielded an imprecise Sm–Nd age of 790 ± 40 Ma (Zhao et al., 1994). The Gairdner Dolerite crosscuts the Kullal Dyke Suite and layered Giles intrusions (e.g. the Hinckley Range intrusion and Michael Hills intrusion). The dykes are medium-grained, intergranular to subophitic dolerite, but show polygonal granoblastic textures where recrystallized. They have slightly enriched primitive mantle-normalized incompatible trace element profiles ($La/Sm_{(PM)}$ = 1.8 – 2.9), and a slight negative niobium anomaly. Neodymium data for two dykes gives ε_{Nd} values of +2.39 and +3.81 (calculated at t = 800 Ma), generally lower than the range of +3.1 to +4.9 for these dykes in the Northern Territory (Scrimgeour et al., 1999) but consistent with the ε_{Nd} values of +2.4 to +4.3 for the Amata Dolerite and rocks of the Gairdner Dolerite in South Australia (Zhao et al., 1994).

Unnamed dykes (c. 750 Ma)

The youngest mafic dykes to intrude the Musgrave Province are a suite of unnamed LREE-depleted dykes. Their orientation varies from east-northeast to northwest. These are medium-grained, massive, ophitic- to subophitic-textured metagabbros that are characterized by distinctive depletions in incompatible trace elements, and by high ε_{Nd} values. The LREE-depleted dykes have La/Sm ratios of 0.8 to 1.5, and flat heavy rare earth element (HREE) profiles (Gd/Yb = 1.3 – 1.7), compared with the other suites of dykes. They also have a slightly negative niobium anomaly and ε_{Nd} values ranging from +4.58 to +4.60.

A three-point Sm–Nd age determination has yielded a 747 ± 48 Ma isochron (GSWA, unpublished data), suggesting that the rocks are either part of the c. 800 Ma magmatic event that produced the Gairdner Dolerite and Amata Dolerite of South Australia (Zhao et al., 1994), or a slightly younger suite, possibly contemporaneous with the 755 Ma Mundine Well Dolerite Suite of northwestern Australia (Wingate and Giddings, 2000).

Additional felsic magmatic events (c. 1000 Ma and c. 625 Ma)

In addition to the felsic magmatic events outlined above, at least two younger periods of felsic magmatism affected the west Musgrave Province. A thin, southwest-trending, undeformed garnet-bearing aplite dyke cuts granites formed during the Musgrave Orogeny immediately to the east of Mount Fanny, and has been dated at 995 ± 8 Ma (GSWA 183597, Kirkland et al., in prep.). This age is similar to a c. 1000 Ma Sm–Nd isochron age determined on an olivine-bearing Kullal dyke from the Musgrave Province (Glikson et al., 1996).

A series of undeformed tourmaline-bearing pegmatites (Fig. 44) intrude massive gabbro in the Murray Range, and have been dated at 625 ± 11 Ma (GSWA 187175, Kirkland et al., 2011i). This igneous age broadly corresponds to the 650–611 Ma magmatic event within the Telfer region of the Paterson Orogeny, in northwestern Western Australia (Rowins et al., 1997).

Although both of these felsic magmatic events appear to be rather inconsequential volumetrically, the significance of the tectonothermal event to which they relate is very difficult to determine. It is likely that extensive dehydration resulting from several previous tectonothermal events had exhausted the capacity of the crust to produce voluminous anatectic melts under most realistic conditions.

Petermann Orogeny

Structural and metamorphic aspects of the Petermann Orogeny have been the subject of intense study over the past 15 years. Camacho and Fanning (1997) and Camacho et al. (1997, 2001, 2009) have focused mainly on the Davenport Shear Zone (Northern Territory) and the timing of deformation. Lambeck and Burgess (1992) proposed that the area between the Woodroffe Thrust and Mann Fault represented a flower structure. Recently, Raimondo et al. (2009, 2010) have looked at the timing, metamorphism, and kinematics of the western portion of the Petermann

Orogeny, and rectified apparently paradoxical shear senses in the same area. Scrimgeour and Close (1999) presented detailed work on the high-pressure assemblages associated with the core of the orogeny.

Deformation during the Petermann Orogeny was focused along the northern margin of the Musgrave Province as east-trending shear zones that dissect the deep crust and divide the province into two main domains characterized by different structural styles and metamorphic grades (Camacho, 1989; Major and Conor, 1993). The Mulga Park Zone north of the Woodroffe Thrust is characterized by amphibolite-facies metamorphism, and is structurally dominated by the Petermann Nappe Complex in the Northern Territory. The Fregon Zone between the Woodroffe Thrust and Mann Fault (Fig. 4) is considered the core of the Petermann Orogen. It is characterized by granulite-facies metamorphism and contains several important faults. From north to south these are the Woodroffe Thrust, Cockburn Shear Zone, Davenport Shear Zone, Mann Fault, Wingellina Fault, and Hinckley Fault (the latter three occurring in the west Musgrave Province). These shear zones were active over short time scales (up to 1.4 m.y.; Camacho et al., 2009). Of these shear zones, only the Woodroffe Thrust shows a reverse sense of movement.

Temperature and pressure estimates from rocks in the Fregon Zone reach 700–800°C and 13–14 kbar, indicating a depth in excess of 40 km (Scrimgeour and Close, 1999; Edgoose et al., 2004). Decompression from high pressures is evident in the same rocks, with distinctive garnet–clinopyroxene symplectites enclosing magmatic pyroxene and hornblende in low-strain zones, and dynamically recrystallized aggregates of clinopyroxene, garnet, hornblende, biotite, and ilmenite in high-strain zones. Plagioclase is typically recrystallized to kyanite and garnet throughout (Clarke and Powell, 1991; Scrimgeour and Close, 1999). Sm–Nd dating of garnet from the high-pressure assemblages described above confirms they grew during the Petermann Orogeny (Camacho, 1997).

On Bates, mylonite zones parallel to, and only a few kilometres south of, the Woodroffe Thrust dip to the south and southwest and display a normal shear sense. These normal kinematics dominate all the way south to the Mann Fault. Farther east, shear zones are thinner and contain only greenschist- to amphibolite-facies fabrics. Their lineations pitch closer to strike, and dextral kinematics have been interpreted (Camacho and McDougall, 2000). In the west Musgrave region, the Mann Fault has sinistrally displaced contaminated gabbros of the Hinckley Range (south of the fault) by 30 km to the west, where they are exposed (north of the fault) as the Murray Range, marking the northeastern edge of the Tjuni Purlka Tectonic Zone. These apparently divergent, strike-slip shear senses on either side of the Petermann orogenic core may represent escape tectonics akin to the strike-slip faults that frame the Himalayan foreland. Within the Tjuni Purlka Tectonic Zone, the continuation of the Mann Fault is lost into a series of northwest-trending splays, and the effects of the Petermann Orogeny decrease rapidly to the southwest. Very little evidence for Petermann-aged deformation is present throughout the Mamutjarra Zone.

The 10 km wide mylonite between the Davenport Shear Zone and Mann Fault is more thoroughly recrystallized, and contains a higher percentage of leucosome generated along individual shear zones than to the north or south (Camacho, 1997; Scrimgeour and Close, 1999). The abrupt, typically <1 m thick, transition to these migmatitic zones highlights the localization of their heat source, which is assumed to be shear heating (Camacho et al., 2001). Zircon interpreted to have crystallized within these leucosomes has been dated at 561 ± 11 Ma (Scrimgeour et al., 1999), providing the most reliable estimate of the age of the Petermann Orogeny. Similar zones of partial melting are found in mylonites in the west Musgrave Province, on Bates. Zircon from syndeformational leucosomes in these mylonites has given an age of 570 ± 25 Ma (GSWA 155735, Walker-Hallam, 2009), and the timing of initial titanite crystallization has been determined to be c. 570 Ma (Raimondo et al., 2009).

The Fregon Zone core of the Petermann Orogeny has been interpreted as a crustal-scale, dextral transpressive system, cored by a pop-up wedge exhumed by channel flow (Lambeck and Burgess, 1992; Camacho and McDougall, 2000; Raimondo et al., 2009, 2010). North-directed transport was accommodated by the Woodroffe Thrust, and south-directed overthrusting was concentrated along the Mann Fault and wider Davenport–Cockburn Shear Zone, which forms the core of the exhumed wedge.

Mineralization in the west Musgrave Province

The first mineral discovery in the west Musgrave region was that of nickeliferous laterite at Wingellina in 1956. The province is well endowed with a number of mineral deposits and occurrences, mostly hosted in rocks of the Warakurna Supersuite, including the mafic–ultramafic Giles intrusions. These include orthomagmatic mineral systems (nickel–copper sulfides; iron–titanium–vanadium oxides) and the above mentioned lateritic nickel deposit. Hydrothermal base and precious metal occurrences are widespread, including veins and stratabound mineral systems. The distribution of mineral deposits and occurrences in the west Musgrave region is shown in Figure 45. Mineral exploration in the region is currently focused largely on hydrothermal systems hosted in felsic rocks, resulting in some recent exciting discoveries (see below). Here, we describe key aspects of mineral systems in the west Musgrave region within the constraints of the limited amount of information and data (published or unpublished) available.

Mineralization in the Warakurna Supersuite

The nickel–copper and PGE potential of the Giles intrusions has attracted the interest of exploration companies for many years. The distribution of nickel–copper sulfide and lateritic nickel occurrences in the Giles intrusions is shown in Figure 45. In addition, poorly explored occurrences have been recently identified northwest of Jameson, and include copper-mineralized

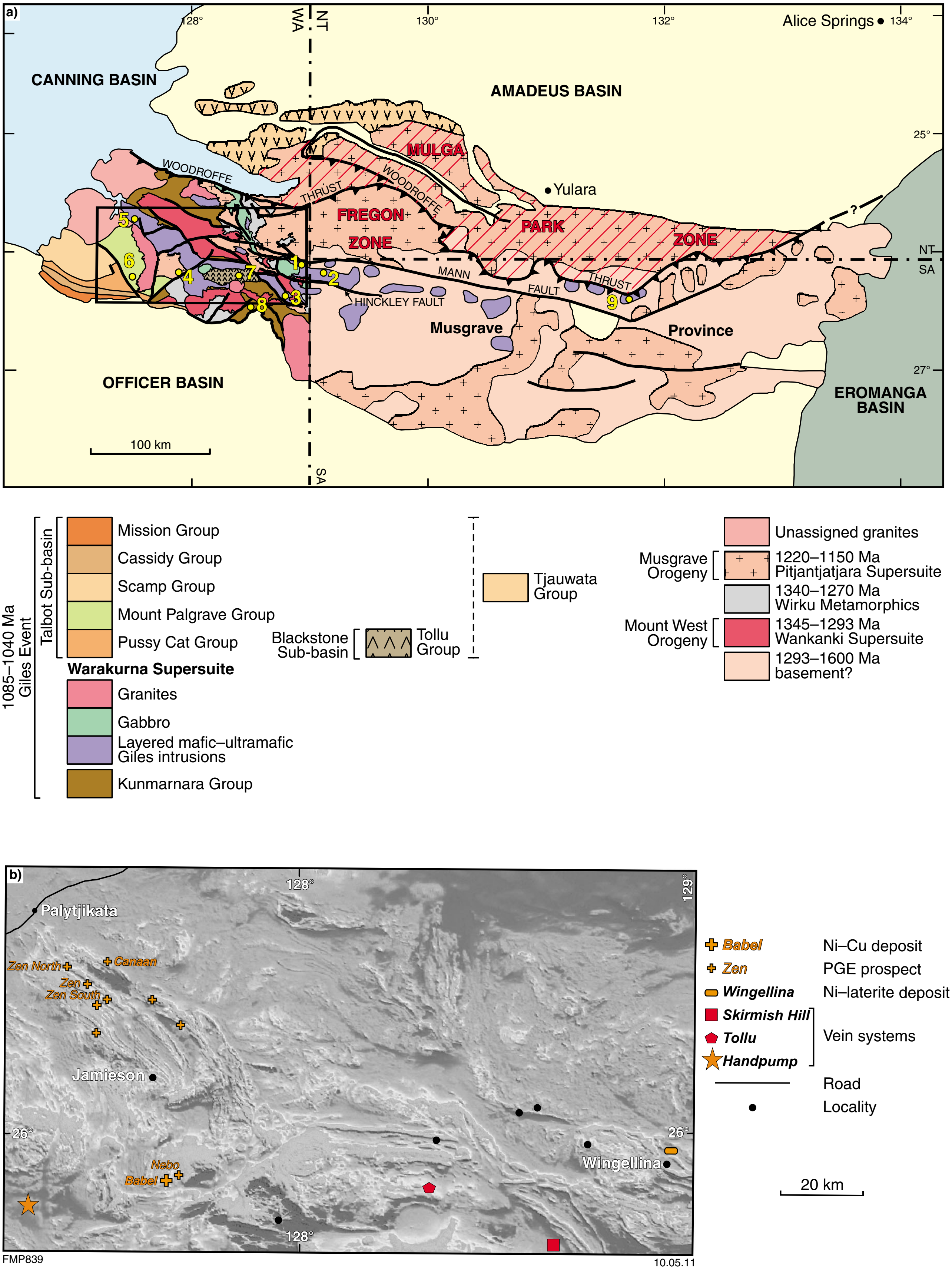

Figure 45. a) simplified map of the Musgrave region and distribution of selected mineral deposits and occurrences: 1) Wingellina, 2) Claude Hills, 3) Bell Rock, 4) Nebo–Babel, 5) Zen–Canaan group, 6) Handpump, 7) Tollu, 8) Skirmish Hill, 9) Mt Caroline; b) Grey-scale TMI image of area outlined in part a), and distribution of nickel–copper and PGE occurrences. After Pirajno et al. (2006).

gabbro and mafic dykes of the Alcurra Dolerite (Howard et al., 2009).

Economically significant mineral deposits discovered to date in the Warakurna Supersuite of the west Musgrave region are:

- Wingellina Hills nickel lateritic ochre deposit, initially estimated to contain 227 Mt @ 1% Ni and 0.07% Co (Acclaim Exploration, 2003)
- Jameson Range stratiform vanadiferous magnetite deposits, estimated at 100 Mt @ 1% V_2O_5 (Daniels, 1974)
- Nebo–Babel disseminated to semi-massive nickel–copper–PGE sulfides, hosted by a gabbronorite intrusion south of the Jameson Range (Seat et al., 2007).

Wingellina nickeliferous ochres and chrysoprase

The world-class Wingellina laterite nickel deposit was discovered by INCO in 1956. The Wingellina laterite is a yellow-brown to dark-brown ochre material (Fig. 46a), which is composed of goethite, manganese oxides, gibbsite, and kaolinite, and is derived from the weathering of dunite and peridotite of the layered Wingellina Hills intrusion. The ochre material is best developed at the base of the Wingellina Hills, where lateritic weathering extends to a depth of at least 200 m (Acclaim Exploration, 2003). The ochres formed by selective leaching of SiO_2 and MgO, which is especially pronounced along shear zones, and the resulting passive concentration of residual alumina, iron oxides, and nickel. The lateritic material is locally cut by semiprecious, pale green chrysoprase. The Wingellina ore is exposed at surface, with thicknesses of up to 200 m and an average thickness of 80 m. The deposit also has a high aspect ratio, and therefore a very low strip ratio (Fig. 46b). The metal resources of the Wingellina deposit are reported at 183 Mt at ~1% Ni and 0.07% Co, with 1.8 Mt of contained metal (Metals X Ltd; <http://metalsx.com.au/operations/wingellina_nickel/>).

Limonitic ochre material is also present in the southeastern part of the Bell Rock intrusion. At this locality, excavations exposed laterite, ochre, and chalcedonic veins above a zone of saprolite. This zone of laterite and ochre has an east–west trend. A grab sample of the ochre material assayed 1.2% Ni (Pirajno, unpublished data).

Nebo–Babel nickel–copper(–PGE) deposit

The Nebo–Babel nickel–copper(–PGE) sulfide deposit is located approximately 25 km south of Jameson, and 125 km west of the Wingellina communities (Fig. 45). In April 2002, Western Mining Corporation (now part of BHP Billiton) announced a drill intersection of 26 m @ 2.45% Ni, 1.78% Cu, and 0.09% Co at the Nebo–Babel prospect. This deposit represents the largest nickel sulfide discovery since that of Voisey's Bay in Canada (Seat et al., 2007). The Nebo–Babel deposit was discovered by conventional deflation lag geochemical sampling (Baker and Waugh, 2004). Resource estimates, obtained from 90 drillholes, are 392 Mt at 0.30% Ni and 0.33% Cu, with about 70% of the total resource hosted in the Babel sector (Seat et al., 2007). PGE within sulfides have combined contents ranging from 103 to 488 ppb (mostly platinum and palladium); the PGE contents from two massive sulfide samples are 798 and 628 ppb. A detailed study of the Nebo–Babel nickel–copper–PGE deposit was carried out by Seat (2008) and Seat et al. (2007, 2009). These works provide a considerable amount of data on the geology, petrography, geochemistry, isotope systematics, and mineralization of Nebo–Babel, and for this reason, the following, which is summarized from Seat (2008) and Seat et al. (2007), is more detailed than other topics in this section.

The mafic–ultramafic intrusion hosting the Nebo–Babel sulfide deposit has been dated at 1068 ± 4 Ma (U–Pb (SHRIMP) date on zircon; Seat, 2008). It has a tubular shape (defined as a chonolith; Bates and Jackson, 1987) trending approximately north-northeast to east, and can be traced for about 5 km. It has a cross section of 1 km by 0.5 km. The chonolith has a gentle west-southwest plunge of less than 10°, and dips to the south at ~15°. The tube-like intrusion was emplaced in felsic orthogneiss of the Pitjantjatjara Supersuite. Seat and co-authors (2009) noted that this basement has whole-rock sulfur abundances of less than 100 ppm, which precludes basement rocks as a possible sulfur contaminant for the precipitation of nickel–copper sulfides (see below). The chonolith intrusion is offset by the Jameson Fault (Fig. 47), which effectively separates or divides it into the Nebo section in the east and the Babel section in the west. The dominant rock types that make up the intrusion comprise gabbronorite and leucogabbronorite. The lithostratigraphy of the intrusion is characterized by an upper marginal breccia zone (MBZ), followed by a chilled margin, variably textured leucogabbronorite (VLGN), melagabbronorite (mela-GN), and mineralized gabbronorite (MGN; present only in the Babel sector), and barren gabbronorite (BGN), which in the Nebo sector is associated with oxide–apatite gabbronorite (OAGN). The base of both sectors contain VLGN with a chilled margin at the contact with the basement rocks, so that VLGN forms a shell around the MGN. A massive and coarse-grained troctolite unit, about 15 m thick, occurs at Babel, and is located between VLGN and BGN in the upper parts of the intrusion. Rhythmic layering is present but small-scale, confined to the upper parts of the Babel sector, and consists of 5–15 cm thick layers of plagioclase–pyroxenite grading upward into gabbronorite. The OAGN is present at Nebo, where it constitutes about 20–30% of the unit, and is characterized by oxide-rich layers 5–30 cm thick, with gradational bases and sharp upper contacts.

The mineralized gabbronorite rocks have a uniform grain size (5–20 mm), and consist of 55–65 vol% plagioclase, 15–25 vol% orthopyroxene, and 5–10 vol% clinopyroxene. Other minerals include ilmenite, magnetite, biotite, and apatite. Sulfides are monoclinic pyrrhotite, pentlandite,

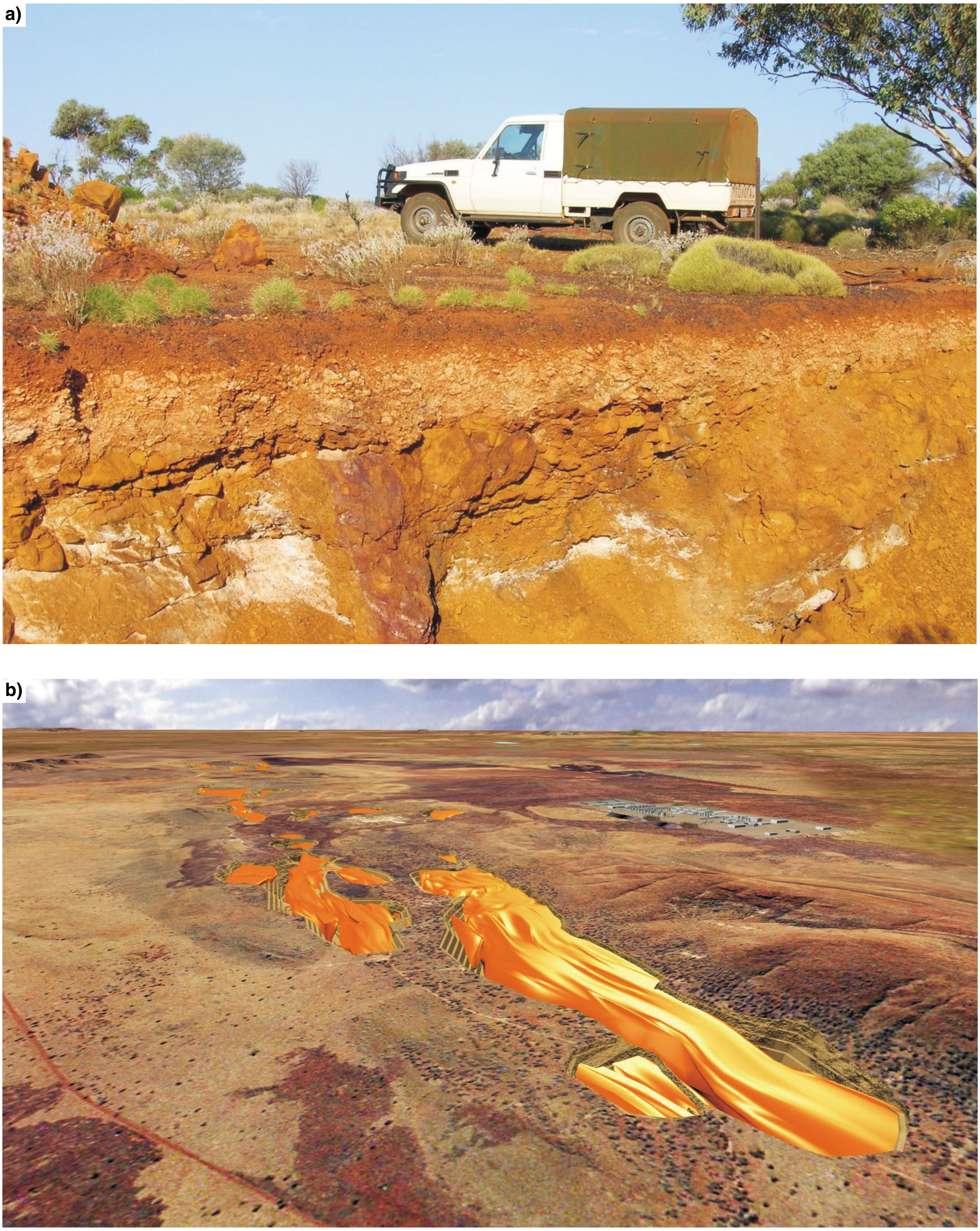

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Figure 46. a) Wingellina nickeliferous ochre material, exposed in an exploration costean; b) 3D computer model of nickel orebody (from Metals X Ltd, <http://metalsx.com.au/operations/wingellina_nickel/>)

chalcopyrite, and pyrite. The sulfide mineralization exhibits two styles: massive, with associated sulfide breccias and stringers; and disseminated, generally interstitial blebs in the gabbronorite unit (MGN). Other sulfides are present, but only in trace amounts, and include bravoite, sphalerite, and galena. Tellurides and altaite are also present, but only detected by scanning electron microscope (SEM). PGE minerals that have been identified are moncheite ($PtTe_2$), merenskyite ($PdTe_2$), and michenerite (PdBiTi).

Sulfur isotopic data show a narrow range of $\delta^{34}S$ values from 0 to +0.8‰ (CDT standard), clearly indicating a mantle source (Fig. 48); these compare well with other systems, such as Jinchuan and Voisey's Bay. Notably, there is a remarkable difference in $\delta^{34}S$ values with magmatic sulfide from the Noril'sk system, where the sulfur was likely derived from country rocks that include evaporites. At Noril'sk, the sulfur introduced from country rocks enabled oversaturation of the mafic melts, thereby promoting the precipitation of sulfides (see Naldrett, 2004, for a review). This does not appear to be the case for the Nebo–Babel mineralization (Seat et al., 2009).

Seat et al. (2007) suggested an emplacement model for the Nebo–Babel intrusion, shown in Figure 49 and briefly discussed here. The intrusion was emplaced as a continuous influx of melt. The initial magma was probably intruded along a shear zone or a fault, more or less parallel to the regional foliation. In the first stage, chilled margins and the VLGN units were emplaced. This is shown by the progressive coarsening of the chilled margins toward the VLGN, and chilled margin xenoliths within the VLGN rocks. Both chilled margin and VLGN units carried sulfides, indicating that these were injected as a series of magma pulses. The emplacement of the VLGN units was followed by the MGN unit (Stage 2), which was intruded into the hot and insulated VLGN core zone, resulting in the breakup of the VLGN unit and in further inflation of the conduit. This magma was also sulfide-oversaturated, as shown by the occurrence of disseminated sulfide blebs. The MGN magma was followed, during stage 3, by a new pulse of more fractionated magma that was intruded between VLGN and MGN, forming the BGN unit. The flow of MGN magma is assumed to have been from the southwest, because the unit thins out towards the northeast, becoming progressively more fractionated in the same direction. Several generations of dykes intruded the Nebo–Babel area, and, at much the same time, post-magmatic hydrothermal alteration occurred, deformation overturned the Nebo–Babel intrusion, and movement along the Jameson Fault bisected the intrusion.

The Nebo–Babel massive and disseminated sulfide ores are confined to the early and more primitive magmatic pulses. The massive sulfides underwent fractional crystallization of a sulfide liquid. This process can

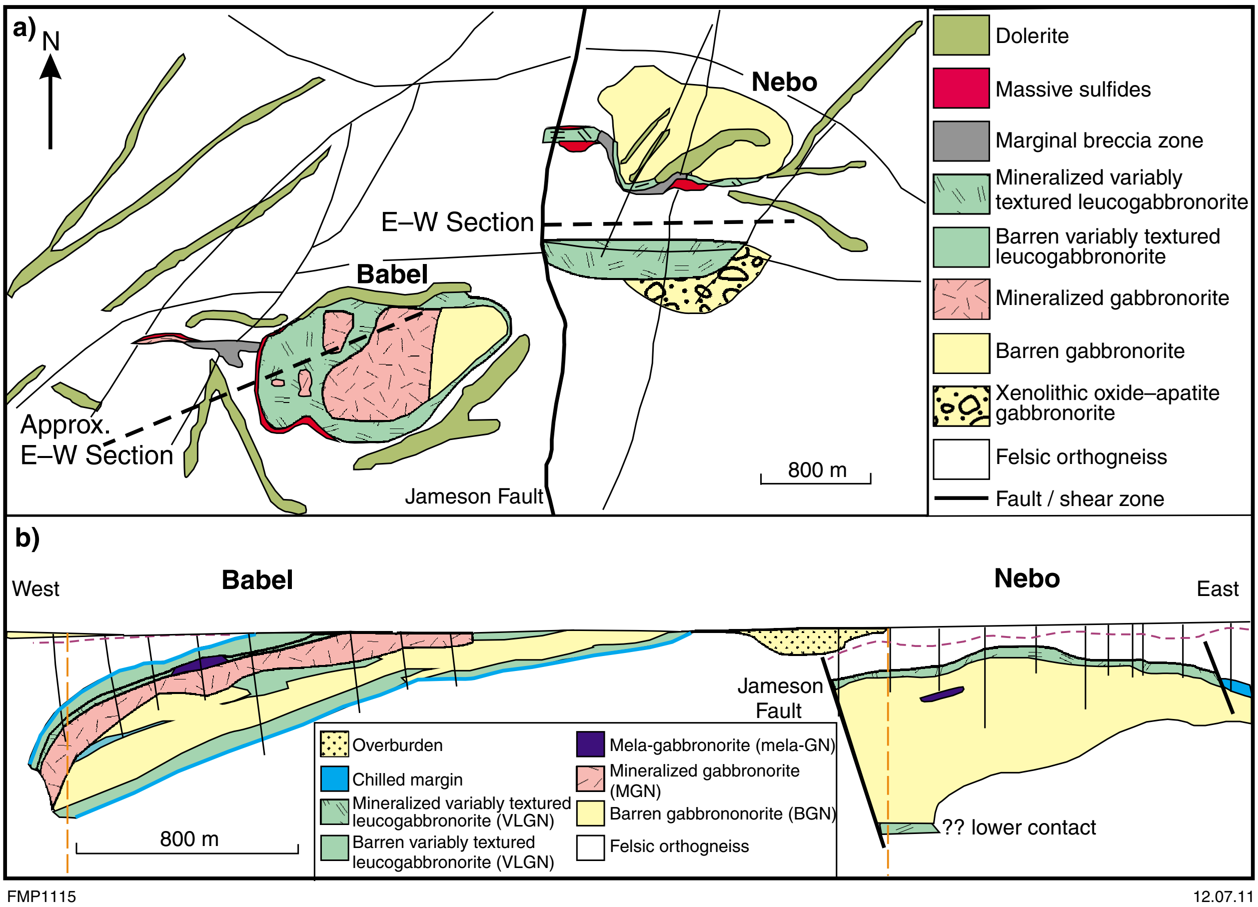

Figure 47. a) simplified geology of the Nebo–Babel chonolithic intrusion; b) east–west section through the intrusion; after Seat et al. (2007).

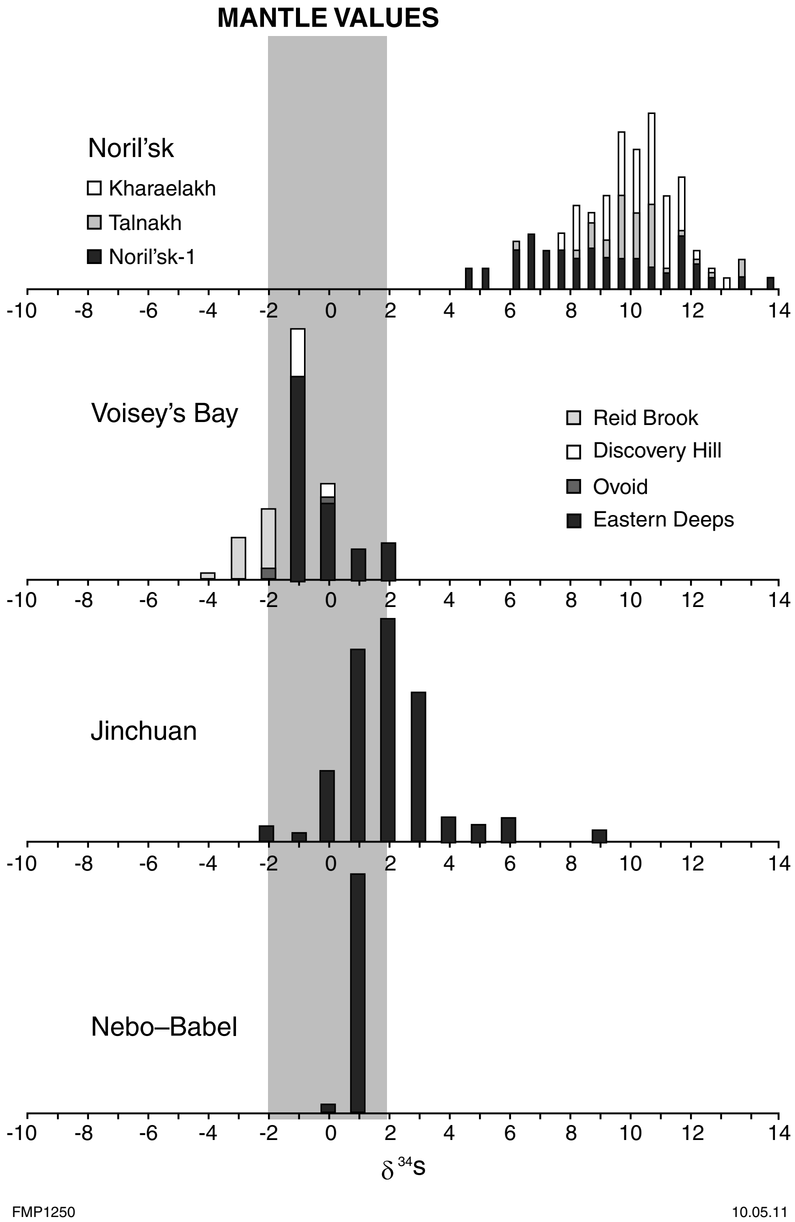

Figure 48. Sulfur isotopic data from Nebo–Babel, Jinchuan, Voisey's Bay, and Noril'sk; details in text. Modified after Seat et al. (2009).

produce an iron-rich cumulate with osmium, iridium, and ruthenium, and a copper-rich liquid enriched in gold, silver, platinum, and palladium. Sulfide globules in chilled margins indicate that sulfide segregation was an early process in the compositional evolution of the parental magma, and, as such, may have occurred prior to its intrusion. Furthermore, the presence of trace amounts of sulfide blebs shows that the entire magmatic system must have been sulfur-saturated. As mentioned above, sulfur contamination from sulfur-rich country rocks (sulfide- or sulfate-bearing) is unlikely to have occurred. Instead, sulfur may have been mantle-derived, and the distribution of sulfides controlled by changes in magma velocity, in turn related to changes in the orientation of the conduit from southwest to east and northeast. Thus, magma flow regime and dynamics would have played a major role in the precipitation and distribution of sulfides in the Nebo–Babel deposit (Seat et al., 2009).

Vanadiferous titanomagnetite

In the Jameson Range, Blackstone Range, and Bell Rock Range troctolite–gabbro intrusions, there are layers and lenses of vanadium-bearing titanomagnetite and ilmenite. These are most abundant in the upper portion of the Jameson intrusion, where they may be of economic importance. In the other two intrusions (Blackstone and Bell Rock), from which the upper magnetite-rich troctolite portion was removed, titanomagnetite forms

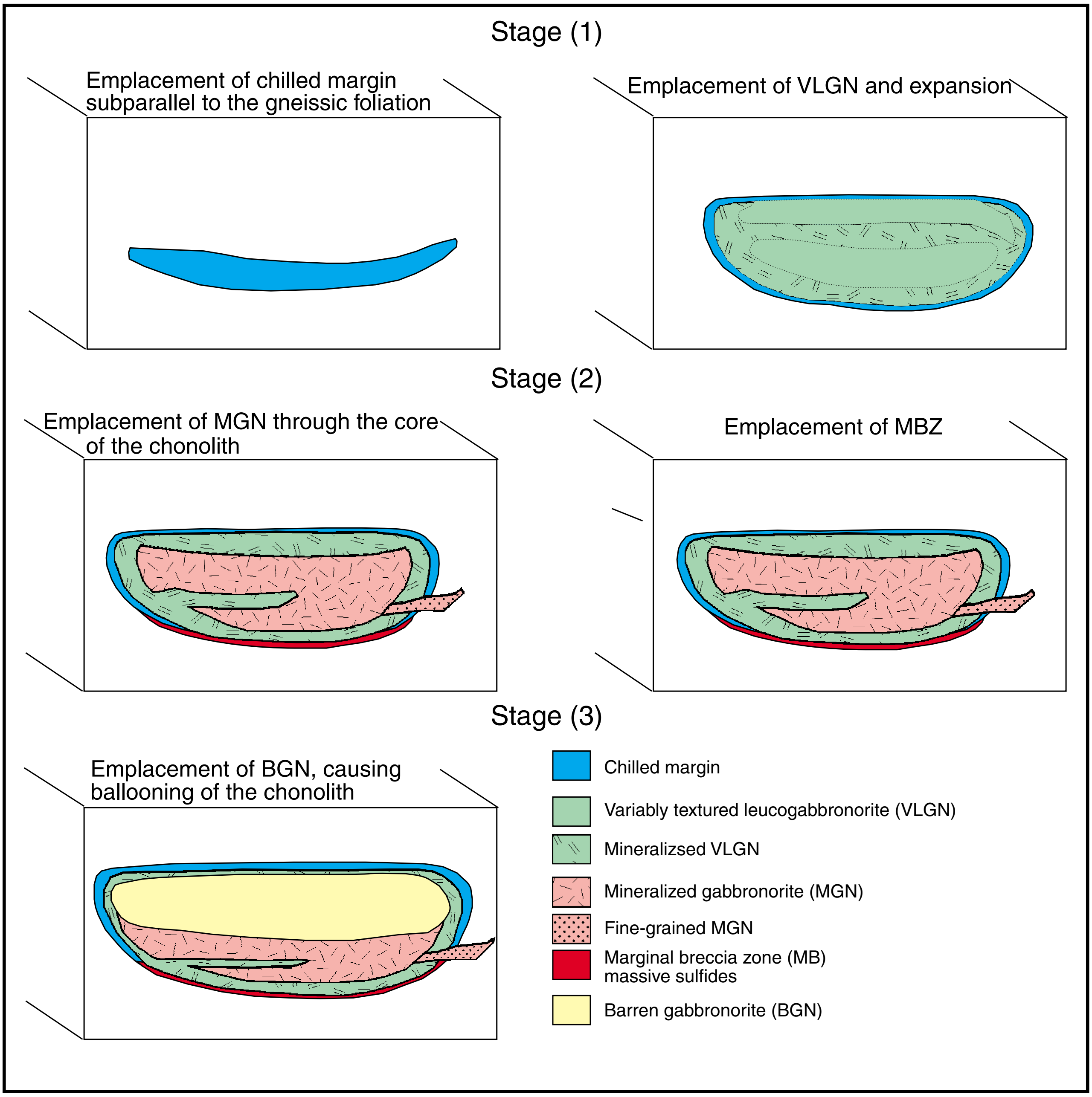

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Figure 49. Schematic representation of the evolution of the Nebo–Babel intrusion; details in text; modified after Seat et al. (2007)

minor, thin, discontinuous, units or lenses no more than 30 cm thick. In other parts of the Giles intrusions, magnetite forms small pods in shear zones (Daniels, 1974). The Jameson Range troctolite–gabbro rocks have been traced along strike for about 66 km, with layering dipping 30° to the southwest. Daniels (1974) recognized four zones: Zone 1 at the base, about 460 m thick and characterized by glomeroporphyritic gabbro; Zone 2, up to 320 m thick and comprising well banded lherzolite and magnetite–ilmenite-bearing lherzolite; Zone 3, about 760 m thick and characterized by rhythmically layered troctolite units; and Zone 4, up to 3000 m thick, a layered sequence of hypersthene troctolite, troctolite, olivine gabbro, and hypersthene gabbro, with titaniferous magnetite bands.

Zone 2 in the northeast of the range contains from 20 to 50 vol. % opaque minerals (probably all titanomagnetite) in the ultramafic layers, with the V_2O_5 tenor estimated at about 1.4 wt%. Zone 4, located in the southwest, has at its base a band of titaniferous magnetite, which has been traced along strike for about 19 km. At one locality, this band reaches a thickness of 15 m. Analyses of samples from this band yield an average of 0.9 wt% V_2O_5 and 23.4 wt% TiO_2 (Daniels, 1974). Zone 4 has more titaniferous magnetite layers towards the upper parts of the sequence, where one of these bands can be traced intermittently for 37 km, with thicknesses of up to 61 m at an average of 0.79 wt% V_2O_5. Daniels (1974) also noted compositional variations of vanadium, titanium, iron, chromium, and phosphorus with stratigraphic height. The higher magnetite bands have lower vanadium and titanium, and higher iron, chromium, and phosphorus, which he attributed to the more advanced fractionation of the liquids.

Hydrothermal gold mineralization and vein systems

The Handpump prospect is a recent discovery of hydrothermal gold mineralization, located on the southern margin of the Palgrave area (formerly Palgrave Cauldron; eastern MOUNT EVELINE), and about 40 km east of Nebo–Babel (Fig. 45; Tan, 2010). In this area, a soil gold anomaly, first reported in the 1990s by Western Mining Corporation Ltd, was followed up by detailed sampling, resulting in the recognition of gold-bearing felsic rocks carrying values of between 0.5 and 1.2 g/t Au (Beadell Resources Ltd, 2009a). A programme of systematic drilling intersected a 300 m wide (?hydrothermal) rhyolitic breccia. Gold assays from one of the drillholes yielded 0.83 g/t Au over 65 m, including zones grading 5.1 g/t Au over 5 m, and 2.3 g/t Au over 15 m. Additional intersections (e.g. 11 m at 1.1 g/t Au; Beadell Resources Ltd, 2009b) have outlined a series of parallel mineralized zones hosted in rhyolitic breccias, steeply dipping to the north.

About 35 km southwest of Wingellina (Fig. 45), a vein system is present on the northeastern side of Skirmish Hill, where traces of copper and gold mineralization have been known since the 1970s (Daniels, 1974; Tyler et al., 1998), hosted in rocks now assigned to the Kunmarnara Group. These veins trend 145º, and have large quartz crystals arranged in splays and fans. Colloform textures and hydraulic breccias are common, but more interesting is the also common presence of bladed textures indicative of boiling fluids. The veins cut through dacitic and granophyric rocks, and importantly the wallrocks display hydrothermal alteration, probably argillic, up to 15 m from the vein. In addition, the wallrocks in the vicinity of the veins are brecciated and traversed by vein stockworks.

Quartz veins are present in areas around the Tollu Pluton, as well as within the pluton (Figs 5 and 45). A sheeted quartz vein system, trending 160º with a possible dip of about 38º to the east, is hosted in flow-banded dacitic or rhyodacitic volcanic rocks (Smoke Hill Volcanics; Tollu Group), which almost everywhere exhibit hyaloclastitic textures suggesting interaction with shallow fresh waters (see below). These veins are probably structurally controlled, along approximately north–south and west-northwest trends, which are dominant late structures in the region (Fig. 5). The wallrocks to the veins do not seem to have visible alteration, although epidote and epidote–?scapolite veins are present in the dacitic and gabbroic rocks within the general area of the sheeted vein system. The Tollu veins are commonly brecciated and cemented by silica. Colloform banding can be seen in several sections of the veins. One of the generations of quartz is characterized by bands of unidirectional, large, acicular quartz crystals. Hematite alteration is present and appears to replace and destroy these unidirectional acicular crystals. A complete paragenesis of mineral phases in these veins may be far more complex and difficult to resolve without systematic sampling. The largest quartz vein is the easternmost, with at least four more subparallel sets exposed about 1 km to the west. One of these veins contains films of chrysocolla and some azurite. About 2 km west of the largest vein, hyaloclastite breccias exhibit thin veins containing quartz, chlorite, and a pink coloured feldspar (possibly adularia).

Exploration potential and discussion

Thermal anomalies associated with upwelling of asthenospheric mantle constitute powerful heat sources in the crust. These are responsible for crustal scale hydrothermal circulation and high-temperature and low-pressure metamorphism, which may result in a wide range of ore deposits in rift systems that form as result of these mantle processes. The Giles intrusions are associated in space and time with bimodal volcanic rocks of the Bentley Supergroup, and various types of 1085 to 1040 Ma granitic rocks, including rapakivi granites. This lithological association is important because it may reflect a genetic relationship similar to that between the mafic to ultramafic Layered Suite of the Bushveld Complex, and the spatially and temporally associated Lebowa Granite Suite and felsic volcanic rocks of the Rooiberg Group, in South Africa (see Pirajno (2000) for an overview and references therein). The felsic rocks associated with the Bushveld Complex are well endowed with a wide range of hydrothermal ore deposits, ranging from greisen-style deposits, to breccia pipes with tin–tungsten mineralization, to epithermal and mesothermal lode-gold and iron oxide – copper – gold (IOCG) deposits. The Musgrave region has a similar potential, as highlighted by the discovery of copper–gold vein style mineralization in the felsic volcanic rocks of the Tollu Group north of the Cavenagh Range (Abeysinghe, 2003).

With respect to orthomagmatic nickel–copper and PGE mineralization, it is important to distinguish deposits that contain nickel and copper as principal ores, with PGE and gold as by-products, from deposits containing PGE as principal ores, with nickel sulphides and copper sulfides as by-products (Maier, 2005). Examples of the first kind are Noril'sk and Voisey's Bay, whereas the Merensky reefs of the Bushveld Complex and the JM reef of the Stillwater Complex are examples of the latter. Sulfides, both massive and disseminated, tend to form near the base of layered intrusions or in embayments of feeder systems. Sulfide veins and disseminations commonly penetrate the footwall rocks. Many of the Giles intrusions consist of ultramafic to mafic successions, and recent geological mapping has revealed that these successions are by no means confined to the northern sectors, but are also found at Mount West, Latitude Hills, BELL ROCK, and in the Hinckley Ranges. The potential for magmatic nickel–copper sulfide ores in these intrusions remains untested. Furthermore, as suggested by Howard et al. (2009) on the basis of structural and age constraints, rocks of the Alcurra Dolerite may host copper–nickel–PGE. This idea builds on the possibility that Alcurra magmas must have been channelled along major conduits, perhaps in a fashion similar to that of Noril'sk and Jinchuan (Naldrett, 2004), allowing repeated pulses of melts to be progressively enriched in sulfur and consequently precipitating sulfides.

There is, as yet, no record of significant primary PGE occurrences in the Giles intrusions, but again, the potential for PGE-rich zones in ultramafic cumulates (e.g. peridotite, pyroxenite) in the basal layers of mafic–ultramafic bodies has not been tested. Maier et al. (2003) found anomalous PGE abundances in the more evolved magnetitite layers of the Stella layered intrusion, South Africa. According to Maier et al. (2003), this style of mineralization is found in those layered complexes that lack chromitites, as is the case for the Giles intrusions. Indeed, PGE mineralization has recently been found associated with the magnetitite-bearing Jameson intrusion at a number of prospects (e.g. Canaan, Zen; Fig. 45; Sullivan, 2006).

Orthomagmatic, such as Nebo–Babel, and perhaps other types of sulfide systems, for example Noril'sk, may be more widespread than realized. However, the actual potential for hydrothermal mineral systems associated with the felsic components of the Giles Event remains largely untested and inadequately considered.

Hydrothermal vein systems, and stratabound copper, lead, silver, zinc, gold, and fluorite mineral occurrences, are widely distributed in the southern part of the west Musgrave Province (Fig. 45). These are all hosted in felsic volcanic and volcaniclastic rocks such as the Smoke Hill Volcanics and the rocks around Skirmish Hill. The veins are structurally controlled (e.g. the Tollu pluton), inviting the speculation that some of these veins may represent the outlying parts of larger mineral systems, such as IOCG, epithermal, or intracontinental-type porphyry molybdenum deposits. In this respect it should be noted that Olympic Dam style deposits, and epithermal and porphyry systems are in fact associated in time and space with A-type granitic intrusions in intraplate rift settings. This is also the case for central Asia, where a large number of mineral deposits are located in rift structures and temporally linked with large igneous provinces (e.g. Borisenko et al., 2006).

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Explanatory Notes

Unassigned Proterozoic felsic unit (P_-mrni-MU)

Legend narrative

Felsic composite granulitic gneiss; migmatitic

Rank	Formation
Parent	P_-mrn-MU
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This migmatitic, felsic, composite granulitic gneiss occurs as rare, metre-scale layers in rocks of the Wirku Metamorphics, with a few larger xenoliths also occurring in metamorphosed granites of the Pitjantjatjara Supersuite in the central parts of BATES. It is invariably associated with, and locally grades into, mafic granulite (P_-mwog-MU). Millimetre- to centimetre-scale banding is defined by grain size, pyroxene content, or transposed leucosomes. Mafic minerals typically make up less than 15% of the rock, and include clinopyroxene (locally retrograded to amphibole), garnet, and biotite. This unit is compositionally similar to metasandstones of the Wirku Metamorphics (P_-WM-mtni) and volcanic rocks of the Wankanki Supersuite (P_-WN-xmfn-mr), but its protolith remains unknown.

Distribution

This felsic granulitic gneiss forms four xenoliths, up to 500 m wide and 1000 m long, in metamorphosed granites of the Pitjantjatjara Supersuite throughout the central parts of BATES. Elsewhere it forms rare, metre-scale layers within rocks of the Wirku Metamorphics.

Lithology

This unit is generally felsic in composition, but is locally gradational to, or interleaved with, mafic granulitic gneiss (P_-mwog-MU) and garnetiferous pelites. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by grain size, orthopyroxene content, or by the presence of transposed leucosomes. The gneiss is usually metatexitic, with transposed, centimetre- to metre-scale leucogranite veins that are likely anatectic leucosomes. It has a granoblastic texture, which, together with the presence of orthopyroxene, confirms that the gneiss reached granulite facies. Mafic minerals rarely make up more than 15% of the rock, and include (in order of abundance) clinopyroxene (locally retrograded to amphibole), garnet, biotite, and rare garnet, the latter of which forms coronas around clinopyroxene. This unit is compositionally similar to migmatitic arkosic metasandstones (P_-WM-mtni) of the Wirku Metamorphics, and felsic volcanic rocks (P_-WN-xmfn-mr) of the Wankanki Supersuite.

Age code	Proterozoic	P_-
Rock type	Meta-igneous felsic	mr
Lithname	Felsic gneiss	n
1st qualifier	–	
2nd qualifier	Migmatitic	i
Tectonic unit code	Musgrave Province	-MU
Rock code		**P_-mrni-MU**

Geochronology

P_-mrni-MU	*Maximum*	*Minimum*
Age (Ma)	1600	1207 ± 11
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Isotopic
Reference	–	Bodorkos et al., 2008

Xenoliths of this granulitic gneiss occur within metamorphosed granites of the Pitjantjatjara Supersuite. The host granites of the Pitjantjatjara Supersuite have yielded a magmatic crystallization age of 1207 ± 11 Ma, which serves as a maximum crystallization age for these gneisses (GSWA 174737, Bodorkos et al., 2008).

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Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Unassigned Proterozoic mafic unit (P_-mwog-MU)

Legend narrative

Medium-grained clinopyroxene–orthopyroxene–garnet mafic granulite; massive to weakly banded; locally shows cm- to m-scale mineralogical banding, possibly primary layering; weakly to moderately migmatitic

Rank	Formation
Parent	P_-mwo-MU
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This pyroxene–garnet, basic to intermediate granulite normally occurs as rare, metre-scale layers within the Wirku Metamorphics, and also as larger xenoliths in metamorphosed granites of the Pitjantjatjara Supersuite east of Mount Fanny. The gneiss is usually metatexitic, with layer-parallel centimetre- to metre-scale anatectic leucosomes. It is laminated to banded on a millimetre- to centimetre-scale, with a granoblastic texture indicative of granulite-facies metamorphism. The combination of garnet in a basic to intermediate igneous groundmass suggests that this unit represents assimilated metasedimentary screens in subvolcanic intrusions.

Distribution

This basic to intermediate granulite forms large xenoliths, up to 2 km in size, within metamorphosed granites of the Pitjantjatjara Supersuite east of Mount Fanny.

Lithology

This granulite is typically medium-grained, and laminated to banded on a millimetre- to centimetre-scale, with banding defined by garnet and pyroxene content. It is always granoblastic textured, which, together with the presence of orthopyroxene, suggests that the gneiss reached granulite facies. The gneiss is usually metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins that are likely anatectic leucosomes. Although the presence of garnet in the rock suggests a metasedimentary parentage, the groundmass is identical to that seen in the basic to intermediate granulites of volcanic parentage interleaved into the better exposures of the Wirku Metamorphics at Mount Aloysius and Mount Holt. Therefore, this unit is tentatively interpreted to represent subvolcanic intrusions that assimilated metasedimentary rocks of the Wirku Metamorphics.

Age code	Proterozoic	P_-
Rock type	Meta-igneous mafic	mw
Lithname	Mafic granulite	o
1st qualifier	–	
2nd qualifier	Garnet	g
Tectonic unit code	Musgrave Province	-MU
Rock code		**P_-mwog-MU**

Geochronology

P_-mrni-MU	*Maximum*	*Minimum*
Age (Ma)	1600	1207 ± 11
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Isotopic
Reference	–	Bodorkos et al., 2008

Xenoliths of this granulitic gneiss occur within metamorphosed granites of the Pitjantjatjara Supersuite. The host granites of the Pitjantjatjara Supersuite have yielded a magmatic crystallization age of 1207 ± 11 Ma, which serves as a maximum crystallization age for these gneisses (GSWA 174737, Bodorkos et al., 2008).

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Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Piti Palya Metamorphics (formerly P_-PP-mh)

The Piti Palya Metamorphics and the Wirku Metamorphics were initially considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

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Wirku Metamorphics (P_-WM-mh) including former Piti Palya Metamorphics (P_-PP-mh)

Legend narrative

Undivided weakly to strongly banded gneiss; typically quartzofeldspathic but includes amphibolitic rocks; mostly derived from sedimentary or volcanosedimentary protoliths

Rank	Group
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Minimum thickness	2000 m
Metamorphic facies	Granulite facies: cordierite – K-feldspar zone

Summary

Apart from rare and isolated outcrops of c. 1400 Ma orthogneiss, the rocks of the Wirku Metamorphics (including the former Pity Palya Metamorphics) form the oldest exposed basement units of the west Musgrave Province. They outcrop in the Latitude Hills area of BELL ROCK (Tjuni Purlka Tectonic Zone), and also in southwest BLACKSTONE (Mamutjarra Zone) where they are engulfed by coeval intrusions of the Wankanki Supersuite. They are sporadically distributed throughout the central part of the Tjuni Purlka Tectonic Zone (on HOLT, northeastern BLACKSTONE, and northern BELL ROCK) and the northern parts of the Walpa Pulka Zone (BATES), as metre- to kilometre-scale inclusions within younger igneous rocks. The Wirku Metamorphics have undergone at least two phases of granulite-facies metamorphism (the latter was at ultrahigh temperature) during the Mount West and Musgrave Orogenies, and as a result, these rocks are now strongly deformed composite gneisses with granoblastic textures. The unit is a supracrustal package of psammites, arkosic metasandstones, pelites, and lesser volcaniclastic and volcanic rocks, deposited from c. 1340 Ma to potentially as late as 1270 Ma. It is possible that the volcanic equivalents of the Wankanki Supersuite and Wirku Metamorphics together formed a continental arc and basin.

Distribution

Rocks of the Wirku Metamorphics are sporadically distributed throughout the west Musgrave Province, within the central Tjuni Purlka Tectonic Zone (on HOLT, northeastern BLACKSTONE, and northern BELL ROCK), northern Walpa Pulka Zone (BATES), and underlying a contiguous 200 km^2 area in the Mamutjarra Zone (southwest BLACKSTONE). In these zones, they form metre- to kilometre-scale inclusions in younger igneous rocks of the Pitjantjatjara and Wankanki Supersuites. In the southern half of BLACKSTONE, kilometre-scale xenoliths of Wirku Metamorphics within granites of the Wankanki Supersuite occur over an area of roughly 1000 km^2, but are typically poorly exposed relative to the host granites, forming only 30% of the already sparse exposure in the area. In the Latitude Hills area of southeast BELL ROCK, these rocks underlie a 63 km^2 area dominated by outcrops of pelite.

Rocks of the Wirku Metamorphics are best exposed as kilometre-scale, low strain, supracrustal ‘rafts’ (from northwest to southeast: at Mount Holt, Mount Aloysius, and Mount West) within the Tjuni Purlka Tectonic Zone, where they comprise ~7% of the surface geology. Culturally sensitive areas tend to coincide with outcrop of these rafts and access is generally limited. The Wirku Metamorphics are poorly exposed (<10% of exposed rock) in the Walpa Pulka Zone, and the mapped distribution in this area, covering roughly 25% of the Walpa Pulka Zone, is mostly based on geophysical interpretation.

Derivation of name

The unit name is derived from the local Aboriginal name for a series of small hills (Wirku Wirku) approximately 5 km to the northeast of Mount Fanny, in central eastern BATES.

Lithology

The Wirku Metamorphics is a supracrustal package of psammites, arkosic metasandstones, pelites, and lesser metavolcaniclastic and metavolcanic rocks; rare calc-silicate layers may also be present. The paragneisses of the Wirku Metamorphics can be broadly divided into the following main lithological units: garnet–hercynite–sillimanite–cordierite pelites; garnet–sillimanite–orthopyroxene pelites; orthopyroxene(–garnet) psammites; garnet-bearing leucosomes; and arkosic metasandstones. A substantial portion of the Wirku Metamorphics is also composed of orthopyroxene–plagioclase(–quartz) gneisses, and granitic gneisses of probable igneous (volcanic) origin that interleaved with the metasediments. Arkosic metasandstones and orthopyroxene–plagioclase (–quartz) gneisses occur as metre- to kilometre-thick layers in the Mount Holt and Mount Aloysius regions (referred to here as the ‘Mount Holt and Mount Aloysius supracrustal rafts’) of the Tjuni Purlka Tectonic Zone, and also as metre-scale inclusions in the Walpa Pulka Zone. These psammitic units make up most of the Wirku Metamorphics. Garnet–sillimanite–orthopyroxene pelites are the most abundant pelitic units in the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone, whereas garnet–hercynite–sillimanite–cordierite pelites only form rare metre-scale layers in these areas. All of the units listed above are gneissic, recrystallized, and variably migmatized.

The Wirku Metamorphics have undergone at least two phases of granulite-facies metamorphism during the Mount West and Musgrave Orogenies. Dating of metamorphic zircon rims accompanying garnet–orthopyroxene(–sillimanite–hercynite–cordierite–quartz) assemblages indicate that the supracrustal package underwent ultrahigh-temperature metamorphism during the Musgrave Orogeny.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic	
Lithname	Psammite and pelite; interlayered	mh
Rock code		**P_-WM-mh**

Depositional environment

Based on granite geochemistry (Smithies et al., 2010), it can be speculated that the volcanic equivalents of the Wankanki Supersuite and the Wirku Metamorphics formed together in a continental arc and basin between c. 1345 and c. 1300 Ma. The dominance of relatively proximal-setting metasedimentary (psammites) and volcanic protoliths to these gneisses imply that the basin was never wide enough to form abyssal plains (Smithies et al., 2009; Evins et al., in press).

Geochronology

P_-WM-mh	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

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Wirku Metamorphics; subunit (P_-WM-mhni) formerly Piti Palya Metamorphics (P_-PP-mhni)

Legend narrative

Pelitic and psammitic gneiss; banded and interlayered; includes garnet–sillimanite–cordierite–hercynite gneiss, quartz–feldspar–garnet–hypersthene gneiss, and quartz–plagioclase–hypersthene–biotite gneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This pelitic and psammitic gneiss unit is a composite gneiss that forms a significant component of the Latitude Hills area and the southwestern BLACKSTONE region. It also forms centimetre- to metre-scale interlayers within all other units of the Wirku Metamorphics. The gneiss is dominantly garnet–hercynite–sillimanite–cordierite pelite, with minor hercynite-free and orthopyroxene–plagioclase(–quartz) volcanic granulite layers. Pelitic layers contain garnet–hercynite–sillimanite–cordierite symplectite lenses in a recrystallized sillimanite–cordierite quartzofeldspathic groundmass. Garnetiferous anatectic leucosomes typically make the gneiss a stromatitic metatexite, and locally overwhelm the unit to form nebulitic diatexite. The sedimentary protolith of this unit was likely a turbidite in the intermediate to distal portions of a submarine fan, deposited between c. 1340 and c. 1317 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

This gneiss forms up to 65% of outcrop in the Latitude Hills area (southeast BELL ROCK) of the Tjuni Purlka Tectonic Zone, and a significant proportion of the southwest BLACKSTONE region of the Mamutjarra Zone. It also forms centimetre- to metre-scale interlayers in all other units of the Wirku Metamorphics. It is particularly well exposed on Latitude Hill, approximate 5 km south of the Michael Hills, but is poorly exposed in the southwest BLACKSTONE area.

Lithology

This pelitic and psammitic gneiss unit is a composite gneiss dominantly of garnet–hercynite–sillimanite–cordierite pelite, with minor hercynite-free layers and quartz–plagioclase–orthopyroxene–biotite (see P_-WM-mnfo) layers. Rare calc-silicate layers may also be present. Garnet-bearing anatectic leucosomes typically make this gneiss a stromatitic metatexite, and locally overwhelm the unit to form nebulitic diatexite. The dominant gneissic paleosome contains garnet–hercynite–sillimanite–cordierite symplectite lenses (up to 1 cm thick and 20 cm long) in a sillimanite–cordierite quartzofeldspathic gneiss. The foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of up to 30% each of garnet (almandine), sillimanite and/or cordierite, 10% hercynite, 5% opaque minerals, and local biotite. Felsic bands are granitic in composition, with significant proportions of perthite and antiperthite; the plagioclase composition is labradorite. Garnet appears in two phases: the earliest phase contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second phase occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two phases: an early, dark-green phase (25–27 wt% FeO) is intergrown with magnetite, ilmenite, and rutile, and occurs as inclusions in garnet porphyroblasts and as millimetre-scale blebs with a second phase of lighter green (~33 wt% FeO) hercynite–cordierite symplectites. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but they may also form lenses that wrap around the earlier garnet phase. Spinel can have a ghanitic component of up to 8 wt% ZnO. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Locally, brownish-red biotite overgrows orthopyroxene and opaque minerals in the matrix. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism. Orthopyroxene (~6 wt% Al_2O_3; MgO/FeO ~ 1) and biotite are rare in this lithology, and their absence from peak metamorphic assemblages attest to dry conditions during ultrahigh-temperature metamorphism.

Minor garnet–sillimanite–orthopyroxene layers are restricted to low-strain domains, indicating that the presence of hercynite may be intimately linked to high-strain conditions. Garnet porphyroblasts up to 1 cm in size, and contain biotite, quartz, plagioclase, and rare hercynite and rutile inclusions. They are mainly almandine in composition, and can make up over 30% of the rock. A finer-grained, more iron-rich phase of garnet is found associated with orthopyroxene in the matrix. Blade-like, euhedral sillimanite can comprise up to 40%

of the rock. Orthopyroxene is uniform in composition (~5.7 wt% Al_2O_3; MgO/FeO ~ 1.2), and is in equilibrium with the finer-grained phase of garnet; it may comprise up to 10% of the rock. Retrograde biotite overgrows the garnet–orthopyroxene assemblage, and usually makes up <2% of the rock. K-feldspars are usually antiperthitic.

The other minor component of this unit is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss (equivalent to P_-WM-mnfo) that is generally intermediate in composition, but ranges overall from felsic to mafic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. It is composed almost entirely of orthopyroxene and plagioclase in a granoblastic texture, with or without quartz. Orthopyroxene content varies from 20 to 50%, and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but was more likely volcanic in origin, based on its grain size, composition, and setting.

Garnet-bearing granites are always associated with the pelitic and psammitic gneiss unit, and in most cases can be shown to be in situ leucosomes derived from their pelitic hosts. They are generally medium- to coarse-grained, white-weathering, leucocratic, garnet–biotite granites with abundant quartz. They are often dynamically recrystallized, as deformation accompanied migmatization. This classic combination of well-layered and garnetiferous gneisses has been interpreted to represent pelites that have undergone partial melting.

The combination of grain size, millimetre- to metre-scale layering, continuation along strike length, and abundance of quartz and aluminous minerals such as sillimanite, hercynite, garnet, and cordierite seen in this gneissic unit all point to a sedimentary protolith. Based on the alternating layered characteristic of this unit, the sedimentary protolith was possibly a distal turbidite.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite and pelite; interlayered	mh
Lithname	Psammitic and pelitic gneiss; interlayered	n
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-WM-mhni**

Geochronology

P_-WM-mhni	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

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Wirku Metamorphics; subunit (P_-WM-mhnl) formerly Piti Palya Metamorphics (P_-PP-mhnl)

Legend narrative

Interleaved quartz–garnet–sillimanite–hercynite (–cordierite) pelitic gneiss, psammite, and thickly bedded quartzite; variably mylonitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss unit is a major component of the Wirku Metamorphics in the Latitude Hills area (southeast Bell Rock) of the Tjuni Purlka Tectonic Zone, where it forms isoclinally folded layers within pelitic gneiss and xenoliths of the nearby mafic–ultramafic rocks of the Giles intrusions. This composite gneiss contains equal proportions of garnet–hercynite–sillimanite–cordierite pelite and grey garnet–hercynite–sillimanite–cordierite quartzite, with minor hercynite-free and orthopyroxene–plagioclase(–quartz) granulite layers. Pelitic layers contain garnet–hercynite–sillimanite–cordierite symplectite lenses in a recrystallized sillimanite–cordierite quartzofeldspathic groundmass. This unit differs from P_-WM-mhni in the presence of thick, continuous quartzite layers. Garnetiferous anatectic leucosomes typically make the gneiss a stromatitic metatexite, and locally overwhelm the unit to form nebulitic diatexite. The sedimentary protolith of this unit was likely a turbidite, deposited between c. 1340 and c. 1270 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly Bates), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly Blackstone and Bell Rock). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

This interleaved pelitic gneiss, psammite, and thickly bedded quartzite unit is the second most abundant unit of the Wirku Metamorphics found in the Latitude Hills area (southeast Bell Rock) of the Tjuni Purlka Tectonic Zone, although this is the only place it occurs as a mappable unit. This unit is best exposed on a large hill 5 km south of Latitude Hill, where it contains mappable interlayers of felsic granulite (see P_-WM-mnfo). On Latitude Hill, it occurs as isoclinally folded layers, up to 100 m wide, in pelitic gneiss (see P_-WM-mhni).

Layered mafic intrusions of the Warakurna Supersuite contain xenoliths, up to 500 m wide, of the interleaved pelitic gneiss, psammite, and thickly bedded quartzite unit along the southern edge of Michael Hills. Elsewhere, the composite gneiss unit forms centimetre- to metre-scale interlayers in most other units of the Wirku Metamorphics.

Lithology

This composite gneiss unit comprises equal proportions of garnet–hercynite–sillimanite–cordierite pelite and grey garnet–hercynite–sillimanite–cordierite quartzite, with minor layers of hercynite-free or quartz–plagioclase–orthopyroxene–biotite gneiss. Garnet-bearing anatectic leucosomes typically make the composite gneiss a stromatitic metatexite, and locally overwhelm the unit to form nebulitic diatexite. The only significant difference between this composite gneiss and the pelitic and psammitic gneiss unit (P_-WM-mhni) is the presence of the quartzite in the present unit.

The dominant gneissic paleosome in the composite gneiss unit contains garnet–hercynite–sillimanite–cordierite symplectite lenses (up to 1 cm thick and 20 cm long) in sillimanite–cordierite quartzofeldspathic gneiss. A foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of up to 30% each of garnet (almandine), sillimanite and/or cordierite, 10% hercynite, 5% opaque minerals, and local biotite. Felsic bands are granitic in composition, with significant proportions of perthite and antiperthite; the plagioclase composition is labradorite. Garnet appears in two phases: the earliest phase contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second phase occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two phases: an early, dark-green phase (25–27 wt% FeO) is intergrown with magnetite, ilmenite, and rutile, and occurs as inclusions in garnet porphyroblasts and as mm-scale blebs with a second phase of lighter-green (~33 wt% FeO) hercynite–cordierite symplectites. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but may also form lenses that wrap around the earlier phase of garnet. Spinel can have a ghanitic component of up to 8 wt% ZnO. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Locally, brownish-red biotite overgrows orthopyroxene and opaque minerals in the matrix. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism. Orthopyroxene (~6 wt% Al_2O_3; MgO/FeO ~ 1) and biotite are rare in this lithology, and their absence from peak metamorphic assemblages attest to dry conditions during ultrahigh-temperature metamorphism.

Minor garnet–sillimanite–orthopyroxene layers are restricted to low-strain domains, indicating that the presence of hercynite may be intimately linked to high-strain conditions. Garnet porphyroblasts, up to 1 cm in size, contain biotite, quartz, plagioclase, and rare hercynite and rutile inclusions. They are mainly almandine in composition, and can make up over 30% of the rock. A finer-grained, more iron-rich phase of garnet is found associated with orthopyroxene in the matrix. Blade-like, euhedral sillimanite can comprise up to 40% of the rock. Orthopyroxene is uniform in composition (~5.7 wt% Al_2O_3; MgO/FeO ~ 1.2), and is in equilibrium with the finer-grained garnet phase; it may comprise up to 10% of the rock. Retrograde biotite overgrows the garnet–orthopyroxene assemblage, and usually makes up <2% of the rock. K-feldspars are usually antiperthitic.

The other minor component of this composite gneiss unit is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss (equivalent to P_-WM-mnfo) that is generally intermediate in composition, but ranges overall from felsic to mafic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. It is composed almost entirely of orthopyroxene and plagioclase in a granoblastic texture with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with > 40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith is probably not sedimentary, but is more likely volcanic in origin based on its grain size, composition, and setting.

Garnet-bearing granites are always associated with the composite gneiss unit, and in most cases can be shown to be in situ leucosomes derived from their pelitic hosts. They are generally medium- to coarse-grained, white-weathering, leucocratic, garnet–biotite granites with abundant quartz. They are often dynamically recrystallized, as deformation accompanied migmatization. This classic combination of well-layered and garnetiferous gneisses has been interpreted to represent pelites that have undergone partial melting.

The combination of grain size, millimetre- to metre-scale layering, continuation along strike length, and abundance of quartz and aluminous minerals such as sillimanite, hercynite, garnet, and cordierite seen in this composite gneiss unit all point to a sedimentary protolith. Based on the alternating layered characteristic of this unit, the sedimentary protolith was possibly a distal turbidite.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite and pelite; interlayered	mh
Lithname	psammitic and pelitic gneiss; interlayered	n
1st qualifier	–	
2nd qualifier	Sillimanite	l
Rock code		**P_-WM-mhnl**

Geochronology

P_-WM-mhnl	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

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Wirku Metamorphics; subunit (P_-WM-mlni) formerly Piti Palya Metamorphics (P_-PP-mlni)

Legend narrative

Medium- to coarse-grained garnet–sillimanite pelitic gneiss; poorly to well banded; metatexitic to diatexitic; rounded garnet porphyroblasts up to 2 cm; locally interlayered with banded to laminated quartzofeldspathic paragneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This metatexitic to diatexitic pelitic gneiss occurs as a northwest-trending lens within granitic rocks of the Wankanki Supersuite on Mount West (southeast BELL ROCK). The gneiss is dominantly garnet–hercynite–sillimanite–cordierite pelite, with minor hercynite-free and orthopyroxene¬¬–plagioclase(–quartz) granulite layers. Pelitic layers contain garnet–hercynite–sillimanite–cordierite symplectite lenses in a recrystallized sillimanite–cordierite quartzofeldspathic groundmass. This metatexitic to diatexitic pelitic gneiss contains a larger proportion of garnetiferous anatectic leucosomes than the associated pelitic and psammitic gneiss (P_-WM-mhni), and commonly forms nebulitic diatexite. The sedimentary protolith of this unit was likely a turbidite, deposited between c. 1340 and c. 1270 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

This metatexitic to diatexitic pelitic gneiss occurs as a single northwest-trending lens, approximately 1500 m long and up to 200 m wide, within granitic rocks of the Wankanki Supersuite, on the northwest face of Mount West (southeast BELL ROCK) in the Tjuni Purlka Tectonic Zone.

Lithology

The metatexitic to diatexitic pelitic gneiss unit is dominated by garnet–hercynite–sillimanite–cordierite pelite, with minor layers of hercynite-free and quartz–plagioclase–orthopyroxene–biotite gneiss. Garnet-bearing anatectic leucosomes typically overwhelm the gneissic protolith to form nebulitic diatexite, and otherwise form stromatitic metatexite. This gneiss differs from pelitic and psammitic gneiss (P_-WM-mhni) only in that it is typically diatexitic rather than metatexitic. The dominant gneissic paleosome contains garnet–hercynite–sillimanite–cordierite symplectite lenses (up to 1 cm thick and 20 cm long) in sillimanite–cordierite quartzofeldspathic gneiss. A foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of up to 30% each of garnet (almandine), sillimanite and/or cordierite, 10% hercynite, 5% opaque minerals, and local biotite. Felsic bands are granitic in composition, with significant proportions of perthite and antiperthite; the plagioclase composition is labradorite. Garnet appears in two phases: the earliest phase contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second phase occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two phases: an early, dark-green phase (25–27 wt% FeO) is intergrown with magnetite, ilmenite, and rutile, and occurs as inclusions in garnet porphyroblasts and as millimetre-scale blebs with a second phase of lighter-green (~33 wt% FeO) hercynite–cordierite symplectites. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but may also form lenses that wrap around the earlier phase of garnet. Spinel can have a ghanitic component of up to 8 wt% ZnO. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Locally, brownish-red biotite overgrows orthopyroxene and opaque minerals in the matrix. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism. Orthopyroxene (~6 wt% Al_2O_3; MgO/FeO ~ 1) and biotite are rare in this lithology, and their absence from peak metamorphic assemblages attest to dry conditions during ultrahigh-temperature metamorphism.

Minor garnet–sillimanite–orthopyroxene layers are restricted to low-strain domains, indicating the presence of hercynite may be intimately linked to high-strain conditions. Garnet porphyroblasts, up to 1 cm, contain biotite, quartz, plagioclase, and rare hercynite and rutile inclusions. They are mainly almandine in composition, and can make up over 30% of the rock. A finer-grained, more iron-rich phase of garnet is found associated with orthopyroxene in the matrix. Blade-like, euhedral sillimanite can comprise up to 40% of the rock. Orthopyroxene is uniform in composition (~5.7 wt% Al_2O_3; MgO/FeO ~ 1.2), and is in equilibrium with the finer-grained garnet phase; it may comprise up to 10% of the rock. Retrograde biotite overgrows the garnet–orthopyroxene assemblage, and usually makes up <2% of the rock. K-feldspars are usually antiperthitic.

The other minor component of this unit is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss (equivalent to P_-WM-mnfo) that is generally intermediate in composition, but ranges overall from acidic to basic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. It is composed almost entirely of orthopyroxene and plagioclase in a granoblastic texture with or without quartz. Orthopyroxene content varies 20–50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates the protolith is probably not sedimentary, but is more likely volcanic in origin based on its grain size, composition, and setting.

Garnet-bearing granites are always associated with the metatexitic to diatexitic pelitic gneiss unit, and in most cases can be shown to be in situ leucosomes derived from their pelitic hosts. The granites are generally medium- to coarse-grained, white-weathering, leucocratic, garnet–biotite granites with abundant quartz. They are often dynamically recrystallized, as deformation accompanied migmatization. This classic combination of well-layered and garnetiferous gneisses has been interpreted to represent pelites that have undergone partial melting.

The combination of grain size, millimetre- to metre-scale layering, continuation along strike length, and abundance of quartz and aluminous minerals such as sillimanite, hercynite, garnet, and cordierite seen in this gneissic unit all point to a sedimentary protolith. Based on the alternating layered characteristic of this unit, the sedimentary protolith was possibly a distal turbidite.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: pelite	ml
Lithname	Pelitic gneiss	n
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-WM-mlni**

Geochronology

P_-WM-mlni	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

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Wirku Metamorphics; subunit (P_-WM-mnfo) formerly Piti Palya Metamorphics (P_-PP-mnfo)

Legend narrative

Laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss interleaved with pelitic gneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

The laminated to banded orthopyroxene-bearing gneiss unit is a basic to intermediate granulite. It is a major component of the composite gneiss unit P_-WM-xmn-mh, and forms rare, centimetre- to metre-scale interlayers in all other units of the Wirku Metamorphics within the Latitude Hill (southeast BELL ROCK) region. This typically intermediate gneiss displays millimetre- to centimetre-scale banding defined by variation in the abundance of orthopyroxene and by anatectic leucosomes. Orthopyroxene content is inversely proportional to quartz content. The absence of aluminous indicator minerals indicates the protolith is probably not sedimentary, but is more likely of volcanic origin based on its age, grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1317 ± 9 Ma obtained for a felsic end-member of this rock type.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

This gneiss unit forms a ~150 m thick layer in pelitic gneisses of the Wirku Metamorphics, 5 km south of Latitude Hill (southeast BELL ROCK). It also forms xenoliths in nearby charnockite of the Pitjantjatjara Supersuite (P_-PJ1-mgmo); is a major component of the composite gneiss unit P_-WM-xmn-mh; and forms rare, centimetre- to metre-scale interlayers in many other units of the Wirku Metamorphics.

Lithology

The laminated to banded orthopyroxene-bearing gneiss unit comprises medium-grained orthopyroxene–plagioclase (–quartz) granulitic gneiss with a typically intermediate composition, but with a compositional range from felsic to mafic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in the orthopyroxene abundance. The gneiss is usually metatexitic, with ubiquitous, layer-parallel, centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some are anatectic leucosomes. The paleosome is composed almost entirely of granoblastic-textured orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but was most likely volcanic in origin based on its age, grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1317 ± 9 Ma (GSWA 184150, Kirkland et al., 2011) obtained for a felsic end-member of this rock type sampled from the southwest of BLACKSTONE.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metamorphic protolith unknown: gneiss	mn
Lithname	Feldspathic gneiss	f
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-WM-mnfo**

Geochronology

P_-WM-mnfo	*Maximum*	*Minimum*
Age (Ma)	1317 ± 9	1317 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2011	Kirkland et al., 2011

No sample of the laminated to banded orthopyroxene-bearing gneiss unit has been directly dated. However, sample GSWA 184150 from the southwest part of BLACKSTONE (Mamutjarra Zone) is a paleosome within a migmatitic, orthopyroxene-bearing felsic granulite, which based on textural similarities is interpreted to represent an end-member to this laminated to banded orthopyroxene-bearing gneiss unit (P_-WM-mnfo). This sample contained simple, oscillatory zoned zircon grains that yielded a crystallization age of 1317 ± 9 Ma (Kirkland et al., 2011). Accordingly, the laminated to banded orthopyroxene-bearing gneiss unit is assigned a similar age.

References

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Wirku Metamorphics; subunit (P_-WM-mtni) including former Piti Palya Metamorphics (P_-PP-mtni)

Legend narrative

Strongly migmatitic quartzofeldspathic granulitic paragneiss; includes diatexite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This migmatitic quartzofeldspathic paragneiss is detectible as aeromagnetic (TMI) and gravity highs within pelitic units of the Wirku Metamorphics, and also occurs as xenoliths engulfed by coeval granites of the Wankanki Supersuite in the southwest BLACKSTONE area. It is best exposed as small lenses and xenoliths in metamorphosed granites of the Pitjantjatjara Supersuite in the Walpa Pulka Zone. Banding in this unit is defined by transposed anatectic leucogranite veins and local garnet-bearing layers. The gneiss ranges from metatexitic to diatexitic, and differs from other psammitic paragneisses (such as P_-WM-mtn) only in the amount of leucosome present. The gneiss comprises large, angular quartz grains, in a finer-grained, granoblastic to dynamically recrystallized feldspathic matrix with minor orthopyroxene and late biotite. The protolith of this quartzofeldspathic paragneiss is interpreted to have been an arkosic metasandstone. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

Overall, this unit is poorly exposed. Nevertheless, the gneiss typically corresponds to strong positive aeromagnetic anomalies on TMI images, and, in this way, forms an excellent marker for tracing fold patterns in the southwestern BLACKSTONE area. It is gradational into less migmatitic quartzofeldspathic gneiss (P_-WM-mtn). The unit is best exposed 5–10 km northeast of Mount Fanny and 5 km south of Mount Gosse in the Walpa Pulka Zone, on BATES; there it occurs as slivers, up to 1 km^2, associated with larger psammitic xenoliths in metamorphosed granites of the Pitjantjatjara Supersuite. It also occurs as xenoliths engulfed by coeval granites of the Wankanki Supersuite in the southwest BLACKSTONE area, and elsewhere it forms metre-scale layers within other units of the Wirku Metamorphics.

Lithology

This generally fine- to medium-grained migmatitic paragneiss unit of the Wirku Metamorphics is banded on a centimetre- to metre-scale, with banding defined by ubiquitous, transposed, layer-parallel, centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. Occasional centimetre-scale, garnet-bearing layers are interleaved with the gneisses, and finer laminations are defined by small accumulations (<5%) of magnetite associated with hercynite and rare garnet. The gneiss ranges from metatexitic to diatexitic, and differs from other psammitic units of the Wirku Metamorphics (P_-WM-mtn) only in the amount of leucosome present. The quartzofeldspathic paragneiss is laminated on the centimetre-scale with a medium to strong foliation defined by all phases in the rock. The gneiss is composed of <3mm, dismembered, undulatory quartz grains, in a finer-grained, granoblastic to dynamically recrystallized feldspathic matrix with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite; however, in the Walpa Pulka Zone the migmatitic quartzofeldspathic paragneiss can contain up to 10% orthopyroxene with garnet coronae, reflecting the high-pressure metamorphism that the domain experienced during the Petermann Orogeny. The protolith to the paragneiss is interpreted to have been an arkosic metasandstone, based on its fine to medium grain size, laminations, continuity along strike length, and the presence of coarser-grained quartz.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite	mt
Lithname	Psammitic gneiss	n
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-WM-mtni**

Geochronology

P_-WM-mtni	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma) (Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

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Wirku Metamorphics; subunit (P_-WM-xmh-mf) formerly Piti Palya Metamorphics (P_-PP-xmh-mf)

Legend narrative

Interlayered metasiliciclastic rocks and metamorphosed felsic volcaniclastic rocks; locally minor pelitic layers; includes metavolcaniclastic rocks belonging to the Wankanki Supersuite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss, derived from interlayered metasiliciclastic and metavolcaniclastic rock, underlies a large proportion of southwest Blackstone (Mamutjarra Zone) where it is surrounded by coeval intrusions of the Wankanki Supersuite. It is interleaved with pelitic gneiss units of the Wirku Metamorphics (P_-WM-mhni), and contains layers, up to 500 m thick, of psammitic gneiss (equivalent to P_-WM-mtni); this latter forms the dominant metasiliciclastic component of the composite gneiss. This composite gneiss comprises equal proportions of psammitic gneiss and intermediate volcanic rock, with minor layers of garnet–hercynite–sillimanite–cordierite pelitic gneiss. It is also contains variably transposed, centimetre-scale, garnetiferous, anatectic leucosomes. The psammite component contains rare orthopyroxene–hercynite–magnetite–garnet laminae and the metavolcaniclastic component contains variable amounts of orthopyroxene and quartz. The protolith to the metavolcaniclastic component was deposited between 1336 ± 11 Ma and 1317 ± 9 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly Bates), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly Blackstone and Bell Rock). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

Composite gneiss, derived from interlayered metasiliciclastic and metavolcaniclastic rock, underlies a contiguous, north-northeasterly trending area of about 200 km^2 in southwest Blackstone (Mamutjarra Zone), where it is surrounded by coeval intrusions of the Wankanki Supersuite. In that same area, it is interleaved with pelitic gneiss units of the Wirku Metamorphics (for example P_-WM-mhni), and contains layers of psammitic gneiss (equivalent to P_-WM-mtni) up to 500 m thick, which form the dominant metasiliciclastic component of the composite gneiss. Along with discrete, mappable units of psammitic gneiss (P_-WM-mtni), this composite unit (P_-WM-xmh-mf) forms kilometre-scale xenoliths within granites of the Wankanki Supersuite over an area of roughly 1000 km^2. This unit is typically very poorly exposed, but is best seen on a few small hills in the southwest corner of Blackstone. In the Latitude Hills area (southeastern Bell Rock), it also forms rare, metre-scale layers in other units of Wirku Metamorphics.

Lithology

This composite gneiss comprises equal proportions of psammitic metasiliciclastic rock and metamorphosed intermediate volcanic or volcaniclastic rock, with minor layers of garnet–hercynite–sillimanite–cordierite granulite. The gneiss is typically metatexitic, with layer-parallel centimetre- to metre-scale, garnetiferous leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The psammite component is banded on a centimetre-scale and laminated on the millimetre-scale; the laminations are defined by accumulations of orthopyroxene and (<5%) magnetite, associated with hercynite and rare garnet. Locally, garnet may form up to 5% of the rock either as <1mm sized rounded grains, or as poorly aligned aggregates. The psammite is comprised of quartz (30–40%), microcline, and plagioclase. The constituent minerals always form a granoblastic texture indicative of granulite-facies metamorphism. Because of their fine to medium grain size, laminations, continuation along strike length, and association with garnetiferous pelites, this component is interpreted to be a metasandstone.

The volcanic or volcaniclastic component of this gneiss is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss, which is generally intermediate in composition, but ranges overall from felsic to mafic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. It is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but is more likely either volcanic or volcaniclastic in origin based on its grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1317 ± 9 Ma obtained for a felsic end-member of this rock type sampled from southwest Blackstone (GSWA 184150, Kirkland et al., 2011a).

Minor pelitic interlayers contain lenses, up to 20 cm long and 1 cm thick, of garnet–hercynite–sillimanite–cordierite symplectite in sillimanite–cordierite quartzofeldspathic gneiss. A foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of garnet, sillimanite, cordierite, hercynite, opaque minerals, and local biotite. Two generations of garnet are found: the earliest generation contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second generation occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two generations: an early, dark-green generation is intergrown with magnetite, ilmenite, and rutile, and occurs as garnet porphyroblast inclusions and as mm-sized blebs with a second generation of lighter green hercynite–cordierite symplectites surrounding them. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but may also form lenses that wrap around the earlier phase of garnet. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 1	Psammite and pelite; interlayered	mh
Rock type 2	Meta-igneous felsic volcanic	
Lithname 2	Metafelsic volcanic rock	-mf
Rock code		**P_-WM-xmh-mf**

Geochronology

P_-WM-xmh-mf	*Maximum*	*Minimum*
Age (Ma)	1336 ± 11	1317 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2011b	Kirkland et al., 2011a

Two samples (GSWA 184150 and 190245) have been taken from this composite gneiss unit, both from the southwest part of Blackstone. Both samples contained unimodal, oscillatory zoned zircon populations. GSWA 184150 is an orthopyroxene-bearing felsic granulite interpreted to be a metavolcanic rock (Evins et al., in press) and yields an age, interpreted to be that of magmatic crystallization, of 1317 ± 9 Ma (Kirkland et al., 2011a). A nearby garnet-bearing quartzofeldspathic interlayer with trace orthopyroxene, biotite, and hercynite (GSWA 190245), also interpreted to be a metavolcanic rock (Evins et al., in press) yields an age, interpreted to that of magmatic crystallization, of 1336 ± 11 Ma (Kirkland et al., 2011b). If both interpretations are correct, then this composite gneiss unit contains at least two volcanic layers of significantly different age.

Parts of the composite gneiss unit are cut by 1321 ± 5 Ma granites of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

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Wirku Metamorphics; subunit (P_-WM-xmh-mn) formerly Piti Palya Metamorphics (P_-PP-xmh-mn)

Legend narrative

Interbedded garnet–sillimanite–hercynite(–cordierite) pelite and laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss unit represents a transition from the more metavolcanic-dominated (P_-WM-xmn-mh) region to the south of Latitude Hill (Tjuni Purlka Tectonic Zone, southeast Bell Rock) to the surrounding pelitic gneisses (P_-WM-mhnl). The composite gneiss is dominated by pelitic gneiss with minor quartzite and intermediate metavolcanic layers. It is also contains variably transposed, centimetre-scale, garnetiferous anatectic leucosomes. The main pelitic component contains garnet–hercynite–sillimanite–cordierite symplectite lenses in a recrystallized sillimanite–cordierite quartzofeldspathic groundmass. The metavolcanic component contains plagioclase, and variable amounts of orthopyroxene and quartz. The protolith to the metavolcanic component was deposited between c. 1340 Ma and 1270 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly Bates), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly Blackstone and Bell Rock). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

Interbedded garnet–sillimanite–hercynite(–cordierite) pelite and laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss forms a 500–1000 m wide domain within a larger area of pelitic gneiss and quartzite, 5 km south of Latitude Hill in the Tjuni Purlka Tectonic Zone (southeast Bell Rock).

Lithology

This composite gneiss unit represents the gradational transition from the more metavolcanic-dominated (P_-WM-xmn-mh) lithological domain to the south of Latitude Hill, to the surrounding pelitic gneisses (P_-WM-mhnl). The unit is dominated by garnet–hercynite–sillimanite–cordierite pelitic gneiss, with minor grey garnet–hercynite–sillimanite–cordierite quartzite, and layers of intermediate metavolcanic rocks. The gneiss is typically metatexitic, with layer-parallel centimetre- to metre-scale, garnetiferous, leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The dominant pelitic component contains garnet–hercynite–sillimanite–cordierite symplectite lenses, up to 20 cm long and 1 cm thick, in sillimanite–cordierite quartzofeldspathic gneiss. A foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of garnet, sillimanite, cordierite, hercynite, opaque minerals, and local biotite. Two generations of garnet are found: the earliest generation contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second generation occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two generations: an early, dark-green generation is intergrown with magnetite, ilmenite, and rutile, and occurs as garnet porphyroblast inclusions and as mm-sized blebs with a second generation of lighter-green hercynite–cordierite symplectites surrounding them. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but may also form lenses that wrap around the earlier phase of garnet. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism.

The other sedimentary component is a quartzite that locally forms persistent layers. It consists of alternating domains of coarse- and fine-grained granoblastic polygonal quartzofeldspathic rock with >50% quartz; feldspar is mainly perthite. Pelitic minerals also concentrate in millimetre- to centimetre-scale layers that include garnet (10–15%), hercynite (5%), prismatic sillimanite (5%), and cordierite (5–10%). Accessory minerals are orthopyroxene, biotite, and opaque minerals. Spinel is surrounded by granoblastic cordierite, or by spinel/cordierite symplectites. Cordierite surrounds garnet; garnet is also separated from quartz and feldspar by a rim of orthopyroxene. The combination of grain size, millimetre- to metre-scale layering, continuation along strike length, and abundance of quartz and aluminous minerals such as sillimanite, hercynite, garnet, and cordierite seen in these components all suggest a sedimentary protolith.

The minor metavolcanic component of this composite gneiss unit is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss, which is generally intermediate in composition, but overall ranges from mafic to felsic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. It is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but was more likely volcanic in origin based on its grain-size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1317 ± 9 Ma (GSWA 184150, Kirkland et al., 2011a) obtained for a felsic end-member of this rock type sampled from the southwest part of BLACKSTONE.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 1	Psammite and pelite; interlayered	mh
Rock type 2	Metamorphic protolith unknown: gneiss	
Lithname 2	Gneiss	-mn
Rock code		**P_-WM-xmh-mn**

Geochronology

P_-WM-xmh-mn	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss.

However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

Kirkland, CL, Wingate, MTD, Evins, PM and Smithies, RH 2009a, 180867: quartz monzonite, Mount Holt; Geochronology Record 838: Geological Survey of Western Australia, 4p.

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Wirku Metamorphics; subunit (P_-WM-xmn-mh) formerly Piti Palya Metamorphics (P_-PP-xmn-mh)

Legend narrative

Interbedded laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss and garnet–sillimanite–hercynite(–cordierite) pelite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss unit forms an enclave of metavolcanic-dominated gneiss separating pelitic gneisses (P_-WM-mhni) from interbedded garnet–sillimanite–hercynite(–cordierite) pelite and laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss (P_-WM-xmh-mn), in an area south of Latitude Hill (southeast BELL ROCK). It is transitional to both of these units, in that it contains a higher proportion of metavolcanic component than the latter, and has layers of intermediate metavolcanic rocks and garnet–hercynite–sillimanite–cordierite pelite in nearly equal proportions. It also contains variably transposed, centimetre-scale, garnetiferous anatectic leucosomes. The metavolcanic component contains plagioclase and variable amounts of orthopyroxene and quartz; the pelite component contains garnet–hercynite–sillimanite–cordierite symplectite lenses in a recrystallized sillimanite–cordierite quartzofeldspathic groundmass. The protolith to the metavolcanic component was deposited between c. 1340 Ma and c. 1270 Ma.

Note: at the time of mapping, the Piti Palya Metamorphics and the Wirku Metamorphics were considered separate units due to the unclear nature of geological relationships between the Walpa Pulka Zone (Wirku Metamorphics) in the northeast (mainly BATES), and the Mamutjarra Zone (Piti Palya Metamorphics) in the southwest (mainly BLACKSTONE and BELL ROCK). It now seems likely that most supracrustal rocks deposited before the Musgrave Orogeny belong to a single depositional basin, although different stratigraphic levels of the depositional sequence might be exposed in different geographic regions. All of these rocks are now grouped into the Wirku Metamorphics (Smithies et al., 2009; Evins et al., in press), even though they remain separated on all 1:100 000 scale maps published before 2011.

Distribution

This composite gneiss unit forms a single north-trending lens, 1400 m long and up to 300 m wide, exposed on the western flank of a small hill 5 km south of Latitude Hill (Tjuni Purlka Tectonic Zone, southeast BELL ROCK). It represents an enclave that separates pelitic gneisses (P_-WM-mhni) to the west, from interbedded garnet–sillimanite–hercynite(–cordierite) pelite and laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss (composite gneiss: P_-WM-xmh-mn) to the east. It differs from the latter only in that it contains greater proportions of the metavolcanic component. Its boundaries with both surrounding units are gradational.

Lithology

This interbedded laminated to banded orthopyroxene-bearing quartzofeldspathic gneiss and garnet–sillimanite–hercynite(–cordierite) pelite unit is a composite gneiss, composed of layers of intermediate metavolcanic rock and garnet–sillimanite–hercynite–cordierite pelitic gneiss, in nearly equal proportions. The gneiss is typically metatexitic, with layer-parallel centimetre- to metre-scale, garnetiferous, leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The volcanic component of this gneiss is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss, which is generally intermediate in composition, but ranges from mafic to felsic. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variation in orthopyroxene content. It is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies 20–50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith is probably not sedimentary, but is more likely volcanic in origin based on its grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1317 ± 9 Ma obtained for a felsic end-member (GSWA 184150, Kirkland et al., 2011a) of this rock type sampled in southwest BLACKSTONE.

The pelitic component contains lenses of garnet–hercynite–sillimanite–cordierite symplectite, up to 20 cm long and 1 cm wide, in a sillimanite–cordierite quartzofeldspathic gneiss. Foliation is defined by 5–10 mm wide, alternating, discontinuous mafic and felsic bands. The mafic bands may be composed of garnet, sillimanite, cordierite, hercynite, opaque minerals, and local biotite. Two generations of garnet are found: the earliest generation contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts; the second generation occurs as inclusion-free rims on early garnet, and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two generations: an early, dark-green generation is intergrown with magnetite, ilmenite, and rutile, and occurs as garnet porphyroblast inclusions and as mm-sized blebs with a second generation of lighter-green hercynite–cordierite symplectites surrounding them. In most cases, the hercynite–cordierite(–garnet) symplectites form lenses or replace individual blades of sillimanite, but may also form lenses that wrap around the earlier phase of garnet. Fine-grained orthopyroxene occurs intermittently along garnet rims, and along cracks in garnet crystals. Together, these assemblages and compositions are indicative of ultrahigh-temperature metamorphism. The combination of grain size, millimetre- to metre-scale layering, continuation along strike length, and abundance of quartz and aluminous minerals such as sillimanite, hercynite, garnet, and cordierite seen in this gneiss all suggest a sedimentary protolith for this component.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metamorphic protolith unknown: gneiss	
Lithname 1	Gneiss	mn
Rock type 2	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 2	Psammite and pelite; interlayered	-mh
Rock code		**P_-WM-xmn-mh**

Geochronology

P_-WM-xmn-mh	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

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Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187115: diatexitic migmatite, Mount Aloysius; Geochronology Record 792: Geological Survey of Western Australia, 6p.

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Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

Wirku Metamorphics; subunit (P_-WM-me)

Legend narrative

Fine- to medium-grained, massive to weakly layered granofels; weakly migmatitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This granofelsic gneiss unit forms large inclusions within granites of the Pitjantjatjara Supersuite in the central parts of BATES, and immediately north of the Mann Fault, in the southern part of BATES. On central BATES, the gneiss is a recrystallized, migmatitic arkosic sandstone, composed of quartz, perthite, and plagioclase with <5% mafic minerals (pyroxene, opaque minerals, garnet, and biotite) that form laminae. The gneiss is locally metatexitic, with layer-parallel and oblique centimetre- to metre-scale leucogranite veins. Near the Mann Fault, this unit is a quartzite with magnetite–garnet–titanite laminations. The protolith to this granofelsic gneiss is interpreted as sediments deposited in a proximal setting between c. 1340 Ma and c. 1270 Ma.

Distribution

This granofelsic gneiss of the Wirku Metamorphics forms inclusions, up to 10 km^2 in size, within granites of the Pitjantjatjara Supersuite, and is exposed in low outcrops approximately 5 km west of Mount Daisy BATES in the central part of BATES. A more quartz-rich variety covers a large 25 km^2 area just north of the Mann Fault in the southern part of BATES, and is best exposed on a small hill 10 km north of the West Hinckley Range.

Lithology

In the central parts of BATES, this granofelsic gneiss unit is a recrystallized arkosic metasandstone, banded at a centimetre- to metre-scale. Banding is defined by variations in grain size, and is locally accompanied by millimetre-scale laminations. The crystal boundaries of constituent minerals always define a well-developed granoblastic texture indicative of granulite-facies metamorphism. The gneiss is locally metatexitic with layer-parallel and oblique centimetre- to metre-scale leucogranite veins. This psammitic gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all mineral components, and typically comprises >20% quartz, perthite, and lesser plagioclase. It is leucocratic, with up to 5% mafic minerals, mainly smears of brown biotite, light-pink to colourless garnet, and opaque minerals. Reaction textures include garnet coronas on biotite, opaque minerals, and quartz–plagioclase–biotite–clinopyroxene aggregates. Hornblende and opaque minerals locally display biotite rims.

Near the Mann Fault, the granofelsic gneiss unit is a quartzite with magnetite–garnet–titanite laminations. The recrystallized assemblage is dominated by quartz grains with sutured boundaries. Lesser clinopyroxene is aligned along a weak but distinct foliation fabric. Because of their fine to medium grain size, high quartz content, laminations, and continuation along strike length, these gneisses are interpreted to be arkosic metasandstones and quartzites.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metamorphic protolith unknown: granofels/hornfels	
Lithname	Granofels/hornfels	me
Rock code		**P_-WM-me**

Geochronology

P_-WM-me	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Wirku Metamorphics; subunit (P_-WM-mhig)

Legend narrative

Metatexitic gneiss comprising cm- to m-thick layers of garnet–orthopyroxene–biotite(–cordierite–hercynite–hornblende) pelite and psammite, with rare quartzite, feldspathic psammite, and calc-silicate layers

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: cordierite – K-feldspar zone

Summary

This metatexitic pelitic and psammitic gneiss unit forms metre-scale layers within other units of the Wirku Metamorphics, and large, mappable outcrops are also found within the Tjuni Purlka Tectonic Zone, particularly at Mount Aloysius (BELL ROCK). The unit is composed of alternating centimetre- to metre-thick layers of garnetiferous pelite and psammite, with rare quartzite layers. Pelitic layers contain garnet porphyroblasts in a recrystallized quartzofeldspathic groundmass, with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. Psammitic layers rarely contain garnet porphyroblasts, but do contain significant orthopyroxene, garnet, and biotite set in a quartzofeldspathic matrix. The paragneiss is cut by locally abundant, variably transposed, garnetiferous and non-garnetiferous leucocratic veins (equivalent to P_-PJ-mgrl of the Pitjantjatjara Supersuite), which represent melts locally derived from the paragneiss during the Musgrave Orogeny. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This metatexitic pelitic and psammitic gneiss unit is ubiquitous as a minor component of composite gneisses throughout all outcrops of the Wirku Metamorphics, but most commonly within the Tjuni Purlka Tectonic Zone. The largest discrete outcrop of this unit is found on the southwest flank of Mount Aloysius (BELL ROCK). It also forms mappable units on Mount Holt (HOLT), and occurs in a kilometre-scale enclave otherwise dominated by volcanic rocks of the Wankanki Supersuite, between Mount Aloysius and Mount Holt.

Lithology

The metatexitic pelitic and psammitic gneiss unit is composed of alternating centimetre- to metre-thick layers of garnetiferous pelite, psammite, and rare quartzite, but also includes transposed veins of leucocratic granite. Together, these form a metatexitic stromatic migmatite. Pelitic layers contain rounded garnet crystals, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. A foliation is defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite, and wraps around the garnet porphyroblasts. Garnet cores usually contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. The plagioclase and biotite inclusions are compositionally different to plagioclase and biotite in the matrix. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in equilibrium, forming clusters within the matrix, and are both locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some pelite layers. Psammitic layers rarely contain garnet porphyroblasts, but do contain up to 10% anhedral orthopyroxene, garnet, and biotite set in a quartzofeldspathic matrix. Antiperthite is common (up to 30%) in both pelitic and psammitic layers, with lesser amounts of perthite (up to 5%). Orthopyroxene is locally retrogressed to amphibole along shear zones.

The paragneiss is cut by locally abundant, variably transposed, garnetiferous and non-garnetiferous leucocratic veins (equivalent to P_-PJ-mgrl of the Pitjantjatjara Supersuite), which have been interpreted as either locally (metre-scale garnetiferous veins) and more distally (non-garnetiferous veins) derived melts of the paragneiss produced during the Musgrave Orogeny. Rare quartzite and arkosic metasedimentary layers make up a minor portion of this unit, and very rare calc-silicate layers are found along the northwest flank of Mount Aloysius. Based on the alternating layered characteristic of this unit, the sedimentary protolith was likely a turbidite.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite and pelite; interlayered	mh
Lithname	Interlayered psammitic and pelitic migmatite	i
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-WM-mhig**

Geochronology

P_-WM-mhig	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

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Wirku Metamorphics; subunit (P_-WM-mhnk)

Legend narrative

Medium-grained kyanite–garnet pelitic gneiss; poorly to well banded; metatexitic to diatexitic; rounded garnet porphyroblasts up to 1 cm in diameter; locally interlayered with medium- to coarse-grained psammite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This kyanite-bearing pelitic and psammitic gneiss unit has only been found at a single isolated outcrop approximately 10 km to the east of Murray Range, in the Walpa Pulka Zone on HOLT. It comprises centimetre- and metre-scale interbeds of medium-grained pelitic gneiss containing rounded garnet porphyroblasts up to 2 cm in size, and garnet-bearing quartzite with accessory prismatic kyanite grains to 1 mm in size. The rock has not been directly dated, but the depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

The kyanite-bearing gneiss unit has been found at a single isolated, small, northwest-trending outcrop, immediately to the north of the northwestern extension of the Fanny Fault, approximately 10 km to the east of Murray Range in the Walpa Pulka Zone, on HOLT.

Lithology

This kyanite-bearing gneiss comprises centimetre- and metre-scale interbeds of medium-grained pelitic gneiss containing rounded garnet porphyroblast up to 2 cm in size, and garnet-bearing quartzite. Only the quartzite component has been sampled (GSWA 189421); it consists of a seriate-textured granoblastic polygonal assemblage greatly dominated by quartz (>95%), with accessory grains of rounded garnet (to 3 mm in size) and accessory prismatic kyanite grains to 1 mm in size. The kyanite is essentially dispersed throughout the rock, but locally forms semicontinuous layers ~1 mm thick. The seriate texture likely reflects a very poorly sorted quartz-sandstone protolith.

The location of this sample site along the Fanny Fault is significant as this fault is known to separate garnet-bearing rocks to the east, from non-garnetiferous rocks to the west (Howard et al., 2006).

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite and pelite; interlayered	mh
Lithname	Psammitic and pelitic gneiss; interlayered	n
1st qualifier	–	
2nd qualifier	Kyanite	k
Rock code		**P_-WM-mhnk**

Geochronology

P_-WM-mhnk	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Wirku Metamorphics; subunit (P_-WM-mlig)

Legend narrative

Diatexitic, coarse-grained garnet–orthopyroxene–biotite(–cordierite) pelite; leucocratic; rounded garnet porphyroblasts up to 2 cm; migmatitic textures range from stromatic to nebulitic to raft migmatite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: cordierite – K-feldspar zone

Summary

The main outcrop of this garnetiferous diatexitic pelite unit forms the core of the Mount Aloysius antiform in the Tjuni Pulka Tectonic Zone (on Bell Rock). This unit lies in the middle of the migmatitic spectrum between more paleosome-rich stromatic migmatites (such as P_-WM-mhig), and leucosome representing local partial melts developed during the Musgrave Orogeny (such as P_-PJ-mgrl). The diatexite contains large garnet porphyroblasts, in a recrystallized quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, and biotite. The main foliation wraps around the garnet porphyroblasts. Biotite and local orthopyroxene and cordierite are found along garnet rims. The protolith to this diatexite is interpreted to be a distally deposited sediment such as a siltstone or mudstone. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

The garnetiferous diatexitic pelite unit is primarily restricted to the Tjuni Purlka Tectonic Zone, where it forms the core of the Mount Aloysius antiform (Bell Rock). The only other mappable occurrences of this unit are two thin (<50 m wide), northwest-trending layers within metavolcanic rocks of the Wankanki Supersuite near Prostanthera Hill (northern Holt). Elsewhere, the garnetiferous diatexitic pelite unit forms metre-wide layers as a major component within metatexitic pelitic and psammitic gneiss (P_-WM-mhig), and as a minor component within composite diatexitic gneiss (P_-WM-xmli-mr) of the Wirku Metamorphics and a composite gneiss unit of the Wankanki Supersuite (P_-WN-xmfn-mh).

Lithology

The paleosome component of the garnetiferous diatexitic pelite unit also forms pelitic layers in several other units of the Wirku Metamorphics (P_-WM-mhig, P_-WM-xmli-mr), and in one unit of the Wankanki Supersuite (P_-WN-xmfn-mh). Where this lithology forms discrete mappable units, it is more migmatitic and the continuous centimetre-scale layering disappears. Migmatitic textures range from stromatic to nebulitic and raft migmatite, but in most cases, the boundary between paleosome and leucosome is blurred. In essence, this unit lies in the middle of the migmatitic spectrum, between more paleosome-rich stromatic migmatites (such as P_-WM-mhig) and end-member leucosomes (equivalent to P_-PJ-mgrl) formed during the Musgrave Orogeny.

The diatexite contains rounded garnet porphyroblasts, up to 2 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, and biotite. Where present, the foliation is best defined by quartz and feldspar, and always wraps around the garnet porphyroblasts. Garnet cores usually contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. The plagioclase and biotite inclusions are compositionally different to plagioclase and biotite in the matrix. Inclusion–free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in equilibrium, forming clusters within the matrix, and are locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some pelite layers. Antiperthite is common (up to 30%), with lesser amounts of perthite (up to 5%).

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: pelite	ml
Lithname	Pelitic migmatite	i
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-WM-mlig**

Geochronology

P_-WM-mlig	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma.

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Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

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Wirku Metamorphics; subunit (P_-WM-mlil)

Legend narrative

Diatexitic, coarse-grained garnet–sillimanite–orthopyroxene–biotite(–cordierite) pelite; leucocratic; rounded garnet porphyroblasts up to 2 cm; migmatitic textures range from stromatic to nebulitic to raft migmatite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: cordierite – K-feldspar zone

Summary

This garnet–sillimanite diatexitic pelite unit is only found as a discrete unit within the innermost core of the Mount Aloysius antiform, in the Tjuni Pulka Tectonic Zone (on Bell Rock). The prominence of sillimanite marks the only difference between this unit and the garnetiferous diatexitic pelite unit (P_-WM-mlig). Like the garnetiferous diatexitic pelite, the garnet–sillimanite diatexitic lies in the middle of the migmatitic spectrum, between more paleosome-rich stromatic migmatites (such as P_-WM-mhig), and leucosome representing local partial melts developed during the Musgrave Orogeny. The diatexite contains large garnets, in a recrystallized matrix with variable amounts of interstitial prismatic sillimanite, and anhedral orthopyroxene, garnet, and biotite. The protolith to this diatexite is interpreted to be a fine-grained sediment deposited in a distal setting, such as a siltstone or mudstone. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This garnet–sillimanite diatexitic pelite only forms a discrete mappable unit in the innermost core of the Mount Aloysius antiform, in the Tjuni Pulka Tectonic Zone (on Bell Rock). Elsewhere, it forms metre-wide layers as minor components within other units of the Wirku Metamorphics (P_-WM-mhig, P_-WM-mlig, P_-WM-xmli-mr) and Wankanki Supersuite (P_-WN-xmfn-mh).

Lithology

The prominence of sillimanite in the garnet–sillimanite diatexitic pelite unit is the only difference between this unit and the garnetiferous diatexitic pelite unit (P_-WM-mlig) that forms the outer core of the Mount Aloysius antiform. The paleosome component of the garnet–sillimanite diatexitic pelite unit also forms pelitic layers in several other units of the Wirku Metamorphics (P_-WM-mlig, P_-WM-mhig, P_-WM-xmli-mr), and in composite gneiss of the Wankanki Supersuite (P_-WN-xmfn-mh). As with the garnetiferous diatexitic pelite unit (P_-WM-mlig), the garnet–sillimanite diatexitic pelite is more migmatitic than other units of the Wirku Metamorphics, and is poorly and discontinuously layered. Migmatitic textures range from stromatic to nebulitic to raft migmatite, but in most cases, the boundary between paleosome and leucosome is blurred. In essence, this unit lies in the middle of the migmatitic spectrum, between more paleosome-rich stromatic migmatites (such as P_-WM-mhig), and the end-member leucosomes (equivalent to P_-PJ-mgrl) formed during the Musgrave Orogeny. The diatexite contains rounded garnet porphyroblasts up to 2 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, and biotite. Where present, the foliation is best defined by quartz and feldspar, and always wraps around the garnet porphyroblasts. Interstitial anhedral orthopyroxene and garnet together form clusters within the matrix.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: pelite	ml
Lithname	Pelitic migmatite	i
1st qualifier	–	
2nd qualifier	Sillimanite	l
Rock code		**P_-WM-mlil**

Geochronology

P_-WM-mlil	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-mnag)

Legend narrative

Medium-grained banded gneiss; quartz- and plagioclase-rich bands alternating with cm-scale bands rich in hornblende–clinopyroxene–garnet–biotite or in clinopyroxene–orthopyroxene–garnet–biotite; protolith unknown

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: clinopyroxene

Summary

This medium-grained banded gneiss is interlayered with other felsic (P_-mrni-MU) and mafic (P_-mwog-MU) granulites, and also occurs as xenoliths within metamorphosed granites of the Pitjantjatjara Supersuite, immediately to the north of Mount Gosse. The gneiss typically contains layer-parallel centimetre- to metre-scale anatectic leucosomes. It is always strongly deformed, and was mylonitized and folded prior to its inclusion as xenoliths into the metamorphosed Pitjantjatjara Supersuite granites. The dominant component is a metasyenogranite with up to 15% mafic minerals (clinopyroxene, amphibole, garnet, and biotite). The gneiss is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in garnet and clinopyroxene content. The depositional age of the protolith to the Wirku Metamorphics in general is constrained to between c. 1340 and 1270 Ma.

Distribution

This medium-grained banded gneiss unit is found immediately to the north of Mount Gosse (Bates, Walpa Pulka Zone), where it is interlayered with felsic (P_-mrni-MU) and mafic (P_-mwog-MU) granulites of an unknown age, in discrete xenoliths up to 2 km^2 in size, within metamorphosed granites of the Pitjantjatjara Supersuite.

Lithology

This banded gneiss is usually metatexitic with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins that are likely to be anatectic leucosomes. It is always strongly deformed, with mylonitization and folding pre-dating inclusion as xenoliths into metagranites of the Pitjantjatjara Supersuite. The dominant component of the gneiss is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in garnet and clinopyroxene content. Compositionally, the dominant component is a metasyenogranite. Mafic minerals rarely make up more than 15% of the rock, and include (in order of abundance) clinopyroxene (locally retrograded to amphibole), garnet, biotite, with rare garnet coronas forming around clinopyroxene. The foliation is defined by flattened clinopyroxene aggregates up to 3 cm long, and also by flattened quartz. Where less deformed or annealed, the fabric is granoblastic polygonal, indicative of granulite-facies metamorphism. This unit is compositionally similar to migmatitic quartzofeldspathic granulitic paragneiss (P_-WM-mtni) of the Wirku Metamorphics, and to composite gneiss of felsic volcanic origin (P_-WN-xmfn-mr) of the Wankanki Supersuite.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metamorphic protolith unknown: gneiss	mn
Lithname	Amphibolitic gneiss	a
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-WM-mnag**

Geochronology

P_-WM-mnag	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-mnfb)

Legend narrative

Staurolite–biotite–garnet–hornblende quartzofeldspathic gneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This staurolite–biotite–garnet–hornblende quartzofeldspathic gneiss unit was identified by Stewart (1997) from a single locality approximately 12 km due south of Mount Gosse, in the east of the Walpa Pulka Zone. The rock has not been directly dated, but the depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This staurolite–biotite–garnet–hornblende quartzofeldspathic gneiss unit was identified by Stewart (1997) from a single locality approximately 12 km due south of Mount Gosse (BATES, MGA 493388E 7153312N), in the east of the Walpa Pulka Zone.

Lithology

Stewart (1997) describes this staurolite–biotite–garnet–hornblende quartzofeldspathic gneiss unit of the Wirku Metamorphics as medium grained and thinly layered, with intermediate to melanocratic composition, and including round feldspars and mafic boudins and lenses. The rock has a granoblastic texture, and comprises zoned oligoclase (35%), mesoperthite (34%), quartz (10%), poikiloblastic hornblende (10%), garnet (5%), biotite (5%), and rounded crystals of yellow staurolite (0.5%). Small, upright, intrafolial early folds have subhorizontal axes, and late southeast-plunging open folds deform layering, foliation, and lineation.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metamorphic protolith unknown: gneiss	mn
Lithname	Feldspathic gneiss	f
1st qualifier	–	
2nd qualifier	Biotite	b
Rock code		**P_-WM-mnfb**

Geochronology

P_-WM-mnfb	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Stewart, AJ 1997, Geology of the BATES 1:100 000 sheet area (4646), Musgrave Block, Western Australia: Australian Geological Survey Organisation, Record 1997/5, 36p.

Wirku Metamorphics; subunit (P_-WM-mtn)

Legend narrative

Fine- to medium-grained quartzofeldspathic gneiss; laminated to banded and interlayered on a cm- to m-scale; typically metatexitic but locally diatexitic; locally intruded by several generations of granite

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This quartzofeldspathic gneiss is detectible as aeromagnetic (TMI) and gravity highs within pelitic units of the Wirku Metamorphics. It is best exposed as mappable layers on Mount Aloysius (northwestern BELL ROCK), and as kilometre-scale xenoliths within metamorphosed early granites of the Pitjantjatjara Supersuite throughout central BATES. Gneissic banding is defined by variations in grain size, by anatectic leucosomes, and by the presence of garnet-bearing layers. Both the psammite and leucosome have been folded at least twice. The gneiss contains large, angular quartz grains, in a finer-grained, granoblastic to dynamically recrystallized feldspathic matrix with minor orthopyroxene and late biotite. In the Walpa Pulka Zone, orthopyroxene grains have garnet coronae due to high-pressure metamorphism during the Petermann Orogeny. These gneisses are interpreted to be arkosic metasandstones. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This quartzofeldspathic gneiss unit is detectible as positive aeromagnetic (TMI) and gravity anomalies within the more pelitic units of the Wirku Metamorphics. It is best exposed on Mount Aloysius in the Tjuni Purlka Tectonic Zone (northwestern BELL ROCK), where it forms mappable ridges up to 400 m wide. It is also the dominant component of heterogeneous Wirku Metamorphics paragneiss units that make up the eastern side of Mount Aloysius (P_-WM-xmt-mh), or form Mount Holt (P_-WM-xmtn-mf: Tjuni Purlka Tectonic Zone, HOLT). Elsewhere in the Tjuni Purlka Tectonic Zone, it forms metre-scale layers in other gneissic units of the Wirku Metamorphics. On BATES, in the Walpa Pulka Zone, the quartzofeldspathic gneiss unit also forms xenoliths up to 15 km^2 in area within metagranitic rocks of the Pitjantjatjara Supersuite. One notable example is on the northern flank of Mount Fanny (central-western BATES), where the gneiss occurs as a 500 m wide xenolith within metagranites formed in the early stages of the Musgrave Orogeny.

Lithology

This quartzofeldspathic gneiss is an arkosic metasandstone (psammite) that is banded on a centimetre- to metre-scale. Where homogenous, the gneissic banding is defined by variations in grain size. Occasional centimetre-scale, garnet-bearing layers are interleaved with the gneisses. The constituent minerals of the gneiss always form a granoblastic texture indicative of granulite-facies metamorphism. The gneiss is usually metatexitic, with ubiquitous, layer-parallel, centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. Both the psammite and leucosome have been folded at least twice. This psammitic gneiss is also laminated on the centimetre-scale, with a medium to strong foliation defined by all mineral phases in the rock. In thin section, the gneiss is composed of <3 mm, dismembered, undulatory quartz grains, within a finer-grained, granoblastic to dynamically recrystallized feldspathic matrix with significant amounts of antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is typically a minor component of the rock (up to 3%), and is altered to biotite. However, in the Walpa Pulka Zone (BATES) the psammite can contain up to 10% orthopyroxene, with microgarnet coronae reflecting the high-pressure metamorphism associated with the Petermann Orogeny. Due to its fine to medium grain size, laminations, continuity along strike length, and presence of coarser-grained quartz, the protolith to this quartzofeldspathic gneiss is interpreted to be an arkosic metasandstone.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Metasedimentary siliciclastic: psammite	mt
Lithname	Psammitic gneiss	n
Rock code		**P_-WM-mtn**

Geochronology

P_-WM-mnfb	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Wirku Metamorphics; subunit (P_-WM-mrog)

Legend narrative

Medium-grained orthopyroxene–plagioclase–garnet–quartz acid to intermediate granulite gneiss; laminated to banded and interlayered with leucogranite veins on a cm- to m-scale; typically metatexitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This orthopyroxene–garnet-bearing granulite ranges from mafic to felsic in composition. It is only found in the nose of the Mount Aloysius antiform, in the Tjuni Pulka Tectonic Zone (in the southwest of BATES), and is laminated to banded on a millimetre- to centimetre-scale with a granoblastic texture indicative of granulite-facies metamorphism. This granulite is very similar to the orthopyroxene-bearing granulite unit (P_-WM-mroo) and the medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi), both of the Wirku Metamorphics, but contains garnet-bearing lenses that are interpreted to be partially assimilated metasedimentary screens in a subvolcanic intrusion. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This orthopyroxene–garnet-bearing granulite unit is only found as two northeast-trending lenses, each up to 300 m in length, interleaved with homogenous granulite (P_WM-mroo) in the nose of the Mount Aloysius antiform (southwest of BATES).

Lithology

This granulite ranges from mafic to felsic in composition, but is generally intermediate. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in garnet and orthopyroxene content. It always has a granoblastic texture, which, together with the presence of orthopyroxene, confirms that the gneiss has been recrystallized at granulite facies. Although the presence of garnet in the rock suggests a metasedimentary parentage, the matrix is identical to the orthopyroxene-bearing granulite (P_-WM-mroo) and the acid to intermediate granulite gneiss (P_-WM-mroi), both of volcanic parentage, that surround the two lenses of orthopyroxene–garnet-bearing granulite. On that basis, the protolith to the lenses is interpreted to reflect the local assimilation of metasedimentary screens into a subvolcanic intrusion. The gneiss is usually metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Meta-igneous felsic	mr
Lithname	Felsic granulite	o
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-WM-mrog**

Geochronology

P_-WM-mrog	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (BELL ROCK), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187115: diatexitic migmatite, Mount Aloysius; Geochronology Record 792: Geological Survey of Western Australia, 6p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

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Wirku Metamorphics; subunit (P_-WM-mroi)

Legend narrative

Medium-grained orthopyroxene–plagioclase(–quartz) acid to intermediate granulite gneiss; laminated to banded and interlayered with leucogranite veins on a cm- to m-scale; typically metatexitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This acid to intermediate granulite gneiss unit typically occurs as rare, metre-scale layers within other units of the Wirku Metamorphics. The largest outcrops are on the eastern flank of Mount Aloysius (northwest Bell Rock), and on a north-trending hill in northwest Finlayson. It is laminated to banded on a millimetre- to centimetre-scale, and is usually metatexitic with transposed leucosomes. It is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. The protolith is interpreted to have been volcanic rock.

Distribution

The largest outcrop of this acid to intermediate granulite gneiss unit is on the eastern flank of Mount Aloysius (northwest Bell Rock), where layers are >10 m thick. It is also the dominant rock type outcropping on a north-trending hill in northwest part of Finlayson. Elsewhere, and particularly to the south of Mount Holt, northeast of Prostanthera Hill (Holt), and in the Cohn Hill area (Cooper), the granulite gneiss is found as rare, metre-scale layers within other units of the Wirku Metamorphics.

Lithology

This medium-grained granulite gneiss unit ranges from mafic to felsic in composition, but is generally intermediate. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. The gneiss is usually metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The rock is very dense relative to other units of the Wirku Metamorphics, and in thin-section it is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith is probably not sedimentary, and is so interpreted to have been volcanic in origin based on grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1319 ± 7 Ma (GSWA 180867, Kirkland et al., 2009a) obtained for a felsic end-member of this rock type sampled south of Mount Holt. This medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) differs from the orthopyroxene-bearing granulite unit (P_-WM-mroo) only in that the former is usually metatexitic.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Meta-igneous felsic	mr
Lithname	Felsic granulite	o
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-WM-mroi**

Geochronology

P_-WM-mroi	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, from the present medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-mroo)

Legend narrative

Medium-grained orthopyroxene–plagioclase(–quartz) acid to intermediate granulite; locally garnetiferous; granoblastic texture; massive to moderately foliated

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This orthopyroxene-bearing granulite unit overall ranges from mafic to felsic in composition. It normally occurs as rare, metre-scale layers within other units of the Wirku Metamorphics, located in the nose and flanks of the Mount Aloysius antiform in the Tjuni Pulka Tectonic Zone (on northwestern Bell Rock and southwestern Bates). It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. The gneiss is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50%, and is inversely proportional to quartz. This granulite unit differs from the medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) only in that the latter is usually metatexitic. In both units, the absence of aluminous indicator minerals indicates that the protolith was probably not sedimentary, but was most likely of volcanic origin based on the grain-size, composition, and setting of the rock. This interpretation is supported by the unimodal zircon population age of 1319 ± 7 Ma obtained for a felsic end-member of these rock types. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

Orthopyroxene-bearing granulite is best exposed in the nose and flanks of the Mount Aloysius antiform in the Tjuni Pulka Tectonic Zone (on northwestern Bell Rock and southwestern Bates), where mappable units are up to 100 m thick. It forms a distinct, massive body in the nose of the Mount Aloysius antiform, where it is associated with layered basic to intermediate orthopyroxene–plagioclase granulites and garnetiferous metasediments of the Wirku Metamorphics. To the east of Mount Fanny (Bates), this unit also forms xenoliths up to 2 km^2 in area within metamorphosed granites of the Pitjantjatjara Supersuite.

Lithology

This medium-grained orthopyroxene-bearing granulite unit ranges from mafic to felsic in composition. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. The rock is very dense relative to other units of the Wirku Metamorphics, and in thin section it is composed almost entirely of a granoblastic assemblage of orthopyroxene and plagioclase with or without quartz. Orthopyroxene content varies from 20 to 50%, and is inversely proportional to quartz, which is absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary; instead, the protolith is interpreted to be volcanic in origin based on its grain size, composition, and setting. This interpretation is supported by the unimodal zircon population age of 1319 ± 7 Ma (GSWA 180867, Kirkland et al., 2009a) obtained for a felsic end-member of this rock type sampled south of Mount Holt. The orthopyroxene-bearing granulite unit (P_-WM-mroo) only differs from the medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) in that the latter is usually metatexitic.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Rock type	Meta-igneous felsic	mr
Lithname	Felsic granulite	o
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-WM-mroo**

Geochronology

P_-WM-mroo	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest BLACKSTONE region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

Kirkland, CL, Wingate, MTD, Evins, PM and Smithies, RH 2009a, 180867: quartz monzonite, Mount Holt; Geochronology Record 838: Geological Survey of Western Australia, 4p.

Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187115: diatexitic migmatite, Mount Aloysius; Geochronology Record 792: Geological Survey of Western Australia, 6p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-xmhn-mf)

Legend narrative

Composite gneiss comprising garnet–orthopyroxene–biotite(–cordierite–hercynite–hornblende) pelite and psammite interlayered with subordinate metamorphosed felsic volcanic and volcaniclastic units; typically metatexitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This composite pelitic and psammitic paragneiss unit represents a gradational zone between the garnetiferous diatexite core (P_-WM-mlig) of the Mount Aloysius antiform in the Tjuni Purlka Tectonic Zone on northwestern Bell Rock, and a supracrustal composite gneiss of the Wankanki Supersuite (P_-WN-xmfn-mh). It also occurs elsewhere in the Tjuni Purlka Tectonic Zone as interlayers in other units of the Wirku Metamorphics. The unit is composed of metre-scale layers of metatexitic (equivalent to P_-WM-mhig) to diatexitic (equivalent to P_-WM-mlig) garnet–orthopyroxene–cordierite–sillimanite pelite, interleaved with thicker layers of felsic volcanic granulite (P_-P_-WN-xmfn-mh). All components show granoblastic textures. The protolith of this composite gneiss was probably a turbidite with interbeds of volcanic material. The sedimentary components of this gneiss have not been directly dated, but the depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This composite pelitic and psammitic paragneiss surrounds the garnetiferous diatexite core (P_-WM-mlig) of the Mount Aloysius antiform in the Tjuni Purlka Tectonic Zone, on northwestern Bell Rock. Here, it represents a 500 m wide gradational zone where the garnetiferous diatexitic pelite becomes more metatexitic and interleaved with composite gneiss that contains metavolcanic rocks of the Wankanki Supersuite (P_-WN-xmfn-mh). Elsewhere, this composite gneiss grades into composite supracrustal gneisses of the Wankanki Supersuite (in order from most to least commonly associated: P_-WN-xmfn-mh, P_-WN-xmfn-ms), but is rarely associated as interlayers in other units of the Wirku Metamorphics. Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the heterogeneous gneiss.

Lithology

This composite pelitic and psammitic paragneiss is composed of metre-scale layers of migmatitic garnetiferous pelite (equivalent to P_-WM-mhig) and domains of diatexitic, garnetiferous pelite (equivalent to P_-WM-mlig), interleaved with layers, 1–10 m thick, of felsic granulite (P_-WN-xmfn-mh). In the pelitic component, migmatitic textures range from stromatic to nebulitic to raft migmatite, but in most cases, the boundary between paleosome and leucosome is blurred. In essence, this unit lies in the middle of the migmatitic spectrum between more paleosome-rich stromatic migmatites, such as P_-WM-mhig, and the end-member leucosomes (for example P_-PJ-mgrl) formed during the Musgrave Orogeny. The migmatitic garnetiferous pelite contains rounded garnets, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. The foliation is defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite, and always wraps around the garnet porphyroblasts. Garnet cores typically contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. Plagioclase and biotite inclusions are different in composition to their constituents in the matrix. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial, anhedral orthopyroxene and garnet are in equilibrium, forming clusters within the matrix that are locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some pelite layers. The diatexite contains larger, up to 2 cm, rounded garnets, although the surrounding matrix contains fewer mafic minerals. Antiperthite is common (up to 30%), with lesser amount of perthite (up to 5%).

The felsic granulite component of this gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all minerals in the rock. It is typically syenogranitic in composition, and is composed of a fine-grained granoblastic to dynamically recrystallized quartzofeldspathic matrix with significant antiperthite, perthite, and local myrmekite. Rare, relict, plagioclase phenocrysts up to 1 mm in size can be seen in thin section. Orthopyroxene is a minor component (up to 3%), and is altered to biotite. This gneissic component is texturally, mineralogically, and compositionally identical to some arkosic metasandstones of the Wirku Metamorphics (P_-WM-mtni), differing only in the absence of obvious quartz clasts and the presence of rare, relict, plagioclase phenocrysts. However, several geochronology samples of this unit obtained elsewhere in the west Musgrave region yielded unimodal age populations of c. 1320 Ma, indicating that the protolith is probably volcanic in origin.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: psammite and pelite; interlayered	mh
Lithname 1	Psammitic and pelitic gneiss; interlayered	n
Rock type 2	Meta-igneous felsic volcanic	
Lithname 2	Metafelsic volcanic rock	-mf
Rock code		**P_-WM-xmhn-mf**

Geochronology

P_-WM-xmhn-mf	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Wirku Metamorphics; subunit (P_-WM-xmli-mr)

Legend narrative

Composite gneiss comprising diatexitic, coarse-grained garnet–orthopyroxene–biotite(–cordierite) pelite, with lesser medium-grained orthopyroxene–plagioclase (–quartz) acid to intermediate granulite gneiss

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This composite diatexitic gneiss occupies the nose of the Mount Aloysius antiform, in the Tjuni Purlka Tectonic Zone of northwest BELL ROCK. It represents a mixture of migmatitic garnetiferous pelites (P_-WM-mlig, P_-WM-mhig) and acid to intermediate granulites (P_-WM-mroo) of the Wirku Metamorphics. It is composed of centimetre- to metre-scale pelite screens within massive orthopyroxene–plagioclase(–quartz) granulite. All components of the gneiss have a granoblastic texture, and are folded around the nose of the Mount Aloysius antiform. The protoliths of this composite gneiss were likely mid-fan to distal turbidites injected by subvolcanic sills of intermediate composition. The sedimentary components of this gneiss have not been directly dated, but the depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This composite diatexitic gneiss occupies the nose of the Mount Aloysius antiform, in the Tjuni Purlka Tectonic Zone of northwest BELL ROCK, where it is exposed over an area of roughly 4 km^2. It represents a mixture of migmatitic garnetiferous pelites (P_-WM-mlig, P_-WM-mhig) and basic to intermediate granulites (P_-WM-mroo) of the Wirku Metamorphics. In exposures on the northwest side of Mount Aloysius, it locally contains mappable layers of garnetiferous pelite. Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the gneiss. The combination of solely garnetiferous pelites and substantial layers of acid to intermediate granulites, even on scale of the less than 10 m, is very rare elsewhere in the west Musgrave Province, as both components are generally minor constituents of the Wirku Metamorphics.

Lithology

This composite diatexitic gneiss is composed of layers of garnetiferous pelite (P_-WM-mhig) up to 10 m thick, and domains (screens) of diatexitic garnetiferous pelite (P_-WM-mlig), in a massive basic to intermediate granulite (P_-WM-mroo). The composite gneiss is locally metatexitic, with layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. All components of the gneiss are foliated, and are folded around the nose of the Mount Aloysius antiform. In the pelitic component, migmatitic textures range from stromatic to nebulitic to raft migmatite, but in most cases, the boundary between paleosome and leucosome is blurred. In essence, this unit lies in the middle of the migmatitic spectrum between more paleosome-rich stromatic migmatites, such as P_-WM-mhig, and the end-member leucosomes (for example P_-PJ-mgrl) formed during the Musgrave Orogeny. The migmatitic garnetiferous pelite contains rounded garnets, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. A foliation defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite always wraps around the garnet porphyroblasts. Garnet cores typically contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. Plagioclase and biotite inclusions are different in composition to their constituents in the matrix. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in equilibrium, forming clusters within the matrix that are locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some pelite layers. The diatexite contains large, rounded, garnets up to 2 cm in size. Antiperthite is common (up to 30%), with lesser amounts of perthite (up to 5%).

The acid to intermediate granulite component of this gneiss is medium-grained and generally not banded. A well-developed foliation is locally defined by all minerals in the rock. Otherwise, the minerals form a polygonal, granoblastic texture indicative of granulite-facies metamorphism. The basic to intermediate granulite component is typically composed of orthopyroxene and plagioclase, in a granoblastic texture with or without quartz. Garnet grains, up to 2 cm in size, are locally present near boundaries with garnetiferous pelites, and are interpreted to be a xenocrystic phase. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals in the massive layers indicates that the protolith was probably not sedimentary, but was more likely to have been intrusive (possibly subvolcanic) based on grain-size, composition, and setting.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: pelite	ml
Lithname 1	Pelitic migmatite	i
Rock type 2	Meta-igneous felsic	
Lithname 2	Metafelsic rock	-mr
Rock code		**P_-WM-xmli-mr**

Geochronology

P_-WM-xmli-mr	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

Kirkland, CL, Wingate, MTD, Evins, PM and Smithies, RH 2009a, 180867: quartz monzonite, Mount Holt; Geochronology Record 838: Geological Survey of Western Australia, 4p.

Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187115: diatexitic migmatite, Mount Aloysius; Geochronology Record 792: Geological Survey of Western Australia, 6p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-xmt-mh)

Legend narrative

Fine to medium grained, laminated feldspathic psammite interlayered with garnet–orthopyroxene–biotite (–cordierite–hercynite–hornblende) pelite and psammite; local calc-silicate interlayers; typically metatexitic

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This interlayered laminated psammitic and garnetiferous pelitic gneiss unit is well-exposed over the eastern third of Mount Aloysius, in the Tjuni Purlka Tectonic Zone of northwest Bell Rock. It also occurs elsewhere throughout the Tjuni Purlka Tectonic Zone and Walpa Pulka Zone, both as metre-scale interlayers in other units of the Wirku Metamorphics, and interbedded with volcanic rocks of the Wankanki Supersuite. The composite gneiss is dominated by metre-scale, pyroxene-bearing arkosic metasandstone (P_-WM-mtni) layers, with lesser interlayers of garnet–orthopyroxene pelite and psammite (P_-WM-mhig, P_-WM-mlig), and rare layers of acid (P_-WN-xmfn-mh) and intermediate (P_-WM-mroi) metavolcanic granulites. It is typically metatexitic, with transposed leucogranite veins and anatectic leucosomes. All components show granoblastic textures, and have been folded at least twice before the Musgrave Orogeny. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This interlayered laminated psammitic and garnetiferous pelitic gneiss is dominated by magnetic psammitic components that are identifiable as positive aeromagnetic (TMI) and gravity anomalies within the more pelitic units of the Wirku Metamorphics. It is well-exposed over the eastern third of Mount Aloysius, in the Tjuni Purlka Tectonic Zone of northwest Bell Rock. It grades into other paragneisses (in order from most to least commonly associated: P_-WM-mtni, P_-WM-mhig, P_-WM-mlig, P_-WM-mroi) and composite gneisses (in order from most to least commonly associated: P_-WM-xmhn-mf, P_-WM-xmli-mr, P_-WM-xmtn-mf) of the Wirku Metamorphics, and also into composite supracrustal gneisses of the Wankanki Supersuite (in order from most to least commonly associated: P_-WN-xmfn-mh, P_-WN-xmfn-ms). Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the heterogeneous gneiss. Therefore, in a sense, this unit occurs as 1–10 m thick interlayers in many outcrops of the Wirku Metamorphics, throughout the Tjuni Purlka Tectonic Zone and Walpa Pulka Zone. However, most outcrop of this unit is confined to the Mount Aloysius region of the Tjuni Purlka Tectonic Zone, with lithologies similar in appearance in the Mount Holt area (Holt) dominated by volcanic rocks of the Wankanki Supersuite.

Lithology

This psammitic and garnetiferous pelitic gneiss unit is dominated by 1–10 m thick arkosic metasandstone (P_-WM-mtni) layers, with lesser interlayers of garnetiferous pelite and psammite (P_-WM-mhig, P_-WM-mlig), and rare layers of acid (P_-WN-xmfn-mh) and intermediate (P_-WM-mroi) granulite; thin calc-silicate layers are very rare. The gneiss is typically metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The entire gneiss (including the leucosome) has been folded at least twice before the Musgrave Orogeny. The constituent minerals of all components typically form a polygonal, granoblastic texture indicative of granulite-facies metamorphism.

The arkosic metasandstone component is banded on a centimetre- to metre-scale. Where the rock is lithologically homogenous, gneissic banding is defined by cyclic changes in grain size, suggestive of relict graded bedding. The arkosic metasandstone is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. The metasandstone is composed of <3 mm, dismembered, undulatory quartz grains in a finer-grained, granoblastic to dynamically recrystallized feldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite.

The psammitic and pelitic component of this gneiss unit is composed of alternating centimetre- to metre-thick layers of garnetiferous pelite, psammite, and transposed leucocratic granite. Together, these form a metatexitic stromatic migmatite. Pelitic layers contain rounded garnets, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic matrix with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. A foliation is defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite, and always wraps around the garnet porphyroblasts. Garnet cores typically contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. Plagioclase and biotite inclusions are different in composition to their counterparts in the groundmass. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in equilibrium, forming clusters within the matrix that are locally retrogressed to biotite. Together garnet, orthopyroxene, and biotite can form up to 30% of some pelite layers. Psammitic layers rarely contain garnet porphyroblasts, but do contain significant (up to 10%) anhedral orthopyroxene, garnet, and biotite set in a quartzofeldspathic matrix. Antiperthite is common (up to 30%) in both psammitic and pelitic layers, along with lesser amounts of perthite (up to 5%). Orthopyroxene is locally retrogressed to amphibole along shear zones. The sedimentary protolith to the psammitic and pelitic component was likely a turbidite, based on that component's alternating layered characteristic.

The acid to intermediate granulite component of this unit is a fine-grained gneiss. It is texturally, mineralogically, and compositionally identical to the main arkosic metasandstone component of the composite gneiss described above, apart from the absence of obvious quartz clasts and presence of occasional relict plagioclase phenocrysts. However, several geochronology samples of this unit obtained elsewhere in the west Musgrave region yielded unimodal age population of c. 1320 Ma, indicating a volcanic protolith for this component.

The basic to intermediate granulite component of this gneiss is medium grained, and composed of orthopyroxene–plagioclase(–quartz). It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. The absence of garnet and other aluminous minerals indicates that the protolith is probably not sedimentary, but is most likely to have been volcanic in origin based on its grain size, composition, and setting.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: psammite	
Lithname 1	Metasandstone	mt
Rock type 2	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 2	Psammite and pelite; interlayered -	mh
Rock code		**P_-WM-xmt-mh**

Geochronology

P_-WM-xmt-mh	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187115: diatexitic migmatite, Mount Aloysius; Geochronology Record 792: Geological Survey of Western Australia, 6p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2011a, 184150: metasandstone, Kampurarr Pirti; Geochronology Record 940: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti; Geochronology Record 932: Geological Survey of Western Australia, 4p.

Wirku Metamorphics; subunit (P_-WM-xmtn-mf)

Legend narrative

Composite gneiss comprising orthopyroxene-bearing psammite and minor pelite interlayered with lesser metamorphosed medium-grained, orthopyroxene-bearing felsic volcanic and volcaniclastic units; locally garnetiferous

Rank	Formation
Parent	Wirku Metamorphics (P_-WM-mh)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

Together with a composite gneiss unit of the Wankanki Supersuite (P_-WN-xmfn-ms), this composite orthopyroxene-bearing gneiss unit of the Wirku Metamorphics makes up the southern two-thirds of the supracrustal sequence exposed at Mount Holt, in the Tjuni Purlka Tectonic Zone on HOLT. Elsewhere, the orthopyroxene-bearing gneiss unit of the Wirku Metamorphics is restricted to metre-scale interlayers associated with the transitional contacts between psammites and felsic metavolcanic rocks, most notably on Mount Aloysius (northwestern BELL ROCK). This composite orthopyroxene-bearing gneiss is composed of metre-scale, pyroxene-bearing arkosic metasandstone (P_-WM-mtni), interleaved with macroscopically identical felsic metavolcanic granulite that forms a component in composite gneiss of the Wankanki Supersuite (P_-WN-xmfn-ms). Although pyroxene-bearing arkosic metasandstone is the dominant component, the composite orthopyroxene-bearing gneiss differs from the interlayered laminated psammitic and garnetiferous pelitic gneiss unit (P_-WM-xmt-mh), also of the Wirku Metamorphics, in that its secondary component is a felsic metavolcanic rock, rather than pelitic and mafic granulite interlayers. The composite orthopyroxene-bearing gneiss is locally metatexitic with transposed leucosomes. The protolith is interpreted to have been a basin deposit proximal to a c. 1320 Ma volcanic source. The depositional age of the protolith to the Wirku Metamorphics is constrained to between c. 1340 and 1270 Ma.

Distribution

This composite orthopyroxene-bearing gneiss unit of the Wirku Metamorphics is intimately associated with a composite supracrustal gneiss of the Wankanki Supersuite (P_-WN-xmfn-ms). Together, they occupy a large (25 x 8 km), northwest-trending area that makes up the southern part of the supracrustal section exposed at Mount Holt, in the Tjuni Purlka Tectonic Zone on HOLT. This unit, and its relationships with the surrounding units, is best exposed along the western flank of a large hill 3 km south of Mount Holt. It represents a place where the metasedimentary rock dominated (P_-WM-mtni) end-member of heterogeneous gneisses is variably interleaved with felsic metavolcanic rocks of the Wankanki Supersuite (P_-WN-xmfn-ms). Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the gneiss. Elsewhere, this unit is restricted to metre-scale interlayers associated with gradational contacts between psammites and felsic metavolcanic rocks, most notably on Mount Aloysius (northwestern BELL ROCK).

Lithology

This composite orthopyroxene-bearing gneiss unit is composed of layers, up to 10 m thick, of arkosic metasandstone of the Wirku Metamorphics (P_-WM-mtni), interleaved with felsic metavolcanic rock of the Wankanki Supersuite (P_-WN-xmfn-ms). Although the dominant component of this gneiss is the arkosic metasandstone (P_-WM-mtni), this composite unit differs from the interlayered laminated psammitic and garnetiferous pelitic gneiss unit (P_-WM-xmt-mh) of the Wirku Metamorphics in that the secondary component of the former gneiss is a felsic metavolcanic rock, as opposed to pelitic and mafic granulite interlayers. The composite orthopyroxene-bearing gneiss is locally metatexitic, with layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The entire gneiss (including the leucosome) has been folded at least twice before the Musgrave Orogeny. The constituent minerals of all components typically form a polygonal, granoblastic texture indicative of granulite-facies metamorphism.

The arkosic metasandstone component of the composite orthopyroxene-bearing gneiss unit is banded on a centimetre- to metre-scale. Where the rock is lithologically homogenous, the gneissic banding is defined by cyclic changes in grain size suggestive of relict graded bedding. The arkosic metasandstone component is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. It is typically composed of dismembered, undulatory, quartz grains <3 mm in size, in a finer-grained, granoblastic to dynamically recrystallized feldspathic matrix with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite.

The felsic metavolcanic component of this gneiss is a leucocratic, fine-grained gneiss. It is texturally, mineralogically, and compositionally identical to the main arkosic metasandstone component of the composite gneiss, apart from the absence of obvious quartz clasts and presence of occasional relict plagioclase phenocrysts. However, a geochronology sample (GSWA 180867, Kirkland et al., 2009a) obtained from this component yielded a unimodal age population of 1319 ± 7 Ma, indicating that the protolith is volcanic.

Age code	Proterozoic	P_-
Stratigraphic code	Wirku Metamorphics	WM-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic: psammite	mt
Lithname 1	Psammitic gneiss	n
Rock type 2	Meta-igneous felsic volcanic	
Lithname 2	Metafelsic volcanic rock	-mf
Rock code		**P_-WM-xmtn-mf**

Geochronology

P_-WM-xmtn-mf	*Maximum*	*Minimum*
Age (Ma)	1340	1270
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., in press	Evins et al., in press

Sixteen samples from the Wirku Metamorphics have been dated by ion microprobe (SHRIMP). Using these samples, an approximate maximum depositional age can be interpreted from an average of the youngest detrital zircon components (c. 1340 Ma; Evins et al., in press). The minimum depositional age is constrained by crosscutting c. 1300 Ma granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone, and a 1319 ± 7 Ma felsic volcanic layer that is interleaved with metasedimentary units of the Wirku Metamorphics south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Together, these ages suggest that protoliths to the Wirku Metamorphics were, in most cases, deposited between 1340 and 1300 Ma. However, some exposures are of paragneisses containing detrital zircon grains with cores apparently as young as c. 1270 Ma. For example, sample GSWA 187115, a medium-grained acid to intermediate granulite gneiss unit (P_-WM-mroi) from the eastern flank of Mount Aloysius (Bell Rock), contains zircon cores with a 1555–1270 Ma age range, and significant c. 1510, 1410, and 1360 Ma detrital populations (Kirkland et al., 2009b); Evins et al. (in press) suggests that c. 1270 Ma is the best estimate for the depositional age of the protolith to this gneiss. However, there is significant difficulty in determining the maximum depositional age for these rocks, as radiogenic-Pb loss was pervasive during the Musgrave Orogeny. Nonetheless, it is possible that the Wirku Metamorphics might include a younger sedimentary unit in the Tjuni Purlka Tectonic Zone.

Two samples, interpreted to be volcaniclastic rocks, have zircon grains sourced solely from the Wankanki Supersuite, and yielded unimodal zircon populations of 1310 ± 7 and 1334 ± 6 Ma (GSWA 184150, Kirkland et al., 2011a; GSWA 190245, Kirkland et al., 2011b); these rocks are tentatively assigned to the Wirku Metamorphics. In the southwest Blackstone region, the minimum depositional age of the Wirku Metamorphics is also constrained by a crosscutting 1321 ± 5 Ma granite of the Wankanki Supersuite (GSWA 184158, Kirkland et al., in prep.).

References

Evins, PM, Kirkland, CL, Wingate, MTD, Smithies, RH, Howard, HM, and Bodorkos, S in press, Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia: Geological Survey of Western Australia, Record.

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Wankanki Supersuite (P_-WN-mg)

Legend narrative

Metagranite and gneiss

Rank	Supersuite
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

Rocks of the Wankanki Supersuite formed between c. 1345 and c. 1293 Ma, and therefore represent the magmatic expression of the Mount West Orogeny. This supersuite outcrops throughout the Tjuni Purlka Tectonic Zone, mainly on BELL ROCK and HOLT, and forms perhaps the most abundant felsic component in the Mamutjarra Zone (mainly BLACKSTONE); no rocks of the Wankanki Supersuite are known to occur within the Walpa Pulka Zone (on BATES). The supersuite is dominated by intrusive rocks. However, fine-grained, laminated to banded, orthopyroxene-bearing rocks, whose protoliths are interpreted as volcanic or volcaniclastic rocks, also occur, particularly in the northwestern part of the Tjuni Purlka Tectonic Zone. These volcanic-derived rocks are interlayered with metamorphosed clastic rocks of the 1340–1270 Ma Wirku Metamorphics; where the volcanic or volcaniclastic rocks dominate, the mixed unit has been assigned to the Wankanki Supersuite.

Rocks of the Wankanki Supersuite typically lie within the compositional range of quartz monzonite to syenogranite, with granodiorite to monzogranite being the dominant rock types. They are generally leucocratic, with up to 12% mafic minerals typically dominated by hypersthene, although the protoliths most likely crystallized hornblende and biotite. All have been metamorphosed to at least the upper amphibolite, and more typically the granulite, facies. The intrusive rocks are weakly to moderately foliated and porphyritic. A strong gneissosity and metatexitic to diatexitic migmatite are locally well developed. Inclusions of metasedimentary rocks of the Wirku Metamorphics are found in many exposures, and range up to several kilometres in length.

Distribution

Rocks of the Wankanki Supersuite occur throughout the Tjuni Purlka Tectonic Zone, mainly on BELL ROCK and HOLT, and form perhaps the most abundant felsic component in the Mamutjarra Zone (mainly BLACKSTONE). The supersuite is dominated by intrusive rocks. However, fine-grained, laminated to banded, orthopyroxene-bearing rocks, whose protoliths are interpreted to have been volcanic or volcaniclastic rocks, form part of the supersuite locally, particularly in the northwestern part of the Tjuni Purlka Tectonic Zone. These volcanic or volcaniclastic rocks are often interbedded with metasedimentary units, forming various mixed units of both the Wankanki Supergroup and Wirku Metamorphics (e.g. P_-WN-xmf-ms, P_-WN-xmfn-ms, P_-WN-xmfn-mh). Volcanic or volcaniclastic units also form a minor component in the southwestern parts of BLACKSTONE, and in this area they are also assigned to the Wirku Metamorphics as a mixed unit of Wankanki Supergroup and Wirku Metamorphics (P_-WM-xmh-mf).

No rocks of the Wankanki Supersuite are known to occur within the Walpa Pulka Zone (on BATES) to the north of the Tjuni Purlka Tectonic Zone.

Derivation of name

Howard et al. (2007) grouped all rocks with igneous crystallization ages falling between c. 1345 and c. 1293 Ma into the Wankanki Supersuite, and termed the crustal event that produced them the Mount West Orogeny. The term ‘Wankanki’ is derived from the local (Pitjantjatjara dialect) name for Mount West (‘Puli Wankanki’), located in the central part of BELL ROCK, which is the type locality for this supersuite.

Lithology

Intrusive rocks of the Wankanki Supersuite typically lie within the compositional range of quartz monzonite to syenogranite, with granodiorite to monzogranite being the dominant rock types. All have been metamorphosed to at least the upper amphibolite, and more typically the granulite, facies, and show a correspondingly wide range of primary and secondary textures and mineralogies. Most samples of intrusive rocks from the Wankanki Supersuite have microtextures that range from hypidiomorphic granular to granoblastic polygonal. The rocks are generally leucocratic, with up to 12% mafic minerals. Weakly metamorphosed examples preserve an igneous mineralogy that includes hornblende > biotite, with clinopyroxene cores to hornblende. More commonly, a high-grade metamorphic assemblage includes hypersthene > biotite > clinopyroxene and hornblende (both green and brown varieties). Where the rocks are porphyritic, perthitic K-feldspar is typically the dominant phenocryst phase, although many samples also contain abundant plagioclase phenocrysts, and plagioclase itself is commonly antiperthitic.

In the area south of the Hinckley Range (on BELL ROCK) and west of Mount Aloysius (on HOLT), many exposures of the Wankanki Supersuite consist of weakly to moderately foliated and porphyritic rock, with tabular to subrounded perthite, and lesser plagioclase phenocrysts to 2 cm. Phenocryst-poor, seriate-textured equivalents also occur in this region. To the west of MacDougall Bluff and south of Peak Hill (on BLACKSTONE), the rocks are moderately to highly porphyritic, with tabular K-feldspar phenocrysts, to 3 cm in size, forming up to 60% of the rock. These phenocrysts are locally strongly aligned, in places defining a trachytic flow-texture. In other areas, for example around Mount West (central BELL ROCK) and in the southern parts of BLACKSTONE, the rocks show a range of metamorphic fabrics from a weakly developed gneissic banding to a strong gneissosity, and metatexitic to diatexitic migmatite is locally well developed. Some outcrops in these areas include panels of migmatite and migmatitic schlieric leucogranite.

The foliation and gneissic banding developed in rocks of the Wankanki Supersuite trends to the northwest within the southeastern part of the Tjuni Purlka Tectonic Zone (on Bell Rock), whereas the trend is typically to the northeast in the southern Blackstone area. In the former region, leucosomes and veins of migmatitic melt are mostly foliation-parallel, but can locally cut the foliation. Compositionally uniform, unfoliated to strongly foliated, leucogranite dykes that crosscut the Wankanki Supersuite have been sampled from the area north of Mount West and dated (GSWA 183509, Kirkland et al., 2007). The crystallization age of 1165 ± 10 Ma obtained from these rocks likely represents the age of deformation in this area. Dating of zircon overgrowths in Wankanki Supersuite rocks from throughout the west Musgrave Province provides a range of metamorphic ages that span the entire Musgrave Orogeny. The main northwest-trending foliation seen in the west Musgrave Province was either produced or rotated (to the northwest) during the Musgrave Orogeny (White et al., 1999; Betts et al., 2002; Belperio, 2009). In contrast, in the southern Blackstone area where neither the regional northwest-trending foliation nor the magmatism related to the Pitjantjatjara Supersuite are strongly developed, the gneissic banding seen in rocks of the Wirku Metamorphics and the Wankanki Supersuite is folded about a northeast-trending fold axis. Here, rare 1–2 m wide dykes of unfoliated porphyritic syenogranite belonging to the Pitjantjatjara Supersuite, intrude parallel to the fold-axis. Dating of these Pitjantjatjara Supersuite granite dykes constrains the minimum age of the foliation and folding in this region to 1201 ± 6 Ma (GSWA 184146, Kirkland et al., 2009a). It is thus likely that the strong northeast-trending foliation seen in the rocks of the Wankanki Supersuite and the Wirku Metamorphics reflects a deformation event that pre-dates the Musgrave Orogeny. This suggestion is consistent with previous observations that the rocks of the Wirku Metamorphics in the Mount Aloysius region (in the northwest of Bell Rock) show at least two phases of deformation that pre-date the intrusion of Pitjantjatjara Supersuite magmas.

Inclusions of metasedimentary rocks belonging to the Wirku Metamorphics are found in many exposures of the Wankanki Supersuite. In the vicinity of Mount West (central Bell Rock), rafts of metasedimentary rock are up to several hundred metres long, whereas in the southern part of Blackstone, aeromagnetic data suggests the presence of rafts up to several kilometres in length.

The rocks of the Wankanki Supersuite are metaluminous, and calcic to calc-alkalic. They show a strong compositional similarity to Phanerozoic granites in continental-arcs, including strong enrichments in barium and relative depletions in niobium (e.g. high La/Nb ratios), although they are generally dominated by more silica-rich rocks, with most Wankanki granites containing >65 wt% SiO_2. Wankanki rocks consistently fall within the field for volcanic-arc granites in tectonic discrimination diagrams, and in this respect they differ from most other granites in the west Musgrave Province, which tend to lie within the within-plate granites field (Smithies et al., 2009).

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-WN-mg**

Geochronology

P_-WN-mg	*Maximum*	*Minimum*
Age (Ma)	1345 ± 7	1293 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2010	Kirkland et al., in prep.

The crystallization age range of the Wankanki Supersuite is constrained to between 1345 ± 7 Ma (GSWA 194393, Kirkland et al., 2010) and 1293 ± 9 Ma (GSWA 183726, Kirkland et al., in prep.). Approximately 20 samples have been dated within this range, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009b; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-mggo)

Legend narrative

Hypersthene–biotite granodiorite to monzogranite; enderbite to charnockite; moderately foliated to gneissic and locally weakly migmatitic; typically feldspar porphyritic and mesocratic

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This hypersthene–biotite granodiorite to monzogranite unit is a locally significant component of the Wankanki Supersuite found in the southwestern corner of BLACKSTONE and southeast corner of COOPER. This unit comprises foliated (in places very weakly) to gneissic, typically feldspar porphyritic, orthopyroxene-bearing quartz diorite and granodiorite to monzogranite. It includes weakly foliated quartz monzodiorite, quartz diorite, and granodiorite that outcrops immediately to the southeast and south of the layered mafic Cavenagh Range intrusion, which was originally assigned to the Warakurna Supersuite (P_-WK-gkhc). However, the crystallization age of c. 1321 Ma obtained for this unit is within the known age range (1345–1293 Ma) for the Wankanki Supersuite.

Distribution

This hypersthene–biotite granodiorite to monzogranite unit is a locally significant component of the Wankanki Supersuite, forming well-exposed outcrops in the Mamutjarra Zone, in the southwestern corner of BLACKSTONE and southeast corner of COOPER (at Borrows Hill).

Lithology

This unit of the Wankanki Supersuite typically comprises foliated to gneissic and locally migmatitic, mesocratic, feldspar-porphyritic rocks in the compositional range of granodiorite to monzogranite. It also includes the weakly foliated hornblende–pyroxene quartz monzodiorite, quartz diorite, and granodiorite that outcrop immediately to the southeast and south of the layered mafic Cavenagh Range intrusion. Because of the typically massive appearance of this rock to the southeast of the Cavenagh Range intrusion, the rocks in that region were originally assigned to the Warakurna Supersuite (P_-WK-gkhc on 1st Edition BLACKSTONE sheets; Smithies et al., 2009a). The rocks of this region, plus those in the area to the south of the Cavenagh Range intrusion, are now known to be locally gneissic and intruded by rocks of the Pitjantjatjara Supersuite, and are now assigned to the Wankanki Supersuite (with which they are geochemically equivalent).

These mesocratic and feldspar porphyritic rocks have a mottled texture produced by pyroxene–biotite-rich clots and stringers, and rarer mafic and microgranitic enclaves, which are weakly to strongly flattened between felsic domains comprising feldspar phenocrysts (that are up to 2 cm in size), or quartz–plagioclase–K-feldspar aggregates. The rocks consist of subequal proportions of perthitic K-feldspar, plagioclase, and quartz. The texture is generally hypidiomorphic granular, although a granoblastic polygonal texture dominates some rocks, or dominates some domains on the thin section scale. Mafic minerals form up to 15% of the rock and are dominated by hypersthene. In some samples, clinopyroxene accompanies orthopyroxene, forming aggregate clots locally altered to, and rimmed by, brown biotite. In other samples, brown or green-brown hornblende replaces clinopyroxene.

At several localities (e.g. WAROX site SXBMUG003391: MGA 407909E 7081736N), rare leucocratic segregations and pegmatite veins cut the prominent northeast-trending foliation or gneissosity. As a result, the age of this fabric, of an associated northeast-directed folding, and of localized migmatization and leucogranite melt segregation, is constrained by the crystallization age of one of these veins, to a minimum age of 1201 ± 6 Ma (GSWA 184146, Kirkland et al., 2009a); however, these fabrics may be as old as the minimum age of the Wankanki Supersuite host (c. 1293 Ma).

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metagranodiorite	g
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-WN-mggo**

Geochronology

P_-WN-mggo	*Maximum*	*Minimum*
Age (Ma)	1321 ± 5	1321 ± 5
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., in prep.	Kirkland et al., in prep.

A single sample (GSWA 184158) of this hypersthene–biotite granodiorite to monzogranite unit (P_-WN-mggo), from southwestern BLACKSTONE, has been dated at 1321 ± 5 Ma (Kirkland et al., in prep.). This falls within the known crystallization age range of the Wankanki Supersuite, which is from c. 1345 to c. 1293 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009b; summarized in Smithies et al., 2009b).

References

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Wankanki Supersuite; subunit (P_-WN-mgmo)

Legend narrative

Hypersthene–biotite(–clinopyroxene–brown-hornblende) charnockitic monzogranite to granodiorite; moderately foliated and locally metatexitic; typically seriate textured but locally with microcline phenocrysts up to 3 cm

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This metamorphosed hypersthene–biotite monzogranite to granodiorite unit outcrops very poorly in the southwestern part of BLACKSTONE, but is inferred, based on aeromagnetic data, to form an extensive Wankanki Supersuite bedrock unit in that part of the Mamutjarra Zone. It is typically leucocratic, moderately to strongly foliated, locally migmatitic, and K-feldspar porphyritic, and might be transitional with other K-feldspar porphyritic units of the Wankanki Supersuite exposed immediately to the north. The crystallization age of c. 1324 Ma obtained for this unit is within the known age range (1345–1293 Ma) of the Wankanki Supersuite.

Distribution

This unit outcrops very poorly in the southwestern part of BLACKSTONE, but is inferred, based on aeromagnetic data, to form an extensive Wankanki Supersuite bedrock unit in that part of the Mamutjarra Zone.

Lithology

This metamorphosed hypersthene–biotite monzogranite to granodiorite is typically leucocratic and moderately to strongly foliated; the unit is locally veined by networks of migmatitic melt, or else shows weakly developed migmatitic banding (metatexite). Flattened clots of biotite, up to 1cm in size, give the rock a mottled texture. The rock is locally porphyritic, particularly in the northern parts of the unit's extent, with thin lath shaped feldspar phenocrysts, up to 2.5 cm in size, aligned parallel to foliation. In this respect, the unit might be transitional with K-feldspar porphyritic units of the Wankanki Supersuite (P_-WN-mgrb) found immediately to the north. Where the unit outcrop is well-developed, it is seen to envelop elongate rafts of metasedimentary rocks of the Wirku Metamorphics. Over the vast areas where outcrop is poor or absent, the presence of these large metasedimentary rafts is interpreted from aeromagnetic data. In both cases, the rafts define typically northeast-trending, large-scale folds consistent with the pre-Musgrave Orogeny foliation direction measured within the region (see P_-WN-mg).

This metamorphosed hypersthene–biotite monzogranite to granodiorite is generally leucocratic, with 5–10% mafic minerals. The texture is seriate and granoblastic polygonal. Microcline and plagioclase (locally antiperthitic) are in similar abundance. Hypersthene is the main mafic mineral, and typically forms elongate grain aggregates that include brown biotite, either clinopyroxene or brown (to brown-green) hornblende, and an opaque mineral surrounding quartz–feldspar domains. The orthopyroxene is variably altered to a light-green ?amphibole.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-WN-mgmo**

Geochronology

P_-WN-mgmo	*Maximum*	*Minimum*
Age (Ma)	1324 ± 7	1324 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009a

A sample of the metamorphosed hypersthene–biotite monzogranite to granodiorite (GSWA 185606), obtained from an outcrop where this unit forms isolated sheets (lenses) and inclusions within younger granites of the Pitjantjatjara Supersuite, gave an age of igneous crystallization of 1324 ± 7 Ma (Kirkland et al., 2009a). This falls within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009b; summarized in Smithies et al., 2009). A rim on a primary igneous zircon gave an age of 1170 ± 3 Ma (Kirkland et al., 2009a), which is interpreted to be both the age of metamorphic recrystallization of the hypersthene–biotite-bearing charnockitic monzogranite to granodiorite, and the age of intrusion of the host granites of the Pitjantjatjara Supersuite.

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Wankanki Supersuite; subunit (P_-WN-mgmu)

Legend narrative

Weakly to strongly foliated, porphyritic metamonzogranite; contains clinopyroxene, orthopyroxene, and hornblende; K-feldspar phenocrysts up to 2 cm; locally mylonitic

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This porphyritic metamonzogranite unit forms one of the most voluminous granite phases of the Wankanki Supersuite. Outcrop occurs within the Tjuni Purlka Tectonic Zone, in a belt that stretches from the vicinity of Mount West on southwestern Bell Rock, to the southern part of Holt. It is a leucocratic to mesocratic, typically medium-grained and porphyritic rock that ranges in composition from quartz monzonite to monzogranite. The rocks have been variably metamorphosed up to granulite facies, and range from weakly to strongly foliated, in places showing the beginnings of gneissic layering. Some outcrops include panels of migmatite and migmatitic schlieric leucogranite at least partly derived through melting of these rocks at deep crustal levels during the Musgrave Orogeny. Samples dated from this porphyritic metamonzogranite unit give ages of intrusion between c. 1322 and 1312 Ma, falling within the known age range (1345–1293 Ma) for the Wankanki Supersuite.

Distribution

This unit forms outcrop in two main regions within the Tjuni Purlka Tectonic Zone. In the vicinity of Mount West on southwestern Bell Rock, the metamonzogranite forms a west-northwest belt that straddles the Michael Hills intrusion. Further to the west-northwest on Holt, the metamonzogranite forms extensive outcrop in the region between Morgan Range and Blackstone Range.

Lithology

The rocks of this porphyritic metamonzogranite unit are leucocratic to mesocratic, typically medium-grained, porphyritic or less commonly seriate, and range in composition from quartz monzonite to monzogranite, with rocks in the monzogranite compositional range being most common. Grain size varies in some outcrops, alternating between sheets of medium-grained weakly porphyritic granite, and of medium- to coarse-grained and locally strongly porphyritic granite. Local inclusions and contorted veins and stringers of medium-grained weakly porphyritic granite within strongly porphyritic granite, and of strongly porphyritic granite in weakly porphyritic granite, suggest magma mixing. The rocks have been variably metamorphosed up to granulite facies, and range from weakly to strongly foliated, locally with a well-developed lineation and in places showing the beginnings of gneissic layering. Some outcrops include panels of migmatite and migmatitic schlieric leucogranite. In the southern part of Holt, this rock is typically a metamorphosed orthopyroxene-bearing monzogranite to quartz monzonite. Samples from the area south of the Hinckley Range (Bell Rock) differ slightly in that they are typically more restricted to the granodiorite to monzogranite compositional range. In all areas, the rocks are generally weakly to moderately foliated, and are typically porphyritic with tabular to subrounded perthite phenocrysts to 2 cm, although seriate-textured examples do occur. The rocks comprise quartz (15–30%), perthite (15–35%), and plagioclase (30–45%); most examples contain both orthopyroxene (up to 10%) and clinopyroxene (up to 5%), as well as green hornblende (up to 8%) and biotite (up to 12%), although rare samples contain no pyroxene. Accessory minerals include magnetite, apatite, and zircon. The texture is reasonably well-developed hypidiomorphic granular, although granoblastic polygonal domains do exist, particularly in some mafic-rich areas. Perthite phenocrysts overgrow plagioclase and quartz. Many grain contacts are concertal, and myrmekite is locally well-developed. In some samples, plagioclase and perthite are rounded and broken, and are mantled by a mortar-textured mosaic of quartz and feldspar. Large anhedral crystals of pyroxene (mainly orthopyroxene) and hornblende (some with clinopyroxene cores), both of igneous origin, are preserved in some samples, particularly in the area south of the Hinckley Range. Orthopyroxene sometimes forms irregular aggregates of optically continuous grains, suggesting an initial phenocryst phase. However, in many cases mafic domains tend to be a finer-grained granoblastic assemblage of plagioclase–hornblende–pyroxene–magnetite–apatite, with later magnetite filling interstitial areas, and biotite forming rims around magnetite. Early orthopyroxene is variably replaced by biotite, or by hornblende and metamorphic clinopyroxene. In the area south of the Hinckley Range, fine-grained polygonal clinopyroxene–biotite intergrowths also rim hornblende in what appears to be a prograde metamorphic reaction.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-WN-mgmu**

Geochronology

P_-WN-mgmu	*Maximum*	*Minimum*
Age (Ma)	1322 ± 6	1312 ± 15
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009	Kirkland et al., in prep.

Two samples from this porphyritic metamonzogranite unit (P_-WN-mgmu) have been dated. GSWA 183492, collected from an area north of Mount West on BELL ROCK, gave an age of igneous crystallization of 1322 ± 6 Ma (Kirkland et al., 2009). GSWA 187151, from an area to the south of the Morgan Range, gave an age of igneous intrusion of 1312 ± 15 Ma (Kirkland et al., in prep.). Two additional samples from north of Mount West on BELL ROCK, are of mylonite developed within this unit therefore and gave slightly younger ages (GSWA 155712 and 155750 gave ages of 1303 ± 54 Ma and 1305 ± 11 Ma respectively; Belperio, 2009) that may represent the age of mylonitic deformation in this area. These ages fall within the known crystallization age range of the Wankanki Supersuite, which is between 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-mgni)

Legend narrative

Migmatitic gneiss; metatexitic to diatexitic; locally stromatic; mainly derived from hypersthene–biotite granodiorite and monzogranite, but includes sedimentary and volcaniclastic protoliths

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

Metatexitic to diatexitic gneiss, including banded migmatitic gneiss and schlieric leucogranite, forms a minor unit of the Wankanki Supersuite that outcrops sporadically in the southwestern part of BLACKSTONE, and within the Tjuni Purlka Tectonic Zone in the central-eastern part of BELL ROCK. These outcrops lie within strongly metamorphosed granite, also of the Wankanki Supersuite, locally with inclusions of paragneiss belonging to the Wirku Metamorphics. This is a highly variable unit, ranging from strongly migmatitic gneiss (metatexite to diatexite) to outcrops containing alternating 1–20 m scale bands of migmatitic gneiss, metatexite, and leucogranitic migmatitic melt or schlieric leucogranite. The unit is interpreted to comprise both gneiss that has undergone in situ migmatization, as well as lenses, sheets and veins of migrated and accumulated migmatitic melt. However, it is not clear whether this migmatization is related to metamorphism during the c. 1345 to 1293 Ma Mount West Orogeny.

Distribution

Mappable units of this metatexitic to diatexitic gneiss unit have been identified at two localities. Sporadic outcrop occurs over a large (4 x 1 km) area in the southwestern part of BLACKSTONE (Mamutjarra Zone), within a unit of metamorphosed porphyritic monzogranite to granodiorite (P_-WN-mggo) belonging to the Wankanki Supersuite. Rare, northwest-trending, linear zones or lens-shaped outcrops of metatexitic to diatexitic gneiss, up to 2 km in length, occur within the Tjuni Purlka Tectonic Zone, to the north of Mount West on southwestern BELL ROCK, where they lie within gneissic granite also belonging to the Wankanki Supersuite.

Lithology

This metatexitic to diatexitic gneiss unit is a highly variable unit ranging from strongly migmatitic gneiss (metatexite to diatexite) to outcrops containing alternating 1–20 m scale bands of migmatitic gneiss, metatexite, and leucogranitic migmatitic melt or schlieric leucogranite. The former outcrop style is typical of exposures in the Mamutjarra Zone (on BLACKSTONE), whereas the latter is the more typical manifestation of this unit in the Tjuni Purlka Tectonic Zone on BELL ROCK. In both cases, the main country rock is strongly metamorphosed granite of the Wankanki Supersuite, locally with inclusions of paragneiss belonging to the Wirku Metamorphics. As the country rock becomes increasingly intruded, and in places net-veined, by migmatitic melt veins adjacent to this migmatitic gneiss unit, particularly on BLACKSTONE, the boundary between country rock and the migmatitic gneiss unit is locally poorly defined (gradational) and somewhat arbitrary. Therefore, this unit is interpreted to comprise both gneiss that has undergone in situ migmatization, and areas (lenses; particularly on BELL ROCK) of migrated and accumulated migmatitic melt. Although this unit has been assigned to the Wankanki Supersuite, it is not certain that the migmatite development occurred, entirely or at all, during the Mount West Orogeny. Ultrahigh-temperature metamorphism and migmatization is a widespread feature of the later Musgrave Orogeny (Smithies et al., 2009, 2010), and further work might result in this unit being reassigned to the Pitjantjatjara Supersuite (Musgrave Orogeny).

On BLACKSTONE, the gneissic granite component (neosome?) of this migmatitic gneiss unit is typically a medium-grained, weakly foliated, leucocratic to mesocratic rock with ~10% mafic minerals. It has a granoblastic granular to polygonal texture indicating a large degree of recrystallization. Quartz (20–25%) is strongly undulose; feldspar is almost all microcline; plagioclase is rare and sodic. Granophyric intergrowths are locally well developed. Hypersthene is the main mafic mineral forming ragged remnants of (once) larger grains; this mineral is intergrown with biotite (?primary) flakes, and is typically surrounded by secondary biotite and quartz–biotite symplectites. Biotite is also scattered throughout as subhedral flakes.

The migmatitic melt-rich component (schlieric leucogranite) of this migmatitic gneiss unit is typically a fine to medium grained and massive to weakly foliated leucocratic rock with a monzogranitic to syenogranitic composition. In thin section, it shows a seriate and locally granoblastic polygonal texture. Quartz makes up 25–30% of the rock and is strongly undulose. Microcline is the main feldspar, although sodic plagioclase is also present. Mafic minerals form <10% of the rock. Hypersthene (~2%) is typically altered to chlorite or a green amphibole. The main mafic mineral is biotite, which forms late anhedral to subhedral crystals along feldspar–quartz grain boundaries, or else forms aggregates with opaque minerals. Green to green-brown hornblende forms larger (earlier) subhedral crystals.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic gneiss	n
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-WN-mgni**

Geochronology

P_-WN-mgni	*Maximum*	*Minimum*
Age (Ma)	1345	1293
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009	Smithies et al., 2009

No sample of this metatexitic to diatexitic gneiss unit has been directly dated, although the known crystallization age range of the Wankanki Supersuite is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009; summarized in Smithies et al., 2009). However, it is not clear that migmatite development occurred during the Mount West Orogeny, and the abundant evidence for widespread and episodic ultrahigh-temperature metamorphism and migmatization throughout the Musgrave Orogeny (Smithies et al., 2009, 2010) provides the possibility that this unit actually belong to the Pitjantjatjara Supersuite (Musgrave Orogeny), rather than the Wankanki Supersuite.

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Wankanki Supersuite; subunit (P_-WN-mgno)

Legend narrative

Orthopyroxene–clinopyroxene–biotite gneissic granite; locally shows cm-scale gneissic banding; gradational with foliated porphyritic metamonzogranite; includes sheets of metatexite and schlieric leucogranite

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

Outcrop of this orthopyroxene-bearing gneissic granite unit (P_-WN-mgno) of the Wankanki Supersuite is confined to part of the Tjuni Purlka Tectonic Zone in the area between Hinckley Range and BELL ROCK Range, in the central-east of BELL ROCK. The rocks are strongly foliated to gneissic, lie in the compositional range of monzogranite (to lesser granodiorite), and locally contain abundant xenoliths, including rafts up to several hundred metres in length, of metasedimentary rocks of the Wirku Metamorphics. Migmatization is locally conspicuous, and includes areas of well-banded metatexite and rare diatexite. An igneous crystallization age of 1321 ± 7 Ma obtained for this unit falls within the known age range (1345–1293 Ma) of the Wankanki Supersuite.

Distribution

This unit of the Wankanki Supersuite is confined to part of the Tjuni Purlka Tectonic Zone, in the central-eastern part of BELL ROCK, where it forms extensive outcrop in the area between Hinckley Range and BELL ROCK Range, straddling Michael Hills and forming part of Mount West.

Lithology

Rocks of this orthopyroxene-bearing gneissic granite unit are leucocratic and weakly porphyritic, falling within the compositional range of monzogranite (to lesser granodiorite). In the vicinity of Mount West, elongate inclusions and rafts of metasedimentary rocks belonging to the Wirku Metamorphics are up to several hundred metres in length. Migmatization of the granite is locally conspicuous, with numerous zones (though not dominant) of well-banded metatexite, and rarer regions where high degrees of melting or melt accumulation has formed diatexite and schlieric leucogranite.

Although rocks of the orthopyroxene-bearing gneissic granite unit are locally porphyritic, with rare rounded feldspar phenocrysts up to 2 cm in length, an apparent porphyritic texture is commonly produced by large domains of coarser-grained quartz and feldspar preserved within a deformed and recrystallized (protomylonitic) finer-grained groundmass. In thin section, the rocks are seriate to weakly porphyritic, containing larger anhedral and locally deformed crystals and aggregates of feldspar and quartz within a finer-grained, granoblastic polygonal, or deformed and recrystallized (protomylonitic), groundmass. In some samples, a generally hypidiomorphic granular texture dominates, although granoblastic polygonal domains still exist. The rocks typically comprise antiperthitic plagioclase (40–50%), quartz (30–35%), microcline or perthite (5–15%), orthopyroxene (3–7%), clinopyroxene (1–4%), biotite (~2%), and opaque minerals (~2%), with accessory apatite, zircon, epidote, and monazite. Mafic minerals occur as larger anhedral grains, or as aggregates of orthopyroxene or orthopyroxene–clinopyroxene, surrounded by biotite and opaque minerals.

Leucosomes and veins of medium-grained, highly felsic leucogranite mostly follow the main northwest foliation seen in this part of the Tjuni Purlka Tectonic Zone, but can also cut foliation locally. Crosscutting relationships with granites of the Pitjantjatjara Supersuite have given this foliation a minimum age of 1165 ± 10 Ma (GSWA 183509, Kirkland et al., 2007), although the deformation of Wankanki Supersuite rocks in the Mamutjarra Zone to the west, must have occurred by 1201 ± 6 Ma as the foliation there is cut by dated granite dykes (e.g. GSWA 184146, Kirkland et al., 2009a). Likewise, overgrowths on zircon grains, interpreted to reflect metamorphic regrowth of zircon in rocks of the Wankanki Supergroup, give ages corresponding to the intrusion of the Pitjantjatjara Supersuite (Smithies et al., 2009, 2010). Thus, the metamorphic event(s) that produced the migmatite zones within the orthopyroxene-bearing gneissic granite unit likely relate to the Musgrave Orogeny.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic gneiss	n
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-WN-mgno**

Geochronology

P_-WN-mgno	*Maximum*	*Minimum*
Age (Ma)	1321 ± 7	1321 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2008	Kirkland et al., 2008

A single sample (GSWA 183496) obtained from BELL ROCK has been dated at 1321 ± 7 Ma (Kirkland et al., 2008). This falls within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009b; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-mgrb)

Legend narrative

Weakly to strongly foliated biotite metasyenogranite; less than 5% mafic minerals; typically with abundant microcline; locally gneissic and contains abundant veins and sheets of schlieric leucogranite

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This biotite metasyenogranite unit is restricted to the Mamutjarra Zone in the southern part of BLACKSTONE, where it outcrops sporadically to the east and west of MacDougall Bluff, and south of Peak Hill. It is inferred to be the most extensive unit of the Wankanki Supersuite south of the Tjuni Purlka Tectonic Zone. The unit directly underlies the major basal unconformity of the Bentley Supersuite, which is well-exposed immediately to the west of MacDougall Bluff and a few kilometres to the south of Peak Hill. The metasyenogranite is weakly to strongly foliated, leucocratic, and moderately to highly porphyritic, with tabular K-feldspar phenocrysts, up to 3 cm in size, forming up to 60% of the rock and in places defining a trachytic flow-texture. An igneous crystallization age of 1312 ± 7 Ma obtained for the unit falls within the known age range (1345–1293 Ma) of the Wankanki Supersuite.

Distribution

This biotite metasyenogranite is restricted to the Mamutjarra Zone in the southern part of BLACKSTONE, where it outcrops sporadically to the east and west of MacDougall Bluff, and south of Peak Hill. It is inferred, mainly on geophysical evidence, to be the most extensive unit of the Wankanki Supersuite occurring within the Mamutjarra Zone.

Lithology

This biotite metasyenogranite is weakly to strongly foliated, typically leucocratic (with <5% mafic minerals), and moderately to highly porphyritic, with tabular K-feldspar phenocrysts up to 3 cm in size locally forming up to 60% of the rock. Feldspar phenocrysts are locally strongly aligned, in places defining a trachytic flow-texture. Particularly in the area to the west of MacDougall Bluff, a northeast-trending tectonic foliation is crenulated along locally well-developed north- to northwest-trending fractures, which are often intruded by fine-grained leucogranite most likely belonging to the Pitjantjatjara Supersuite.

Rocks of the biotite metasyenogranite unit show a seriate and granoblastic polygonal texture in thin section. Feldspar–feldspar and feldspar–quartz grain boundaries are locally highly scalloped, and myrmekite is common. Quartz (20–35%) is strongly undulose, and forms single large crystals, or aggregates of polygonal crystals or lobate blebs, in feldspar. Larger feldspar grains are typically perthite (including both microcline microperthite and braid perthite), enclose groundmass feldspar and quartz, and likely represent an early phenocryst phase in the protolith. Plagioclase is minor and in some rocks is antiperthitic. In the groundmass, feldspar comprises roughly equal proportions of microcline and albite. Biotite is the only mafic silicate mineral, and is partially to totally altered to chlorite. Opaque oxides form anhedral masses associated with biotite or along grain boundaries, or else form finer-grained subhedral to euhedral grains dusted throughout feldspar crystals. Fluorite and epidote are rare late alteration minerals associated with altered patches of biotite.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Biotite	b
Rock code		**P_-WN-mgrb**

Contact relationships

This biotite metasyenogranite is an extensive unit of the Wankanki Supersuite that directly underlies the major basal unconformity of the Bentley Supersuite. This unconformity is well-exposed immediately to the west of MacDougall Bluff and a few kilometres to the south of Peak Hill, in the southern part of BLACKSTONE. To the northwest of MacDougall Bluff, the metasyenogranite contains inclusions of paragneiss belonging to the Wirku Metamorphics. In the central-southern part of BLACKSTONE, the unit is inferred (based on geophysical images) to contain extensive, elongate, rafts of paragneiss, and to be intruded by units of both the Pitjantjatjara Supersuite and the Warakurna Supersuite.

Geochronology

P_-WN-mgrb	*Maximum*	*Minimum*
Age (Ma)	1312 ± 7	1312 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009a

A single sample of biotite metasyenogranite (GSWA 185581), taken approximately 7 km to the west of MacDougall Bluff on BLACKSTONE, has been dated at 1312 ± 7 Ma (Kirkland et al., 2009a). This falls within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009b; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-mgrn)

Legend narrative

Strongly foliated to gneissic, medium- to coarse-grained hornblende leucosyenogranite

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies: green hornblende

Summary

This strongly foliated to gneissic hornblende leucosyenogranite unit of the Wankanki Supersuite outcrops as a small inclusion within metamorphosed syenogranite of the Pitjantjatjara Supersuite in the southwestern part of Blackstone (Mamutjarra Zone). It typically comprises strongly foliated gneissic granite, but locally shows a well-developed gneissosity that is folded about a north-northeasterly trending fold axis. Granite dykes that intrude the fold axes have been subsequently metamorphosed, and a 1201 ± 6 Ma crystallization age obtained for this generation of dykes imposes a minimum age on folding, and a maximum age on the late metamorphism.

Distribution

This strongly foliated to gneissic hornblende leucosyenogranite is a minor component of the Wankanki Supersuite, restricted to a small (1.5 km longest axis) exposure in the southwestern part of Blackstone (Mamutjarra Zone; at MGA 417000E 7088300N), where it is enclosed within metamorphosed syenogranite of the Pitjantjatjara Supersuite (P_-PJ-mgrb).

Lithology

This strongly foliated to gneissic hornblende leucosyenogranite unit essentially exists as a large inclusion within metamorphosed syenogranite (P_-PJ-mgrb) of the Pitjantjatjara Supersuite. It typically comprises strongly foliated gneissic granite, but locally shows a well-developed gneissosity. The gneissosity is locally cut by strongly recrystallized quartz veins, and both veins and gneissosity are subsequently folded about a north-northeasterly trending fold axis. Northerly trending, 1–2 m wide dykes of porphyritic syenogranite, belonging to the Pitjantjatjara Supersuite, intrude parallel to the fold-axes, and have subsequently been mylonitized along the margins, metamorphosed, and partially melted, yielding local, randomly oriented, migmatitic melt patches.

The rock is highly leucocratic, containing <5% mafic minerals. It has a seriate texture and is locally granoblastic polygonal; mortar textures are also well developed. Quartz (20–25%) is strongly recrystallized and undulose. K-feldspar is the only feldspar with larger grains of perthite, which in places have an outer zone of microcline microperthite. Green hornblende is the main mafic mineral, and forms large subhedral crystals or, more commonly, anhedral crystals or deformed aggregates. These aggregates also include opaque minerals and rare biotite, and tend to occur along quartz and/or feldspar grain boundaries.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Gneissose	n
Rock code		**P_-WN-mgrn**

Geochronology

P_-WN-mgrn	*Maximum*	*Minimum*
Age (Ma)	1345	1293
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009	Smithies et al., 2009

This strongly foliated to gneissic hornblende leucosyenogranite unit has not been directly dated, but is inferred to form part of the Wankanki Supersuite, which has a known crystallization age range of 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009a; summarized in Smithies et al., 2009). The unit is cut by northerly trending, 1–2 m wide dykes of porphyritic syenogranite, which are intruded parallel to the north-trending fold-axes, have been subsequently mylonitized along the margins, metamorphosed, and partially melted yielding local, randomly oriented, migmatitic melt patches. These dykes are interpreted to belong to the Pitjantjatjara Supersuite, and within this part of the Mamutjarra Zone, granite dykes in similar structural settings have yielded a crystallization age of 1201 ± 6 Ma (GSWA 184146, Kirkland et al., 2009b). This date provides a minimum age both on folding and early high-grade metamorphism associated with development of the gneissosity, and a maximum age on the migmatitic metamorphism.

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Wankanki Supersuite; subunit (P_-WN-mgsy)

Legend narrative

Mylonite derived from metamorphosed granite or gneiss

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mylonitized granite unit represent a range of felsic Wankanki Supersuite lithologies that have been mylonitized or ultra-mylonitized. Although such mylonites are quite common, they only form units extensive enough to be portrayed at map scale on BELL ROCK, in the area between Hinckley Range and BELL ROCK Range.

Distribution

As a coherent unit, mylonitized granite of the Wankanki Supersuite is confined to part of the Tjuni Purlka Tectonic Zone in the central-eastern region of BELL ROCK, in the area between Hinckley Range and BELL ROCK Range, where it occurs as northeast-trending zones within earlier units of the Wankanki Supersuite. Although northeast-trending mylonites are quite common in this region, they only rarely form units extensive enough to be portrayed at map scale.

Lithology

This mylonitized granite represents a range of felsic Wankanki Supersuite lithologies that have been mylonitized or ultra-mylonitized.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic schist	s
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-WN-mgsy**

Geochronology

P_-WN-mgsy	*Maximum*	*Minimum*
Age (Ma)	1345	1293
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009	Smithies et al., 2009

This mylonitized granite unit has not been directly dated, although the age range of the protolith granites or gneisses is expected to cover the full crystallization age range of the Wankanki Supersuite, extending from 1345 ± 7 to 1293 ± 9 Ma with most ages lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009; summarized in Smithies et al., 2009). Generally, mylonitic deformation either accentuates or cuts the main foliation developed in rocks of the Wankanki Supersuite, and on that basis this deformation is likely to relate to either the Musgrave or Petermann Orogeny.

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Wankanki Supersuite; subunit (P_-WN-xmf-ms)

Legend narrative

Metafelsic volcanic rocks mixed with interlayered psammite and pelite

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This interleaved felsic metavolcanic and metasiliciclastic gneissic unit is the only volcanic representative of the Wankanki Supersuite found within the Tjuni Purlka Tectonic Zone, forming a significant component of the supracrustal sequences exposed in the Mount Holt (HOLT) and Mount Aloysius (mainly on BELL ROCK) regions. It also occurs as 1–10 m thick interlayers within many outcrops of Wirku Metamorphics, throughout the Tjuni Purlka Tectonic Zone. This gneiss is dominated by c. 1320 Ma felsic granulite derived from volcanic rocks, with lesser interlayers of arkosic metasandstones, pelites, and intermediate volcanic to volcaniclastic rocks, all deposited from 1345 Ma to potentially as late as 1297 Ma.

Distribution

Interleaved felsic metavolcanic and metasiliciclastic gneiss is the only volcanic representative of the Wankanki Supersuite found within the Tjuni Purlka Tectonic Zone, forming a significant component of the supracrustal sequences exposed in, and between, the Mount Holt (central HOLT) and Mount Aloysius (mainly northwest BELL ROCK) regions. Outcrop of this unit covers nearly half of Mount Aloysius, where it is well-exposed and forms ridges tracing a major northwest-trending antiform (the Aloysius antiform). The unit is also interleaved with units of the Wirku Metamorphics, including a unit (P_-WM-xmhn-mf) gradational between this volcanic-dominated gneissic unit and the pelitic rocks (P_-WM-mlig) that form the core of the Aloysius antiform.

On HOLT, the interleaved felsic metavolcanic and metasiliciclastic gneiss unit is intimately associated with a composite paragneiss of the Wirku Metamorphics (P_-WM-xmtn-mf). Together, they occupy a northwest-trending area, 25 km long and up to 8 km wide, that forms most of the bedrock extent of supracrustal sequences in the Mount Holt region. It represents the volcanic-dominated end-member of the heterogeneous gneisses, containing variable amounts of arkosic metasandstones of the Wirku Metamorphics (P_-WM-mtni), and felsic metavolcanic rocks of the Wankanki Supersuite. On Mount Holt, this gneiss occurs as interlayers, up to 1 km thick, in psammitic to pelitic gneisses of the Wirku Metamorphics (P_-WM-mhig). It also occurs as poorly exposed inclusions, up to 3 km^2 in size, in mylonitic granites formed during the early Musgrave Orogeny (P_-PJ1- mgry), in an area 10 km northeast of Mount Holt.

This unit is interlayered with most paragneisses of the Wirku Metamorphics (in order from most to least commonly associated: P_-WM-mtni, P_-WM-xmhn-mf, P_-WM-mroo, P_-WM-mlig). Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the heterogeneous gneiss. Therefore, in a sense, this unit occurs as 1–10 m thick interlayers within many Wirku Metamorphics outcrops, throughout the Tjuni Purlka Tectonic Zone.

Lithology

This interleaved felsic metavolcanic and metasiliciclastic gneissic unit is dominated by 1–10 m thick layers of felsic granulite derived from volcanic rocks, interleaved with lesser, metre-thick metasedimentary layers of the Wirku Metamorphics, including metatexitic and diatexitic garnetiferous pelite (P_-WM-mhig, P_-WM-mlig), arkosic metasandstone (P_-WM-mtni), and intermediate–basic granulite (P_-WM-mroo). The gneiss is locally metatexitic, with layer-parallel and oblique centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The entire gneiss (including the leucosome) has been folded at least twice before the Musgrave Orogeny. The constituent minerals of all components typically form a polygonal, granoblastic texture indicative of granulite-facies metamorphism.

The felsic granulite (metavolcanic) component of this gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. It is typically syenogranitic in composition, and is composed of a fine-grained granoblastic to dynamically recrystallized quartzofeldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Rare, relict, plagioclase phenocrysts, up to 1 mm in size, can be seen in thin section. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. This felsic granulite component is texturally, mineralogically, and compositionally identical to some arkosic metasandstones of the Wirku Metamorphics (P_-WM-mtni), apart from the absence of obvious quartz clasts and the presence of rare plagioclase phenocrysts seen in the present unit. However, several geochronology samples of this unit obtained elsewhere in the Tjuni Purlka Tectonic Zone yielded unimodal age populations of c. 1320 Ma, indicating that the protolith is most likely volcanic in origin.

The metatexite component of the gneiss unit contains rounded garnet porphyroblasts, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic groundmass with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. Foliation is defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite, and always wraps around the garnet porphyroblasts. Garnet cores typically contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. Plagioclase and biotite inclusions are different in composition to their counterparts in the groundmass. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in textural equilibrium, forming clusters within the matrix that are locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some metatexitic pelite layers. The diatexite contains larger, rounded, garnet porphyroblasts, up to 2 cm in size, in a similar, though less mafic, groundmass. Antiperthite is common (up to 30%), with lesser amounts of perthite (up to 5%). Both the metatexite and diatexite are interpreted to represent a metasiltstone to metamudstone.

The arkosic metasandstone component is banded on a centimetre- to metre-scale. Where homogenous, gneissic banding is defined by variations in grain size. The constituent minerals always form a granoblastic texture indicative of granulite-facies metamorphism. The metasandstone component of the gneiss is usually metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. Both the psammite and leucosome have been folded at least twice. This psammitic gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. They are usually composed of <3 mm, dismembered, undulatory quartz grains in a finer-grained, granoblastic to dynamically recrystallized feldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. Because of its fine to medium grain size, laminations, continuation along strike length, and the presence of coarser-grained quartz, the protolith to this component is interpreted to have been an arkosic metasandstone.

The intermediate to basic granulite component is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss, ranging overall from acidic to basic in composition, although generally intermediate. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. These rocks are very dense relative to other units of the Wirku Metamorphics. In thin section, they are composed almost entirely of orthopyroxene and plagioclase, in a granoblastic texture with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but is most likely volcanic in origin based on its grain size, composition, and setting.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic volcanic	
Lithname 1	Metafelsic volcanic rock	mf
Rock type 2	Metamorphic protolith unknown: schist	
Lithname 2	Schist	-ms
Rock code		**P_-WN-xmf-ms**

Geochronology

P_-WN-xmf-ms	Maximum	Minimum
Age (Ma)	1319 ± 7	1319 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009a

The protolith age of the metavolcanic component in this interleaved felsic metavolcanic and metasiliciclastic gneissic unit is directly constrained by the 1319 ± 7 Ma crystallization age obtained for a felsic volcanic layer (GSWA 180867, Kirkland et al., 2009a) sampled 4 km south of Mount Holt (central HOLT). Approximately 10 km northeast of Mount Holt, this gneiss is engulfed by mylonitic granite formed during the early Musgrave Orogeny (P_-PJ1-mgry), and the protolith to this mylonitic granite has a crystallization age of 1205 ± 6 Ma (GSWA 187274, Kirkland et al., 2009b). The youngest detrital zircon components obtained from rocks either adjacent to, or interleaved with, the interleaved felsic metavolcanic and metasiliciclastic gneiss unit yields a maximum depositional age of 1320 ± 14 Ma (GSWA 187103,Kirkland et al., 2009c; GSWA 187109, Kirkland et al., 2009d; GSWA 187115, Kirkland et al., 2009e), dates consistent with the interpolated age of the volcanic component mentioned above, and within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009f; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-xmfn-mh)

Legend narrative

Composite gneiss with felsic volcanic and volcaniclastic units interlayered on a cm- to m-scale with psammite, garnetiferous pelite, and rare calc-silicate rocks; typically metatexitic and cut by leucogranite veins

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss forms ridges that trace the Mount Aloysius antiform, mainly in the northwestern parts of Bell Rock. It is interleaved with most paragneisses of the Wirku Metamorphics, and as such, it typically forms 1–10 m thick interlayers in many outcrops of Wirku Metamorphics throughout the Tjuni Purlka Tectonic Zone. Cuspate margins between enclaves of this unit and granites of the Wankanki Supersuite indicate that the rocks forming the enclaves were deposited, folded, and swamped by granite over a short time period. This relationship is supported by the similar radiometric ages obtained for all components. The composite gneiss is dominated by c. 1320 Ma felsic metavolcanic granulite, with lesser interlayers of garnetiferous anatectic leucosomes, pelites, arkosic metasandstones, and intermediate volcanic to volcaniclastic rocks of the Wirku Metamorphics; the protoliths to the latter were deposited from 1345 Ma to potentially as late as 1297 Ma.

Distribution

This composite gneiss unit of the Wankanki Supersuite traces the large-scale refolded fold represented by the Aloysius antiform. It outcrops over nearly half of Mount Aloysius in the northwestern parts of Bell Rock, where it is well-exposed and often forms ridges. It is interleaved with a unit of the Wirku Metamorphics (P_-WM-xmhn-mf) that is gradational between this volcanic-dominated composite gneiss and the rocks that form the pelitic core (P_-WM-mlig, Wirku Metamorphics) of the Aloysius antiform. This Wankanki composite gneiss is transitional to components in most paragneisses of the Wirku Metamorphics (in order from most to least associated: P_-WM-mtni, P_-WM-xmhn-mf, P_-WM-mroo, P_-WM-mlig). Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the heterogeneous gneiss. Therefore, in a sense, this unit occurs as 1–10 m thick interlayers within many outcrops of Wirku Metamorphics, throughout the Tjuni Purlka Tectonic Zone. The composite gneiss is also found in a 25 km long, northwest-trending region 15 km west of Mount Aloysius in the Tjuni Purlka Tectonic Zone, where it is intruded by, and forms rafts within, more or less coeval granites of the Wankanki Supersuite (P_-WN-mgmu). In this area, the granitic host is better exposed, but it contains xenoliths, hundreds of metres in length, of this folded composite gneiss with cuspate margins, indicating that the enclaves and host are of similar age.

Lithology

This composite gneiss with felsic volcanic, volcaniclastic, and clastic layers is composed of 1–10 m thick layers of felsic granulite, interleaved with metre-scale metasedimentary layers belonging to the Wirku Metamorphics, including metatexitic and diatexitic garnetiferous pelite (P_-WM-mhig, P_-WM-mlig), arkosic metasandstone (P_-WM-mtni), and intermediate–basic granulite (P_-WM-mroo). Rare calc-silicate layers may also be present.

The felsic granulite component of this gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. It is typically syenogranitic in composition, being composed of a fine-grained granoblastic to dynamically recrystallized quartzofeldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Rare, relict, plagioclase phenocrysts, up to 1 mm in size, can be seen in thin section. Orthopyroxene is a minor component of the rock (up to 3%) and is altered to biotite. This gneissic component is texturally, mineralogically, and compositionally identical to some arkosic metasandstones of the Wirku Metamorphics (P_-WM-mtni), apart from the absence of obvious quartz clasts and the presence of rare plagioclase phenocrysts seen in the current unit. However, several geochronology samples of this unit obtained elsewhere in the west Musgrave region yielded unimodal age populations of c. 1320 Ma, indicating that the protolith is most likely of volcanic origin.

The metatexite component of the gneiss unit contains rounded garnet porphyroblasts, up to 1 cm in size, in a recrystallized (sometimes dynamically) quartzofeldspathic groundmass with variable amounts of interstitial orthopyroxene, garnet, sillimanite, and biotite. The foliation is defined by orthopyroxene, biotite, quartz, feldspars, and local sillimanite, and always wraps around the garnet porphyroblasts. Garnet cores typically contain quartz, plagioclase, or biotite inclusions, along with rare hercynite and rutile. Plagioclase and biotite inclusions are different in composition to their counterparts in the groundmass. Inclusion-free garnet rims, up to 2 mm thick, are found in several samples, but are similar in composition (almandine) to garnet cores. Biotite and local orthopyroxene and cordierite are found along garnet rims. Interstitial anhedral orthopyroxene and garnet are in textural equilibrium, forming clusters within the matrix that are locally retrogressed to biotite. Together, garnet, orthopyroxene, and biotite can form up to 30% of some metatexitic pelite layers. The diatexite contains larger, rounded garnet porphyroblasts, up to 2 cm in size, in a similar, though less mafic, groundmass. Antiperthite is common (up to 30%), with lesser amounts of perthite (up to 5%). Both the metatexite and diatexite are interpreted to represent a metasiltstone to metamudstone.

The arkosic metasandstone component is banded on a cm- to m-scale. Where homogenous, the gneissic banding is defined by variations in grain size. The constituent minerals always form a granoblastic texture indicative of granulite-facies metamorphism. The metasandstone component of the gneiss is usually metatexitic, with ubiquitous, layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. Both the psammite and leucosome have been folded at least twice. This psammitic gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. They are usually composed of <3 mm, dismembered, undulatory quartz grains in a finer-grained, granoblastic to dynamically recrystallized feldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. Because of its fine to medium grain size, laminations, continuation along strike length, and the presence of coarser-grained quartz, the protolith to this component is interpreted to have been an arkosic metasandstone.

The intermediate to basic granulite component is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss ranging from acidic to basic composition, although generally intermediate. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by variations in orthopyroxene content. These rocks are very dense relative to other units of the Wirku Metamorphics. In thin section, they are composed almost entirely of orthopyroxene and plagioclase, in a granoblastic texture with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, with quartz being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith was probably not sedimentary, but was most likely volcanic in origin based on its grain-size, composition, and setting.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic volcanic	mf
Lithname 1	Felsic gneiss derived from volcanic rock	n
Rock type 2	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 2	Psammite and pelite; interlayered	mh
Rock code		**P_-WN-xmfn-mh**

Geochronology

P_-WN-xmfn-mh	*Maximum*	*Minimum*
Age (Ma)	1319 ± 7	1319 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009a

The protolith age of the metavolcanic component in this interleaved felsic metavolcanic and metasiliciclastic gneissic unit is directly constrained by the 1319 ± 7 Ma (GSWA 180867, Kirkland et al., 2009a) crystallization age obtained for a felsic volcanic layer sampled 4 km south of Mount Holt (central HOLT). Approximately 10 km northeast of Mount Holt, this gneiss is engulfed by mylonitic granite formed during the early Musgrave Orogeny (P_-PJ1-mgry), and the protolith to this mylonitic granite has a crystallization age of 1205 ± 6 Ma (GSWA 187274, Kirkland et al., 2009b). The youngest detrital zircon components obtained from rocks either adjacent to, or interleaved with, the interleaved felsic metavolcanic and metasiliciclastic gneissic unit yield a maximum depositional age of 1320 ± 14 Ma (GSWA 187103, Kirkland et al., 2009c; GSWA 187109, Kirkland et al., 2009d; GSWA 187115, Kirkland et al., 2009e), dates consistent with the interpolated age of the volcanic component mentioned above, and within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009f; summarized in Smithies et al., 2009).

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Wankanki Supersuite; subunit (P_-WN-xmfn-mr)

Legend narrative

Composite gneiss comprising leucocratic felsic volcanic units interlayered on a cm- to m-scale with orthopyroxene–plagioclase felsic granulite; locally metatexitic and cut by variably transposed leucogranite veins

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This unit traces the nose of the Mount Aloysius antiform in the northwestern corner of BELL ROCK, where it is associated with mafic granulite bearing units of the Wirku Metamorphics. The composite gneiss is composed of decimetre- to decametre-scale layers of felsic granulite, interleaved with centimetre- to metre-scale layers of intermediate–basic granulite (equivalent to P_-WM-mroo of the Wirku Metamorphics). Both components are laminated, granoblastic, and contain moderate amounts of variably transposed leucocratic granite veins. This composite gneiss differs from the volcanic-dominated unit (P_-WN-xmfn-mh) in that it does not contain metasedimentary interlayers. The felsic component of this composite gneiss contains <5% orthopyroxene, whereas the intermediate to basic components contain 20 to 50% orthopyroxene, with the amount inversely proportional to quartz content. The absence of peraluminous minerals indicates that the protolith was probably not sedimentary, but was more likely volcanic based on its grain size, composition, and setting.

Distribution

This composite gneiss unit forms a 500 m wide layer that traces the nose of the Aloysius antiform in the northwestern corner of BELL ROCK, and also forms a large portion of the northwest face of Mount Aloysius. Farther to the northwest, it forms a 6 km^2 xenolith within granites of the early Pitjantjatjara Supersuite (P_-PJ1-mgmu). It is also associated with mafic granulite bearing units of the Wirku Metamorphics (P_-WM-xmli-mr, P_-WM-mroo).

Lithology

The composite gneiss unit is composed of layers of felsic granulite up to 10 m thick, interleaved with centimetre- to metre-scale layers of intermediate to basic granulite (equivalent to P_-WM-mroo of the Wirku Metamorphics); rare calc-silicate layers may also be present. Compositionally, the gneiss spans a range from leucocratic syenite to gabbro; however, contacts between individual layers (felsic, and intermediate to basic components) are sharp. All lithological components are laminated on the millimetre- to metre-scale, and contain moderate amounts of variably transposed leucocratic granite veins.

The felsic granulite component differs from the volcanic-dominated unit (P_-WN-xmfi-ms) in that the former does not contain metasedimentary interlayers. It is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. This component is leucocratic and typically syenitic to syenogranitic in composition, being composed of a fine-grained granoblastic to dynamically recrystallized quartzofeldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Rare, relict, plagioclase phenocrysts, up to 1 mm in size, can be seen in thin section. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. This gneissic component is texturally, mineralogically, and compositionally identical to some arkosic metasandstones of the Wirku Metamorphics (P_-WM-mtni), differing only in the absence of obvious quartz clasts and the presence of rare plagioclase phenocrysts in the present unit. However, several geochronology samples of this unit obtained elsewhere in the west Musgrave region yielded unimodal age populations of c. 1320 Ma, indicating that the protolith is most likely volcanic in origin.

The intermediate to basic granulite component is a medium-grained orthopyroxene–plagioclase(–quartz) granulite gneiss that is generally intermediate, but ranged overall from acidic to basic in composition. It is laminated to banded on a millimetre- to centimetre-scale, with banding defined by orthopyroxene content. The rock is very dense relative to other units of the Wirku Metamorphics, and at first glance appears to be a restite. However, in thin section this component is composed solely of orthopyroxene and plagioclase in a granoblastic texture with or without quartz. Orthopyroxene content varies 20–50% and is inversely proportional to quartz content, with quartz forming up to 10% of rocks with 20% orthopyroxene, and being absent from most rocks with >40% orthopyroxene. The absence of garnet and other aluminous minerals indicates that the protolith is not sedimentary, but is most likely of volcanic origin based on its grain size, composition, and setting.

As both components appear to have volcanic protoliths, this composite gneiss represents the only purely volcanic lithological unit of the Wankanki Supersuite.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic volcanic	mf
Lithname 1	Felsic gneiss derived from volcanic rock	n
Rock type 2	Meta-igneous felsic	
Lithname 2	Metafelsic rock	-mr
Rock code		**P_-WN-xmfn-mr**

Geochronology

P_-WN-xmfn-mr	*Maximum*	*Minimum*
Age (Ma)	1319	1319
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Kirkland et al., 2009	Kirkland et al., 2009

The age of the volcanic components of this gneiss is indirectly constrained by the 1319 ± 7 Ma (GSWA 180867, Kirkland et al., 2009) crystallization age of a felsic volcanic layer from a similar unit (P_-WN-xmfn-ms) sampled 35 km west-northwest of Mount Aloysius.

References

Kirkland, CL, Wingate, MTD, Evins, P and Smithies, RH 2009, 180867: quartz monzonite, Mount Holt; Geochronology Record 838: Geological Survey of Western Australia, 4p.

Wankanki Supersuite; subunit (P_-WN-xmfn-ms)

Legend narrative

Composite gneiss comprising medium-grained, orthopyroxene-bearing felsic volcanic and volcaniclastic units; local m-scale interlayers of orthopyroxene-bearing psammite and minor pelite

Rank	Formation
Parent	Wankanki Supersuite (P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This composite gneiss of the Wankanki Supersuite is intimately associated with composite paragneiss of the Wirku Metamorphics (P_-WM-xmtn-mf). Together, they occupy a northwest-trending area, approximately 25 km long and 8 km wide, between Mount Aloysius and Mount Holt in the southeastern part of HOLT. The composite gneiss of the Wankanki Supersuite differs from the paragneiss of the Wirku Metamorphics only in its dominance of volcanic over psammitic protoliths. Elsewhere, composite gneiss of the Wankanki Supersuite is restricted to metre-scale interlayers associated with interfaces between psammitic gneiss and felsic metavolcanic rocks, most notably on Mount Aloysius. This composite gneiss is composed of metre-scale, pyroxene-bearing arkosic metasandstone, interleaved with macroscopically identical felsic metavolcanic granulites of the Wankanki Supersuite. The gneiss is locally metatexitic, with transposed leucosomes.

Distribution

This composite gneiss is intimately associated with a composite paragneiss of the Wirku Metamorphics (P_-WM-xmtn-mf). Together, they occupy a northwest-trending area, approximately 25 km long and 8 km wide, between Mount Aloysius and Mount Holt in the southeastern part of HOLT. The composite gneiss, and its relationship to the surrounding units, is best observed along the western flank of a large hill 3 km south of Mount Holt (central HOLT). The composite gneiss of the Wankanki Supersuite also represents the volcanic-dominated end-member of the heterogeneous Wirku Metamorphics gneisses with variable amounts of arkosic metasandstones (P_-WM-mtni). Due to the gradational nature of these units, boundaries between them are drawn wherever one gneissic component increases enough in abundance to dominate the overall composition of the gneiss. On Mount Holt, the composite gneiss occurs as interlayers, up to 1 km thick, in psammitic to pelitic gneisses of the Wirku Metamorphics (P_-WM-mhig). It also occurs as poorly exposed inclusions, to 3 km^2 in area, within mylonitic granites formed during the early Musgrave Orogeny (P_-PJ1-mgry), in an area 10 km northeast of Mount Holt. Elsewhere in the west Musgrave region this unit is restricted to metre-scale interlayers associated with interfaces between psammites and felsic metavolcanic rocks, most notably on Mount Aloysius.

Lithology

This composite gneiss is composed of layers of arkosic metasandstone of the Wirku Metamorphics (P_-WM-mtni), up to 10 m thick, interleaved with macroscopically identical felsic metavolcanic rocks of the Wankanki Supersuite. It differs from a different unit of the Wirku Metamorphics (P_-WM-xmtn-mf) only in that the volcanic-rock component of the present unit dominates over the psammitic component. The gneiss is locally metatexitic, with layer-parallel centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. The entire gneiss (including the leucosome) has been folded at least twice before the Musgrave Orogeny. The constituent minerals of all components typically form a polygonal, granoblastic texture indicative of granulite-facies metamorphism.

The arkosic metasandstone component is banded on a centimetre- to metre-scale. Where homogenous, gneissic banding is defined by variations in grain size. The constituent minerals always form a granoblastic texture indicative of granulite-facies metamorphism. The metasandstone component of the gneiss is usually metatexitic, with ubiquitous, layer-parallel, centimetre- to metre-scale leucogranite veins, often with mesocratic margins, suggesting that at least some of the veins are anatectic leucosomes. Both the psammite and leucosome have been folded at least twice. This psammitic gneiss is laminated on the centimetre-scale, with a medium to strong foliation defined by all phases in the rock. They are usually composed of <3 mm, dismembered, undulatory quartz grains in a finer-grained, granoblastic to dynamically recrystallized feldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments can be seen in less recrystallized varieties. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. Because of its fine to medium grain size, laminations, continuation along strike length, and the presence of coarser-grained quartz, the protolith to this component is interpreted to have been an arkosic metasandstone.

The felsic metavolcanic component of this gneiss is a leucocratic, fine-grained granitic gneiss. It is texturally, mineralogically, and compositionally identical to the main arkosic metasandstone component of the composite gneiss described above, apart from the absence of obvious quartz clasts and the presence of occasional, relict, plagioclase phenocrysts. However, a geochronology sample (GSWA 180867, Kirkland et al., 2009a) obtained from this component yielded a unimodal age population of c. 1320 Ma, suggesting that the protolith was volcanic.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic volcanic	mf
Lithname 1	Felsic gneiss derived from volcanic rock	n
Rock type 2	Metamorphic protolith unknown: schist	
Lithname 2	Schist	-ms
Rock code		**P_-WN-xmfn-ms**

Geochronology

P_-WN-xmfn-ms	*Maximum*	*Minimum*
Age (Ma)	1319 ± 7	1319 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009a

The age of the volcanic component of this gneiss is directly constrained by the 1319 ± 7 Ma crystallization age obtained for a felsic volcanic layer from this unit sampled 4 km south of Mount Holt (GSWA 180867, Kirkland et al., 2009a). Approximately 10 km northeast of Mount Holt, this gneiss is engulfed by mylonitic Early Pitjantjatjara Supersuite granite (P_-PJ1-mgry), which has a crystallization age of 1205 ± 6 Ma (GSWA 187274, Kirkland et al., 2009b).

References

Kirkland, CL, Wingate, MTD, Evins, P and Smithies, RH 2009a, 180867: quartz monzonite, Mount Holt; Geochronology Record 838: Geological Survey of Western Australia, 4p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2009b, 187274: porphyritic granite, Murray Range; Geochronology Record 825: Geological Survey of Western Australia, 4p.

Wankanki Supersuite; subunit (P_-WN-xmgn-mg)

Legend narrative

Interleaved orthopyroxene–clinopyroxene–biotite gneissic granite and fine- to medium-grained schlieric orthopyroxene(–hornblende)-bearing leucogranite

Rank	Formation
Parent	Wankanki Supersuite P_-WN-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: orthopyroxene

Summary

This interleaved gneissic granite and schlieric leucogranite unit outcrops within the central part of the Tjuni Purlka Tectonic Zone (central-eastern part of BELL ROCK). The unit is composed of a gneissic, porphyritic monzogranite (P_-WN-mgno), interleaved with a finer-grained schlieric leucogranite. Compositionally and texturally, the leucogranite component resembles another Wankanki Supersuite composite gneiss unit (P_-WN-xmfn-ms), and may therefore have a volcanic or subvolcanic protolith. Migmatization of the granite is locally conspicuous with the formation of layer-parallel to oblique leucosomes. This composite gneiss also contains screens of Wirku Metamorphics in the Mount West vicinity. The crystallization age of the protoliths to the gneiss is constrained to c. 1320 Ma.

Distribution

This interleaved gneissic granite and schlieric leucogranite unit of the Wankanki Supersuite is confined to part of the Tjuni Purlka Tectonic Zone in the central-eastern part of BELL ROCK, forming extensive outcrop in the area between the BELL ROCK Range and Michael Hills. It is best exposed as the western, northern, and southern faces of Mount West.

Lithology

This unit is a composite gneiss composed of a gneissic porphyritic monzogranite (P_-WN-mgno), interleaved with a finer-grained schlieric leucogranite. Migmatization of the granite is locally conspicuous; there are numerous (though not dominant) zones of well-banded metatexite, and rarer regions where high degrees of melting or melt accumulation have formed diatexite. Leucosomes and veins of medium-grained, highly felsic leucogranite mostly follow the foliation, but can locally cut foliation.

The coarser-grained, weakly porphyritic component of the gneiss contains rare rounded feldspar phenocrysts up to 2 cm in length. An apparent porphyritic texture is commonly produced by large domains of coarser-grained quartz and feldspar, preserved within a deformed dynamically recrystallized, finer-grained groundmass. In thin section, the rocks are seriate to weakly porphyritic, containing larger anhedral and locally deformed crystals, and aggregates of feldspar and quartz, in a finer-grained granoblastic groundmass. In some samples, a generally hypidiomorphic granular texture dominates, although granoblastic polygonal domains still exist. The coarser-grained, weakly porphyritic component typically comprises antiperthitic plagioclase (40–50%), quartz (30–35%), microcline or perthite (5–15%), orthopyroxene (3–7%), clinopyroxene (1–4%), biotite (~2%), and opaque minerals (~2%), with accessory apatite, zircon, epidote, and monazite. Mafic minerals occur as larger anhedral grains, or else as aggregates of orthopyroxene or orthopyroxene–clinopyroxene surrounded by biotite and opaque minerals.

The fine- to medium-grained component is a blue-grey, equigranular leucogranite to granodiorite. It contains millimetre- to centimetre-scale laminae and schlieren of orthopyroxene, and occasional feldspar phenocrysts up to 1 cm. Overall, mafic minerals make up <5% of this gneissic component. The felsic groundmass is deformed to partially recrystallized, and contains vermicular quartz. Compositionally and texturally this component does not differ from felsic volcanic components in other units of the Wankanki Supersuite (such as P_-WN-xmfn-ms), and may therefore also have a volcanic or subvolcanic protolith. However, the exact nature of contacts between the two components of this composite gneiss cannot be clearly established, and this interpretation remains uncertain.

Age code	Proterozoic	P_-
Stratigraphic code	Wankanki Supersuite	WN-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic intrusive	mg
Lithname 1	Granitic gneiss	n
Rock type 2	Meta-igneous felsic intrusive	
Lithname 2	Metagranitic rock	-mg
Rock code		**P_-WN-xmgn-mg**

Contact relationships

This interleaved gneissic granite and schlieric leucogranite unit is intruded by granites of the Pitjantjatjara Supersuite (P_-PJ-mgmu), and by apophyses of intrusive bodies emplaced during the early stages of the Giles Event (Warakurna Supersuite), such as the BELL ROCK and The Wart intrusions. Foliation development in the porphyritic component of this gneiss (equivalent to P_-WN-mgno) is constrained by crosscutting unfoliated leucogranites dated at c. 1156 Ma (GSWA 183509, Kirkland et al., 2007).

Geochronology

P_-WN-xmgn-mg	*Maximum*	*Minimum*
Age (Ma)	1324 ± 4	1321 ± 3
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	White et al., 1999	Kirkland et al., 2008

White et al. (1999) sampled several variants of this gneiss from Mount West. Layered felsic gneiss resembling this unit yielded a protolith crystallization age of 1324 ± 4 Ma. A sample of the porphyritic component of this gneiss (P_-WN-mgno) was dated at 1321 ± 3 Ma (GSWA 183496, Kirkland et al., 2008). These ages are within the known crystallization age range of the Wankanki Supersuite, which is from 1345 ± 7 to 1293 ± 9 Ma, with most dates lying within a narrow period between c. 1326 and 1312 Ma (White et al., 1999; Kirkland et al., 2008, 2009; summarized in Smithies et al., 2009).

References

Kirkland, CL, Wingate, MTD and Bodorkos, S 2007, 183509: leucogranite dyke, Mount West; Geochronology Record 724: Geological Survey of Western Australia, 4p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183496: orthogneiss, Mount West; Geochronology Record 747: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2009, 183492: K-feldspar porphyritic granite, Mount West; Geochronology Record 757: Geological Survey of Western Australia, 4p.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

White, RW, Clarke, GL and Nelson, DR 1999, SHRIMP U–Pb zircon dating of Grenville-age events in the western part of the Musgrave Block, central Australia: Journal of Metamorphic Geology, v. 17, p. 465–481.

Unassigned Proterozoic granitic unit (P_-mg-MU)

Legend narrative

Metagranite; undivided

Rank	Formation
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This unassigned unit includes metagranitic rocks that form minor outcrops scattered throughout Bates. It is likely that most of these rocks belong to the Pitjantjatjara Supersuite, although it is also possible that some might include rocks as young as c. 995 Ma, the age of the oldest felsic rocks post-dating the Musgrave Orogeny in the Walpa Pulka Zone.

Distribution

This unassigned metamorphosed granite unit includes metagranitic rocks that form outcrops scattered throughout Bates.

Lithology

This unassigned metamorphosed granite unit covers rocks, potentially of a wide compositional and age range, that cannot be justifiably assigned to any established granitic unit.

Age code	Proterozoic	P_-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Tectonic unit code	Musgrave Province	-MU
Rock code		**P_-mg-MU**
Additional lithology		Metagranitic rock

Geochronology

P_-mg-MU	*Maximum*	*Minimum*
Age (Ma)	1220	995
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009	Kirkland et al., in prep.

The age of rocks within this unassigned metamorphosed granite unit is unknown, but is almost certainly constrained between the maximum age of the Pitjantjatjara Supersuite (c. 1220 Ma; Smithies et al., 2009) and the 995 ± 8 Ma age of a microgranitic (aplitic) dyke that cuts rocks of the Pitjantjatjara Supersuite to the southeast of Mount Fanny (GSWA 183597, Kirkland et al., in prep.).

References

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

Pitjantjatjara Supersuite (P_-PJ-xg-o)

Legend narrative

Metagranite and gneiss

Rank	Supersuite
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny. The supersuite comprises massive to strongly foliated rocks of granitic protolith with subordinate felsic gneiss and mafic granulite, and dominates both bedrock and outcrop in the north and northeast of the west Musgrave Province (Walpa Pulka Zone). These rocks are notably less common in the southwest of the west Musgrave Province (Mamutjarra Zone). The magmatic crystallization ages of these rocks show a broad trend towards younger ages in the southwest, and their distribution pattern shows an antithetic relationship to rocks of the older Wankanki Supersuite. Most granites of the Pitjantjatjara Supersuite are metaluminous, K-rich, A-type granites.

Distribution

Rocks of the Pitjantjatjara Supersuite are voluminous, and are distributed throughout the Musgrave Province. They dominate both bedrock and outcrop in the north and northeast of the west Musgrave Province (Walpa Pulka Zone), where they form large plutonic bodies. They are notably less common in the southwest of the west Musgrave Province (Mamutjarra Zone), where they mainly occur as dykes, small intrusions, or as migmatitic melt veins and sheets. Their distribution pattern is antithetic to rocks of the older Wankanki Supersuite.

Derivation of name

The name 'Pitjantjatjara Supersuite' was first used by Edgoose et al. (2004) for rocks formerly grouped into the 'Kulgera Suite' by Major and Conor (1993).

Lithology

Rocks of the Pitjantjatjara Supersuite represent the magmatic expression of the Musgrave Orogeny. This is the oldest orogenic event to have clearly affected all areas of the west Musgrave Province, involving intense deformation and widespread crustal reworking. Most rocks of the Pitjantjatjara Supersuite have been metamorphosed at granulite-facies conditions, in some cases as a result of thermal peaks late in the Musgrave Orogeny, but mostly as a result of the 1085–1040 Ma Giles Event. Parts of the Musgrave region were once deeply buried beneath Neoproterozoic sedimentary basins, with rapid differential uplift of the Walpa Pulka Zone (mainly BATES) and possibly some fault-bound blocks within the Tjuni Purlka Tectonic Zone (mainly on HOLT) during the c. 550 Ma Petermann Orogeny, exposing metamorphic assemblages that reflect pressures as high as 10–14 kbar (Scrimgeour and Close, 1999). The metamorphosed rocks of the Pitjantjatjara Supersuite range from statically recrystallized and unfoliated, to strongly foliated and mylonitized. Rocks with granitic protoliths greatly dominate the supersuite at the present exposure level, although rafts of metagabbro form a minor component of the supersuite in the Walpa Purlka Zone, and rare norite dykes occur in the Mamutjarra Zone (COOPER). In the Walpa Pulka Zone and the northeastern parts of the Tjuni Purlka Tectonic Zone, rocks of the Pitjantjatjara Supersuite can be broadly divided, based on age of intrusion, into an early (P_-PJ1-; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. Outcrop of the early Pitjantjatjara Supersuite is mainly restricted to the Tjuni Purlka Tectonic Zone and southwestern part of the Walpa Pulka Zone, whereas outcrop of the late Pitjantjatjara Supersuite occurs throughout the west Musgrave Province but is concentrated in the northeastern part of the Walpa Pulka Zone.

The primary (protolith) mineralogy of most granites in the Pitjantjatjara Supersuite was an essentially anhydrous assemblage of quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, and biotite, although late hornblende locally rims pyroxene. However, retrograde recrystallization is locally associated with foliation development, resulting in the partial to near-complete alteration of pyroxene to hornblende, actinolite, and biotite. Garnet occurs in rocks north of the Mann Fault and east of the Fanny Fault, typically forming fine-grained coronas that separate the mafic minerals, including orthopyroxene, from feldspar, and reflecting a high-pressure metamorphic assemblage exhumed during the Petermann Orogeny.

Granites of the Pitjantjatjara Supersuite can be broadly subdivided into three lithological groups. The first and most voluminous group, found in both the early and late Pitjantjatjara Supersuites, typically ranges from granodiorite to syenogranite, although the full range is from monzodiorite to alkali-feldspar granite. Where primary igneous textures are preserved, this group commonly includes rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of a primary orthopyroxene-bearing mineralogy, and on that basis can be classified as charnockites. This porphyritic granodiorite–syenogranite group dominates the outcrop in the Walpa Pulka Zone, occurring as large composite plutonic bodies, and forms smaller plutons and dykes in the Tjuni Purlka Tectonic Zone. Within the Mamutjarra Zone, these rocks are mostly restricted to dykes and minor intrusions, although in the northwest of that zone (FINLAYSON and COOPER) they form a widespread, but non-continuous, collection of small intrusions.

This first group of Pitjantjatjara Supersuite granites typically does not contain abundant enclaves, and, despite other local evidence for mixing or mingling (e.g. dykes terminating in chains of lobate inclusions), there is no field evidence at the present level of exposure for significant physical interaction between individual granite intrusions, or between these and any other magma batches. Several broad intrusion styles are identified. Most exposures show significant variations in texture (from seriate to porphyritic to megacrystic) and grain size on a scale of a metre to many tens of metres, suggesting that larger bodies are composite intrusions of numerous individual dykes and sills. Geochemical data show that individual intrusions, or collections of intrusions (forming individual granite suites), are either compositionally heterogeneous throughout, or else show a systematic compositional variation that parallels the northwest trend of major shear zones (Smithies et al., 2010).

The second group of Pitjantjatjara Supersuite granites is entirely restricted to the Tjuni Purlka Tectonic Zone, and comprises locally schlieric biotite–orthopyroxene leucogranites typically in the monzogranite to syenogranite compositional range. These form veins and sheets that cut and engulf earlier rocks of the Wirku Metamorphics and Wankanki Supersuite. Originally thought to be restricted to the late Pitjantjatjara Supersuite (P_-PJ2-mgsi, P_-PJ2-jmgs-mn), petrographically and geochemically identical rocks are now also known from the early (P_-PJ1-mgmu) Pitjantjatjara Supersuite (Smithies et al., 2010).

The third group of Pitjantjatjara Supersuite granites consists of a granofelsic and schlieric leucogranite unit (P_-PJ2-mge). The protolith to these rocks formed sheets and veins that intruded and engulfed all earlier lithologies, including other members of the supersuite and older paragneisses, within the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. They are interpreted as locally derived anatectic melts, and mainly belong to the late Pitjantjatjara Supersuite.

Geochemical data from both the Northern Territory (Edgoose et al., 2004) and Western Australia (Smithies et al., 2010) indicate that the felsic rocks (apart from the felsic granofels) of the Pitjantjatjara Supersuite are compositionally uniform across the entire Musgrave Province. Granites of the Pitjantjatjara Supersuite are silicic (57–78 wt% SiO_2) and K-rich rocks with high total alkali content (Na_2O + K_2O to 10.3 wt%) and high incompatible trace element concentrations, features consistent with an A-type classification. Smithies et al. (2010) subdivided the granites of the Pitjantjatjara Supersuite in Western Australia into several geochemically coherent suites; of these, only the Mirturtu Monzogranite (P_-PJ2mt-) is distinguishable on the current 1:100 000 series maps (Bates; Howard et al., 2006).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Igneous granitic	g
Rock type 2	Igneous mafic intrusive	-o
Rock code		**P_-PJ-xg-o**

Geochronology

P_-PJ-xg-o	*Maximum*	*Minimum*
Age (Ma)	1219 ± 12	1148 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2008	Kirkland et al., in prep.

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province, from the Walpa Pulka Zone (Bates), has a protolith magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite with a protolith magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.) and a metanorite dyke with a protolith magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma).

The youngest late Pitjantjatjara Supersuite granite in the Walpa Pulka Zone has been dated at 1157 ± 9 Ma (GSWA 189254, Kirkland et al., in prep.), and is an unfoliated granite dyke that cuts an early Musgrave Orogeny foliation. Zircons from early Pitjantjatjara Supersuite granites commonly have rims with ages reflecting growth (or regrowth) during late Musgrave Orogeny events.

Most Pitjantjatjara Supersuite granites in the Mamutjarra Zone have magmatic crystallization ages between 1179 ± 10 Ma (GSWA 189452, Kirkland et al., in prep.) and 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.).

The northeastern part of the Tjuni Purlka Tectonic Zone contains deformed granite plutons with early Pitjantjatjara Supersuite ages similar to those in the western part of the adjacent Walpa Pulka Zone. In the southwest, the Tjuni Purlka Tectonic Zone contains late Pitjantjatjara Supersuite granites similar to those in the adjacent part of the Mamutjarra Zone. Apart from these occurrences, Pitjantjatjara Supersuite granites in the Tjuni Purlka Tectonic Zone consist of schlieric biotite–orthopyroxene leucogranites (P_-PJ1-mgmu, P_-PJ2-mgsi, P_-PJ2-jmgs-mn) intruded throughout the Musgrave Orogeny, which provided dates ranging from 1200 ± 5 Ma (GSWA 185339, Kirkland et al., 2009) to 1156 ± 3 Ma (GSWA 183509, Kirkland et al., 2007).

Mafic magmatism did not form a significant component of the Musgrave Orogeny, as seen at present outcrop level. Mafic dykes of this age are extremely rare, and the granites themselves do not typically contain mafic enclaves. Nevertheless, rare leucogabbro intruded the Walpa Pulka Zone during the late Musgrave Orogeny at 1190 ± 9 Ma (GSWA 174594, Bodorkos and Wingate, 2008), and rare norite dykes cut the Mamutjarra Zone at 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010).

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Pitjantjatjara Supersuite (P_-PJ1-mg)

Legend narrative

Metagranite and gneiss

Rank	Suite
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny — the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. In the Walpa Pulka Zone and adjacent parts of the Tjuni Purlka Tectonic Zone, these rocks have been divided, based on age, into an early (P_-PJ1- in code notation; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009, 2010). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. Outcrop of the early Pitjantjatjara Supersuite is mainly restricted to the Tjuni Purlka Tectonic Zone and southwestern part of the Walpa Pulka Zone, whereas outcrop of the late Pitjantjatjara Supersuite occurs throughout the west Musgrave Province but is concentrated in the northeastern part of the Walpa Pulka Zone. Apart from this slight difference in geographic range, there appears to be no significant difference between the rocks of the early and late Pitjantjatjara Supersuite in terms of deformation, metamorphic and primary mineralogy, and compositional range (Smithies et al., 2010), except that mafic rocks (which are in any case a very rare component of the Pitjantjatjara Supersuite) are unknown from the early Pitjantjatjara Supersuite. Most granites of the Pitjantjatjara Supersuite are metaluminous, K-rich, A-type granites.

Distribution

Rocks of the Pitjantjatjara Supersuite are voluminous, and are distributed throughout the Musgrave Province. Outcrop of the early Pitjantjatjara Supersuite is mainly restricted to the Tjuni Purlka Tectonic Zone (mainly on HOLT) and southwestern part of the Walpa Pulka Zone (BATES), to the southwest of the Fanny Fault, where it forms large plutonic bodies. These plutons are best exposed in the region around Mount Fanny in the central-western part of BATES. Small and less continuous outcrop of early Pitjantjatjara Supersuite granites occurs in the area south of Boundary Peak and Latitude Hills (BELL ROCK), and around Prostanthera Hill (HOLT).

Lithology

In the Walpa Pulka Zone, rocks of the Pitjantjatjara Supersuite have been divided, based on age, into an early (P_-PJ1- in code notation; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009, 2010). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. Apart from a slight difference in geographic range, there appears to be no significant difference between the rocks of the early and late Pitjantjatjara Supersuite in terms of deformation, metamorphic and primary mineralogy, and compositional range (Smithies et al., 2010), except that mafic rocks (which are in any case a very rare component of the Pitjantjatjara Supersuite) are unknown from the early Pitjantjatjara Supersuite. As a result, the following description also summarizes the description for the parent Pitjantjatjara Supersuite unit (P_-PJ-xg-o), and is virtually identical to the description for the late Pitjantjatjara Supersuite (P_-PJ2-mg).

Most rocks of the early Pitjantjatjara Supersuite have been metamorphosed at granulite-facies conditions, and range from statically recrystallized and unfoliated to strongly foliated and mylonitized. The primary (protolith) mineralogy of most of these granites was an essentially anhydrous assemblage of quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, and biotite, although late hornblende locally rims pyroxene, becoming a significant component of the primary mafic mineralogy of the more evolved granites in the supersuite. In addition, retrograde recrystallization is locally associated directly with foliation development, resulting in the partial to near-complete alteration of pyroxene to hornblende, actinolite, and biotite. Garnet occurs in rocks north of the Mann Fault and east of the Fanny Fault, typically as fine-grained coronas that separate the mafic minerals, including orthopyroxene, from feldspar, and reflecting a high-pressure metamorphic assemblage exhumed during the Petermann Orogeny.

Granites of the early Pitjantjatjara Supersuite can be broadly subdivided into two lithological groups. The first and most voluminous group typically ranges from granodiorite to syenogranite, although the full range is from monzodiorite to alkali-feldspar granite. Where primary igneous textures are preserved, this group commonly includes rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of a primary orthopyroxene-bearing mineralogy, and on that basis can be classified as charnockites. This porphyritic granodiorite–syenogranite group dominates the Walpa Pulka Zone, occurring as large composite plutonic bodies, and forming smaller plutons and dykes in the Tjuni Purlka Tectonic Zone. These rocks are very rare within the Mamutjarra Zone, where they are restricted to dykes and minor intrusions.

This first group of Pitjantjatjara Supersuite granites typically do not contain abundant enclaves, and despite other local evidence for mixing or mingling (e.g. dykes terminating in chains of lobate inclusions), there is no widespread field evidence at the present level of exposure for significant physical interaction between individual granite intrusions, or between these and any other magma batches. Several broad intrusion styles are identified. Most exposures show significant variations in texture (from seriate to porphyritic to megacrystic) and grain size on a scale of a metre to many tens of metres, suggesting that the larger bodies are typically composite intrusions of numerous individual dykes and sills. Geochemical data show that individual intrusions, or collections of intrusions (forming individual granite suites), are either compositionally heterogeneous throughout, or else show a systematic compositional variation that parallels the northwest trend of major shear zones (Smithies et al., 2010).

The second group of Pitjantjatjara Supersuite granites is entirely restricted to the Tjuni Purlka Tectonic Zone, and comprises locally schlieric biotite–orthopyroxene leucogranites typically in the monzogranite to syenogranite compositional range. These form veins and sheets that cut and engulf earlier rocks of the Wirku Metamorphics and Wankanki Supersuite. Originally thought to be restricted to the late Pitjantjatjara Supersuite (P_-PJ2-mgsi, P_-PJ2-jmgs-mn), petrographically and geochemically identical rocks are now also known from the early (P_-PJ1-mgmu) Pitjantjatjara Supersuite (Smithies et al., 2010).

Geochemical data from both the Northern Territory (Edgoose et al., 2004) and Western Australia (Smithies et al., 2010) indicate that the felsic rocks of the Pitjantjatjara Supersuite are compositionally uniform across the entire Musgrave Province. Granites of the Pitjantjatjara Supersuite are silicic (57–78 wt% SiO_2) and K-rich rocks with high total alkali content (Na_2O + K_2O to 10.3 wt%) and high incompatible trace element concentrations, features consistent with an A-type classification.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-PJ1-mg**

Geochronology

P_-PJ1-mg	*Maximum*	*Minimum*
Age (Ma)	1219 ± 12	1195 ± 4
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2008	Kirkland et al., 2008

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has a protolith magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone and include a metagranite with a protolith magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a protolith magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma).

In the Walpa Purlka Zone and the northeastern parts of the Tjuni Purlka Tectonic Zone, the combined age populations for rocks of the Pitjantjatjara Supersuite can be divided into two broad but distinct groups: an older group (P_-PJ1-), reflecting magmatism between c. 1220 and 1200 Ma; and a younger group (P_-PJ2-), reflecting magmatism between c. 1190 and 1150 Ma. However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. The youngest known early Pitjantjatjara Supersuite granite, an unfoliated charnockite, is from the southeastern part of the Tjuni Purlka Tectonic Zone, and has been dated at 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

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Pitjantjatjara Supersuite; subunit (P_-PJ1-mggo)

Legend narrative

Pyroxene metagranodiorite to metamorphosed quartz monzodiorite; commonly charnockitic; mafic minerals with garnet coronas; contains subhedral dark-grey K-feldspar phenocrysts up to 3 cm

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This metamorphosed pyroxene granodiorite to quartz monzodiorite unit forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite. It outcrops to the north of the Mann Fault, primarily in the western part of the Walpa Pulka Zone on Bates. This unit contains 15–25% primary orthopyroxene and clinopyroxene. Metamorphic garnets typically form pink fine-grained coronas separating mafic minerals from feldspar. A single sample has been dated at 1215 ± 13 Ma.

Distribution

The best exposure of this metamorphosed pyroxene granodiorite to quartz monzodiorite unit occurs in an area approximately 10–20 km east of Mount Fanny on Bates (within an 5 km radius of MGA 470399E 7150690N). The unit is restricted to north of the Mann Fault, mainly in the western part of Bates, although small outcrops also occur further west on Holt.

Lithology

This metamorphosed pyroxene granodiorite to quartz monzodiorite unit includes rocks that are fine to medium grained, weakly to moderately foliated, grey and mesocratic, seriate to (more typically) feldspar porphyritic, and range in composition from quartz monzodiorite to granodiorite. They typically contain dark-grey subhedral phenocrysts of plagioclase and K-feldspar up to 1 cm in size, and subhedral to rounded, dark-grey K-feldspar phenocrysts around 2 cm in size and commonly mantled (by plagioclase; i.e. rapakivi texture), all within a fine- to medium-grained groundmass. Groundmass mafic minerals locally form clots up to 5 mm in size.

In thin section, the groundmass is granoblastic polygonal to (more rarely) granoblastic elongate textured, including aligned polygonal trains of mafic minerals. Quartz never forms significantly more than ~20% of the mode, and plagioclase and K-feldspar (typically perthite) are generally equal in abundance. Mafic minerals make up 15–25% in total, and dominated by either orthopyroxene or clinopyroxene, which occur either as single anhedral (igneous) grains or as pyroxene aggregates. Opaque minerals (both magnetite and ilmenite) are primary. Secondary or metamorphic mafic minerals include garnet, hornblende (or actinolite), and biotite. Apatite and titanite are common accessory minerals. Garnet typically forms pink, fine-grained coronas separating mafic minerals from feldspar. These coronas are locally mantled by orthopyroxene–plagioclase worm-like symplectites.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metagranodiorite	g
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-PJ1-mggo**

Geochronology

P_-PJ1-mggo	*Maximum*	*Minimum*
Age (Ma)	1215 ± 13	1215 ± 13
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2008a	Bodorkos et al., 2008a

This metamorphosed pyroxene granodiorite to quartz monzodiorite unit belongs to the early Pitjantjatjara Supersuite. The youngest early Pitjantjatjara Supersuite granite known is from the southeastern part of the Tjuni Purlka Tectonic Zone, and has yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008b). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma). A quartz diorite from the present metamorphosed pyroxene granodiorite to quartz monzodiorite unit, sampled about 9 km east of Mount Fanny (Bates), yielded an age of 1215 ± 13 Ma, interpreted to be the age of igneous crystallization (GSWA 174558, Bodorkos et al., 2008a). An additional age of 1174 ± 11 Ma, obtained from zircon rims, is interpreted as the age of high-grade metamorphism.

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Pitjantjatjara Supersuite; subunit (P_-PJ1-mgm)

Legend narrative

Metamonzogranite; weakly to strongly foliated and banded; locally gneissic; commonly a composite rock including remnants of older granulitic gneiss; locally migmatitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This weakly to strongly foliated metamonzogranite unit forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite; this unit dominates outcrop on and around Mount Fanny in the central-western part of the Walpa Pulka Zone (on Bates), and shows extensive textural variation. The unit is dominated by a mesocratic to highly leucocratic, medium- to coarse-grained granite recrystallized at granulite facies. This metagranite varies between two end members: a moderately to strongly foliated, mottled-textured metamonzogranite, with sparse rounded feldspar phenocrysts up to 2.5 cm in size; and a banded and gneissic monzogranite.

Distribution

This foliated metamonzogranite unit dominates outcrop on Mount Fanny (Bates), and also forms many smaller outcrops within a 10 km radius of Mount Fanny. The distribution extent is mainly within a broad northwesterly trending zone, about 12 km wide and 20 km long, that straddles the Fanny Fault.

Lithology

Outcrops of this weakly to strongly foliated metamonzogranite unit show extensive textural variation. The unit is dominated by a mesocratic to highly leucocratic, medium- to coarse-grained granite recrystallized at granulite facies, which varies between two textural end members. The more common end member is a moderately to strongly foliated, mottled-textured metamonzogranite, with sparse rounded feldspar phenocrysts up to 2.5 cm in size. The other end member is a banded and gneissic monzogranite, characterized by wavy, discontinuous to semi-continuous, centimetre-scale banding, with leucocratic bands of fine- to medium-grained quartz and feldspar, and melanocratic bands rich in biotite partially rimmed by pink garnet. As all textural gradations between these two varieties have been observed, the wide variation in mineral proportions and phenocryst abundance reflects a range of protolith compositions.

There is no consistent mineralogical difference between the two rock types. Both are typically granoblastic polygonal to granoblastic elongate in texture, with mortar textures commonly well developed around feldspar grains. Mineral assemblages include quartz, plagioclase, antiperthite, microperthite, opaque minerals, garnet, pale green clinopyroxene, green hornblende, orthopyroxene (hypersthene), brown biotite, with accessory zircon, apatite, titanite, and epidote. In some samples, hornblende dominates over calcic pyroxene. A rock sampled approximately 3.5 km east of Mount Fanny (GSWA 174737: on Bates, at MGA 460511E 7147960N) is one of the most mesocratic examples of the strongly foliated, mottled-textured monzogranite end member, containing 25–30% mafic minerals, with brown biotite > green hornblende > opaque minerals > garnet. In contrast, a similarly mesocratic sample at the southern base of Mount Fanny (GSWA 174794: on Bates, at MGA 458053E 7146949N) contains brown hornblende > orthopyroxene > clinopyroxene, with only minor, late biotite and no garnet. In this latter sample, brown hornblende is a metamorphic replacement of earlier clinopyroxene. Where present, garnet typically forms fine-grained coronas that separate all other mafic minerals (including metamorphic hornblende) from the feldspars.

The high-grade metamorphic mineral assemblages observed within these rocks are varied. The main assemblages are likely to have been orthopyroxene–clinopyroxene–garnet or orthopyroxene – clinopyroxene – brown hornblende, and probably reflect a significant difference in pressure within the granulite facies. The green hornblende found in many samples of this rock is likely to be a result of amphibolite-facies re-equilibration.

Rocks of this unit have been locally migmatized, particularly in more intensely deformed outcrops. Such outcrops may contain patches, veins, bands, and lenses of medium- to coarse-grained, equigranular to slightly porphyritic (containing 3–5 cm rounded feldspar phenocrysts), schlieric leucogranite or granofels, which represent aggregated and locally migrated melt fractions. Melt bands are often surrounded by mafic selvages. Layers of massive to moderately foliated leucocratic granofels, up to 50 cm wide, normally intrude parallel to foliation, but can locally cut it at a low angle. The migmatites have been recrystallized, and on the southwest side of Mount Fanny they locally define a banding that is cut by a later foliation defined by grain flattening.

Rocks of the weakly to strongly foliated metamonzogranite unit locally contain xenoliths and rafts of mafic granulite and mafic granulitic gneiss. These inclusions appear particularly abundant within the mylonitized mottled-textured gneissic granites north of Mount Fanny; on the southern flank of Mount Fanny, the gneissic granite forms the felsic component of a composite mafic–felsic migmatitic gneiss unit (P_-PJ-xmwo-mg).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
Rock code		**P_-PJ1-mgm**

Contact relationships

This weakly to strongly foliated metamonzogranite unit locally includes very well-banded to laminated quartzofeldspathic gneiss. Although this gneiss forms in a number of ways, the resulting banded rocks are commonly difficult to distinguish in the field. Texturally gradational contacts show that the protolith to some of these banded and laminated gneisses was the medium- to coarse-grained mottled textured granitic gneiss end member. In these cases, the banding or lamination may be the result of flattening, shearing, or a combination of both. Where shearing was the dominant process, the banding or lamination is typically more discontinuous and the mafic minerals define a lineation. In almost all cases, the original mylonitic fabric has been recrystallized, resulting in blastomylonites. At some localities, very well banded to laminated quartzofeldspathic gneiss is clearly older than this metamorphosed monzogranite and banded and gneissic monzogranite unit. This gneiss can sometimes be distinguished from gneisses derived through the deformation of the metamorphosed monzogranite and banded and gneissic monzogranite unit itself due to the typically more continuous banding or lamination in the older unit, which is also usually highly migmatitic. At numerous localities, the older banded to laminated quartzofeldspathic gneiss forms inclusions with the gneissic monzogranite unit; approximately 3 km to the east of Mount Fanny (on Bates, at MGA 460419E 7148019N), a large east-trending raft of the quartzofeldspathic gneiss (Wirku Metamorphics) is preserved within both the strongly foliated metamorphosed monzogranite and within granofelsic rocks that have swamped that monzogranite. Elsewhere (e.g. on Bates, at MGA 460502E 7146662N), foliated metamorphosed monzogranite has intruded the quartzofeldspathic gneiss, forming veins and dykes that are now parallel to banding in the gneiss.

Schlieric leucogranite or granofels (migmatitic melt) has locally intruded and swamped the metamorphosed banded and gneissic monzogranite and the composite gneiss unit on a large scale, and now forms the main rock type in areas to the east and southeast of Mount Fanny (e.g. on Bates, between MGA 460134E 7149745N and MGA 460502E 7147630N).

Geochronology

P_-PJ1-mgm	*Maximum*	*Minimum*
Age (Ma)	1219 ± 12	1219 ± 12
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2008	Bodorkos et al., 2008

This weakly to strongly foliated metamonzogranite unit belongs to the early Pitjantjatjara Supersuite. One sample of this metamonzogranite unit represents the oldest early Pitjantjatjara Supersuite granite identified so far, having a crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008).

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-mgmn)

Legend narrative

Strongly foliated to gneissic, porphyritic metaleucogranite; locally migmatitic and intruded by schlieric leucogranite; K-feldspar phenocrysts up to 2 cm; locally mylonitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This strongly foliated to gneissic, porphyritic leucogranite unit forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite. These rocks are inferred to form a large and continuous bedrock unit that stretches from south of Mount Aloysius (northwest Bell Rock), northwestward for almost 65 km to the central-western edge of Holt. As such, the observed and inferred distribution of the unit is contained entirely within the Tjuni Purlka Tectonic Zone.

Distribution

Rocks of the strongly foliated to gneissic, porphyritic leucogranite unit form minor, scattered outcrop in the northwest corner of Bell Rock and southeast corner of Holt. These rocks are inferred to form a large and continuous bedrock unit that stretches from south of Mount Aloysius (northwest Bell Rock), northwestward for almost 65 km to the central-western edge of Holt. As such, the observed and inferred distribution of the unit is contained entirely within the Tjuni Purlka Tectonic Zone.

Lithology

This unit typically consists of metamorphosed biotite–orthopyroxene-bearing monzogranite, containing abundant K-feldspar phenocrysts up to 3 cm in size. The gneissosity is variably defined by the presence of attenuated sheets of fine- to coarse-grained granoblastic leucocratic granulite (likely migmatitic melt sheets), and attenuated rafts and inclusions of fine- to medium-grained granoblastic, intermediate (quartz–feldspar–pyroxene) granulite. The rafts and inclusions of intermediate granulite are locally derived from the country rock, which comprises both metamorphosed volcaniclastic rocks assigned to the Wirku Metamorphics and metamorphosed granites (now gneisses) of the Wankanki Supersuite — both rock types are related to magmatism during the Mount West Orogeny (Smithies et al., 2009).

In thin section, this K-feldspar porphyritic biotite–orthopyroxene-bearing monzogranite is a mesocratic rock with a well-developed granoblastic polygonal to aligned texture, and typically forms well-developed mortar-textures along grain boundaries. Apart from elongate granoblastic aggregates of perthitic K-feldspar (representing deformed phenocrysts), the groundmass is dominated by plagioclase (plagioclase > K-feldspar). Biotite, as fine anhedral crystals or aggregates, forms up to 8% of the rock, and is typically smeared along the foliation plane. Orthopyroxene remains as anhedral relicts partially altered to, and surrounded by, biotite.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Gneissose	n
Rock code		**P_-PJ1-mgmn**

Geochronology

P_-PJ1-mgmn	*Maximum*	*Minimum*
Age (Ma)	1220	1195
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Bodorkos et al., 2008	Kirkland et al., 2008

This strongly foliated to gneissic, porphyritic leucogranite unit has not been directly dated but is inferred to be part of the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-mgmo)

Legend narrative

Charnockite; orthopyroxene–clinopyroxene(–hornblende) metamonzogranite; massive to weakly foliated; feldspar porphyritic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This massive to weakly foliated and feldspar porphyritic charnockite unit is part of the 1220–1200 Ma early Pitjantjatjara Supersuite. It forms scattered outcrop to the south of Latitude Hills, in the southeastern part of the Tjuni Purlka Tectonic Zone on BELL ROCK, and has a crystallization age of 1198 ± 5 Ma.

Distribution

Rocks of this massive to weakly foliated and feldspar porphyritic charnockite unit form minor, scattered outcrop in the area to the south of Latitude Hills, in the southeastern part of the Tjuni Purlka Tectonic Zone on BELL ROCK. These rocks are inferred to form part of the bedrock as a large and continuous pluton up to 10 km wide and 15 km long.

Lithology

This feldspar porphyritic charnockite unit is typically massive to weakly foliated, although it is locally cut by mylonite zones and pseudotachylite veins, both likely related to deformation during the Petermann Orogeny. The rocks are medium- to coarse-grained, and show a mottled texture produced by the presence of subhedral plagioclase crystals up to 1 cm in size, which form up to 70% of the rock. These crystals weather to a black colour, and resemble mafic clots on weathered surfaces. Mafic minerals form crystals up to 5 mm in length, and are typically aligned with the foliation. The rock contains angular to rounded mafic clots up to 20 cm in size. Some of the clots are texturally similar to the host and are likely to be cognate. Other clots are texturally dissimilar to the host, some consisting of previously mylonitic rock and others of the paragneiss (Wirku Metamorphics) that forms country rock to the charnockite intrusion.

In thin section, the rock shows a locally well-developed granoblastic polygonal texture. Quartz forms ~20% of the rock, with antiperthite in greater abundance than microcline. Mafic minerals form ~15% of the rock, and are dominated by orthopyroxene (with minor clinopyroxene), which is often rimmed by granoblastic polygonal grains, and aggregates of hornblende and hornblende plus opaque minerals.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-PJ1-mgmo**

Contact relationships

Rocks of the massive to weakly foliated and feldspar porphyritic charnockite unit (P_-PJ1-mgmo) intrude paragneisses of the Wirku Metamorphics and metamorphosed granites and orthogneisses of the Wankanki Supersuite, and have been intruded by gabbros belonging to the Giles Suite (Warakurna Supersuite). Angular xenoliths found within the charnockite mostly belong to the Wirku Metamorphics.

Geochronology

P_-PJ1-mgmo	*Maximum*	*Minimum*
Age (Ma)	1198 ± 5	1198 ± 5
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009	Kirkland et al., 2009

This massive to weakly foliated and feldspar porphyritic charnockite unit belongs to the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma). A feldspar porphyritic charnockite sample from this unit, collected approximately 6.5 km south of Latitude Hill (GSWA 185590), has yielded a crystallization age of 1198 ± 5 Ma (Kirkland et al., 2009).

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009, 185590: charnockite, Latitude Hill; Geochronology Record 764: Geological Survey of Western Australia, 6p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-mgmu)

Legend narrative

Weakly to strongly foliated, porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite; K-feldspar phenocrysts up to 2 cm; locally mylonitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This weakly to strongly foliated, porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite unit forms part of the Pitjantjatjara Supersuite. It is entirely restricted to the Tjuni Purlka Tectonic Zone, forming a zone that extends from north of Michael Hill (Bell Rock) to north of the Blackstone Range (Holt).

Distribution

Both the outcrop and inferred bedrock extent of this weakly to strongly foliated, porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite unit is entirely restricted to the Tjuni Purlka Tectonic Zone, forming a zone that extends from north of Michael Hill (Bell Rock) to north of the Blackstone Range (Holt).

Lithology

This metamonzogranite unit is a typically medium-grained leucogranitic rock that ranges from weakly foliated to mylonitic. Dynamically recrystallized mylonitic fabrics occur locally, with less mylonitic domains showing well-developed mortar textures. The rock consists predominantly of K-feldspar, with subordinate quartz, plagioclase, clinopyroxene, and biotite, plus minor orthopyroxene, hornblende, titanite, and Fe–Ti oxide minerals. Accessory phases include apatite and zircon. Anhedral K-feldspar makes up 70 modal % of the sample, and most grains exhibit albite exsolution textures. K-feldspar locally occurs as phenocrysts, up to 2 cm in size, some of which are ovoid and mantled (i.e. rapakivi texture). Quartz forms small, interstitial, anhedral grains, and makes up 8 modal% of the rock. Sodic plagioclase is a very minor interstitial phase. Mafic minerals comprise only a small percentage of this rock. Biotite is typically altered to green chlorite–leucoxene aggregates. Green clinopyroxene grains, up to 2 mm long, are partially retrogressed to hornblende. Dark aggregates of clinopyroxene are spatially associated with Fe–Ti oxide minerals, hornblende, large apatite prisms (to 1 mm), euhedral titanite, and zircon. A sample taken from a dyke-like intrusion of this unit into paragneiss (Wirku Metamorphics), on the southern flank of Mount Aloysius (GSWA 187103: MGA 456829E 7121725N), contains pale-pink garnet; this is not a common feature of this unit, and it is likely that the garnet is a xenocrystic phase.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-PJ1-mgmu**

Contact relationships

Rocks of this metamonzogranite unit intrude paragneisses of the Wirku Metamorphics and metamorphosed granites and orthogneisses of the Wankanki Supersuite, and have in turn been intruded by gabbros of the Giles Suite (Warakurna Supersuite). Although originally intrusive, most contacts are now mylonitic.

Geochronology

P_-PJ1-mgmu	*Maximum*	*Minimum*
Age (Ma)	1191 ± 4	1187 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009b

This weakly to strongly foliated, porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite unit (P_-PJ1-mgmu) was originally included within the early Pitjantjatjara Supersuite based on the extent of deformation observed in some of the early-visited outcrops. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma). Two metamonzogranite (P_-PJ1-mgmu) samples, taken from the southern flanks of Mount Aloysius, have been recently dated, yielding magmatic crystallization ages of 1191 ± 4 Ma and 1187 ± 7 Ma (GSWA 187103, Kirkland et al., 2009a; GSWA 187105, Kirkland et al., 2009b). This age range lies between that of the early and late Pitjantjatjara Supersuite. Thus, although this unit was originally placed within the early Pitjantjatjara Supersuite, future geochronological work may result in this unit being reassigned to the late Pitjantjatjara Supersuite.

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Kirkland, CL, Bodorkos, S, Wingate, MTD, Smithies, RH and Evins, PM 2009a, 187103: granoblastic garnetiferous granite, Mount Aloysius; Geochronology Record 795: Geological Survey of Western Australia, 5p.

Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187105: foliated schlieric leucogranite, Mount Aloysius; Geochronology Record 796: Geological Survey of Western Australia, 6p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-mgru)

Legend narrative

Massive to moderately foliated, porphyritic, pyroxene(–hornblende–biotite) metasyenogranite; typically leucocratic; abundant K-feldspar phenocrysts up to 5 cm; local trachytic texture; locally garnetiferous

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This massive to moderately foliated, porphyritic, pyroxene(–hornblende–biotite) metasyenogranite unit (P_-PJ1-mgru) forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite. The unit is restricted to the Tjuni Purlka Tectonic Zone, lying between Lehmann Hills and Butterfly Hill, in the central-northern part of HOLT.

Distribution

The outcrop and interpreted bedrock extent of this porphyritic pyroxene(–hornblende–biotite) metasyenogranite unit is entirely restricted to the Tjuni Purlka Tectonic Zone, lying between Lehmann Hills and Butterfly Hill, in the central-northern part of HOLT. Within that area, the metamorphosed syenogranites form several scattered low hills and whalebacks.

Lithology

This porphyritic pyroxene(–hornblende–biotite) metasyenogranite unit is typically massive to moderately foliated and leucocratic. It contains abundant (up to ~35%) K-feldspar phenocrysts that are tabular to subhedral, and up to 5 cm in size. However, the texture is locally seriate, demonstrating a complete range in grain size, or else shows two dominant phenocryst size populations. Where there are two phenocryst sizes, the smaller lath population (1–1.5 cm euhedral laths) is accentuated on weathered surfaces and shows a strong preferred alignment, possibly a flow foliation; the larger phenocrysts are 2.5 – 4.0 cm in size and subhedral to subrounded. Outcrop found on a small hill (at WAROX site RHSMUG001646: MGA 430237E 7156598N) ~8 km to the west of Murray Range (HOLT) is dominated by fine-grained granite, with sparse but well-aligned (trachytic) K-feldspar phenocrysts to 4 cm; here, the granite is in direct contact with migmatitic paragneiss. To the west of this hill, the fine-grained granite grades continuously into the strongly K-feldspar porphyritic coarse-grained granite.

In thin section, the rock is seriate-textured to porphyritic, leucocratic, moderately foliated, and comprises quartz (~25%), braid microperthite (~65%), orthopyroxene (~9%), biotite and hornblende (each <1%), and magnetite (~1%). The rock is a charnockitic syenogranite.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-PJ1-mgru**

Contact relationships

This porphyritic pyroxene(–hornblende–biotite) metasyenogranite unit mainly intrudes paragneisses of the Wirku Metamorphics, which themselves commonly form rafts within the metamorphosed syenogranite. Close to its contacts with other units, the metamorphosed syenogranite often contains 1–5 m wide panels of migmatitic paragneiss. The metamorphosed syenogranite is locally intruded by, and included within, variably feldspar porphyritic, fine- to medium-grained granofelsic granite (mainly P_-PJ2-mge), and is also intruded and invaded by sheets of pegmatite and inhomogeneous fine grained to pegmatitic leucogranite.

Geochronology

P_-PJ1-mgru	*Maximum*	*Minimum*
Age (Ma)	1217 ± 12	1205 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., in prep.	Kirkland et al., 2009

This massive to moderately foliated, porphyritic, pyroxene(–hornblende–biotite) metasyenogranite unit belongs to the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma). A sample of this metasyenogranite unit (P_-PJ1-mgru; GSWA 187166, Kirkland et al., in prep.) has yielded a crystallization age of 1217 ± 12 Ma; a mylonitized equivalent (GSWA 187274, Kirkland et al., 2009) yielded a crystallization age of 1205 ± 6 Ma.

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2009, 187274: porphyritic granite, Murray Range; Geochronology Record 825: Geological Survey of Western Australia, 4p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-mgry)

Legend narrative

Mylonitic, medium- to coarse-grained, leucocratic metasyenogranite; quartz ribbons up to 2 cm in a feldspathic groundmass

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mylonitic, leucocratic metamonzogranite to metasyenogranite unit forms a north-northwesterly trending, southwest-dipping, sinistral-normal, syn-magmatic shear zone along the southwestern edge of a major shear zone that cuts the Murray Range (Murray Range shear zone), in the Tjuni Purlka Tectonic Zone on HOLT. It contains abundant inclusions of Wirku Metamorphics, Wankanki Supersuite, and composite gneisses comprising both of these older lithologies. In this region, the mylonitic unit is the deformed equivalent of the porphyritic pyroxene(–hornblende–biotite) metasyenogranite unit (P_-PJ1-mgru), which is characterized by K-feldspar phenocrysts up to 5 cm in size.

Distribution

This strongly deformed to mylonitic granite forms a north-northwesterly trending sheet, up to 25 km long and 2 km wide, along the southwestern edge of a major shear zone that cuts the Murray Range (Murray Range shear zone), in the Tjuni Purlka Tectonic Zone on HOLT. The sheet dips moderately to the southwest, and represents a sinistral-normal syn-magmatic shear zone. The granite outcrops in several localities along this zone, forming hills up to 1 km long and 400 m wide. The zone is cut at its northern end by the east-trending Walu Fault, and is sinistrally displaced 12 km to the west.

Lithology

This mylonitic, leucocratic metamonzogranite to metasyenogranite unit is the deformed equivalent of the porphyritic pyroxene(–hornblende–biotite) metasyenogranite unit (P_-PJ1-mgru), outcrop of which can be found to the west.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-PJ1-mgry**

Geochronology

P_-PJ1-mgry	*Maximum*	*Minimum*
Age (Ma)	1217 ± 12	1205 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., in prep.	Kirkland et al., 2009

This mylonitic, leucocratic metamonzogranite to metasyenogranite unit belongs to the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

A sample of this mylonitic unit (GSWA 187274, Kirkland et al., 2009) yielded a crystallization age of 1205 ± 6 Ma; a sample of the protolith metasyenogranite unit (P_-PJ1-mgru; GSWA 187166, Kirkland et al., in prep.) has yielded a crystallization age of 1217 ± 12 Ma.

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD, Bodorkos, S and Smithies, RH 2009, 187274: porphyritic granite, Murray Range; Geochronology Record 825: Geological Survey of Western Australia, 4p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-jmg-md)

Legend narrative

Strongly foliated to gneissic, porphyritic metamonzogranite with schlieren, rafts, and screens of metasedimentary rock

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This unit of K-feldspar porphyritic metamonzogranite with abundant schlieren, rafts, and screens of metasedimentary granulite is best exposed on the flanks of Mount Aloysius, in the Tjuni Purlka Tectonic Zone in the northwest of Bell Rock. At that locality, the rock is gneissic, although elsewhere it is less deformed and contains abundant K-feldspar phenocrysts, up to 2 cm in size, forming up to 70% of the rock.

Distribution

This K-feldspar porphyritic metamonzogranite with abundant schlieren, rafts, and screens of metasedimentary granulite is best exposed on the flanks of Mount Aloysius, in the Tjuni Purlka Tectonic Zone in the northwest of Bell Rock. A strongly deformed variant occupies the core of a northwest-trending synform south of Mount Aloysius. A small, 1 km^2, round outcrop of this xenolith-rich unit is emplaced into the large supracrustal succession exposed to the south of Mount Holt (Holt).

Lithology

This K-feldspar porphyritic and xenolith-rich metamonzogranite is typically a medium-grained leucogranitic rock, which is mostly gneissic but ranges from weakly foliated to mylonitic. Dynamically recrystallized mylonitic fabrics occur locally, with less mylonitic domains showing well-developed mortar textures. The K-feldspar porphyritic metamonzogranite that dominates this unit is equivalent to the foliated and porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite unit (P_-PJ1-mgmu).

On the eastern face of Mount Aloysius, the unit is a medium-grained K-feldspar porphyritic gneiss, with ghosts and schlieren of intermediate to basic granulite (P_-WM-mroo) that can form up to 30% of the rock. On the southern flank of Mount Aloysius, the granitic gneiss contains screens of pelitic and psammitic rock (P_-WM-mhig and P_-WM-xmt-mh) belonging to the Wirku Metamorphics. The gneiss contains progressively fewer of these inclusions when moving north and west from Mount Aloysius.

The rock consists predominantly of K-feldspar with subordinate quartz, plagioclase, clinopyroxene, and biotite, and minor orthopyroxene, hornblende, titanite, and Fe–Ti oxide minerals. Accessory phases include apatite and zircon. Anhedral K-feldspar makes up 70 modal% of the sample, and most grains exhibit albite exsolution textures. K-feldspar locally occurs as phenocrysts, up to 2 cm in size, some of which are ovoid and mantled (i.e. rapakivi texture). Quartz forms small, interstitial, anhedral grains, and makes up 8 modal% of the rock. Sodic plagioclase is a very minor interstitial phase. Mafic minerals comprise only a small percentage of this rock. Biotite is typically altered to green chlorite–leucoxene aggregates. Green clinopyroxene grains, up to 2 mm long, are partially retrogressed to hornblende. Dark aggregates of clinopyroxene are spatially associated with Fe–Ti oxide minerals, hornblende, large apatite prisms (to 1 mm), euhedral titanite, and zircon.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Mixed or xenolith/ inclusion bearing	Xenolith/inclusion bearing	j
Rock type 1	Meta-igneous felsic intrusive	
Lithname 1	Metagranitic rock	mg
Rock type 2	Metasedimentary siliciclastic	
Lithname 2	Metasiliciclastic rock; undivided	-md
Rock code		**P_-PJ1-jmg-md**

Geochronology

P_-PJ1-jmg-md	*Maximum*	*Minimum*
Age (Ma)	1191 ± 4	1187 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009a	Kirkland et al., 2009b

The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

Two samples of the foliated and porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite (P_-PJ1-mgmu) that dominates this xenolith-rich composite unit (P_-PJ1-jmg-md) have been dated. These samples (GSWA 187103 and 187105; both from the southern flanks of Mount Aloysius) yielded magmatic crystallization ages of 1191 ± 4 Ma and 1187 ± 7 Ma, respectively (Kirkland et al., 2009a,b). This age range lies between within that of both the early and late Pitjantjatjara Supersuite; future geochronological work may result in this unit being reassigned to the late Pitjantjatjara Supersuite.

References

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Kirkland, CL, Bodorkos, S, Wingate, MTD, Smithies, RH and Evins, PM 2009a, 187103: granoblastic garnetiferous granite, Mount Aloysius; Geochronology Record 795: Geological Survey of Western Australia, 5p.

Kirkland, CL, Bodorkos, S, Wingate, MTD and Smithies, RH 2009b, 187105: foliated schlieric leucogranite, Mount Aloysius; Geochronology Record 796: Geological Survey of Western Australia, 6p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-xmg-mgr)

Legend narrative

Seriate to porphyritic pyroxene–biotite–hornblende metamonzogranite; interleaved and mingled with metasyenogranite to metamonzogranite; locally with relict flow texture

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mixed seriate to porphyritic granite and flow-textured syenogranite unit is a minor component of the early Pitjantjatjara Supersuite that forms rare outcrop in the southeastern part of the Walpa Pulka Zone, on Bates. It occurs where sheets of seriate to porphyritic granite are mixed (interleaved) with co-magmatic sheets of syenogranitic rock. A metamorphic mineralogy, including garnet coronas formed around mafic minerals, reflects recrystallization at the high-pressure granulite facies, probably during the Petermann Orogeny.

Distribution

This mixed seriate to porphyritic granite and flow-textured syenogranite unit forms rare outcrop in the southeastern part of the Walpa Pulka Zone, on Bates. It is best exposed on the northwestern slopes of Mount Gosse (Bates, MGA 491812E 7140970N).

Lithology

The main components of this mixed seriate to porphyritic granite and flow-textured syenogranite unit are pale-grey, seriate to weakly porphyritic granite containing laths of K-feldspar up to 1 cm in size, and unfoliated trachytic-textured syenogranite, the latter of which forms abundant xenoliths in the former granite. These xenoliths vary from isolated occurrences, to series of aligned xenoliths (disaggregated dyke), to discrete dykes that form locally lobate and scalloped contacts with the host granite. Elsewhere, the mixed seriate to porphyritic granite and flow-textured syenogranite unit includes up to 50% strongly porphyritic and locally trachytic-textured granite. The mixing style ranges from sheeted intrusions to syn-magmatic mingling; all three magmatic components are demonstrably co-magmatic.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic intrusive	
Lithname 1	Metagranitic rock	mg
Rock type 2	Meta-igneous felsic intrusive	-mg
Lithname 2	Metasyenogranite	r
Rock code		**P_-PJ1-xmg-mgr**

Geochronology

P_-PJ1-xmg-mgr	*Maximum*	*Minimum*
Age (Ma)	1220	1195
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Bodorkos et al., 2008	Kirkland et al., 2008

This mixed seriate to porphyritic granite and flow-textured syenogranite unit has not been directly dated, but is inferred to be part of the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

References

Bodorkos, S, Wingate, MTD and Kirkland, CL 2008, 174737: foliated metamonzogranite, Mount Fanny; Geochronology Record 718: Geological Survey of Western Australia, 5p.

Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Pitjantjatjara Supersuite; subunit (P_-PJ1-xmgg-mg)

Legend narrative

Weakly foliated to gneissic pyroxene granodiorite, quartz monzodiorite, and monzogranite; intruded by, and included within, fine- to medium-grained schlieric orthopyroxene(–hornblende)-bearing metaleucogranite

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ1-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This weakly foliated to gneissic metagranodiorite, metamorphosed quartz monzodiorite, metamonzogranite, and fine- to medium-grained schlieric metaleucogranite unit forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite. It is a composite unit that formed as voluminous schlieric leucogranite intruded into a range of porphyritic granite units also belonging to the early Pitjantjatjara Supersuite (including P_-PJ1-mggo, P_-PJ1-mgmu, and P_-PJ1-mgru).

Distribution

This composite weakly foliated to gneissic metagranodiorite, metamorphosed quartz monzodiorite, metamonzogranite, and fine- to medium-grained schlieric metaleucogranite unit forms low, scattered outcrop in an area approximately 10 km west of Mount Aloysius, along the central-southern part of the Tjuni Purlka Tectonic Zone, and across the boundary between HOLT, BELL ROCK, and BLACKSTONE.

Lithology

The weakly foliated to gneissic metagranodiorite, metamorphosed quartz monzodiorite, metamonzogranite and fine- to medium-grained schlieric metaleucogranite unit is a composite unit that forms part of the 1220–1200 Ma early Pitjantjatjara Supersuite. It comprises voluminous schlieric leucogranite that intruded into a range of porphyritic granite units also of the early Pitjantjatjara Supersuite, including:

- P_-PJ1-mggo (pyroxene metagranodiorite to metamorphosed quartz monzodiorite; commonly charnockitic; mafic minerals with garnet coronas; subhedral dark-grey K-feldspar phenocrysts up to 3 cm);
- P_-PJ1-mgmu (weakly to strongly foliated, porphyritic, leucocratic clinopyroxene–orthopyroxene–hornblende metamonzogranite; K-feldspar phenocrysts up to 2 cm; locally mylonitic);
- P_-PJ1-mgru (massive to moderately foliated, porphyritic, pyroxene(–hornblende–biotite) metasyenogranite; typically leucocratic; abundant K-feldspar phenocrysts up to 5 cm; local trachytic texture; locally garnetiferous).

The voluminous schlieric leucogranite itself includes a number of rock units, including:

- P_-PJ-mgmu (weakly to strongly foliated, porphyritic leucocratic metamonzogranite; contains clinopyroxene, orthopyroxene, and hornblende; K-feldspar phenocrysts up to 2 cm; locally mylonitic);
- P_-PJ2-mgsi (fine- to medium-grained, schlieric, orthopyroxene(–hornblende)-bearing metaleucogranite; weakly to strongly foliated; locally abundant xenoliths and layers of metatexitic to diatexitic granite and gneiss);
- P_-PJ2-jmgs-mn (fine- to medium-grained, schlieric, orthopyroxene(–hornblende)-bearing metaleucogranite; weakly to strongly foliated; abundant xenoliths and rafts of sedimentary and granitic gneiss).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ1-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous felsic intrusive	mg
Lithname 1	Metagranodiorite	g
Rock type 2	Meta-igneous felsic intrusive	
Lithname 2	Metagranitic rock	-mg
Rock code		**P_-PJ1-xmgg-mg**

Geochronology

P_-PJ1-xmgg-mg	*Maximum*	*Minimum*
Age (Ma)	1220	1195
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Bodorkos et al., 2008	Kirkland et al., 2008

This strongly foliated to gneissic, porphyritic leucogranite unit (P_-PJ1-mgmn) has not been directly dated but is inferred to be part of the early Pitjantjatjara Supersuite. The oldest early Pitjantjatjara Supersuite granite identified so far, from the Walpa Pulka Zone, yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest early Pitjantjatjara Supersuite granite is from the southeastern part of the Tjuni Purlka Tectonic Zone, and yielded a magmatic crystallization age of 1195 ± 4 Ma (GSWA 183459, Kirkland et al., 2008). Thus, the age range for the early Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1195 ± 4 Ma (i.e. 1220–1200 Ma).

References

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Kirkland, CL, Wingate, MTD and Bodorkos, S 2008, 183459: charnockite, Latitude Hill; Geochronology Record 722: Geological Survey of Western Australia, 5p.

Pitjantjatjara Supersuite (P_-PJ2-mg)

Legend narrative

Metagranite and gneiss

Rank	Suite
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny — the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. In the Walpa Pulka Zone and adjacent parts of the Tjuni Purlka Tectonic Zone, these rocks have been divided, based on age, into an early (P_-PJ1- in code notation; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009, 2010). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. Outcrop of the early Pitjantjatjara Supersuite is mainly restricted to the Tjuni Purlka Tectonic Zone and southwestern part of the Walpa Pulka Zone, whereas outcrop of the late Pitjantjatjara Supersuite occurs throughout the west Musgrave Province but is concentrated in the northeastern part of the Walpa Pulka Zone. Apart from this slight difference in geographic range, there appears to be no significant difference between the rocks of the early and late Pitjantjatjara Supersuite in terms of deformation, metamorphic and primary mineralogy, and compositional range (Smithies et al., 2010), except that mafic rocks (which are in any case a very rare component of the Pitjantjatjara Supersuite) are unknown from the early Pitjantjatjara Supersuite. Most granites of the Pitjantjatjara Supersuite are metaluminous, K-rich, A-type granites.

Distribution

Rocks of the Pitjantjatjara Supersuite are voluminous, and are distributed throughout the west Musgrave Province. Rocks of the late Pitjantjatjara Supersuite form significant outcrop in the north and northeast of the west Musgrave Province (Walpa Pulka Zone), where they form large, composite, intrusive bodies; in particular, the area around and between Mount Gosse and Mount Daisy Bates (central to southeastern BATES) is dominated by outcrop of these rocks. Rocks of the late Pitjantjatjara Supersuite are notably less common in the central and southwest of the west Musgrave Province (Tjuni Purlka Tectonic Zone and Mamutjarra Zone), where they mainly occur as dykes, small intrusions, or as migmatitic melt veins and sheets.

Lithology

In the Walpa Pulka Zone and adjacent parts of the Tjuni Purlka Tectonic Zone, rocks of the Pitjantjatjara Supersuite have been divided, based on age, into an early (P_-PJ1- in code notation; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009, 2010). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. Apart from a slight difference in geographic range, there appears to be no significant difference between the rocks of the early and late Pitjantjatjara Supersuite in terms of deformation, metamorphic and primary mineralogy, and compositional range (Smithies et al., 2010), except that mafic rocks (which are in any case a very rare component of the Pitjantjatjara Supersuite) are unknown from the early Pitjantjatjara Supersuite. As a result, the following description also summarizes the description for the parent Pitjantjatjara Supersuite unit (P_-PJ-xg-o), and is virtually identical to the description for the early Pitjantjatjara Supersuite (P_-PJ1-mg).

Most rocks of the late Pitjantjatjara Supersuite have been metamorphosed at granulite-facies conditions, and range from statically recrystallized and unfoliated, to strongly foliated and mylonitized. The primary (protolith) mineralogy of most of these granites was an essentially anhydrous assemblage of quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, and biotite, although late hornblende locally rims pyroxene. However, retrograde recrystallization is locally associated directly with foliation development, resulting in the partial to near-complete alteration of pyroxene to hornblende, actinolite, and biotite. Garnet occurs in rocks north of the Mann Fault and east of the Fanny Fault, typically as fine-grained coronas that separate the mafic minerals, including orthopyroxene, from feldspar, and reflecting a high-pressure metamorphic assemblage exhumed during the Petermann Orogeny.

Granites of the late Pitjantjatjara Supersuite can be broadly subdivided into three lithological groups. The first and most voluminous group typically ranges from granodiorite to syenogranite, although the full range is from monzodiorite to alkali-feldspar granite. Where primary igneous textures are preserved, this group commonly includes rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of a primary orthopyroxene-bearing mineralogy and on that basis can be classified as charnockites. This porphyritic granodiorite–syenogranite group dominates the Walpa Pulka Zone, occurring as large composite plutonic bodies, and forming smaller plutons and dykes in the Tjuni Purlka Tectonic Zone. These rocks are mostly restricted to dykes and minor intrusions within the Mamutjarra Zone, although in the northwest of that zone (FINLAYSON and COOPER) they form a widespread but non-continuous collection of small intrusions.

This first group of late Pitjantjatjara Supersuite granites typically do not contain abundant enclaves, and despite other local evidence for mixing or mingling (e.g. dykes terminating in chains of lobate inclusions), there is no field evidence at the present level of exposure for significant physical interaction between individual granite intrusions, or between these and any other magma batches. Several broad intrusion styles are identified. Most exposures show significant variations in texture (from seriate to porphyritic to megacrystic) and grain size on a scale of a metre to many tens of metres, suggesting that the larger bodies are typically composite intrusions of numerous individual dykes and sills. Geochemical data show that individual intrusions, or collections of intrusions (forming individual granite suites) are either compositionally heterogeneous throughout, or else show a systematic compositional variation that parallels the northwest trend of major shear zones (Smithies et al., 2010).

The second group of late Pitjantjatjara Supersuite granites is entirely restricted to the Tjuni Purlka Tectonic Zone, and comprises locally schlieric biotite–orthopyroxene leucogranites typically in the monzogranite to syenogranite compositional range. These form veins and sheets that cut and engulf earlier rocks of the Wirku Metamorphics and Wankanki Supersuite. Originally thought to be restricted to the late Pitjantjatjara Supersuite (P_-PJ2-mgsi and P_-PJ2-jmgs-mn), petrographically and geochemically identical rocks are now also known from the early Pitjantjatjara Supersuite (P_-PJ1-mgmu; Smithies et al., 2010), and it is clear that this group of rocks formed throughout much of the Musgrave Orogeny.

The third group of late Pitjantjatjara Supersuite granites consists of a granofels and schlieric leucogranite unit (P_-PJ2-mge). The protoliths to these rocks formed sheets and veins that intruded and engulfed all earlier lithologies, including other members of the supersuite as well as older paragneisses, within the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. They are interpreted as locally derived anatectic melts. Like the schlieric biotite–orthopyroxene leucogranites, the granofels and schlieric leucogranite unit was originally thought to be restricted to the late Pitjantjatjara Supersuite, but is now thought to have formed throughout much of the Musgrave Orogeny.

Geochemical data from both the Northern Territory (Edgoose et al., 2004) and Western Australia (Smithies et al., 2010) indicate that the felsic rocks (apart from the felsic granofels) of the early and late Pitjantjatjara Supersuite are compositionally uniform across the entire Musgrave Province. Granites of the Pitjantjatjara Supersuite are silicic (57–78 wt% SiO_2) and K-rich rocks with high total alkali content ($Na_2O + K_2O$ to 10.3 wt%) and high incompatible trace element concentrations, features consistent with an A-type classification. Smithies et al. (2010) subdivided the granites of the Pitjantjatjara Supersuite in Western Australia into several geochemically coherent suites; of these, only the Mirturtu Monzogranite (P_-PJ2mt-) is distinguishable on current 1:100 000 series maps (Bates; Howard et al., 2006).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ2-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-PJ2-mg**

Geochronology

P_-PJ2-mg	*Maximum*	*Minimum*
Age (Ma)	1188 ± 4	1148 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., in prep.	Kirkland et al., in prep.

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke that has yielded a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma).

In the Walpa Purlka Zone and northeastern parts of the Tjuni Purlka Tectonic Zone, the combined age populations for rocks of the Pitjantjatjara Supersuite can be divided into two broad but distinct groups: an older group (P_-PJ1-), reflecting magmatism between c. 1220 and 1200 Ma; and a younger group (P_-PJ2-), reflecting magmatism between c. 1190 and 1150 Ma. However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite. The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

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Pitjantjatjara Supersuite; subunit (P_-PJ2-mge)

Legend narrative

Fine to medium grained, massive to weakly banded granofels and metamorphosed schlieric leucogranite; typically less than 5% mafic minerals; seriate to K-feldspar porphyritic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

During the first stages of mapping in the west Musgrave Province, and as a result of early geochronological results (relating to rocks on Bates), the protoliths to this granofels and schlieric leucogranite unit were thought to have been intruded during the late Musgrave Orogeny, from c. 1190 to 1150 Ma. On that basis, the unit was assigned to the late Pitjantjatjara Supersuite; however, subsequent geochronological data indicated that the granites of this unit also formed throughout much of the early stages of the orogeny, with crystallization ages as old as c. 1200 Ma. Protoliths to this granofels and schlieric leucogranite unit intruded other members of the Pitjantjatjara Supersuite as well as older paragneisses, within the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. The unit is best exposed in the central-western parts of Bates, around Mount Fanny. It is typically a medium- to pale-grey, fine- to medium-grained rock with a well-developed granoblastic polygonal to granoblastic elongate texture, and forms sheets or veins in, or else swamps, rocks emplaced during the earlier parts of the Musgrave Orogeny. It is interpreted to represent pooled migmatitic melts related to the high-temperature granulite-facies conditions that persisted throughout the Musgrave Orogeny. A metamorphic mineralogy, including garnet coronas formed around mafic minerals, reflects recrystallization at the high-pressure granulite facies, probably during the Petermann Orogeny.

Distribution

Outcrop of this granofels and schlieric leucogranite unit is confined to the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. It occurs throughout the Walpa Pulka Zone on Bates, with the best exposures found up to 15 km to the north and northwest of Surveyor General's Corner, and in an area extending up to 10 km around Mount Fanny. In the Tjuni Purlka Tectonic Zone, this granofels and schlieric leucogranite forms a northwest-trending outcrop about 5km to the west of Butterfly Hill in the central to eastern part of Holt, and also forms scattered outcrop in the northern part of Finlayson.

Lithology

These rocks typically range from fine to medium grained, from seriate to K-feldspar porphyritic, and from medium- to pale-grey to highly leucocratic and white. A well-developed granoblastic polygonal to granoblastic elongate texture is commonly visible in hand specimen; in thin section, a granoblastic elongate texture developed in many specimens overprints an earlier mylonitic fabric — i.e. the rocks are blastomylonitic. This schlieric leucogranite differs from the massive granofels primarily in containing a higher proportion of mafic minerals, which occur as wisps and wispy clots of strongly aligned crystals. At some localities (e.g. Bates, in the area of MGA 456681E 7146477N), the schlieric textures coincide with blastomylonitic fabrics, and the wispy trains of mafic minerals might in part be tectonic; however, the schlieric texture is interpreted to be primarily igneous in origin. The compositional range of this unit is from monzogranite to syenogranite. Mafic minerals typically comprise <5% in the massive granofels, but may be as much as 15% of some schlieric leucogranites. Orthopyroxene and brown biotite, plus lesser clinopyroxene, are the most common mafic minerals. Accessory apatite, allanite, zircon, muscovite, and opaque minerals also occur. Garnet is rare, and in some case is restricted to blastomylonitic rocks (e.g. GSWA 174743: Bates, MGA 462221E 7151393N) or bands (sometimes accompanied by green hornblende; e.g. GSWA 174792: Bates, MGA 456681E 7146477N). Garnet forms fine-grained coronas separating all other mafic minerals (including opaque minerals and biotite) from feldspar. Brown hornblende occurs in a schlieric leucogranite 5 km southeast of Mount Gosse (on Bates, MGA 498865E 7138028N), forming elongate aggregate trains of granoblastic elongate crystals, in some cases with clinopyroxene cores.

Textures are usually inequigranular or polygonal granoblastic. Some strongly foliated rocks show flattening of rare feldspar phenocrysts, or spindle-shaped zones of granoblastic feldspar or feldspar–quartz aggregates; their protolith texture was clearly seriate to porphyritic. Local development of a strong, fine-scale banding or lamination accompanies, and overprints, incipient migmatization. At an outcrop 9 km southwest of Mount Gosse (on Bates, MGA 490717E 7133273N), narrow bands of mafic magma show mingling textures with the granofels. These provide very rare evidence for a mafic magmatic component in the Pitjantjatjara Supersuite. Orthopyroxene and garnet are often not recognisable in hand specimen in more leucocratic samples of the granofels (but not in the case of the schlieric leucogranites), and so the mafic mineral assemblages provide no basis for estimating metamorphic grade in the field. For this reason, the term 'granofels' is retained, despite clear evidence from thin section studies that these rocks have crystallized at the granulite facies.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ2-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic granofels/hornfels	e
Rock code		**P_-PJ2-mge**

Contact relationships

At some localities (e.g. Bates, around MGA 460565E 7147986N), the granofels and schlieric leucogranite components of this unit are transitional. Outcrop typically contains abundant inclusions of older gneissic rocks, and there is a complete transition from older gneisses containing dykes and net-vein complexes of granofels and schlieric leucogranite, through older gneisses swamped by granofels and schlieric leucogranite, to sheets of granofels and schlieric leucogranite virtually free of gneissic inclusions.

Geochronology

P_-PJ2-mge	*Maximum*	*Minimum*
Age (Ma)	1201 ± 6	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Inferred
References	Kirkland et al., 2011a	Smithies et al., 2009, 2010

A sample of this granofels and schlieric leucogranite (GSWA 174736, Bodorkos et al., 2008a) yielded a magmatic crystallization age of 1180 ± 7 Ma. This sample intruded, and contained xenoliths of, metasyenogranite (P_-PJ1-mgmu), a sample of which yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008b), with zircon rims dating a high-grade metamorphic event at 1171 ± 12 Ma, the latter being within error of the age of the granofels and schlieric leucogranite unit. Although initially thought to be restricted to the late part of the Musgrave Orogeny, it has now been established that the massive to weakly banded granofels and metamorphosed schlieric leucogranite unit also formed throughout much of the early stages of the orogeny. Magmatic crystallization ages from examples in the Tjuni Purlka Tectonic Zone range between 1201 ± 6 Ma (GSWA 187174, Kirkland et al., 2011a) and 1183 ± 7 Ma (GSWA 187172, Kirkland et al., 2011b).

References

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Pitjantjatjara Supersuite; subunit (P_-PJ2-mgrg)

Legend narrative

Fine- to coarse-grained leucocratic syenogranite; large grain size variation at hand specimen scale; graphic texture; locally garnetiferous; pelite and psammite inclusions

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This fine- to coarse-grained, leucocratic syenogranite unit is restricted to the Tjuni Purlka Tectonic Zone on Holt, where it forms sparse and poor-quality outcrop. The unit is typically heterogeneous in terms of grain size, and contains locally abundant xenoliths of paragneisses of the Wirku Metamorphics, and older granites belonging to the Pitjantjatjara Supersuite. The syenogranites are inferred to belong to the later part of the Musgrave Orogeny, and on that basis, are thought to have intruded between c. 1190 and c. 1150 Ma.

Distribution

This fine- to coarse-grained, leucocratic syenogranite unit is restricted to the Tjuni Purlka Tectonic Zone on Holt, particularly in the region between Murray Range and Lehmann Hill where it forms sparse and poor-quality outcrop.

Lithology

Rocks of this fine- to coarse-grained, leucocratic syenogranite unit are poorly outcropping and no samples were obtained. The unit is typically quite heterogeneous in terms of grain size, and locally contains abundant xenoliths of paragneisses (belonging to the Wirku Metamorphics) and older granites belonging to the Pitjantjatjara Supersuite (in particular, the pyroxene metasyenogranite P_-PJ1-mgru).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ2-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-PJ2-mgrg**

Geochronology

P_-PJ2-mgrg	*Maximum*	*Minimum*
Age (Ma)	1190	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

Rocks of this fine- to coarse-grained, leucocratic syenogranite unit have not been directly dated, but are inferred to form part of the late Pitjantjatjara Supersuite (Smithies et al., 2009, 2010). The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

References

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

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Pitjantjatjara Supersuite; subunit (P_-PJ2-mgsi)

Legend narrative

Fine- to medium-grained, schlieric, orthopyroxene(–hornblende)-bearing metaleucogranite; weakly to strongly foliated; locally abundant xenoliths and layers of metatexitic to diatexitic granite and gneiss

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

Rocks mapped as part of this fine- to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit (P_-PJ2-mgsi) are restricted to rare outcrops along the faulted margins of the Tjuni Purlka Tectonic Zone on Holt and Bell Rock. However, these rocks have been grouped, along with other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-jmgs-mn), into a single suite (Smithies et al., 2010) that forms mappable outcrops within the southeastern part of the Tjuni Purlka Tectonic Zone. They have also been incorporated into a combined unit dominated by rocks of the older Wankanki Supergroup (P_-WN-xmgn-mg) in the northwestern part of the same zone. These rocks are typically very leucocratic and strongly foliated metamorphosed monzogranites and syenogranites, which contain igneous orthopyroxene and igneous or metamorphic hornblende. They form extensive dykes and sheets engulfing and including country rock, particularly in the vicinity of major faults. Country-rock xenoliths are common, often giving the rock a schlieric appearance, which is particularly enhanced by subsequent deformation caused by movement along the faults formed form magma conduits. These rocks were emplaced throughout much of the Musgrave Orogeny, with samples dated from 1210 ± 10 Ma to 1155 ± 7 Ma.

Distribution

Rocks mapped as part of this fine-to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit are restricted to rare outcrops preserved along the faulted margins of the Tjuni Purlka Tectonic Zone, on Holt and Bell Rock. They are interpreted, based on geophysical data (an area of low TMI response), to form a large region of buried bedrock immediately north of the Blackstone Range. However, these rocks have been grouped, along with other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-jmgs-mn), into a single suite (Smithies et al., 2010). Discrete, mappable exposures of rocks within this combined unit (suite) are also restricted to the Tjuni Purlka Tectonic Zone, particularly the faulted margins on the southeastern part of the zone. These leucogranites do occur throughout the northwestern part of the Tjuni Purlka Tectonic Zone, but only as smaller dykes and sheets incorporated into a combined unit dominated by rocks of the older (country rock) Wankanki Supergroup (P_-WN-xmgn-mg).

Lithology

Although initially mapped as four separate units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi and P_-PJ2-jmgs-mn), the rocks grouped here are all typically metamorphosed leucocratic monzogranites to syenogranites that show a similar range in mineralogy, texture, structure, and outcrop style, and all are restricted to virtually the same tectonic zone (Tjuni Purlka Tectonic Zone). Smithies et al. (2010) showed that together these rocks form a geochemically coherent suite distinct from all other suites of Pitjantjatjara Supersuite granites. Inferred and radiometric ages for this group of rocks indicate their intrusion was more or less continuous throughout the entire Musgrave Orogeny.

Where they form large outcrops (e.g. along the northeast side of Bell Rock Range on Bell Rock), these rocks grouped here are typically fault bounded, and Smithies et al. (2010) suggested that the extensive northwest-trending array of faults within the Tjuni Purlka Tectonic Zone greatly facilitated intrusion of the granites. More typically, the granites grouped here form extensive dykes and sheets, engulfing and including country rock, particularly in the vicinity of major faults. Country-rock xenoliths are common, often giving the rock a schlieric appearance, which is enhanced by subsequent deformation caused by movement along the faults formed from earlier magma conduits. The rock types grouped here form several mappable outcrops in the southeastern part of the Tjuni Purlka Tectonic Zone, but dykes and sheets of these rocks cannot be individually mapped to the northwest (i.e. on Finlayson).

The rocks grouped here range from mesocratic to (more typically) highly leucocratic, and from seriate-textured to rocks that contain abundant subhedral phenocrysts of K-feldspar up to 2.5 cm in size. Massive to weakly foliated samples are rare, the rocks being more typically moderately to strongly foliated, with mylonitic textures commonly developed in proximity to faults and shear zones. In thin section, the rocks commonly contain strongly undulose quartz, and boundaries between larger grains show well-developed mortar textures, or local myrmekite. In several cases, large rounded to subrounded feldspar crystals lie in a seriate groundmass of granoblastic-polygonal to granoblastic-aligned quartz and feldspar.

These rocks comprise quartz (10–40%), perthite (30–50%), plagioclase (5–20%; in places antiperthitic), green hornblende (2–5%, but up to 15% in strongly foliated rocks), orthopyroxene (3–10%), biotite (4–8%), clinopyroxene (1–4%), magnetite (1–2%), and accessory zircon, monazite, apatite, rutile, and fluorite. Green hornblende is typically a late-magmatic to (more commonly) secondary or metamorphic mineral that rims and replaces orthopyroxene and, in some cases, biotite.

With the increasing development of deformational fabric, a greater proportion of original pyroxene (plus biotite and magnetite) is replaced by hornblende, which is strongly aligned within the foliation plane. Orthopyroxene (hypersthene) is typically anhedral, and is commonly partially to totally replaced by an assemblage comprising biotite, quartz, and feldspar.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ2-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic schist	s
1st qualifier	–	
2nd qualifier	Migmatitic	i
Rock code		**P_-PJ2-mgsi**

Contact relationships

Rocks of this fine- to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit, along with the other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-jmgs-mn) that Smithies et al. (2010) grouped into a geochemically coherent suite, are confined to the Tjuni Purlka Tectonic Zone. All pre-Musgrave Orogeny rocks found within the Tjuni Purlka Tectonic Zone (Wirku Metamorphics: P_-WM-mh; Wankanki Supersuite: P_-WN-mg), plus the earlier units of the Pitjantjatjara Supersuite (P_-PJ1-mg), have been intruded by, and locally included within, these leucogranites.

Geochronology

P_-PJ2-mgsi	*Maximum*	*Minimum*
Age (Ma)	1210 ± 10	1155 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009	Kirkland et al., in prep.

These schlieric, orthopyroxene-bearing metaleucogranites, along with the other lithologically similar units that Smithies et al. (2010) grouped into a geochemically coherent suite, were intruded into the Tjuni Purlka Tectonic Zone during all stages of the Musgrave Orogeny (Smithies et al., 2010).

Three samples from this group of rocks have been directly dated. A mylonitic leucogranite (GSWA 185339), emplaced along the faulted southern margin of the Hinckley Range (Bell Rock), yielded an age of 1210 ± 10 Ma, which was interpreted to be the igneous crystallization age (Kirkland et al., 2009). A leucogranite sheet (GSWA 190231) that cuts granites of the late Pitjantjatjara Supersuite (P_-PJ2-mgrg) in the central-western part of Holt yielded an age of 1155 ± 7 Ma, which was also interpreted as the igneous crystallization age (Kirkland et al., 2010). A similar leucogranite sheet, occurring within granites of the Wankanki Supersuite (P_-WN-xmgn-mg) in the northwestern part of Finlayson, has yielded a magmatic crystallization age of 1158 ± 9 Ma (GSWA 194367, Kirkland et al., in prep.).

In addition to these direct dates, the dating of metasedimentary xenoliths within leucogranite from around the Prostanthera Hill region in the north of Holt, yields metamorphic ages that almost certainly reflect the intrusive age of the enveloping leucogranites. Three other dates, interpreted as reflecting both the metamorphism of the sedimentary rocks (Wirku Metamorphics) and the igneous crystallization age of the host granite, include 1201 ± 6 Ma (GSWA 187174, Kirkland et al., 2011), 1200 ± 5 Ma (GSWA 187196, Kirkland et al., in prep.), and 1197 ± 10 Ma (GSWA 187179, Kirkland et al., in prep.).

References

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Pitjantjatjara Supersuite; subunit (P_-PJ2-jmgs-mn)

Legend narrative

Fine- to medium-grained, schlieric, orthopyroxene (–hornblende)-bearing metaleucogranite; weakly to strongly foliated; abundant xenoliths and rafts of sedimentary and granitic gneiss

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

Rocks mapped within this fine-to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit with abundant metasedimentary rafts are restricted to rare outcrops preserved along the faulted margins of the Tjuni Purlka Tectonic Zone on HOLT. However, these rocks have been grouped, along with other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi), into a single suite (Smithies et al., 2010) that forms mappable outcrops within the southeastern part of the Tjuni Purlka Tectonic Zone, and has been incorporated within a combined unit dominated by rocks of the older Wankanki Supergroup (P_-WN-xmgn-mg) in the northwestern part of this same zone. These rocks are typically very leucocratic and strongly foliated metamorphosed monzogranites and syenogranites that contain igneous orthopyroxene and igneous or metamorphic hornblende. They form extensive dykes and sheets engulfing and including country rock, particularly in the vicinity of major faults. Country-rock xenoliths are common, often giving the rock a schlieric appearance, which is particularly enhanced by subsequent deformation caused by movement along the faults formed from earlier magma conduits. The intrusion of these units occurred throughout much of the Musgrave Orogeny, with samples dated from 1210 ± 10 Ma to 1155 ± 7 Ma.

Distribution

This fine-to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit with abundant metasedimentary rafts is restricted to rare outcrops preserved near the faulted margins of the Tjuni Purlka Tectonic Zone on HOLT. However, this unit has been grouped, along with other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi), into a single suite (Smithies et al., 2010). Discrete, mappable exposures of rocks of this combined unit (suite) are also restricted to the Tjuni Purlka Tectonic Zone, particularly to the faulted margins on the southeastern part of this zone. The leucogranites do occur throughout the northwestern part of the Tjuni Purlka Tectonic Zone, but only as smaller dykes and sheets incorporated into a combined unit dominated by rocks of the older (country rock) Wankanki Supergroup (P_-WN-xmgn-mg).

Lithology

Although initially mapped as four separate units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi and P_-PJ2-jmgs-mn), the rocks grouped here are all typically metamorphosed leucocratic monzogranites to syenogranites that show a similar range in mineralogy, texture, structure, and outcrop style, and all are restricted to the same tectonic zone (Tjuni Purlka Tectonic Zone). Smithies et al. (2010) showed that together these rocks form a geochemically coherent suite distinct from all other suites of Pitjantjatjara Supersuite granites. Isotopic ages obtained for this group of rocks indicate their intrusion was more or less continuous throughout the entire Musgrave Orogeny.

Where they form large outcrops (e.g. along the northeast side of BELL ROCK Range on BELL ROCK), the rocks grouped here are typically fault bounded, and Smithies et al. (2010) suggested that the extensive northwest-trending array of faults within the Tjuni Purlka Tectonic Zone greatly facilitated the intrusion of these granites. More typically, the granites grouped here form extensive dykes and sheets engulfing and including country rock, particularly in the vicinity of major faults. Country-rock xenoliths are common, often giving the rock a schlieric appearance, which is particularly enhanced by subsequent deformation caused by movement along the faults formed from earlier magma conduits. The rocks grouped here form several mappable outcrops in the southeastern part of the Tjuni Purlka Tectonic Zone, but dykes and sheets of these rocks cannot be individually mapped to the northwest (i.e. on FINLAYSON).

The rock types grouped here range from mesocratic to (more typically) highly leucocratic, and from seriate-textured to rocks that contain abundant subhedral phenocrysts of K-feldspar up to 2.5 cm in size. Massive to weakly foliated samples are rare, the rocks being more typically moderately to strongly foliated, with mylonitic textures commonly developed in proximity to faults and shear zones. In thin section, the rocks commonly contain strongly undulose quartz, and boundaries between larger grains show well-developed mortar textures or local myrmekite. In several cases, large rounded to subrounded feldspar crystals lie in a seriate groundmass of granoblastic polygonal to granoblastic aligned quartz and feldspar.

These rocks comprise quartz (10–40%), perthite (30–50%), plagioclase (5–20%; in places antiperthitic), green hornblende (2–5%, but up to 15% in strongly foliated rocks), orthopyroxene (3–10%), biotite (4–8%), clinopyroxene (1–4%), magnetite (1–2%), and accessory zircon, monazite, apatite, rutile, and fluorite. Green hornblende is typically a late-magmatic to (more commonly) secondary or metamorphic mineral, which rims and replaces orthopyroxene and, in some cases, biotite. With increasing development of deformational fabric, a greater proportion of original pyroxene (plus biotite and magnetite) is replaced by hornblende grains that are strongly aligned with the foliation plane. Orthopyroxene (hypersthene) is typically anhedral, and is partially to totally replaced by an assemblage comprising biotite, quartz, and feldspar.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ2-
Mixed or xenolith/ inclusion bearing	Xenolith/inclusion bearing	j
Rock type 1	Meta-igneous felsic intrusive	mg
Lithname 1	Granitic schist	s
Rock type 2	Metamorphic protolith unknown: gneiss	
Lithname 2	Gneiss	-mn
Rock code		**P_-PJ2-jmgs-mn**

Contact relationships

Rocks of this fine-to medium-grained, schlieric, orthopyroxene-bearing metaleucogranite unit with abundant metasedimentary rafts (P_-PJ2-jmgs-mn), along with the other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi) that Smithies et al. (2010) grouped into a geochemically coherent suite, are confined to the Tjuni Purlka Tectonic Zone where intrusion appears to have been strongly fault-controlled. Intrusion occurred during all stages of the Musgrave Orogeny (Smithies et al., 2010). All pre-Musgrave Orogeny rocks found within the Tjuni Purlka Tectonic Zone (Wirku Metamorphics: P_-WM-mh; Wankanki Supersuite: P_-WN-mg), plus earlier units of the Pitjantjatjara Supersuite (P_-PJ1-mg), have been intruded by, and locally included within, these leucogranites.

Geochronology

P_-PJ2-jmgs-mn	*Maximum*	*Minimum*
Age (Ma)	1210 ± 10	1155 ± 7
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2009	Kirkland et al., 2010

Rocks of this unit, along with the other lithologically similar units (P_-PJ-mgmu, P_-PJ1-mgmu, P_-PJ2-mgsi) that Smithies et al. (2010) grouped into a geochemically coherent suite, intruded into the Tjuni Purlka Tectonic Zone during all stages of the Musgrave Orogeny (Smithies et al., 2010). Three samples from this group have been directly dated. A mylonitic leucogranite (GSWA 185339) emplaced along the faulted southern margin of the Hinckley Range (Bell Rock) yielded an age of 1210 ± 10 Ma, which was interpreted to be the igneous crystallization age (Kirkland et al., 2009). A leucogranite sheet (GSWA 190231) that cuts a late Pitjantjatjara Supersuite granite (P_-PJ2-mgrg) in the central-western part of Holt yielded an age of 1155 ± 7 Ma, which was also interpreted to be the igneous crystallization age (Kirkland et al., 2010). A similar leucogranite sheet within granites of the Wankanki Supersuite (P_-WN-xmgn-mg) in the northwestern part of Finlayson yielded a magmatic crystallization age of 1158 ± 9 Ma (GSWA 194367, Kirkland et al., in prep.).

In addition to these direct dates, the dating of metasedimentary xenoliths within leucogranite from the Prostanthera Hill region in the north of Holt, yielded metamorphic ages that almost certainly reflect the intrusive age of the enveloping leucogranites. Three dates, interpreted as reflecting both metamorphism of the sedimentary rocks (Wirku Metamorphics) and the igneous crystallization age of the host granite, include 1201 ± 6 Ma (GSWA 187174, Kirkland et al., 2011), 1200 ± 5 Ma (GSWA 187196, Kirkland et al., in prep.), and 1197 ± 10 Ma (GSWA 187179, Kirkland et al., in prep.).

References

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UMUTJU GRANITE (P_-PJ2um-mg)

Legend narrative

Medium- to coarse-grained hornblende–pyroxene(–garnet) metagranite

Rank	Suite
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Umutju Granite (part of the Umutju Suite of Edgoose et al., 2004) forms part of the late Pitjantjatjara Supersuite, having crystallization ages in the range 1192–1144 Ma. This unit does not outcrop in the west Musgrave Province, but is inferred to dominate the bedrock geology beneath regolith cover in the northeastern part of the Walpa Pulka Zone (in the northern part of BATES), based on mapping of the Musgrave Province in the Northern Territory (Edgoose et al., 2004) and geophysical data. The unit is dominated by medium- to coarse-grained hornblende–pyroxene granite metamorphosed at granulite facies. The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny — the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. These rocks have been divided, based on age of intrusion, into an early (P_-PJ1-; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009).

Distribution

The Umutju Granite does not outcrop in the west Musgrave Province, but is inferred to dominate the bedrock geology beneath regolith cover in the northeastern part of the Walpa Pulka Zone (in the northern part of BATES), based on mapping of the Musgrave Province in the Northern Territory (Edgoose et al., 2004) and geophysical data. It is the main basement lithology found throughout, and to the north of, the Mann Ranges in the Northern Territory (Edgoose et al., 2004).

Lithology

The Umutju Granite forms part of the late Pitjantjatjara Supersuite. The unit does not outcrop in the west Musgrave Province, but has been described by Edgoose et al. (2004) using outcrops in the Northern Territory. Although the primary mineralogy typically includes clinopyroxene, or clinopyroxene–hornblende and porphyritic rocks, with either plagioclase or K-feldspar phenocrysts, the Umutju Granite is also subdivided based on slight mineralogical and textural variations. Metamorphic assemblages that include garnet, clinopyroxene, and biotite are particularly well-developed where these rocks have been mylonitized.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, UMUTJU GRANITE	PJ2um-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-PJ2um-mg**

Geochronology

P_-PJ2um-mg	*Maximum*	*Minimum*
Age (Ma)	1175 ± 10	1145 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Edgoose et al., 2004	Edgoose et al., 2004

The Umutju Granite forms part of the late Pitjantjatjara Supersuite, which was emplaced from 1190 to 1150 Ma, during the later stage of the Musgrave Orogeny (Smithies et al., 2009, 2010). Edgoose et al. (2004) reported Kober Pb–Pb dating of zircons from four samples in the Northern Territory, which gave ages, interpreted to be magmatic crystallization ages, in the range of 1175–1145 Ma. An additional sample gave a crystallization age of 1120 ± 9 Ma, although it is not clear whether this sample is from the Umutju Granite or a 'post-tectonic' suite (Edgoose et al., 2004).

References

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POTTOYU GRANITE (P_-PJ2po-mg)

Legend narrative

Medium- to coarse-grained hornblende–pyroxene(–garnet) metagranite

Rank	Suite
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pottoyu Granite (part of the 'Pottoyu Suite' of Edgoose et al., 2004) forms part of the late Pitjantjatjara Supersuite, having crystallization ages in the range 1192–1144 Ma. It does not outcrop in the west Musgrave Province, but is inferred to dominate the bedrock geology (beneath regolith cover) in the region north of the Woodroffe Thrust on the northern part of BATES, based on mapping of the Musgrave Province in the Northern Territory (Edgoose et al., 2004) and geophysical data. The unit is dominated by fine- to coarse-grained, foliated, coarsely porphyritic biotite granite, metamorphosed at the upper amphibolite facies. The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny — the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. These rocks have been divided, based on age of intrusion, into an early (P_-PJ1-; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009).

Distribution

The Pottoyu Granite does not outcrop in the west Musgrave Province, but is inferred to dominate the bedrock geology (beneath regolith cover) in the region north of the Woodroffe Thrust on the northern part of BATES, based on mapping of the Musgrave Province in the Northern Territory (Edgoose et al., 2004) and on geophysical data. It is the main basement lithology found throughout the Pottoyu Hills and Petermann Ranges in the Northern Territory (Edgoose et al., 2004).

Lithology

The Pottoyu Granite forms part of the late Pitjantjatjara Supersuite. The unit does not outcrop in the west Musgrave Province, but has been described by Edgoose et al. (2004) from exposures in the Northern Territory, where it is dominated by foliated, coarsely porphyritic, biotite granite. The Pottoyu Granite typically contains biotite, with subordinate titanite and opaque minerals; epidote and allanite are also locally present. The mineralogy varies depending on metamorphic grade; hornblende occurs in migmatitic outcrops in the south, whereas chlorite locally occurs in lower-grade regions to the north. The porphyritic phase is characterized by rounded K-feldspars, generally 1–3 cm but up to 8 cm in diameter, which commonly display a rapakivi texture.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, POTTOYU GRANITE	PJ2po-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-PJ2po-mg**

Geochronology

P_-PJ2po-mg	*Maximum*	*Minimum*
Age (Ma)	1192 ± 13	1144 ± 12
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Edgoose et al., 2004	Edgoose et al., 2004

The Pottoyu Granite (the 'Pottoyu Suite' of Edgoose et al., 2004) forms part of the late Pitjantjatjara Supersuite, which was emplaced from 1190 to 1150 Ma during the later stage of the Musgrave Orogeny (Smithies et al., 2009, 1010). Edgoose et al. (2004) reported on SHRIMP U–Pb and Kober Pb–Pb dating of zircons from four Pottoyu Granite samples from the Northern Territory. These gave ages in the range of 1192 to 1144 Ma, all of which were interpreted to be magmatic crystallization ages.

References

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Mirturtu Suite (P_-PJ2mt-mg)

Legend narrative

Metagranite and gneiss

Rank	Suite
Parent	Pitjantjatjara Supersuite (P_-PJ2-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pitjantjatjara Supersuite can be subdivided into several geochemically coherent suites (Smithies et al., 2010). Of these, the Mirturtu Monzogranite is the only suite distinguishable on the current 1:100 000 series geological maps, forming isolated outcrop in the central-eastern part of BATES. The Mirturtu Monzogranite falls within the late Pitjantjatjara Supersuite, which was emplaced from 1190 to 1150 Ma during the later stage of the Musgrave Orogeny (Smithies et al., 2009, 2010). The Mirturtu Monzogranite shows a narrower range of intrusive ages, covering from 1183 ± 9 to 1176 ± 6 Ma (Bodorkos et al., 2006a–d, 2008).

Distribution

Rocks of the Mirturtu Monzogranite are restricted to the northeastern part of the Walpa Pulka Zone on BATES, with the main exposure forming a range about 1 km south of Hubert Soak (BATES, MGA 489100E 7144200N).

Derivation of name

This name of this suite is derived from the Mirturtu Camp in southeastern BATES (Howard et al., 2006).

Lithology

The Mirturtu Monzogranite falls within the late Pitjantjatjara Supersuite. There appears to be no significant lithological difference between the rocks of the Mirturtu Monzogranite and any other rocks of the late Pitjantjatjara Supersuite.

These rocks have been metamorphosed at granulite-facies conditions, and range from statically recrystallized and unfoliated, to strongly foliated and mylonitized. The primary (protolith) mineralogy of most of these granites was an essentially anhydrous assemblage of quartz–plagioclase–K-feldspar–orthopyroxene–clinopyroxene–biotite, although late hornblende locally rims pyroxene. However, retrograde recrystallization is locally associated directly with foliation development, resulting in the partial- to near-complete alteration of pyroxene to hornblende, actinolite, and biotite. Garnet typically occurs as fine-grained coronas that separates the mafic minerals, including orthopyroxene, from feldspars, and reflects a high-pressure metamorphic assemblage exhumed during the Petermann Orogeny.

Although typically in the monzogranite compositional range, rocks of the Mirturtu Monzogranite range from granodiorite to syenogranite. Where primary igneous textures are preserved, these include rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of a primary orthopyroxene-bearing mineralogy, and on that basis can be classified as charnockites.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, Mirturtu Suite	PJ2mt-mg
Rock type	Meta-igneous felsic intrusive	
Rock code		**P_-PJ2mt-mg**

Geochronology

P_-PJ2mt-mg	*Maximum*	*Minimum*
Age (Ma)	1183 ± 9	1176 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2006c	Bodorkos et al., 2006d

Rocks of the Mirturtu Monzogranite form part of the late Pitjantjatjara Supersuite (Smithies et al., 2009, 2010). The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

However, five dated samples obtained directly from the Mirturtu Suite (GSWA 180300, 180262, 180270, 180256, and 174538) show a much narrower range of intrusive ages, extending from 1183 ± 9 to 1176 ± 6 Ma (Bodorkos et al., 2006a–d, 2008).

References

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Bodorkos, S, Love, GJ and Wingate, MTD 2006d, 180256: metagranodiorite, Hubert Soak; Geochronology Record 649: Geological Survey of Western Australia, 5p.

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Mirturtu Suite; subunit (P_-PJ2mt-mggu)

Legend narrative

Hornblende–garnet granodioritic augen gneiss; typically strongly foliated to blastomylonitic; local composite gneiss including interleaves and inclusions derived from the Wirku Metamorphics

Rank	Formation
Parent	Mirturtu Suite (P_PJ2mt-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This hornblende–garnet granodioritic augen gneiss unit forms a minor unit in the Mirturtu Suite of the late Pitjantjatjara Supersuite. Outcrop of this suite lies entirely to the north of the Mann Fault, and is scattered widely throughout the southeastern part of BATES. The metamorphic mineralogy of the hornblende–garnet granodioritic augen gneiss reflects recrystallization at the high-pressure granulite facies, probably during the Petermann Orogeny. The protoliths to these rocks intruded between c. 1190 and c. 1155 Ma during the later part of the Musgrave Orogeny.

Distribution

This hornblende–garnet granodioritic augen gneiss unit forms limited rubbly outcrop, approximately 4.5 km to the southeast of Mount Gosse, in the southeastern part of BATES (MGA 498667E 7137797N).

Lithology

This augen gneiss is locally mylonitic, incorporated into a zone of shearing between older quartzofeldspathic granulitic gneiss of the Wirku Metamorphics and structurally overlying granofels. It is typically a mesocratic, medium-grained (to very fine grained in ultramylonites) rock, with highly stretched K-feldspar augens that locally form up to 25% of the rock. It is interleaved with, intrudes, and contains inclusions of, quartzofeldspathic granulitic gneiss (Wirku Metamorphics), but shows only structural contact with the overlying granofels.

Sample GSWA 180283 (taken from this unit's type locality) is a medium-grained, K-feldspar porphyritic blastomylonite. Felsic domains are of granoblastic quartz and feldspar. Elongate domains of granoblastic polygonal feldspar represent original phenocrysts. Quartz ribbons are common. Mafic domains are 1 to 5 mm thick, highly elongate, and comprise granoblastic polygonal assemblages of garnet, clinopyroxene, and hornblende, with lesser amounts of biotite and opaque minerals. Polygonal grains of hornblende rim larger anhedral grains of clinopyroxene. Garnet is clear (inclusion-free) and pink in the groundmass or in coronas; however, large anhedral garnets also occur and typically comprise cores rich in quartz inclusions, surrounded by clear pink rims. The mylonitic fabric is early (early- to syn-metamorphic) and has been recrystallized, most likely at upper amphibolite facies, but the garnet cores (in porphyroblasts) provide evidence for a possible earlier metamorphic event.

In samples collected from elsewhere in the west Musgrave Province (e.g. GSWA 174716: BATES, MGA 474185E 7147627N), much of the mafic assemblage has been recrystallized to an assemblage comprising clinopyroxene, green hornblende, garnet, and biotite, although large cores of clinopyroxene are also preserved and possibly represent primary minerals. Textures are typically granoblastic elongate, indicating post-mylonitic recrystallization to blastomylonite, most likely at upper amphibolite facies. Garnets form distinct porphyroblasts, which are up to 5 mm in size, with cores crowded with inclusions of quartz, biotite, and ?feldspar, surrounded by inclusion-free rims. These mylonitic rocks provide evidence for two phases of, or at least protracted, garnet growth.

Regionally, the hornblende–garnet granodioritic augen gneiss unit varies in terms of the proportions of interleaves and inclusions within quartzofeldspathic granulitic gneiss. These interleaves and inclusions are locally abundant in the vicinity of the type locality, but are rare in outcrops to the west of Mount Daisy Bates (e.g. around BATES, MGA 474185E 7147627N).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, Mirturtu Suite	PJ2mt-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metagranodiorite	g
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-PJ2mt-mggu**

Geochronology

P_-PJ2mt-mggu	*Maximum*	*Minimum*
Age (Ma)	1176 ± 6	1183 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2006c	Bodorkos et al., 2006d 2006d

Rocks of the Mirturtu Monzogranite form part of the late Pitjantjatjara Supersuite (Smithies et al., 2009, 2010). The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

Despite this, five samples dated from the Mirturtu Suite (GSWA 180300, 180262, 180270, 180256, and 174538) show a much narrower range of intrusive ages, extending from 1183 ± 9 to 1176 ± 6 Ma (Bodorkos et al., 2006a–d, 2008).

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Mirturtu Suite; subunit (P_-PJ2mt-mgmo)

Legend narrative

Pyroxene–biotite–hornblende metamonzogranite and minor metamorphosed granodiorite to quartz monzodiorite; typically with garnet coronas around mafic minerals; seriate to porphyritic with K-feldspar phenocrysts up to 5 cm

Rank	Formation
Parent	Mirturtu Suite (P_-PJ2mt-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This pyroxene–biotite–hornblende monzogranite is the main unit of the Mirturtu Suite, and occurs widely throughout the southeastern part of Bates. The pyroxene–biotite–hornblende monzogranite unit ranges from weakly to strongly foliated to locally mylonitic, is typically leucocratic and grey weathering, is medium- to coarse-grained, and seriate to feldspar porphyritic. Garnet typically forms as fine, sugary coronas that separate the mafic minerals from feldspars. The metamorphic mineralogy reflects recrystallization at high-pressure granulite facies during the Petermann Orogeny. The protoliths to these rocks intruded between c. 1190 and c. 1155 Ma, during the later part of the Musgrave Orogeny (late Pitjantjatjara Supersuite).

Distribution

This pyroxene–biotite–hornblende monzogranite is the main unit is the dominant lithology of the Mirturtu Suite, and occurs widely throughout the southwestern part of Bates, covering probably as far north as the Woodroffe Thrust, and as far west as a number of isolated outcrops 2–3 km to the northeast of Amy Giles Hill (southwestern Bates).

Lithology

This monzogranite unit ranges from weakly to strongly foliated to locally mylonitic, is typically leucocratic and grey weathering, is medium- to coarse-grained, and seriate to feldspar porphyritic. Monzogranite is the dominant lithology but the full compositional range is from quartz monzodiorite and granodiorite to syenogranite. A finer-grained, pale-grey, seriate to porphyritic granite locally intrudes, or is intruded by, the medium- to coarse-grained variety, and geochemical data suggest the two rock types are co-genetic.

Feldspar phenocrysts consist of tabular to rounded K-feldspar (mainly perthite) grains up to 4 cm long, some of which are mantled by plagioclase (rapakivi texture). Plagioclase phenocrysts also occur and reach 2 cm in size. The rock typically contains 10–15% mafic minerals, but may include up to 35% mafic minerals. These locally form clots up to 2 cm in size, which are commonly strongly flattened parallel to foliation. Subrounded to rounded xenoliths, ranging upwards in size from a few centimetre, are also locally common, and consist of mafic and felsic gneiss, and granulitic gneiss.

In outcrop, the less foliated examples of this unit preserve igneous textures. In thin section, there is a range in textures from weakly recrystallized (i.e. near-primarily igneous) to totally recrystallized granoblastic polygonal or granoblastic elongate. Mortar textures are well-developed in the recrystallized samples. Most, though not all, mylonitic fabrics have been recrystallized (i.e. blastomylonitic). If these mylonites relate to the Petermann Orogeny, they must pre-date the thermal peak of that orogeny.

Quartz typically forms >25% of the mode. Where preserved, perthite phenocrysts engulf all matrix phases. In many recrystallized rocks, both plagioclase and perthite are preserved as monomineralic polygonal aggregates. Clinopyroxene and green hornblende are the main mafic minerals. Clinopyroxene occurs both as a subhedral primary phase and as recrystallized polygonal aggregates. In some samples (e.g. GSWA 180253), clinopyroxene is bright green, suggesting a sodic composition. Primary hornblende is rarely preserved. Hornblende more commonly rims clinopyroxene or forms clots or aggregates of polygonal grains, in places surrounding a clinopyroxene core. Orthopyroxene is commonly found, but is always less abundant than clinopyroxene. It usually occurs as a remnant igneous phase (making these rocks are charnockitic) and is locally strongly replaced by an assemblage of feldspar, biotite, and quartz. Biotite is common in some rocks, and is invariably metamorphic in origin, forming as oriented flakes or as replacement rims around earlier mafic minerals. Opaque minerals, including both ilmenite and magnetite, are a common accessory and are locally altered to biotite and titanite. Apatite and titanite are common primary accessory phases, and sillimanite forms as needles in feldspar.

Garnet forms primarily as fine, sugary coronas that separate the mafic minerals from feldspars, and occurs less commonly as isolated, anhedral, syn- to post-tectonic crystals overgrowing oriented biotite. Metamorphic mineralogy indicates granulite-facies peak conditions.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, Mirturtu Suite	PJ2mt-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-PJ2mt-mgmo**

Geochronology

P_-PJ2mt-mgmo	*Maximum*	*Minimum*
Age (Ma)	1176 ± 6	1183 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2006c	Bodorkos et al., 2006d

Rocks of the Mirturtu Monzogranite form part of the late Pitjantjatjara Supersuite (Smithies et al., 2009, 2010). The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

However, five samples dated from the Mirturtu Suite (GSWA 180300, 180262, 180270, 180256, and 174538) show a much narrower range of intrusive ages, extending from 1183 ± 9 to 1176 ± 6 Ma (Bodorkos et al., 2006a–d, 2008).

References

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Mirturtu Suite; subunit (P_-PJ2mt-mgmy)

Legend narrative

Mylonitic pyroxene–biotite–hornblende metamonzogranite; K-feldspar porphyritic (rapakivi granite) and locally charnockitic

Rank	Formation
Parent	Mirturtu Suite (P_-PJ2mt-mg)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mylonitic pyroxene–biotite–hornblende monzogranite unit is the mylonitic equivalent of the pyroxene–biotite–hornblende metamonzogranite unit (P_-PJ2mt-mgmo); the unit forms a minor component of the Mirturtu Suite, found throughout the southeastern part of BATES. Mylonitic deformation of these rocks also occurred during the Petermann Orogeny, but significant mylonitic deformation before that event (during either the late Musgrave Orogeny or the Giles Event) cannot be ruled out. The protoliths to these rocks intruded between c. 1190 and c. 1155 Ma during the later part of the Musgrave Orogeny (late Pitjantjatjara Supersuite).

Distribution

Outcrop of this mylonitic pyroxene–biotite–hornblende monzogranite unit is mainly restricted to a small area on BATES (around MGA 486710E 7146062N).

Lithology

Rocks of this mylonitic pyroxene–biotite–hornblende monzogranite unit are mylonitized examples of pyroxene–biotite–hornblende metamonzogranite (P_-PJ2mt-mgmo), also of the Mirturtu Suite. In some of these mylonites, garnet porphyroblasts deflect the mylonitic foliation defined by the alignment of biotite and hornblende, and are likely to reflect syn-mylonitic growth. In other cases, the garnet porphyroblasts have grown at a post-mylonitic stage and enclose oriented biotite crystals. These contrasting relationships suggest that peak metamorphic conditions outlasted mylonite development.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite, Mirturtu Suite	PJ2mt-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-PJ2mt-mgmy**

Geochronology

P_-PJ2mt-mgmy	*Maximum*	*Minimum*
Age (Ma)	1183 ± 9	1176 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2006C	Bodorkos et al., 2006d

Rocks of the Mirturtu Monzogranite form part of the late Pitjantjatjara Supersuite (Smithies et al., 2009, 1010). The oldest late Pitjantjatjara Supersuite granite identified so far, from the Tjuni Purlka Tectonic Zone, yielded a magmatic crystallization age of 1188 ± 4 Ma (GSWA 187171, Kirkland et al., in prep.). The youngest late Pitjantjatjara Supersuite granite is from the Mamutjarra Zone, and yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.). Thus, the age range for the late Pitjantjatjara Supersuite within the west Musgrave Province is from 1188 ± 4 Ma to 1148 ± 6 Ma (i.e. 1190–1150 Ma).

However, five samples dated from the Mirturtu Suite (GSWA 180300, 180262, 180270, 180256, and 174538) show a much narrower range of intrusive ages, extending from 1183 ± 9 to 1176 ± 6 Ma (Bodorkos et al., 2006a–d, 2008).

A SHRIMP U–Pb zircon age of 570 ± 25 Ma, obtained from the rim of a zircon within a sample of this migmatitic mylonite (GSWA 155737: BATES, MGA 486710E 7146062N), indicated that the mylonitic deformation of these rocks occurred at least during the Petermann Orogeny (Walker-Hallam, 2006). However, significant mylonitic deformation cannot be ruled out prior to that event (e.g. during the latest Musgrave Orogeny and during the Giles Event).

References

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Pitjantjatjara Supersuite; subunit (P_-PJ-mg)

Legend narrative

Metagranite and gneiss

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

The Pitjantjatjara Supersuite (Edgoose et al., 2004; formerly the 'Kulgera Suite' of Major and Conor, 1993) incorporates all igneous rocks formed during the c. 1220 to 1150 Ma Musgrave Orogeny — the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. In the Walpa Pulka Zone and adjacent parts of the Tjuni Purlka Tectonic Zone, these rocks have been divided, based on age, into an early (P_-PJ1- in code notation; 1220–1200 Ma) and late (P_-PJ2-; 1190–1150 Ma) Pitjantjatjara Supersuite (Howard et al., 2006; Smithies et al., 2009, 2010). However, it should be noted that on a province-wide scale, granitic magmatism was more or less continuous throughout the Musgrave Orogeny. In this respect, the division between the older and younger group is somewhat arbitrary, but is retained here as a useful way of subdividing the supersuite.

There appears to be no significant difference between the early and late Pitjantjatjara Supersuite rocks in terms of deformation, metamorphic and primary mineralogy, and compositional range, although they are, as a group, compositionally distinct from the granites of all other supersuites within the west Musgrave Province (Smithies et al., 2010). In cases where the granites are inferred or known (for example, based on geochemistry) to belong to the Pitjantjatjara Supersuite, but cannot be reasonably allocated to either the early or late Pitjantjatjara Supersuite, the rocks remain unassigned (P_-PJ-mg). Most granites of the Pitjantjatjara Supersuite are metaluminous, K-rich, A-type granites.

Distribution

Rocks of the Pitjantjatjara Supersuite form a voluminous component found throughout the west Musgrave Province.

Lithology

Most rocks of the Pitjantjatjara Supersuite have been metamorphosed at granulite-facies conditions, and as such they range from statically recrystallized and unfoliated, to strongly foliated and mylonitized. The primary (protolith) mineralogy of most of the granites was an essentially anhydrous assemblage of quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, and biotite; although late hornblende locally rims pyroxene, becoming a significant component of the primary mafic mineralogy of the supersuite's more evolved granites. In addition, retrograde recrystallization is locally associated directly with foliation development, resulting in the partial- to near-complete alteration of pyroxene to hornblende, actinolite, and biotite. Garnet occurs in rocks north of the Mann Fault and east of the Fanny Fault, typically as fine-grained coronas that separate the mafic minerals, including orthopyroxene, from feldspars, and reflecting a high-pressure metamorphic assemblage exhumed during the Petermann Orogeny.

Granites of the Pitjantjatjara Supersuite can be broadly subdivided into three lithological groups. The first and most voluminous group typically ranges from granodiorite to syenogranite, although the full range is from monzodiorite to alkali-feldspar granite. Where primary igneous textures are preserved, this group commonly includes rounded rapakivi-textured feldspar phenocrysts up to 5 cm in diameter. Many of these rocks retain evidence of a primary orthopyroxene-bearing mineralogy, and on that basis can be classified as charnockites. This porphyritic granodiorite–syenogranite group dominates the Walpa Pulka Zone as large composite plutonic bodies, and also forms smaller plutons and dykes in the Tjuni Purlka Tectonic Zone. Within the Mamutjarra Zone these rocks are mostly restricted to dykes and minor intrusions, although they form a widespread but non-continuous collection of small intrusions in the northwest of the same zone (Finlayson and Cooper).

This first group of Pitjantjatjara Supersuite granites typically do not contain abundant enclaves, and despite other local evidence for mixing or mingling (e.g. dykes terminating in chains of lobate inclusions), there is no field evidence at the present level of exposure for significant physical interaction between individual granite intrusions, or between these and any other magma batches. Several broad intrusion styles are identified. Most exposures show significant variations in texture (from seriate to porphyritic to megacrystic) and grain size on a scale of a metre to many tens of metres, suggesting that the larger bodies are typically composite intrusions of numerous individual dykes and sills. Geochemical data show that individual intrusions, or collections of intrusions (forming individual granite suites), are either compositionally heterogeneous throughout, or else show a systematic compositional variation that parallels the northwest trend of major shear zones (Smithies et al., 2010).

The second group of Pitjantjatjara Supersuite granites is entirely restricted to the Tjuni Purlka Tectonic Zone, and comprises locally schlieric biotite–orthopyroxene leucogranites typically in the monzogranite to syenogranite compositional range. These form veins and sheets that cut and engulf earlier rocks of the Wirku Metamorphics and Wankanki Supersuite. Originally thought to be restricted to the late Pitjantjatjara Supersuite (P_-PJ2-mgsi, P_-PJ2-jmgs-mn), petrographically and geochemically identical rocks are also known from the early Pitjantjatjara Supersuite (P_-PJ1-mgmu), and it is now clear that this group of rocks formed throughout much of the Musgrave Orogeny (Smithies et al., 2010).

The third group of Pitjantjatjara Supersuite granites consists of a granofelsic and schlieric leucogranite unit. The protoliths to these rocks formed sheets and veins that intruded and engulfed all earlier lithologies, including other members of the supersuite and older paragneisses, within the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. They are interpreted as locally derived anatectic melts. Like the schlieric biotite–orthopyroxene leucogranites, the granofelsic and schlieric leucogranite unit was originally thought to be restricted to the late Pitjantjatjara Supersuite, but is now thought to have formed throughout much of the Musgrave Orogeny.

Geochemical data from both the Northern Territory (Edgoose et al., 2004) and Western Australia (Smithies et al., 2010) indicate that the felsic rocks (apart from the felsic granofels) of the early and late Pitjantjatjara Supersuite to be compositionally uniform across the entire Musgrave Province. Granites of the Pitjantjatjara Supersuite are silicic (57–78 wt% SiO_2) and K-rich rocks with high total alkali content ($Na_2O + K_2O$ to 10.3 wt%) and high incompatible trace element concentrations, features consistent with an A-type classification. Smithies et al. (2010) subdivided the granites of the Pitjantjatjara Supersuite into several geochemically coherent suites. Of these, only the Mirturtu Monzogranite (P_-PJ2mt-) of the late Pitjantjatjara Supersuite is distinguishable on the current 1:100 000 series geological maps (BATES).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	
Lithname	Metagranitic rock	mg
Rock code		**P_-PJ-mg**

Geochronology

P_-PJ-mg	*Maximum*	*Minimum*
Age (Ma)	1219 ± 12	1148 ± 6
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos et al., 2008	Kirkland et al., in prep.

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgmu)

Legend narrative

Weakly to strongly foliated, porphyritic leucocratic metamonzogranite; contains clinopyroxene, orthopyroxene, and hornblende; K-feldspar phenocrysts up to 2 cm; locally mylonitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This porphyritic leucocratic metamonzogranite unit forms a large northwest-trending lens in the Tjuni Purlka Tectonic Zone, on the northeast side of the Bell Rock Range (BELL ROCK). It is intruded by leucocratic veins presumably of similar age to the granite, and interleaved with an older felsic granulite that likely belongs to the Wankanki Supersuite (P_-WN-xmg-mgi). This medium- to coarse-grained, weakly foliated, rapakivi granite contains variable amounts of mantled perthite phenocrysts in a quartzofeldspathic groundmass. Green hornblende locally forms along mylonitic planes. Pyroxene is generally absent, but accessory fluorite is locally present.

Distribution

This porphyritic leucocratic metamonzogranite unit is exposed as a 7 km long hill, parallel to the northeast side of the Bell Rock Range (BELL ROCK), where it forms a large northwest-trending lens in the Tjuni Purlka Tectonic Zone. There, the unit is associated with thin layers of granite belonging to granite of the late Pitjantjatjara Supersuite (P_-PJ2-mgsi). Just to the northeast on the southwest face of Mount West, it forms two, 100 m wide veins, in gneiss belonging to the Wankanki Supersuite (P_-WN-xmg-mgi). The western contact between this unit and the Bell Rock intrusion is mylonitic. In the Tjuni Purlka Tectonic Zone, this granite is intruded by leucocratic veins presumably of similar age as the granite, and interleaved with an older felsic granulite that likely belongs to the Wankanki Supersuite (P_-WN-xmgn-mg). Farther west, in the Mamutjarra Zone, this granite forms a poorly exposed basement high surrounded by Mummawarrawarra Basalt.

Lithology

This unit comprises medium- to coarse- grained, weakly foliated, rapakivi granite, with variable amounts (5–30%) of euhedral to ovoid, mantled, K-feldspar phenocrysts up to 2 cm in size, set in a quartzofeldspathic groundmass. More deformed varieties can have a mottled appearance. Dynamically recrystallized mylonitic fabrics occur locally, with less mylonitic domains showing well-developed mortar textures. Quartz grains (20–30%) show undulose extinction. Perthite is in higher abundance than plagioclase, and locally forms anhedral phenocrysts up to 1 cm in size; locally, euhedral hornblende crystals are isolated within these phenocrysts. Green hornblende (5–15%) locally forms clots up to 1.5 cm in size, or larger crystals, in mylonitic planes, and typically develops a thin rim of brown biotite, or else biotite and opaque minerals. Pyroxene is generally absent. Epidote and chlorite alteration can be seen along brittle fractures. Accessory fluorite can be found locally.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-PJ-mgmu**

Geochronology

P_-PJ-mgmu	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This unit has not been dated directly, but it is inferred to form part of the well-dated Mesoproterozoic Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgr)

Legend narrative

Hornblende–biotite–pyroxene metasyenogranite and metamonzogranite; mafic minerals with garnet coronas; seriate to porphyritic; rounded K-feldspar phenocrysts up to 5 cm; commonly with rapakivi texture

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This seriate to porphyritic metasyenogranite unit is part of the Pitjantjatjara Supersuite, which intruded other members of the supersuite and older paragneisses, throughout the northeastern part of the Walpa Pulka Zone (on Bates) where it is now exposed as small tor-covered hills up to 1 km^2 in size. Outcrop is typically composite or inhomogeneous, comprising two or more textural or mineralogical variants intruding as a series of 5–10 m scale sheets, locally showing mixing or mingling relationships with other units of the Pitjantjatjara Supersuite. A metamorphic mineralogy, including garnet coronas formed around mafic minerals, reflects recrystallization at the high-pressure granulite facies, probably during the Petermann Orogeny.

Distribution

Rocks of this seriate to porphyritic metasyenogranite unit are found in the Walpa Pulka Zone, mainly in an area approximately 2–5 km southeast of Mount Daisy Bates and also approximately 10 km southwest of Mount Gosse (Bates).

Lithology

Outcrop of this seriate to porphyritic syenogranite unit is typically composite or inhomogeneous, comprising two or more textural or mineralogical variants intruding as a series of 5–10 m scale sheets. The rocks range from medium to coarse grained, and have a mottled texture produced through the weak to moderate deformation of large mafic clots that generally consist of hornblende (?retrogressed clinopyroxene), but also include clinopyroxene in less K-feldspar rich rocks (monzogranites). In general, there appears to be a complete transition between seriate textured clinopyroxene-bearing monzogranites and K-feldspar porphyritic, hornblende-bearing syenogranites. There seems to be considerable overlap between this unit and other seriate to porphyritic granitic rock units of the Pitjantjatjara Supersuite, including components of the Mirturtu Monzogranite suite (P_-PJ2mt-).

K-feldspar phenocrysts are predominantly perthite, and may comprise up to 40% of the rock. In some rocks, there is a more or less continuous range of K-feldspar crystal sizes, including phenocrysts up to 5 cm in size. Elsewhere, the grain size population appears to be either singular or bimodal; in either case, the large phenocryst are typically more rounded, and are commonly mantled by a thin (up to 3 mm) rim of plagioclase (i.e. rapakivi texture).

A weak to moderate recrystallization of the rocks, with domains where quartz and feldspar grain boundaries approach a polygonal texture, can be seen at the thin-section scale. Despite this, hornblende, which forms up to 15% of the mode, preserves a ragged habit, forming large individual crystals or aggregate clots up to 1 cm in size. Pyroxene grains form the cores to hornblendes and are more abundant in rocks of monzogranitic compositions than in syenogranites. Biotite forms as a secondary or late-crystallizing mineral, rimming hornblende and opaque minerals (ilmenite and magnetite), or else forming fine-grained quartz–biotite aggregates. These aggregates possibly represent xenolithic material; alternatively, they may represent a retrograde recrystallization product of orthopyroxene (in contact with feldspar), which seems to be the case for similar aggregates found in less evolved granitic rocks elsewhere in the Pitjantjatjara Supersuite. Garnet typically forms as fine, sugary coronas that separate the hornblende and opaque minerals from feldspars. The metamorphic mineralogy indicates granulite-facies peak conditions.

These rocks are cut by typically east-trending mylonitic and blastomylonitic zones, with the more strongly mylonitized examples subsequently forming the preferential sites of migmatization, most likely during the Petermann Orogeny. At a small outcrop approximately 5.2 km to the southeast of Mount Daisy Bates (Bates, MGA 485333E 7148885N), the seriate to porphyritic syenogranite unit is intruded by a series of generally northwest- and northeast-trending dykes of fine to medium grained, grey, seriate to porphyritic monzogranite. These dykes were also the preferential sites of subsequently mylonite development, and of syn- to post-deformational migmatization.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
Rock code		**P_-PJ-mgr**

Geochronology

P_-PJ-mgr	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This unit has not been directly dated, but is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the Bates region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgrb)

Legend narrative

Weakly to strongly foliated, fine- to medium-grained biotite–hornblende metasyenogranite; typically seriate textured, locally with microcline phenocrysts up to 3 cm; locally abundant xenoliths of felsic gneiss

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This metamorphosed biotite–hornblende syenogranite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, has intruded other members of that supersuite plus rocks of the Wankanki Supersuite and older paragneisses of the Wirku Metamorphics, in the Mamutjarra Zone of southwestern BLACKSTONE. The unit is typically fine to medium grained, and leucocratic, with up to 10% mafic minerals — mainly brown biotite or hornblende. It is seriate-textured to porphyritic, has perthite phenocrysts up to 3 cm in size, and is weakly to strongly foliated. Although this unit has not been directly dated, it locally forms northeast-trending dykes that, elsewhere in this region, reflect post-tectonic granite intrusions formed along the axial planes of folds developed before c. 1200 Ma.

Distribution

Small outcrops of this metamorphosed biotite–hornblende syenogranite unit are interpreted to represent a large (7–8 km diameter), subrounded, weakly magnetized zone identified using aeromagnetic (TMI) data in the central part of BLACKSTONE (e.g. at WAROX site RHSMUG001210: MGA 412134E 7085426N). The aeromagnetic anomaly is interpreted to be a pluton that intrudes earlier rocks of the Wankanki Supergroup and Wirku Metamorphics. These metasyenogranites also form locally northeast-trending dykes that, elsewhere in this region, variably reflect syn- to post-tectonic granite intrusions formed along the axial planes of folds.

Lithology

This metamorphosed biotite–hornblende syenogranite unit typically comprises fine- to medium-grained, and leucocratic granites, containing up to 10% mafic minerals. The rocks are seriate-textured to porphyritic, have perthite phenocrysts up to 3 cm in size, and are weakly to strongly foliated, with local schlieric banding.

The texture of these rocks is mainly granoblastic polygonal, with locally well-developed mortar textures. Quartz is strongly recrystallized and undulose. Feldspar is mainly represented by K-feldspar, with larger grains (phenocrysts) of perthite having an outer zone of microcline microperthite, and small grains being typically microcline microperthite. Feldspar–feldspar and feldspar–quartz boundaries are typically scalloped, and myrmekitic intergrowths are common. The main mafic minerals are late, subhedral brown biotite, and secondary hornblende. The latter can be either green or brown, is subhedral to anhedral, and may form crystals that partially enclose feldspar and quartz, or else form deformed aggregates that include biotite and opaque minerals and occur along quartz and/or feldspar grains. Subhedral green alteration patches are possibly after hypersthene. Late epidote and fluorite alteration is locally associated with biotite.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Biotite	b
Rock code		**P_-PJ-mgrb**

Contact relationships

This metamorphosed syenogranite typically contains abundant inclusions, rafts, and panels of gneissic country rock (Wirku Metamorphics and Wankanki Supersuite), and locally forms discrete dykes (e.g. WAROX site RHSMUG001235) that intrude along the northeast-trending fracture planes that are axial planar to folding in the gneissic country rock. Field relationships suggest that the intrusion of these rocks was into country rocks already at a high-metamorphic grade, and occurred after the formation of large-scale, northeast-trending folds developed within the country rocks.

Geochronology

P_-PJ-mgrb	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This syenogranite unit has not been directly dated, but it is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

Within the southwestern corner of BLACKSTONE (Mamutjarra Zone), granite related to the Pitjantjatjara Supersuite locally forms thin, northeast-trending outcrops (too small to show at map scale) characteristic of the structural setting of some of the present metamorphosed syenogranite unit exposures — i.e. axial planar to the large-scale folds developed within the gneissic country rock. Three of these granites have been dated: GSWA 184146 (MGA 408788E 7081514N) yielded a magmatic crystallization age of 1201 ± 6 Ma (Kirkland et al., 2009a); GSWA 185610 (MGA 405758E 7083884N) yielded a magmatic crystallization age of 1199 ± 5 Ma (Kirkland et al., 2009b); and GSWA 184147 (MGA 408863E 7081534N) yielded a magmatic crystallization age of 1164 ± 14 Ma (Kirkland et al., 2009c). There is no correlation between the age of the rock and the intensity of deformation in these dykes, suggesting that folding significantly pre-dates the intrusion of granites into axial planar fractures, and therefore prior to c. 1201 Ma. Nevertheless, include biotite-bearing syenogranitic rocks are found in intrusions of both ages, and it is not clear to which event (c. 1165 or 1200 Ma) this metamorphosed syenogranite unit relates.

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgrf)

Legend narrative

Porphyritic metasyenogranite to metamonzogranite; abundant euhedral K-feldspar phenocrysts up to 2 cm; locally with relict flow texture

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This porphyritic flow-textured metasyenogranite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, has intruded other members of that supersuite plus older paragneisses (Wirku Metamorphics) in the Walpa Pulka Zone to the north of the Mann Fault. This is a minor unit that forms a single mappable body (an east-trending dyke), on BATES, but also forms smaller dykes, xenoliths in other units, and components of mixed lithological units. A metamorphic mineralogy, including garnet coronas formed around mafic minerals, reflects recrystallization at the high-pressure granulite facies, probably during the Petermann Orogeny.

Distribution

This porphyritic flow-textured metasyenogranite unit is minor unit that forms a single mappable body (an east-trending dyke), in the Walpa Pulka Zone on BATES (at MGA 485287E 7139294N). However, this rock type also forms smaller dykes, xenoliths in other units, and components of mixed lithological units (including magma mingled units), at a number of localities throughout the southeastern part of BATES.

Lithology

This metasyenogranite unit is characterized by preferentially aligned, lath-shaped K-feldspar phenocrysts, typically ~2 cm long and 0.5 cm wide, which comprise up to 40% of the rock. In thin section, the rock generally preserves an igneous texture. The lath-shaped K-feldspar (perthite) phenocrysts overgrow groundmass quartz and plagioclase, indicating that the flow alignment of those phenocrysts must have happened at a relatively advanced stage of magma crystallization. Hornblende is the main mafic mineral, forming <10% of the mode, mainly as a late intergranular phase; no pyroxene is observed. Biotite is a secondary or late-crystallizing mineral rimming hornblende and opaque minerals (ilmenite and magnetite) or else forming fine-grained quartz–biotite aggregates. These aggregates possibly represent xenolithic material; alternatively, they are a retrograde recrystallization product of orthopyroxene (in contact with feldspar), as seems to be the case for similar aggregates found in less evolved granitic rocks of the Pitjantjatjara Supersuite. Garnet typically forms as fine, sugary coronas that separate the hornblende and opaque minerals from feldspars. The metamorphic mineralogy indicates formation at granulite-facies peak conditions.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Felsic/feldspathic; K-metasomatized	f
Rock code		**P_-PJ-mgrf**

Geochronology

P_-PJ-mgrf	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

The porphyritic flow-textured metasyenogranite has not been directly dated, but is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Walker-Hallam, A 2009, Complex strain in mylonites from the western Musgraves, north of the Mann Fault, Western Australia: Geological Survey of Western Australia, Record 2009/14, 33p.

Pitjantjatjara Supersuite; subunit (P_-PJ-mgrl)

Legend narrative

Moderately foliated, medium- to coarse-grained leucocratic syenogranite; irregular quartz blebs up to 2 cm in a feldspathic groundmass

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This leucocratic metamorphosed syenogranite unit forms a variably transposed anatectic leucosome in rocks of the Wirku Metamorphics and in volcanic rock units of the Wankanki Supersuite. It traces an earlier fold generation to the Mount Aloysius antiform (northwest BELL ROCK), and underlies the majority of the Cohn Hill region (COOPER), where it is garnetiferous, often silicified, uniformly mylonitic, and preferentially exposed compared to the pelitic paleosomes that accompany it. The syenogranite only forms an in situ leucosome in very pelitic units of the Wirku Metamorphics. Elsewhere, it has likely been lit-par-lit injected parallel or subparallel to sedimentary or volcanic layering. Within the Tjuni Purlka Tectonic Zone, the syenogranite contains large quartz lenticels and rare orthopyroxene – garnet – opaque minerals – biotite lamellae, in a dynamically recrystallized quartzofeldspathic groundmass. A crystallization age of 1193 ± 5 Ma obtained for this unit was determined from Mount Aloysius; this age correlates well with the peak metamorphic ages of zircon rims from other samples in the area. Despite this, it is unclear if the age obtained is characteristic of the unit in general.

Distribution

This leucocratic metamorphosed syenogranite unit is the anatectic leucosome of the Wirku Metamorphics, which is also found in volcanic units of the Wankanki Supersuite. It often forms ridges when mylonitized or silicified. It underlies the majority of the 60 km^2 Cohn Hill region of the Mamutjarra Zone (COOPER), where it is garnetiferous, often silicified, uniformly mylonitic, and is preferentially exposed when compared to associated pelitic paleosomes. On Mount Aloysius in the Tjuni Purlka Tectonic Zone (BELL ROCK), the unit forms layers, up to 300 m wide, tracing an earlier fold generation of the Mount Aloysius antiform. Elsewhere in the Tjuni Purlka Tectonic Zone, the unit forms variably transposed centimetre- to metre-scale layers in the following units (in order of abundance): P_-WM-mlig, P_-WM-mlil, P_-WM-mhig, P_-WN-xmfi-ms, P_-WM-xmhg-mf, P_-WM-xmt-mh, P_-WM-mtni, P_-WM-xmlg-mr, and P_-WM-mroi. In the Latitude Hills area of the Tjuni Purlka Tectonic Zone (BELL ROCK), this syenogranite forms variably transposed centimetre- to metre-scale layers in units P_-WM-mhni and P_-WM-mhnl; in the Cohn Hill area it forms variably transposed centimetre- to metre-scale layers in units P_-WM-mlgn, P_-WM-mlgl, and to a lesser degree, P_-WM-mli.

Lithology

Leucocratic metamorphosed syenogranite is an anatectic leucosomal component found in several units of the Wirku Metamorphics, and also in volcanic rock units of the Wankanki Supersuite. It only occurs as an in situ leucosome in the very pelitic units of the Wirku Metamorphics, specifically P_-WM-mlig, P_-WM-mlil, P_-WM-mhig, P_-WM-mlgn, and P_-WM-mhni. In these cases, it is petrographically, compositionally, and texturally indistinguishable from the Wirku Metamorphics diatexite unit, P_-WM-mlig. Elsewhere, it has likely been lit-par-lit injected parallel or subparallel to sedimentary or volcanic layering in rocks of Wirku Metamorphics and the Wankanki Supersuite, derived from an external area undergoing high-grade metamorphism. This granite is quartz-rich (up to 50%), and ranges in composition from syenogranite to monzogranite, being more typically the former, as most of its paleosome sources were biotite-poor with more plagioclase than K-feldspar. The composition is expressed as a medium- to fine-grained, moderately foliated to mylonitic arrangement of dynamically recrystallized quartz (always undulatory and typically sutured), plagioclase, and K-feldspar. Less deformed varieties display interlocking textures between the felsic components. In rare cases, the granite may be pegmatitic. The granite is always very leucocratic, with only trace opaque minerals rimmed by biotite, but rare 1 cm wide laminae may contain up to 5% orthopyroxene, 2% garnet, 2% opaque minerals, and 1% brown biotite. Locally, the rock presents a spotted appearance caused in the Cohn Hill area (Mamutjarra Zone) by subhedral, inclusion-free, pink, syn- to post-tectonic garnets up to 1 cm in size, and by grey, irregular quartz lenses, up to 2 cm, in the Tjuni Purlka Tectonic Zone.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Leucocratic	l
Rock code		**P_-PJ-mgrl**

Geochronology

P_-PJ-mgrl	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This leucocratic metamorphosed syenogranite unit (P_-PJ-mgrl) has been sampled for geochronology on the eastern face of Mount Aloysius, in the Tjuni Purlka Tectonic Zone on Bell Rock (GSWA 187113), and on the north face of Minnie Hill in the Cohn Hill area of the Mamutjarra Zone on Cooper (GSWA 194379). Sample 187113 yielded a magmatic crystallization age of 1193 ± 5 Ma (Kirkland et al., 2009), which correlates well with peak metamorphic ages of zircon rims from other samples in the area. Sample 194379 (Kirkland et al., 2011) contained a substantial zircon component inherited from the paleosome. Homogenous individual grains and rims were interpreted to represent the magmatic crystallization age of the granite. Unfortunately, all have undergone partial- to near-complete Pb loss during a metamorphic overprint, yielding a spread of concordant ages from 1273 to 1229 Ma (Kirkland et al., 2011). This is typical of all geochronological samples from the Cohn Hill area, and is indicative of ultrahigh-temperature metamorphism during the time of this granite's emplacement. Smithies et al. (2010) suggested that ultrahigh-temperature metamorphism extended throughout the entire Musgrave Orogeny, either continuously or as a punctuated process. Hence, the 1193 ± 5 Ma date from GSWA 187113 likely dates only one episode of syenogranite formation, and the effective maximum and minimum ages for this unit are the same as those of the Musgrave Orogeny itself.

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgro)

Legend narrative

Weakly foliated, fine- to medium-grained biotite–orthopyroxene metasyenogranite

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This weakly foliated, metamorphosed, biotite–orthopyroxene syenogranite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, has intruded other members of that supersuite plus rocks of the Wankanki Supersuite and older paragneisses of the Wirku Metamorphics, within the Mamutjarra Zone in southwestern BLACKSTONE. This unit comprises fine- to medium-grained, massive to weakly foliated, highly leucocratic syenogranite with <5% mafic minerals. It outcrops as linear intrusions, typically in zones of migmatization, which are interpreted to be accumulations of migmatitic melt fractions. The lack of a strong tectonic fabric suggests that these rocks formed after the development of major, pre-c. 1200 Ma, northeast-trending folds.

Distribution

This is a minor unit of the Pitjantjatjara Supersuite that outcrops in the southwestern corner of BLACKSTONE, typically forming linear intrusions.

Lithology

This metasyenogranite unit comprises fine- to medium-grained, massive to weakly foliated, highly leucocratic metasyenogranite with <5% mafic minerals. The rocks typically contain abundant angular to rounded country-rock xenoliths, and are locally schlieric. They typically outcrop in zones of migmatization, and are interpreted to be accumulations of migmatitic melt fractions that have wholly to partially rid themselves of restitic components.

The rocks typically have a seriate and allotriomorphic granular texture. Quartz (20–25%) is strongly undulose. Feldspar is almost all microcline; plagioclase is rare and locally antiperthitic. Myrmekitic intergrowths are common. Biotite is the main mafic mineral, and is scattered throughout as subhedral flakes. Iron-rich orthopyroxene (?ferrohypersthene) forms anhedral remnants of (once) larger grains, is intergrown with biotite flakes, and is typically surrounded by biotite and quartz–biotite symplectites.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Orthopyroxene	o
Rock code		**P_-PJ-mgro**

Geochronology

P_-PJ-mgro	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This metasyenogranite unit has not been directly dated, but is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009). The lack of a strong tectonic fabric in this weakly foliated, metamorphosed, biotite–orthopyroxene syenogranite unit (P_-PJ-mgro) suggests that these rocks formed after major, pre- c. 1200 Ma, northeast-trending folds (see P_-PJ-mgrb).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgsy)

Legend narrative

Mylonitic and blastomylonitic, seriate to porphyritic granitic rock

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This deformed metagranite unit represents strongly mylonitized outcrops, mainly of unassigned seriate to porphyritic granitic rocks belonging to the Mesoproterozoic Pitjantjatjara Supersuite, intruded into older paragneisses (Wirku Metamorphics) and metagranites (Wankanki Supersuite), mainly in the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone (mainly on Bates and Holt, but also on Blackstone and Bell Rock). To the north of the Mann Fault (Walpa Pulka Zone, Bates), the mylonites are garnetiferous, and the relationships between garnet porphyroblasts and biotite suggest that mylonitic deformation occurred before, both during and after high-grade metamorphism. Metamorphism in this region is presumed to relate to the Petermann Orogeny, but some of the mylonitic deformation might also relate to an earlier deformation event.

Distribution

This deformed metagranite unit represents strongly mylonitized outcrops, mainly of unassigned seriate to porphyritic granitic rocks belonging to the Mesoproterozoic Pitjantjatjara Supersuite, found predominantly in the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone (mainly on Bates and Holt, but also on Blackstone and Bell Rock).

Lithology

This mylonitic seriate to porphyritic granite ranges from very fine to medium grained. Where the rocks are strongly mylonitized, all mafic minerals are entirely recrystallized to a strongly aligned assemblage comprising combinations of clinopyroxene, green hornblende, garnet, and biotite. Textures are typically granoblastic elongate, indicating post-mylonitic recrystallization to form blastomylonites, most likely at upper amphibolite to granulite facies. Rarer examples of primary mylonitic fabrics are also found, these and possibly indicate a later phase of mylonite formation. Ribbon quartz and elongate trains of polygonal mafic aggregate crystals are common. In many samples, strongly elongate monomineralic polygonal aggregates of feldspar (typically K-feldspar > plagioclase) indicate an originally porphyritic protolith.

To the north of the Mann Fault (Walpa Pulka Zone, Bates), the mylonites are garnetiferous. Fine-grained garnet coronas surrounding earlier mafic minerals have been deformed, and a later stage of garnet growth produces discrete porphyroblasts up to 5mm in size. In some cases, these porphyroblasts deflect a mylonitic foliation defined by the alignment of biotite and hornblende, and are likely to reflect syn-mylonitic growth. In other cases (e.g. GSWA 180262: Bates, MGA 488835E 7141487N), the garnet porphyroblasts have grown at a post-mylonitic stage and enclose oriented biotite crystals. These contrasting relationships, if related to a single event, suggest that peak metamorphic conditions outlasted mylonite development. Alternatively, there may have been two distinct periods of mylonitic deformation.

Approximately 2.5 km southeast of Mount Daisy Bates (i.e. at Bates, MGA 482761E 7149680N), an east-trending mylonitic zone in seriate to porphyritic granitic rocks has not been strongly recrystallized, and shows only a weakly granoblastic quartzofeldspathic mineralogy. Strong alignment of biotite in this rock (sample GSWA 174708) post-dates the crystallization of anhedral green hornblende and garnet crystals, but is pre- to syn-tectonic with respect to the crystallization of subhedral prismatic epidote (i.e. greenschist facies mylonite, compared to the upper amphibolite facies conditions inferred for development of the majority of similarly oriented mylonites on Bates).

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic schist	s
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-PJ-mgsy**

Geochronology

P_-PJ-mgsy	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This unit has not been directly dated, but is inferred to form part of the well-dated Mesoproterozoic Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the Bates region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgml)

Legend narrative

Massive, fine- to medium-grained, leucocratic metamonzogranite; typically equigranular

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This leucocratic metamonzogranite unit occurs as a fault-bounded sliver in the Tjuni Purlka Tectonic Zone, within the western part of Holt. It is an undeformed, pyroxene-bearing, fine- to medium-grained, leucocratic metamonzogranite.

Distribution

This very minor leucocratic metamonzogranite unit occurs in the Tjuni Purlka Tectonic Zone within the western part of Holt, where it is interpreted on aeromagnetic (TMI) data to form a northwest-trending and steeply dipping sliver of bedrock, up to 6.5 km long and 1 km wide, fault bounded against rocks of the younger Kunmarnara Group. Within that area, the only outcrop is a small boulder 1 m across.

Lithology

This leucocratic metamonzogranite is a fine- to medium-grained rock composed of undeformed quartz, plagioclase, and K-feldspar forming an allotriomorphic to hypidiomorphic texture, with 3% interstitial mafic minerals comprising 2% clinopyroxene and 1% orthopyroxene.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Leucocratic	l
Rock code		**P_-PJ-mgml**

Geochronology

P_-PJ-mgml	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This unit has not been directly dated, but is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the Bates region in the Walpa Pulka Zone (Walker-Hallam, 2009).

References

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgmy)

Legend narrative

Mylonitic, medium-grained, porphyritic metamonzogranite; K-feldspar phenocrysts up to 2 cm

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mylonitic metamonzogranite unit forms both the central zone of the Mann Fault (BATES) and a folded shear zone south of Mount Aloysius (BELL ROCK); at the latter locality, the unit is the mylonitic equivalent of P_-PJ1-mgmu. In this unit, K-feldspar phenocrysts are still visible, but pyroxene has been retrogressively recrystallized to amphibole and biotite. The quartzofeldspathic matrix is typically dynamically recrystallized. At higher strain, the rock becomes fine-grained and contains rare garnet. The protolith to one of these mylonites crystallized at 1200 ± 5 Ma, and was metamorphosed at 1180 ± 7 Ma, although it is most likely that mylonitic deformation occurred at many stages throughout the Musgrave Orogeny, and that the unit protolith includes several ages of Pitjantjatjara Supersuite granites.

Distribution

This mylonitic unit forms the 2 km wide central zone of the Mann Fault, which strikes eastwards along the southern part of BATES, extending from the Western Australia border to the western edge of BATES. It is best exposed on a large, 3 km long hill north of Mount Aloysius (BELL ROCK). South of Mount Aloysius, it forms a 1 km wide shear zone that has been folded into a southwest-vergent, northwest-plunging, reclined synform. Around Mount Aloysius, this unit is interpreted as the strongly deformed equivalent of porphyritic metamonzogranite unit (P_-PJ1-mgmu) that formed during the early stages of the Musgrave Orogeny.

Lithology

K-feldspar phenocrysts are still visible in this mylonitic metamonzogranite unit, but pyroxene has been retrogressively metamorphosed to amphibole and biotite. The quartzofeldspathic matrix is typically dynamically recrystallized. In local mylonitic C–S fabrics, C planes are typically formed by quartz and biotite, whereas biotite alone forms S planes. In areas of higher strain, the rock becomes an ultramylonite, characterized by <1 cm wide felsic layers separated by 1 mm lamellae containing relatively more biotite, amphibole, and trace garnet.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metamonzogranite	m
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-PJ-mgmy**

Geochronology

P_-PJ-mgmy	*Maximum*	*Minimum*
Age (Ma)	1220	565 ± 24
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Isotopic
References	Smithies et al., 2009, 2010	Raimondo et al., 2009

GSWA 185339, from the western Champs de Mars area (along the Hinckley Fault) of the Tjuni Purlka Tectonic Zone (BELL ROCK), belongs to the present mylonitic metamonzogranite unit (P_-PJ-mgmy) and is a mylonitic version of monzogranite formed during the early stages of the Musgrave Orogeny (in this case, P_-PJ1-mgmu). Zircons from this sample yielded a magmatic crystallization age of 1200 ± 5 Ma, and a metamorphic crystallization age of 1180 ± 7 Ma (Kirkland et al., 2009). However, mylonitization of this unit appears to have occurred more than once after emplacement of the protolith, and likely several times during the Musgrave Orogeny itself. The latest stage of mylonitization along the Mann Fault occurred during the 540–590 Ma Petermann Orogeny (Raimondo et al., 2009), and as such the inclusion of some rocks within this unit might be based on fabrics developed much later than the Musgrave Orogeny.

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgnu)

Legend narrative

Granitic gneiss; weakly to moderately banded; typically augen-bearing; locally mylonitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This augen-bearing granitic gneiss unit is restricted to the Walpa Pulka Zone, where it is typically found either near, or in contact with, other rocks of the Mesoproterozoic Pitjantjatjara Supersuite in the southeastern corner of BATES. The gneiss is strongly foliated, locally banded and laminated, and likely blastomylonitic. Most of these rocks are interpreted to belong to the early part of the Pitjantjatjara Supersuite, but many may in fact be part of the late Pitjantjatjara Supersuite.

Distribution

This augen-bearing granitic gneiss unit is restricted to part of the Walpa Pulka Zone in the southeastern corner of BATES, and is typically, though not invariably, found either near, or in contact with, other rocks of the Pitjantjatjara Supersuite.

Lithology

In some outcrops, the augen-bearing granitic gneiss is banded on a 20–100 cm scale, with alternating bands defined primarily by changes in either or both the proportions of augens or groundmass grain size. Laminated varieties also occur (e.g. BATES, MGA 490604E 7133564N), and comprise a fine-grained rock with millimetre-scale banding, and rare to moderately common K-feldspar augens, up to 2 cm in size, typically wrapped by the layering. Many of these outcrops are likely to be blastomylonitic. An outcrop on the northern side of Mount Gosse (around BATES, MGA 491804E 7140885N), comprises alternating interleaves of the granitic gneiss and of garnet-porphyroblastic, fine- to medium-grained felsic gneiss. It is not clear whether the fine- to medium-grained felsic gneiss is a blastomylonitic version of this augen-bearing granitic gneiss, or elongate xenoliths of an earlier felsic gneiss.

The groundmass to this augen-bearing granitic gneiss is typically medium-grained, although the well-laminated rocks are characteristically fine-grained. In thin section, the rocks have a blastomylonitic, granoblastic elongate fabric. K-feldspar (perthite) augens form 2–40% of the rock, and range in size up to 3 cm, with rare augens to 5 cm in size. In thin section, augens are typically preserved as elongate, monomineralic polygonal aggregates of feldspar. Mafic minerals typically account for about 10–15% of the rocks, but may form up to 25% of the mode. Green hornblende is the most common, typically forming elongate polygonal aggregates that define the foliation and wrap around the augens. Highly elongate mafic domains (originally large mafic crystals, or mafic aggregates or clots) include smaller subdomains of monomineralic polygonal aggregates of hornblende and garnet, suggesting an earlier, coarser-grained hornblende–garnet assemblage. Many polygonal aggregates of hornblende surround larger anhedral crystals of clinopyroxene. In general, the proportion of hornblende to pyroxene increases as the mylonitic fabric becomes stronger. Titanite and apatite are abundant accessory phases.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic gneiss	n
1st qualifier	–	
2nd qualifier	Augen	u
Rock code		**P_-PJ-mgnu**

Geochronology

P_-PJ-mgnu	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This augen-bearing granitic gneiss unit (P_-PJ-mgnu) is typically found near, or in contact with, other rocks of the Pitjantjatjara Supersuite, and locally appears to grade into rocks of the same supersuite (e.g. at BATES, MGA 497852E 7137866N). Elsewhere, the gneiss is cut by dykes also belonging to the Pitjantjatjara Supersuite. Consequently, it is likely that much of the augen-bearing granitic gneiss unit represents granite belonging to the early part of the Pitjantjatjara Supersuite; however, it is not clear that this applies to all outcrops of the gneiss.

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgny)

Legend narrative

Mylonitic granitic gneiss; typically augen-bearing

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mylonitic augen-bearing granitic gneiss unit is derived from the augen-bearing granitic gneiss unit (P_-PJ-mgnu), which is restricted to the Walpa Pulka Zone in the southeastern corner of BATES, where it is typically found near, or in contact with, other rocks of the Mesoproterozoic Pitjantjatjara Supersuite.

Distribution

This mylonitic augen-bearing granitic gneiss unit is derived from the augen-bearing granitic gneiss unit (P_-PJ-mgnu), which is restricted to the Walpa Pulka Zone in the southeastern corner of BATES.

Lithology

This mylonitic augen-bearing granitic gneiss unit is the mylonitic equivalent of the augen-bearing granitic gneiss (P_-PJ-mgnu) of the Pitjantjatjara Supersuite.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Granitic gneiss	n
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-PJ-mgny**

Geochronology

P_-PJ-mgny	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This mylonitic augen-bearing granitic gneiss unit (P_-PJ-mgny) and its undeformed equivalent (P_-PJ-mgnu) are typically found near, or in contact with, other rocks of the Pitjantjatjara Supersuite, and locally appear to grade into rocks of the same supersuite (e.g. at BATES, MGA 497852E 7137866N). Elsewhere, the mylonitic gneiss is cut by dykes also belonging to the Pitjantjatjara Supersuite. Consequently, it is likely that much of the augen-bearing granitic gneiss unit represents mylonitized granite belonging to the early part of the Pitjantjatjara Supersuite; however, it is not clear that this applies to all outcrops of this unit.

The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mgrs)

Legend narrative

Moderately to strongly foliated, porphyritic, pyroxene (–hornblende–biotite) metasyenogranite; typically leucocratic; abundant elongate K-feldspar phenocrysts up to 5 cm; locally garnetiferous

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This porphyritic pyroxene metasyenogranite unit forms a minor component of the Mesoproterozoic Pitjantjatjara Supersuite. It underlies a 5 km^2 area along the eastern flank of the Murray Range, approximately 1.5 km north of Ilurpa Bore (HOLT, MGA 442700E 7154600N) in the Tjuni Purlka Tectonic Zone. The rock is a moderately foliated to mylonitic, K-feldspar porphyritic syenogranite, with pyroxene, amphibole (retrograde pyroxene), and biotite as significant mafic components. Garnet occurs locally.

Distribution

Metasyenogranite of this unit forms a minor component of the Mesoproterozoic Pitjantjatjara Supersuite. It underlies a 5 km^2 area along the eastern flank of the Murray Range, approximately 1.5 km north of Ilurpa Bore (HOLT, MGA 442700E 7154600N) in the Tjuni Purlka Tectonic Zone. There, it forms a sheet that dips moderately to steeply to the north-northwest. The unit also forms a mylonitic sheet on hilltops to the north of Butterfly Hill (HOLT).

Lithology

This porphyritic pyroxene metasyenogranite unit comprises moderately foliated to mylonitic metasyenogranite, with elongate and locally rapakivi-textured K-feldspar phenocrysts up to 5 cm long. Its mafic mineralogy comprises biotite and pyroxene, the latter variably retrogressed to hornblende. Sugary garnet locally rims pyroxene. The rock is typically strongly sheared. It locally contains fine-grained gabbro xenoliths, which become black folia where the rock is sheared.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous felsic intrusive	mg
Lithname	Metasyenogranite	r
1st qualifier	–	
2nd qualifier	Schistose	s
Rock code		**P_-PJ-mgrs**

Contact relationships

This unit is intruded by olivine gabbros of the Warakurna Supersuite (P_-WKg1-ol).

Geochronology

P_-PJ-mgrs	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

This unit has not been directly dated, but is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-jmg-mh)

Legend narrative

Weakly to strongly foliated, medium- to coarse-grained, equigranular metaleucosyenogranite; locally contains rounded garnet up to 2 cm; rafts of metatexitic psammite and pelite

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This metamorphosed leucosyenogranite with metatexitic paragneiss rafts is the anatectic leucosomal portion of several Wirku Metamorphics units found on Mount Aloysius, in the Tjuni Purlka Tectonic Zone on Bell Rock. This unit differs from the leucocratic metamorphosed syenogranite unit (P_-PJ-mgrl) in having abundant rafts, screens, and inclusions of paleosome. It is a raft migmatite that bridges the gap between paleosome (Wirku Metamorphics; P_-WM-mlig) and pure anatectic leucosome (Pitjantjatjara Supersuite; P_-PJ-mgrl). Paleosome inclusions are dominantly metatexitic psammites and intermediate granulites, with minor pelites and felsic granulites of the Wirku Metamorphics and Wankanki Supersuite. The weakly to moderately foliated metamorphosed leucosyenogranite component is composed of quartz, plagioclase, and K-feldspar, all with interlocking grain boundaries. It is typically leucocratic (<5% orthopyroxene), with mafic components increasing towards the inclusions (i.e. more garnet near pelitic rafts, and more orthopyroxene near intermediate granulites). Locally, the unit contains irregular quartz lenticels up to 2 cm in size. One sample of this granite was emplaced at 1193 ± 5 Ma, which correlates well with the peak metamorphic ages of zircon rims obtained from other samples in the area. However, it is unclear if that age is representative of the unit in general.

Distribution

This mixed unit is confined to the Tjuni Purlka Tectonic Zone, with most mappable units found on Mount Aloysius in the northwest of Bell Rock. On the northern face of Mount Aloysius, the unit forms a 100 m wide layer that traces a tight to isoclinal fold generation earlier than the Mount Aloysius antiform. It covers an area of nearly 6 km^2 on the eastern side of Mount Aloysius, where it is best exposed. On the western border of Holt, an enclave, 2 km long and up to 400 m wide, of garnetiferous leucosome with abundant metatexitic rafts is poorly exposed and surrounded by Warakurna Supersuite leucogabbro. The leucosyenogranite is ubiquitous as centimetre- to metre-scale gneissic leucosomes throughout the Wirku Metamorphics in the Tjuni Purlka Tectonic Zone; however, in those instances it is not inclusion-rich, and has been mapped as the unit P_-PJ-mgrl.

Lithology

This metamorphosed leucosyenogranite with metatexitic paragneiss rafts unit is an anatectic leucosome of the Wirku Metamorphics, differing from the leucocratic metamorphosed syenogranite unit (P_-PJ-mgrl) only in that the former contains abundant 1–10 m wide rafts, screens, and inclusions of paleosome. It is essentially a raft migmatite or agmatite, transitional between a diatexitic, garnetiferous Wirku Metamorphics paleosome (P_-WM-mlig) and an anatectic leucosome (P_-PJ-mgrl). This granite is quartz-rich (up to 50%), and ranges in composition from syenogranite to monzogranite being more typically the former as most of its paleosome sources are biotite-poor and have more plagioclase than K-feldspar. The granite is typically medium- to fine-grained, and is weakly to moderately foliated. It is composed of blue-grey quartz, plagioclase, and K-feldspar, all with interlocking grain boundaries. The granite is locally coarse-grained, and may contain sparse K-feldspar phenocrysts, up to 2 cm in size. The granite is typically leucocratic (<5% orthopyroxene) with the amount of mafic components increasing near inclusions (i.e. more garnet near pelitic rafts, and more orthopyroxene near intermediate granulites). Where associated with pelitic units of the Wirku Metamorphics (such as P_-WM-mlig and P_-WM-mhig), the unit is compositionally and texturally indistinguishable from diatexite (P_-WM-mlig) microscopically, and contains rounded garnets up to 2 cm in size; elsewhere, garnets are typically absent. The rock locally presents a spotted appearance caused by blue-grey, irregular quartz lenticels, up to 2 cm in size.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Mixed or xenolith/ inclusion bearing	Xenolith/inclusion bearing	j
Rock type 1	Meta-igneous felsic intrusive	
Lithname 1	Metagranitic rock	mg
Rock type 2	Metasedimentary siliciclastic: psammite and pelite; interlayered	
Lithname 2	Psammite and pelite; interlayered	-mh
Rock code		**P_-PJ-jmg-mh**

Geochronology

P_-PJ-jmg-mh	*Maximum*	*Minimum*
Age (Ma)	1220	1150
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

The leucocratic syenogranite component of this unit was sampled for geochronology, on the eastern face of Mount Aloysius in the Tjuni Purlka Tectonic Zone (GSWA 187113). It yielded a magmatic crystallization age of 1193 ± 5 Ma (Kirkland et al., 2009), which correlates well with peak metamorphic ages of zircon rims obtained from other samples in the area. Smithies et al. (2010)

suggested that ultrahigh-temperature metamorphism continued throughout the entire Musgrave Orogeny, either continuously or as a punctuated process. Hence, the 1193 ± 5 Ma date from GSWA 187113 likely dates only one episode of syenogranite formation, and the effective maximum and minimum ages for this unit are those of the Musgrave Orogeny itself.

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Pitjantjatjara Supersuite; subunit (P_-PJ-xmwo-mg)

Legend narrative

Medium-grained, mesocratic to leucocratic clinopyroxene–orthopyroxene mafic granulite interleaved with weakly to strongly foliated and banded monzogranitic gneiss; locally migmatitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This mixed mafic granulite and monzogranitic gneiss unit is part of the Mesoproterozoic Pitjantjatjara Supersuite. It forms rare, scattered outcrops in the Walpa Pulka Zone, to the north of the Mann Fault on BATES. It likely represents a zone where mafic granulites (P_-PJ-mwol) derived from a c. 1190 Ma leucogabbroic protolith, have intruded and are extensively tectonically interleaved with felsic rocks formed during the early part of the Musgrave Orogeny.

Distribution

This mixed mafic granulite and monzogranitic gneiss unit (P_-PJ-xmwo-mg) outcrops in the Walpa Pulka Zone, to the north of the Mann Fault on BATES. The only mappable exposure is a northeast-trending outcrop found at the southern tip of Mount Fanny.

Lithology

This composite unit is interpreted to be comprised entirely of components derived from the Pitjantjatjara Supersuite, occurring primarily as alternating layer-parallel sheets. Mafic granulite dominates, and can be correlated with the medium-grained, leucocratic clinopyroxene–orthopyroxene mafic granulite (granulite after leucogabbro) unit (P_-mwol), or migmatitic clinopyroxene–garnet mafic granulite units (P_PJ-mwo, P_PJ-mwog). The protolith to the mafic granulite appears to have intruded the felsic component, which is generally a weakly to strongly foliated and banded, and locally migmatitic monzogranitic gneiss unit, although most contacts are now tectonic. On the southern tip of Mount Fanny (BATES, MGA 458067E 7146850N), migmatitic veins crosscut shallow, west-plunging fold hinges.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous mafic	mw
Lithname 1	Mafic granulite	o
Rock type 2	Meta-igneous felsic intrusive	
Lithname 2	Metagranitic rock	-mg
Rock code		**P_-PJ-xmwo-mg**

Geochronology

P_-PJ-xmwo-mg	*Maximum*	*Minimum*
Age (Ma)	1220	1190
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Bodorkos and Wingate, 2008

This mixed mafic granulite and monzogranitic gneiss unit has not been directly dated, although a sample of the leucocratic clinopyroxene–orthopyroxene mafic granulite (granulite after leucogabbro) unit (P_PJ-mwol; GSWA 174594: BATES, MGA 490563E 7133432N), which forms the mafic component of this mixed unit, has yielded a magmatic (protolith) age of 1190 ± 9 Ma (Bodorkos and Wingate, 2008). As a result, this date also represents a minimum age for this mixed gneissic unit.

The felsic component of the mixed gneiss is inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mwo)

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous mafic	mw
Lithname	Mafic granulite	o
Rock code		**P_-PJ-mwo**

Legend narrative

Fine- to medium-grained clinopyroxene–garnet mafic granulite; massive to weakly banded; locally shows mm-scale metamorphic mineralogical banding

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This clinopyroxene–garnet mafic granulite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, outcrops in the Walpa Pulka Zone, to the north of the Mann Fault on BATES. Dating of a leucocratic mafic granulite (P_PJ-mwol) elsewhere on BATES gives an age of c. 1190 Ma, an age consistent with the observation that the mafic Pitjantjatjara Supersuite units are mainly interleaved with the older felsic units of the supersuite.

Distribution

This clinopyroxene–garnet mafic granulite unit of the Mesoproterozoic Pitjantjatjara Supersuite forms very minor outcrop in the Walpa Pulka Zone, to the north of the Mann Fault on BATES. It forms several outcrops on the eastern side of Mount Fanny (central-western BATES), and another approximately 7 km south of Mount Gosse (southeastern BATES).

Lithology

This unit is typically a fine- to medium-grained, massive, mafic granulite with a polygonal granoblastic texture. The major mineral assemblage includes plagioclase (commonly antiperthitic), orthopyroxene, pale-green clinopyroxene, and brown hornblende; the brown hornblende pseudomorphs pyroxene. The minor mineral assemblage includes quartz (<5%), brown biotite, chlorite, garnet, and opaque minerals. The mafic mineral content varies 40–70%, and protolith compositions likely included gabbro, norite, and pyroxenite. Aggregates of polygonal crystals of orthopyroxene, clinopyroxene, and brown biotite are sometimes present. Exsolution of magnetite in pyroxene grains along cleavage planes and fractures is common. Fine-grained garnet aggregates form coronas separating the pyroxene and opaque minerals from feldspars.

Outcrop of the mafic granulite commonly defines dyke-like bodies. In the Mount Fanny area (central-western BATES) and to the north of Mount Daisy Bates (southwestern BATES), these bodies are oriented roughly north–south. To the south of Mount Gosse and east of Mount Fanny, the mafic granulite shows sharp intrusive contacts with a quartzofeldspathic granulitic paragneiss of the Wirku Metamorphics (P_-WM-mh).

Geochronology

P_-PJ-mwo	*Maximum*	*Minimum*
Age (Ma)	1220	1190
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Bodorkos and Wingate, 2008

This clinopyroxene–garnet mafic granulite unit has not been directly dated, but a sample of leucocratic clinopyroxene–orthopyroxene mafic granulite (P_PJ-mwol) (GSWA 174594: BATES, MGA 490563E 7133432N), assumed to be of a similar age, yielded a magmatic (protolith) age of 1190 ± 9 Ma (Bodorkos and Wingate, 2008). These rocks are inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mwog)

Legend narrative

Medium-grained clinopyroxene–garnet mafic granulite; massive to weakly banded; locally shows cm- to m-scale mineralogical banding, possibly primary layering; weakly to moderately migmatitic

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This medium-grained clinopyroxene–garnet mafic granulite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, outcrops in the Walpa Pulka Zone, to the north of the Mann Fault on southern Bates. Dating of a leucocratic mafic granulite elsewhere on Bates gives an age of c. 1190 Ma, consistent with the observation that the mafic Pitjantjatjara Supersuite units are mainly interleaved with the older felsic units of the supersuite.

Distribution

This medium-grained clinopyroxene–garnet mafic granulite unit forms several small outcrops in the Walpa Pulka Zone to the north of the Mann Fault, and also in the area up to 5 km to the east of Amy Giles Hill on southwestern Bates.

Lithology

This granulite unit consists of a medium-grained, granoblastic-textured, massive mafic granulite. It includes tightly folded migmatitic melt bands, up to 3 cm thick, and melt patches. The major mineral assemblage of the mafic granulite component includes plagioclase, orthopyroxene, pale-green clinopyroxene, and brown hornblende; the brown hornblende pseudomorphs pyroxene. Mafic minerals comprise up to 50% of the rock. The minor mineral assemblage includes quartz (<5%), brown biotite, chlorite, garnet, and opaque minerals. Fine-grained garnet aggregates form coronas separating the pyroxene and opaque minerals from feldspars.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous mafic	mw
Lithname	Mafic granulite	o
1st qualifier	–	
2nd qualifier	Garnet	g
Rock code		**P_-PJ-mwog**

Geochronology

P_-PJ-mwog	*Maximum*	*Minimum*
Age (Ma)	1220	1190
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Bodorkos and Wingate, 2008

This medium-grained clinopyroxene–garnet mafic granulite unit has not been directly dated, but a sample of leucocratic clinopyroxene–orthopyroxene mafic granulite (P_-mwol; GSWA 174594: Bates, MGA 490563E 7133432N), assumed to be of a similar age, has yielded a magmatic (protolith) age of 1190 ± 9 Ma (Bodorkos and Wingate, 2008). These rocks are inferred to form part of the well-dated Pitjantjatjara Supersuite — the magmatic expression of the Musgrave Orogeny. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (Bates), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the Bates region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Pitjantjatjara Supersuite; subunit (P_-PJ-mwol)

Legend narrative

Medium-grained, leucocratic, clinopyroxene–orthopyroxene mafic granulite (granulite after leucogabbro)

Rank	Formation
Parent	Pitjantjatjara Supersuite (P_-PJ-xg-o)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Granulite facies: undivided

Summary

This leucocratic clinopyroxene–orthopyroxene mafic granulite unit, part of the Mesoproterozoic Pitjantjatjara Supersuite, outcrops in the Walpa Pulka Zone, to the north of the Mann Fault on BATES. Dating obtained from this unit gives an age of c. 1190 Ma, consistent with the observation that the mafic Pitjantjatjara Supersuite units are mainly interleaved with the older felsic units of the supersuite.

Distribution

The only substantial outcrops of this leucocratic clinopyroxene–orthopyroxene mafic granulite unit are two exposures on the north and eastern edge of Mount Fanny, on BATES.

Lithology

This leucocratic clinopyroxene–orthopyroxene mafic granulite unit is typically fine grained, with a granoblastic polygonal texture. It comprises up to 60% plagioclase, with major quartz, clinopyroxene, and orthopyroxene. Minor minerals include opaque minerals (mainly magnetite), hornblende, chlorite, and garnet. It locally includes magnetite-rich seams, and weak layering defined by variations in the proportions of feldspar. The protolith is typically leucogabbronorite, but may also range to leucogabbro.

Age code	Proterozoic	P_-
Stratigraphic code	Pitjantjatjara Supersuite	PJ-
Rock type	Meta-igneous mafic	mw
Lithname	Mafic granulite	o
1st qualifier	–	
2nd qualifier	Leucocratic	l
Rock code		**P_-PJ-mwol**

Contact relationships

The protolith to this leucocratic clinopyroxene–orthopyroxene mafic granulite appears to have intruded an older felsic component of the Pitjantjatjara Supersuite. Leucocratic mafic granulite is locally in sharp contact with mylonitic monzogranitic gneiss. The type locality for this unit is on the northeast side of Mount Fanny (GSWA 174615: BATES, MGA 458038E 7149429N), where it overlies monzogranite of the Pitjantjatjara Supersuite, and grades into migmatitic mafic granulite of the same supersuite. At one outcrop south of Mount Gosse, the unit forms an inclusion within granitic gneiss.

Geochronology

P_-PJ-mwol	*Maximum*	*Minimum*
Age (Ma)	1190 ± 9	1190 ± 9
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Bodorkos and Wingate, 2008	Bodorkos and Wingate, 2008

A sample of this leucocratic mafic granulite derived from a leucogabbroic protolith (GSWA 174594: BATES, MGA 490563E 7133432N), yielded a SHRIMP U–Pb zircon age of 1190 ± 9 Ma, which is interpreted as the age of protolith crystallization (Bodorkos and Wingate, 2008). This age is consistent with Pitjantjatjara Supersuite rocks dated from elsewhere in the west Musgrave Province. The oldest Pitjantjatjara Supersuite outcrop identified so far within the west Musgrave Province is from the Walpa Pulka Zone (BATES), and has yielded a magmatic crystallization age of 1219 ± 12 Ma (GSWA 174737, Bodorkos et al., 2008). The youngest rocks are from the Mamutjarra Zone, and include a metagranite that has yielded a magmatic crystallization age of 1148 ± 6 Ma (GSWA 189522, Kirkland et al., in prep.), and a metanorite dyke with a magmatic crystallization age of 1149 ± 10 Ma (GSWA 194376, Kirkland et al., 2010). Thus, the age range of the Pitjantjatjara Supersuite within the west Musgrave Province is from 1219 ± 12 Ma to 1148 ± 6 Ma (i.e. 1220–1150 Ma), although slightly younger Pitjantjatjara granites (c. 1120 Ma) are known from the Northern Territory (Edgoose et al., 2004), and anatectic melts as young as 1121 ± 11 Ma, the results of high-grade metamorphism in the late stages of the Musgrave Orogeny, are noted from the BATES region in the Walpa Pulka Zone (Walker-Hallam, 2009).

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Unassigned Proterozoic mafic unit (P_-mof-MU)

Legend narrative

Massive, fine- to coarse-grained, metamorphosed anorthosite; dark weathering

Rank	Formation
Parent	Unnamed unit (P_-mo-MU)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This meta-anorthosite forms a very small intrusion in the southeast portion of BATES. The unit is coarse grained, containing plagioclase, interstitial clinopyroxene, and minor apatite. Garnet coronas rim both pyroxene and plagioclase grains, and Fe–Ti oxides occur along clinopyroxene grain margins. The age of the unit is unknown, although the rock is likely to belong to the Warakurna Supersuite.

Distribution

This meta-anorthosite forms one small intrusion, in the southeastern part of BATES.

Lithology

This meta-anorthosite unit is coarse grained, containing plagioclase, interstitial clinopyroxene, and minor apatite. Garnet coronas rim both pyroxene and plagioclase grains, and Fe–Ti oxides occur along clinopyroxene grain margins.

Age code	Proterozoic	P_-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Meta-anorthosite	f
Tectonic unit code	Musgrave Province	-MU
Rock code		**P_-mof-MU**

Contact relationships

Limited exposure suggests that this meta-anorthosite either intruded into, or is included within, a large expanse of Pitjantjatjara Supersuite granite (P_-PJ-mg).

Geochronology

P_-mof-MU	*Maximum*	*Minimum*
Age (Ma)	1220	1040
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

The age of this intrusion is unknown, but is likely constrained between the maximum age of the Musgrave Orogeny and minimum age of the Giles Event (Smithies et al., 2009, 2010).

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Unassigned Proterozoic mafic unit (P_-mog-MU)

Legend narrative

Metagabbro; typically granoblastic with pyroxene aggregates, and garnet coronas on mafic minerals

Rank	Formation
Parent	Unnamed unit (P_-mo-MU)
Tectonic units	Musgrave Province, PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This metagabbro outcrops as three intrusions on the south-central portion of BATES. The metagabbro is medium to coarse grained, containing primary clinopyroxene, plagioclase, and ilmenite, with coronas of garnet, Fe-rich cummingtonite, and quartz all forming on clinopyroxene. The age of the unit is unknown, but has been placed stratigraphically between the Pitjantjatjara and Warakurna Supersuites.

Distribution

This metagabbro unit outcrops as three small intrusions, on the south-central portion of BATES.

Lithology

The unit is a medium to coarse grained, foliated to granoblastic-textured metagabbro, containing primary clinopyroxene, plagioclase, and ilmenite. Pyroxene grains develop coronas of garnet, Fe-rich cummingtonite, and quartz. Also present are minor chlorite grains and irregular blebs of pyrite and chalcopyrite.

Age code	Proterozoic	P_-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro	g
Tectonic unit code	Musgrave Province	-MU
Rock code		**P_-mog-MU**

Contact relationships

This metagabbro unit intrudes into granite of the Pitjantjatjara Supersuite (P_-PJ1-mggo).

Geochronology

P_-mog-MU	*Maximum*	*Minimum*
Age (Ma)	1220	1040
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Smithies et al., 2009, 2010	Smithies et al., 2009, 2010

The age of this intrusion is unknown, but is likely constrained between the maximum age of the Musgrave Orogeny and minimum age of the Giles Event (Smithies et al., 2009, 2010).

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Kunmarnara Group (P_-KR-xs-b)

Legend narrative

Undivided siliciclastic and mafic volcanic rocks

Rank	Group
Parent	Bentley Supergroup (P_-BE-xs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); SMOKE HILL VOLCANICS (P_-TLs-f)
Minimum thickness	700 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

The Kunmarnara Group (P_-KR-xs-b) — comprising the MacDougall Formation and the Mummawarrawarra Basalt — was deposited unconformably over Mesoproterozoic rocks of the Musgrave Province, along the (presently) westerly to west-northwesterly trending margins of a rift basin traced by the northern sides of the Blackstone and Finlay Ranges.

The MacDougall Formation lies at the base of the Kunmarnara Group, and comprises poorly sorted, arkosic sandstones, and quartz-pebble conglomerates. The rocks of this unit are typically deformed and metamorphosed to form a muscovite-bearing quartzite found along the northern edge of the rift. The unit it contains local garnets, produced by contact metamorphism during the emplacement of the oldest mafic Giles Suite intrusions (P_-WKg1) during the 1085–1040 Ma Giles Event. The detrital zircon population of the McDougall Formation is dominated by an 1172 ± 8 Ma source, which forms the maximum depositional age for the Kunmarnara Group (Evins et al., 2010).

The Mummawarrawarra Basalt conformably overlies the MacDougall Formation, and comprises a stack of metre-scale thick, typically basaltic andesite, flow units. The layers range from massive plagioclase-phyric to highly amygdaloidal. This basalt is metamorphosed to amphibolite facies in proximity to the oldest mafic intrusions of the Giles Suite, often occurring as inclusions within these intrusions. Whereas the MacDougall Formation and Mummawarrawarra Basalt are cut by the oldest mafic intrusions of the Giles Suite (P_-WKg1), the overlying layers of the Tollu Group are clearly younger than P_-WKg1. As a result, the former two formations have been split from the Tollu Group, together forming the Kunmarnara Group (Smithies et al., 2009).

Distribution

Outcrop of the Kunmarnara Group is concentrated along the northwest-trending, southwestern boundary of the Tjuni Purlka Tectonic Zone. The northern portion of this unit forms a 3–5 km wide by 100 km long, west- to northwest-striking, gently to moderately south-southwest dipping belt that runs along the northern side of the Finlay (FINLAYSON) and Blackstone (BLACKSTONE–HOLT) ranges. Its continuation to the south, on BELL ROCK, is as a 10 x 50 km, northwest-trending, shallow-plunging, regional syncline. The west-trending southern portion of the unit forms a belt up to 12 km long and 2 km wide on BLACKSTONE, where it defines the southern limb of a syncline cored by younger units of the Tollu Group. This southern limb most likely continues west to underlie ~80 km² of the Mount Blythe area on COOPER, and east to MacDougall Bluff (southeastern BLACKSTONE) where the Kunmarnara Group and its external and internal contacts are well exposed. Metamorphosed equivalents of the Kunmarnara Group are interpreted to form west-northwesterly trending upright folds within a 38 x 10 km fault-bounded block that straddles the boundary between the northern portions of the FINLAYSON and HOLT map sheets.

The MacDougall Formation forms low outcrops and linear ridges in dune country. In lower lying areas, the unit forms saprolitic or limonitic ferricrete mounds, and may underlie plains of abundant quartz colluvium sourced from its vein-quartz pebbles. The Mummawarrawarra Basalt forms significant hills only when unmetamorphosed, as is the case along the southern limb of the Blackstone syncline at MacDougall Bluff and Mummawarrawarra Hill (on central BLACKSTONE), and south of Mount Blythe on COOPER. Elsewhere, the Mummawarrawarra Basalt forms low hills, rubbly mounds, or occurs as mesoscopic xenoliths enclosed in the better exposed, layered gabbros of the oldest mafic Giles Suite intrusions (P_-WKg1).

Derivation of name

The name ‘Kunmarnara Group’ was first used by Smithies et al. (2009), and is named after Kunmarnara Bore, which is located approximately 4 km east of MacDougall Bluff and 10 km north of Skirmish Hill, in the southeast of BLACKSTONE.

Lithology

Daniels (1974) placed the MacDougall Formation and Mummawarrawarra Basalt at the bottom of the Tollu Group, noting that inclusions of the Mummawarrawarra Basalt could be found in the mafic–ultramafic rocks of the Giles intrusions. However, radiometric dating of rocks that crosscut the Kunmarnara units, and of the Smoke Hill Volcanics (interpreted by Daniels (1974) to lie conformably above the Kunmarnara Group), required the Kunmarnara units to be split from the overlying Tollu Group (Smithies et al., 2009). Close et al. (2003) tentatively correlated the Kunmarnara units with lower units of the Tjauwata Group in the Bloods Range of the

Northern Territory, but the c. 1075 Ma Puntitjata Rhyolite, within the Tjauwata Group, may actually post-date many of the Giles intrusions.

The pristine, fine- to coarse-grained, muddy to arkosic, poorly sorted sandstones and matrix-supported conglomerates of the MacDougall Formation (P_-KRd-sg) are preserved in the Blackstone syncline, at MacDougall Bluff (BLACKSTONE), and at Mount Blythe (COOPER). At Mount Blythe, cross-bedding in layers 1–10 m thick show paleocurrent indicators that suggest a depositional system flowing away from the Blackstone syncline area (Daniels, 1974). An overwhelming majority of pebbles contained within the MacDougall Formation are of vein quartz. The source of this vein quartz remains enigmatic, as quartz veins are not abundant in the basement. On the contrary, quartz veins often crosscut the MacDougall Formation, being most abundant in regions of the west Musgrave Province where the Kunmarnara Group is exposed.

Rocks of the MacDougall Formation are metamorphosed to transitional greenschist–amphibolite facies (P_-KRd-mxsm), and are mylonitized (P_-KRd-mxym) along the northern margin (and to the north) of the Finlay Range (HOLT). Daniels (1974) considered these rocks to be older than the Bentley Supergroup due to their deformation and metamorphic grade. However, their compositional similarity to the rocks described above, and their stratigraphic position with respect to the Giles intrusions, indicates they are most likely the metamorphosed equivalent of the MacDougall Formation. These rocks typically range from phyllitic, to meta-arkosic, to quartzitic, depending on muscovite and feldspar content. Centimetre-scale lenses of magnetite are locally abundant. Near some of the layered mafic Giles intrusions, the growth of small, 1 mm diameter garnet crystals overprints a consistently dextral-normal C–S fabric defined by muscovite (C-planes) and recrystallized quartz (S-planes). This relationship suggests that the sediments were deformed before the emplacement of the Giles intrusions. However, the opposite relationship can be seen where the rocks are mylonitized at the basal contact of the MacDougall Formation in southeast FINLAYSON, which is indicative of later shearing along this anisotropy.

The Mummawarrawarra Basalt comprises a stack of individual 1–5 m thick flow units, which range in composition from basaltic to andesitic, with most being basaltic andesite. The layers range from massive and non-amygdaloidal to very amygdaloidal, and from non-porphyritic to plagioclase-porphyritic. Amygdales have locally coalesced to form pockets or layers parallel to flow-layering. Pipe vesicles occur locally. In thin section, the Mummawarrawarra Basalt (P_-KRm-bbg) is a fine-grained hypocrystalline and seriate-textured rock, comprising acicular to lath-shaped plagioclase, relict clinopyroxene, rare olivine phenocrysts, and an interstitial glassy groundmass with lobate amygdales (now quartz, epidote, and chlorite).

The rock locally contains up to 10% euhedral plagioclase phenocrysts and glomerophenocrysts, both up to 8 mm in size, within a subophitic matrix. Macroscopically, this plagioclase-phyric microgabbro is difficult to distinguish from later plagioclase-phyric gabbros (P_-WKg1 to P_-WKg3), dykes and sills of which intrude it to form a mixed unit (P_-KRm-xmb-mo).

Mafic minerals in the Mummawarrawarra Basalt are variably to completely altered to actinolite or epidote, particularly adjacent to mafic intrusions of the Giles Suite. Where metamorphosed, the Mummawarrawarra Basalt is characterized by a strong aeromagnetic (TMI) response, whereas elsewhere, where epidote alteration predominates, the unit is non-magnetic.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group	KR-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Sedimentary siliciclastic	s
Rock type 2	Igneous mafic volcanic	-b
Rock code		**P_-KR-xs-b**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Contact relationships

The lower contact of the Kunmarnara Group is best exposed in central-western BLACKSTONE and in central-eastern BLACKSTONE, where rocks of the MacDougall Formation unconformably overly metamorphosed granite of the Wankanki Supersuite. The lower contact is also completely exposed on a small hill in southeast FINLAYSON, and at Mount Blythe on COOPER. The former exposure is a faulted unconformity occurring between mylonitized and brecciated rocks of the MacDougall Formation (P_-KRd-mxym) and metamorphosed granites of the Pitjantjatjara Supersuite, whereas the latter is an unconformity between sandstone of the MacDougall Formation (P_-KRd-sg) and mylonitic high-grade gneisses of the Wirku Metamorphics. A sill of Mummawarrawarra Basalt intrudes along this unconformity, joining feeder dykes to the main flows overlying the MacDougall Formation. The upper contact of the Kunmarnara Group is not exposed, and is interpreted to have been above the current exposure level of the Musgrave Province. The Mummawarrawarra Basalt is typically intruded by sills and layered chambers, up to 10 km thick, which form the oldest mafic intrusions of the Giles Suite (P_-WKg1).

Geochronology

P_-KR-xs-b	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al.,1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A direct date from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, and can also be interpreted as a minimum age of deposition of the Mummawarrawarra Basalt (Smithies et al., 2009). The maximum age of deposition is constrained by the youngest detrital zircon population (1172 ± 8 Ma, Evins et al., 2010) obtained from rocks of the MacDougall Formation, which forms the base of the Kunmarnara Group.

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MUMMAWARRAWARRA BASALT (P_-KRm-bbg)

Legend narrative

Vesicular and amygdaloidal basalt, basaltic andesite, and andesite; locally plagioclase porphyritic; epidotized

Rank	Formation
Parent	Kunmarnara Group (P_-KR-xs-b)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f)
Underlying units	MACDOUGALL FORMATION (P_-KRd-sg)
Maximum thickness	1100 m
Metamorphic facies	Greenschist facies: undivided

Summary

The main outcrops of the Mummawarrawarra Basalt occur at MacDougall Bluff, Mummawarrawarra Hill (BLACKSTONE), and Mount Blyth (COOPER). The unit also forms xenoliths within the basal parts of the layered Blackstone intrusion, both along the northern foothills of Blackstone Range (HOLT), and within and immediately north of the Jameson Range (FINLAYSON). The Mummawarrawarra Basalt conformably overlies sedimentary rocks of the MacDougall Formation, the oldest unit of the Kunmarnara Group, and was intruded by the layered mafic intrusive rocks of the Giles Suite at c. 1075 Ma. The basalt unit of the Mummawarrawarra Basalt comprises a stack of 1–5 m thick flow units, which range in composition from basaltic to andesitic, with most being basaltic andesite. The layers range from massive and non-amygdaloidal to very amygdaloidal, and from non-porphyritic to rocks containing up to 5% euhedral plagioclase phenocrysts and glomerophenocrysts, both up to 6 mm in size.

Distribution

The main outcrops of the Mummawarrawarra Basalt are found on BLACKSTONE and COOPER. On the western side of BLACKSTONE, the unit forms an east-trending outcrop immediately east of the Cavenagh Range; on the eastern side of BLACKSTONE it forms the main part of MacDougall Bluff and Mummawarrawarra Hill. The unit is also well exposed on, and south of, Mount Blyth in the central parts of COOPER. The Mummawarrawarra Basalt also outcrops on the western side of BELL ROCK, forming a series of hills approximately 10–15 km to the south of the western end of BELL ROCK Range. Rounded to elongate xenoliths of Mummawarrawarra Basalt are enclosed within the basal parts of the layered Blackstone intrusion (a mafic intrusion representing the earliest phase of the Giles Suite), both along the northern foothills of the Blackstone Range (HOLT), and within, and immediately north of, the Jameson Range (FINLAYSON).

Lithology

The Mummawarrawarra Basalt consists of a stack of flow units each 1–5 m thick, which range in composition from basaltic to andesitic, with most being basaltic andesite. The layers range from massive and non-amygdaloidal to very amygdaloidal, and from non-porphyritic to rocks containing up to 5% euhedral plagioclase phenocrysts and glomerophenocrysts, both up to 6 mm in size. Outcrop at MacDougall Bluff also includes layers of well-bedded andesitic tuff containing rounded inclusions of amygdaloidal lava. The estimated thickness of the sequence at MacDougall Bluff is about 1100 m.

Where the rocks are amygdaloidal, the quartz–epidote–calcite-filled amygdales range in size up to 2 cm, and vary in shape from spheroidal to examples that have been flattened parallel to flow layering. Pipe vesicles (amygdales) occur locally, and are up to 15 cm long. Amygdales have also locally coalesced to form pockets or layers parallel to flow layering. Strong epidote alteration is a very common feature of the Mummawarrawarra Basalt.

A small, fault-bounded outcrop lies immediately northeast of the Cavenagh Range. Here, the unit is lithologically diverse, and locally consists of amygdaloidal basalt with up to 50% amygdales. It also includes feathery to granophyric-textured and weakly vesicular gabbro, which grades continuously to vesicular acicular-textured basalt, and then to tuffaceous rocks containing accretionary lapilli (WAROX site RHSMUG0001290). In this area, the unit also includes doleritic layers containing a randomly oriented framework of small (~1 mm) plagioclase laths with ~30% intergranular clinopyroxene.

In the area east of Cavenagh Range, the Mummawarrawarra Basalt was locally intruded by abundant dolerite and gabbro sills, particularly in the margins of layered mafic Giles Suite intrusions such as the Cavenagh Range intrusion, forming a mixed unit (P_-KRm-xmb-mo).

In thin section, samples of the Mummawarrawarra Basalt from MacDougall Bluff are usually fine-grained, hypocrystalline, and seriate-textured, comprising 40–50% acicular to lath-shaped plagioclase crystals (heavily altered to epidote, chlorite, and carbonate), ~20% relict clinopyroxene crystals (some phenocrysts), rare olivine phenocrysts, 10–20% interstitial glassy groundmass (commonly with plagioclase needles, and now altered to epidote, quartz, and chlorite), and lobate amygdales (now consisting of quartz, epidote, and chlorite). Samples taken closer to the Cavenagh Range are more typically actinolite-rich, rather than epidote-altered. They comprise a fine-grained, feathery textured assemblage of acicular to lath-shaped plagioclase, partially enclosed in a mass of actinolite. The actinolite has replaced primary clinopyroxene and interstitial glass. The primary texture was seriate to porphyritic or glomeroporphyritic, with plagioclase phenocrysts to 7 mm in size.

A sample taken from outcrop immediately northeast of the Cavenagh Range (GSWA 185634 at WAROX site RHSMUG0001272), consists of a massive, unfoliated, fine- to medium-grained rock, with rare, rounded, quartz-filled amygdales up to 3 mm in size. This rock contains stumpy to lath-shaped plagioclase crystals (~40%) up to 3 mm in size, forming an interlocking framework. Olivine (~15%), which most likely crystallized before plagioclase, forms rounded to subhedral crystals, and is partly to totally altered to serpentine. Clinopyroxene (~15%) is an intergranular mineral, but also commonly subophitically encloses plagioclase, and is partially altered to actinolite. Opaque minerals form ~10% of the rock, and are also intergranular. An intergranular groundmass (10–20%) is hypocrystalline, and consists of acicular plagioclase and clinopyroxene, with common micro-amygdales less than 1mm in size.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group, MUMMAWARRAWARRA BASALT	KRm-
Rock type	Igneous mafic volcanic	
Lithname	Basalt	bb
1st qualifier	Vesicular/amygdaloidal	g
Rock code		**P_-KRm-bbg**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Contact relationships

The Mummawarrawarra Basalt conformably overlies sedimentary rocks of the MacDougall Formation, which is the oldest unit of the Kunmarnara Group. At Mount Blyth, peperitic contacts between these two units indicate that the sedimentary rocks were unconsolidated at the time of basalt extrusion. Layered mafic intrusive rocks of the Giles Suite, and in particular, the Blackstone, Finlay, and Cavenagh intrusions, were emplaced within the Mummawarrawarra Basalt at c. 1075 Ma. The Kunmarnara Group and associated layered intrusions were then uplifted and eroded down to the level of the layered intrusions prior to deposition of the Tollu Group, between c. 1070 and 1026 Ma.

Geochronology

P_-KRm-bbg	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample obtained from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered BELL ROCK intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, and can also be interpreted as a minimum age of deposition of this basalt unit (Smithies et al., 2009). The maximum age of deposition is constrained by the youngest detrital zircon population (1172 ± 8 Ma; Evins et al., 2010) obtained from rocks of the MacDougall Formation, which forms the base of the Kunmarnara Group.

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MUMMAWARRAWARRA BASALT (P_-KRm-xmb-mo)

Legend narrative

Amygdaloidal basalt to andesite interleaved and intruded by microgabbro locally containing orthopyroxene oikocrysts and plagioclase glomerophenocrysts; typically metamorphosed to lower amphibolite facies

Rank	Member
Parent	Kunmarnara Group, MUMMAWARRAWARRA BASALT (P_-KRm-bbg)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f)
Underlying units	MACDOUGALL FORMATION (P_-KRd-sg)
Maximum thickness	300 m
Metamorphic facies	Greenschist facies: undivided

Summary

This mixed basalt–gabbro unit outcrops sporadically along the southern margin of the Blackstone syncline in an east-trending belt extending between the Cavenagh Range and the Tollu granite pluton (Blackstone), and also forms scattered outcrop along the northeastern margins of the Finlay intrusion on central Finlayson. This mixed unit groups those outcrops of the Mummawarrawarra Basalt marginal to the layered Giles intrusions, with those that contain a high proportion of gabbro sills and dykes related to the emplacement of those layered intrusions.

Distribution

This mixed basalt–gabbro unit outcrops sporadically along the southern margin of the Blackstone syncline in an east-trending belt extending between the Cavenagh Range and the Tollu granite pluton (Blackstone), where it separates the unmixed Mummawarrawarra Basalt (P_-KRm-bbg) unit from layered mafic intrusions of the Giles Suite. The unit also forms scattered outcrop in valleys and low hills between ridges of metamorphosed MacDougall Formation (P_-KRd-sg and P_-KRd-mxsm) on the northeastern margins of the Finlay intrusion, on central Finlayson. At the latter locality, the unit forms a discontinuous band up to 6 km long at the base of the Finlay–Jameson intrusion. Rare, small (<10 m) exposures of metamorphosed basalt, found between the Finlay and Jameson ranges, likely represent xenoliths or screens of this unit.

Lithology

The contact between the Mummawarrawarra Basalt and a series of layered mafic Giles intrusions (Giles Suite), exposed in an east-trending belt between the Cavenagh Range and the Tollu granite pluton (Blackstone), is characterized by greenschist- to amphibole-facies recrystallization of the Mummawarrawarra Basalt and the intrusion of abundant microgabbro sills and dykes. The result is this mixed basalt–gabbro unit (P_-KRm-xmb-mo). Although, the basaltic (basalt to andesite) rocks locally preserve their primary texture, particularly in the southern part of the unit, they are more typically weakly foliated, and show the strong recrystallization of clinopyroxene. It is likely that amphibolite-facies recrystallization is best developed close to layer-parallel faults. Intrusive microgabbro sills and dykes are almost certainly related to the layered mafic intrusions to the north, but are also variably metamorphosed to the amphibolite facies.

Typical basaltic to andesitic rocks in this unit are fine-grained, holocrystalline, and weakly foliated, and contain 40–50% plagioclase, occurring as sub-aligned euhedral to subhedral laths. Primary clinopyroxene grains form up to 50% of the rock, and crystallized either as an intergranular phase, or subophitically enclosing plagioclase, but are now partly to totally recrystallized to a granoblastic polygonal mass of green hornblende. Blebs of magnetite occur throughout the rock, forming up to 10% of the mode.

A single sample of recrystallized intrusive rock (GSWA 185605, at WAROX site RHSMUG001207) differs from this typical metabasalt in that it is slightly coarser grained, and contains rounded orthopyroxene oikocrysts up to 8 mm in size.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group, MUMMAWARRAWARRA BASALT	KRm-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Meta-igneous mafic volcanic	mb
Rock type 2	Meta-igneous mafic intrusive	-mo
Rock code		**P_-KRm-xmb-mo**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Contact relationships

This mixed basalt–gabbro unit is a subdivision of the Mummawarrawarra Basalt, which conformably overlies sedimentary rocks of the MacDougall Formation; together, the MacDougall Formation and Mummawarrawarra Basalt form the Kunmarnara Group. Layered mafic intrusive rocks of the Giles Suite, in particular the Blackstone, Finlay, and Cavenagh intrusions, were emplaced within the Mummawarrawarra Basalt at c. 1075 Ma, and are the likely source of the gabbro intrusions that form part of this mixed unit. On Blackstone, this mixed basalt–gabbro unit is cut by the Tollu pluton (P_-WK-grb); the contact between this unit and the overlying metamorphosed MacDougall Formation (P_-KRd-mxsm) is not exposed, but is assumed to be conformable (although deformed) based on the contact between their unmetamorphosed equivalents at Mount Blythe. Both the Kunmarnara Group and associated layered Giles intrusions were uplifted and eroded down to the level of the layered intrusions prior to deposition of the Tollu Group, between c. 1070 and 1026 Ma.

Geochronology

P_-KRm-xmb-mo	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

Inclusions of this mixed basalt–gabbro unit within the basal portions of the Finlay–Jameson layered mafic intrusion (P_-WKg1) indicate that the basalt–gabbro unit is older than the oldest phase of the Giles Suite. A sample from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, and can also be interpreted as a minimum age of deposition of this basalt unit (Smithies et al., 2009). The maximum age of deposition is constrained by the youngest detrital zircon population (1172 ± 8 Ma, Evins et al., 2010) obtained from the rocks of the MacDougall Formation, which forms the base of the Kunmarnara Group. On Blackstone, this unit is cut by the 1073 ± 6 Ma Tollu pluton (P_-WK-grb; GSWA 185583, Kirkland et al., 2009).

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MACDOUGALL FORMATION (P_-KRd-sg)

Legend narrative

Quartz-pebble conglomerate and sandstone

Rank	Formation
Parent	Kunmarnara Group (P_-KR-xs-b)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	MUMMAWARRAWARRA BASALT (P_-KRm-bbg)
Metamorphic facies	Greenschist facies: undivided

Summary

The MacDougall Formation is the oldest unit of the Kunmarnara Group, and consists of interbedded, coarse-grained arkosic sandstone, pebbly arkose, pebble beds, and matrix-supported conglomerate. A muscovite-bearing quartzite (P_-KRd-mxsm) is thought to represent a strongly deformed equivalent to this unit. The MacDougall Formation forms thin, sporadic, east-trending outcrop immediately east of the Cavenagh Range on the western side of Blackstone, and a similarly thin, sporadic belt of outcrop along the southwestern base of MacDougall Bluff on the southeastern side of Blackstone. It is perhaps best exposed in the Mount Blyth area, in the central parts of Cooper.

Distribution

The MacDougall Formation forms thin, sporadic, east-trending outcrop immediately east of the Cavenagh Range on the western side of Blackstone, and a similarly thin, sporadic belt of outcrop along the southwestern base of MacDougall Bluff on the eastern side of Blackstone. It is perhaps best exposed in the Mount Blyth area, in the central parts of Cooper.

Muscovite-bearing quartzite (P_-KRd-mxsm), also thought to form part of the MacDougall Formation, outcrops sporadically along the northern edge of the Blackstone and Finlay Ranges, where it is interpreted to reflect a bedrock unit, forming a continuous, 1–2 km wide, west- to west-northwesterly trending belt that parallels the northern edge of these ranges. This quartzite unit is best exposed in the northwest of Holt, 5–10 km south of Mount Muir, where it forms northwest-trending ridges, up to 200 m wide and 5 km long, that trace the northeast limb of a large, west-northwesterly trending fold.

Lithology

The MacDougall Formation is the oldest unit of the Kunmarnara Group, and consists of interbedded coarse-grained arkosic sandstone, pebbly arkose, pebble beds, and matrix-supported conglomerate. A muscovite-bearing quartzite (P_-KRd-mxsm) is thought to represent a strongly deformed equivalent to this unit. Most pebbles are well-rounded, 2–3 cm in size, and consist of vein quartz. On Blackstone, the unit has a maximum thickness of ~500 m, dips at a shallow to moderate angle (typically ~30°) to the north or northeast, unconformably overlies porphyritic granite, and is conformably overlain by lavas of the Mummawarrawarra Basalt. The sandstones locally show well-developed cross-bedding, and, according to Daniels (1974), preserve paleocurrent indicators suggesting the depositional system flowed away from the area between MacDougall Bluff (southeast Blackstone) and Mount Blyth (Cooper).

A sample taken from outcrop east of the Cavenagh Range (Blackstone, WAROX site RHSMUG001189, GSWA 185597) is typical of this formation, and includes two domains: coarse-grained sandstone and pebble conglomerate. The sandstone is very poorly sorted, comprising subrounded to angular clasts up to 5 mm in size, mainly of quartz but also containing feldspar and quartz–feldspar rock fragments. The matrix consists of muscovite–sericite, is locally epidote-rich, and most likely reflects the low- to medium-grade contact metamorphism of an initially clay-rich or feldspathic matrix. The conglomerate domain is clast-supported (just), and comprises subrounded to subangular pebbles of quartz and (rarely) cherty siltstone within a matrix of muscovite (sericite) and epidote.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group, MACDOUGALL FORMATION	KRd-
Rock type	Sedimentary siliciclastic	s
Lithname	Conglomerate + sandstone	g
Rock code		**P_-KRd-sg**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Contact relationships

The MacDougall Formation (P_-KRd-sg) conformably overlies older basement gneiss of the Musgrave Province. Contacts with the overlying Mummawarrawarra Basalt are conformable, and peperitic contacts observed at Mount Blyth (Cooper) indicate that the sandstones and conglomerates were unconsolidated at the time of basaltic eruption.

Geochronology

P_-KRd-sg	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

Detrital zircon age spectra from three widely spaced (separated by >80 km along strike) samples of the MacDougall Formation (GSWA 190233, Kirkland et al., in prep.; GSWA 194420, Kirkland et al., 2010; GSWA 190292, Kirkland et al., 2011c; Evins et al., 2010) provide little insight into the source of the vein quartz pebbles. The majority of concordant detrital zircon grains from these samples are derived from the Pitjantjatjara Supersuite (72% in GSWA 190233, 57% in GSWA 194420, and 46% in GSWA 190292); these detrital zircons have a significant age component at c. 1170 Ma (1172 ± 8 Ma; Evins et al., 2010).

A sample obtained from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, and can also be interpreted as a minimum depositional age for the MacDougall Formation (Smithies et al., 2009).

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MACDOUGALL FORMATION; subunit (P_-KRd-mxsm)

Legend narrative

Strongly foliated quartz-pebble conglomerate, feldspathic sandstone, muscovite quartzite, and phyllite; metamorphosed; locally garnetiferous near mafic intrusions

Rank	Member
Parent	MACDOUGALL FORMATION (P_-KRd-sg)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	MUMMAWARRAWARRA BASALT (P_-KRm-bbg)
Metamorphic facies	Greenschist facies: muscovite zone

Summary

This muscovite quartzite is part of the MacDougall Formation (P_-KRd-sg), and forms low, sandy outcrops and linear ridges along a westerly to west-northwesterly trending belt that dips under the Blackstone and Finlay–Jameson intrusions of the Giles Suite. The unit also traces a large, west-northwesterly trending fold south of Mount Muir (Holt), and is interpreted to form the unexposed bedrock in the southeast corner of the Bell Rock map sheet. This metasedimentary base to the Kunmarnara Group is composed of centimetre- to metre-scale layers rich in quartz, muscovite, and magnetite. Contact metamorphism from nearby Giles intrusions promoted the growth of garnet in some areas. This muscovite quartzite unit is invariably strongly deformed (typically schistose), and is ubiquitously invaded by quartz veins. Its fluvial sandstone–conglomerate protolith was deposited between c. 1172 Ma and c. 1075 Ma in an intracontinental rift setting.

Distribution

This muscovite quartzite unit outcrops as low sandy outcrops and linear ridges throughout dune country. In lower lying areas, it forms saprolitic or limonitic ferricrete mounds, and may underlie plains formed of abundant quartz colluvium sourced from its vein quartz pebbles. This muscovite quartzite unit is also interpreted to form a bedrock unit, poorly exposed within a semi-continuous, westerly to west-northwesterly trending belt up to 2 km wide, paralleling the northern edge of the Blackstone and Finlay Ranges. However, the unit is best exposed in the northwest of Holt, 5–10 km south of Mount Muir, where it forms northwest-trending ridges, up to 200 m wide and 5 km long, that trace the northeast limb of a large, west-northwesterly trending fold. On aeromagnetic (TMI) images, this structure is highlighted by the high magnetite content with this quartzite unit. This unit also outcrops as three low mounds in the southeast corner of Bell Rock.

Lithology

Daniels (1974) considered these rocks to be older than the Bentley Supergroup due to their deformation and metamorphic grade, but their compositional similarity to the unmetamorphosed MacDougall Formation (P_-KRd-sg), and stratigraphic position with respect to the mafic intrusions of the Giles Suite, suggest that they are more likely the metamorphosed version of the MacDougall Formation. Therefore, this muscovite quartzite is interpreted to form the basal unit of the Kunmarnara Group. The unit is a centimetre- to metre-scale layered, muscovite-rich metasedimentary rock, with protoliths including fine- to coarse-grained muddy sandstone, coarse-grained arkosic sandstone, pebbly arkose, and matrix-supported conglomerate. The rock is both quartz- (up to 70%) and muscovite-rich (10–30%), typically with <10% feldspars preserved. Magnetite and zircon are common accessory minerals. Discontinuous, magnetite-rich (up to 35%) bands, up to 1 cm wide, are locally present. Pebbles are rarely preserved, but are almost exclusively composed of vein quartz. They are typically stretched into cigar-shapes with axial ratios approaching 10:1. Rare amphibolite layers are present west of the Finlay Range; these are likely transposed and metamorphosed feeder dykes linked to the overlying Mummawarrawarra Basalt. This metasediment is also heavily intruded by centimetre- to metre-wide quartz veins (particularly 5 km south of Prostanthera Hill on northern Holt) that are typically transposed and occasionally boudinaged slightly oblique to layering.

Invariably strongly deformed, the rock's muscovite content is typically high enough to classify it as a phyllite, reflecting the hydrous metamorphism of an initially clay-rich or feldspathic matrix. Within 1 km of the larger Giles intrusions, this unit contains garnet crystals up to 6 mm in size, which have fine magnetite inclusions and myrmekitic intergrowths. These likely reflect contact metamorphism related to the emplacement of the Giles intrusions. The schistose C–S fabric typical of this unit is defined by muscovite and dynamically recrystallized and crystallographically aligned quartz (S component), overgrown by 1–10 mm long blades of muscovite (C component). Where garnet is present, this C–S fabric wraps around it, indicating that deformation post-dated the metamorphic heat source (likely the Giles intrusions). Overall, the fabric is often folded and crenulated. Fold asymmetry and the schistose C–S fabric consistently indicate dextral-normal shear sense, across the entire west Musgrave Province.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group, MACDOUGALL FORMATION	KRd-
Rock type	Metasedimentary siliciclastic: psephite	mx
Lithname	Psephitic schist	s
1st qualifier	–	
2nd qualifier	Muscovite	m
Rock code		**P_-KRd-mxsm**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Contact relationships

This muscovite quartzite unit overlies older basement gneiss of the Musgrave Province. The contact is exposed as an ultramylonite in the southeast of FINLAYSON. On Mount Blythe, the same contact, between an unmetamorphosed MacDougall Formation (P_-KRd-sg) and the Wirku Metamorphics, is an unconformity. The contact between this muscovite quartzite unit and the overlying metamorphosed Mummawarrawarra Basalt is not exposed, but is assumed to be conformable (although deformed), based on the contact between their unmetamorphosed equivalents seen at Mount Blythe.

Geochronology

P_-KRd-mxsm	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

Detrital zircon age spectra obtained from a sample (GSWA 190233) of this muscovite quartzite, located 5 km south of Mount Muir, shows a dominant late Musgrave Orogeny (1172 ± 8 Ma) peak defined by eight analyses (Kirkland et al., in prep.; Evins et al., 2010), which constrains the maximum age of deposition for this unit. A nearly identical detrital zircon spectrum, including a peak at 1177 ± 7 Ma (24 analyses), was obtained from GSWA 190292 (Kirkland et al., 2011c; Evins et al., 2010) sampled from this unit where the belt dips underneath the Finlayson Range. A sample obtained from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered BELL ROCK intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, and can also be interpreted as the minimum depositional age of the MacDougall Formation (Smithies et al., 2009).

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Kunmarnara Group; subunit (P_-KR-xmd-mb)

Legend narrative

Unassigned metasiliciclastic and metamafic volcanic rocks

Rank	Formation
Parent	Kunmarnara Group (P_-KR-xs-b)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o)
Metamorphic facies	Greenschist facies: undivided

Summary

This sparsely exposed, composite metamorphosed unit of MacDougall Formation and Mummawarrawarra Basalt forms west-northwesterly trending, upright folds within a large, east-trending, fault-bounded block that straddles the border between the northern portions of the FINLAYSON and HOLT map sheets. The siliciclastic component of this unit is typically schistose, and composed of centimetre- to metre-scale layers rich in quartz, muscovite, and magnetite. The metabasaltic component of this unit is a fine-grained amphibolite comprising actinolite, chlorite, plagioclase, and recrystallized quartz, and lies in the centre of an interpreted anticline. This metabasaltic component is locally epidotized; both components are ubiquitously invaded by quartz veins.

Distribution

This composite metamorphosed unit of MacDougall Formation and Mummawarrawarra Basalt forms within an east-trending area, around 38 x 10 km in size, straddling the border between the northern portions of the FINLAYSON and HOLT map sheets. The bedrock geology in this region is interpreted to be a fault-bound block of undivided, metamorphosed Kunmarnara Group (P_-KR-xs-b), containing west-northwesterly trending, upright folds. Exposure of the composite unit (P_-KR-xmd-mb) is sparse and consists of a few, low, layered, saprolitic mounds, centred around quartz veins on the northwest of HOLT. Nearby, more readily identifiable muscovite quartzite of the MacDougall Formation (P_-KRd-mxsm) forms more substantial ridges. One amphibolite outcrop is present in the centre of an interpreted anticline in this area.

Lithology

This is a composite unit representing the metamorphosed equivalent of the Kunmarnara Group. The metamorphosed siliciclastic component of this unit is a centimetre- to metre-scale layered, muscovite-rich metasediment, with protoliths including fine- to coarse-grained muddy sandstone, coarse-grained arkosic sandstone, pebbly arkose, and matrix-supported conglomerate. The rock is both quartz- (up to 70%) and muscovite-rich (10–30%), typically with <10% feldspars preserved. Magnetite and zircon are common accessory minerals. Discontinuous, magnetite-rich (up to 35%) bands, up to 1 cm wide, are locally present. Pebbles are rarely preserved, but are almost exclusively composed of vein quartz. This metasedimentary rock is also heavily intruded by centimetre- to metre-wide quartz veins that are typically transposed and occasionally boudinaged slightly oblique to layering. Invariably strongly deformed, the rock's muscovite content is typically high enough to classify it as a phyllite, reflecting the hydrous metamorphism of an initially clay-rich or feldspathic matrix.

The metabasaltic component of this unit is a fine-grained amphibolite seen in the centre of an interpreted anticline. It comprises 50% green actinolite, 15% chlorite, 20% anhedral plagioclase, and 10% anhedral, recrystallized quartz. Actinolite forms the strong foliation, occurring as blades, up to 1 x 3 mm, partially replaced by chlorite. Very fine grained, euhedral epidote appears along grain boundaries. This component is also locally epidotized and intruded by quartz veins.

Age code	Proterozoic	P_-
Stratigraphic code	Kunmarnara Group	KR-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Metasedimentary siliciclastic	md
Rock type 2	Meta-igneous mafic intrusive	-mb
Rock code		**P_-KR-xmd-mb**

Depositional environment

The association of coarse-grained fluvial sedimentary rocks (MacDougall Formation) and basaltic andesites and andesites with a high-K intraplate geochemistry (Mummawarrawarra Basalt) seen in the Kunmarnara Group suggests deposition in an intracontinental rift-type setting.

Geochronology

P_-KR-xmd-mb	*Maximum*	*Minimum*
Age (Ma)	1172	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Evins et al., 2010	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample from layered mafic intrusive rocks of the Giles Suite emplaced within the Mummawarrawarra Basalt yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered BELL ROCK intrusion. Hence, an age of c. 1075 Ma can be inferred for these layered intrusions, and can also be interpreted as a minimum age of deposition of the Mummawarrawarra Basalt (Smithies et al., 2009). The maximum age of deposition is constrained by the youngest detrital zircon population (1172 ± 8 Ma, Evins et al., 2010) obtained from rocks of the MacDougall Formation, which forms the base of the Kunmarnara Group.

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Warakurna Supersuite (P_-WK-xo-f)

Legend narrative

Layered mafic–ultramafic intrusions; undivided

Rank	Supersuite
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

The Warakurna Supersuite groups all igneous intrusive and extrusive rocks related to the c. 1085 to 1040 Ma Giles Event. These rocks outcrop over an area of approximately 1.5 million km^2, extending from Western Australia into South Australia and the Northern Territory, together forming the Warakurna Large Igneous Province (Wingate et al., 2004). The intrusive rocks are dominantly mafic, including abundant and widespread dolerite sill and dyke swarms, but also include layered mafic–ultramafic intrusions (for example the Giles intrusions), and locally voluminous granitic sills, plugs, and plutons. In the west Musgrave region, rocks of the Warakurna Supersuite have intruded into, and overlie, rocks of the west Musgrave Province. Within this area, the supergroup is lithologically diverse, and includes several generations of granite intrusion (P_-WK-g) and mafic to ultramafic intrusions (P_-WKg-), as well as their mafic to felsic volcanic equivalents that form the magmatic components of the Bentley Supergroup (P_-BE-xs-f). The mafic to ultramafic intrusions are further subdivided, based on age and lithological range, into early, major, layered, mafic–ultramafic intrusions (Giles intrusions: P_-WKg1-), massive gabbro intrusions (P_-WKg2-), and late gabbro and ferrogabbro intrusions (formerly P_-WKg3-; now Alcurra Dolerite suite, P_-WKA-).

Distribution

The Warakurna Supersuite groups all igneous intrusive and extrusive rocks related to the c. 1085 to 1040 Ma Giles Event. These rocks outcrop over an area of approximately 1.5 million km^2, extending from Western Australia into South Australia and the Northern Territory, together forming the Warakurna Large Igneous Province (Wingate et al., 2004; Morris and Pirajno, 2005). Rocks in this supersuite also include the sill complexes and dykes of the Paleoproterozoic Earaheedy Basin, Mesoproterozoic Edmund Basin, and Neoproterozoic Collier Basin (Bangemall Supergroup) within the Capricorn Orogen. The Collier and Edmund sill complex alone is estimated to cover an area of about 143 000 km^2, with individual sills traceable for more than 60 km, and reaching in excess of 100 m in thickness. In some areas, sills may account for up to 60% of the total stratigraphic thickness. On the northern margin of the Earaheedy Basin, this sill complex (Glenayle Dolerite) extends for about 150 km east-southeast and about 60 km in a northerly direction, and becomes buried by Permian glacigene sedimentary rocks to the east. Individual sills may reach up to 100 m in thickness, although some sills consist of several thin (1–2 m) sheets separated by sedimentary rocks. The total thickness of the Glenyale Dolerite is not known, but geophysical data suggest that it may extend to depths of 3–4 km. Further east, basalt of a similar age becomes buried by the sedimentary rocks of the Officer Basin, and is intersected at a depth of 1600 m below the surface in the GSWA Empress 1 drillhole (Stevens and Apak, 1999).

Layered mafic–ultramafic rocks (Giles intrusions), mafic dykes (Alcurra Dolerite), felsic dykes, granitic rocks, and remnants of bimodal volcanics (basalt and rhyolite of the Bentley Supergroup), all of the same age, intrude and unconformably overlie the Musgrave Province in central Australia, and constitute part of the eastern portion of the Warakurna Large Igneous Province. The Giles intrusions (Giles Suite) include at least 20 variably deformed and metamorphosed sheet-like bodies that extend for roughly 550 km along an easterly trend, with a total north–south extent of over 100 km. Recent gravity surveys in Western Australia indicate that at least some of these intrusions may be linked at depth. Granitic rocks appear to form a significant component of the supersuite only within the Musgrave region, where they form stocks and dykes within, and marginal to, mafic to ultramafic rocks of the Giles intrusions, and larger plutons within gneisses and metamorphosed granites of the Musgrave Province, intruded between c. 1075 and 1050 Ma.

Lithology

In the Musgrave region, the Giles intrusions include gabbro, anorthosite, troctolite, gabbronorite, norite, pyroxenite (both clino- and ortho-), dunite, and peridotite. Granophyres are present both as dykes, and as masses up to 60 m thick locally capping layered gabbros. These rocks range from unmetamorphosed to those recrystallized in the granulite facies. In some cases, recrystallization is a result of contact with intrusions of subsequent magma batches; however, garnet coronas formed around mafic minerals in some intrusions points to a high-pressure regional-style metamorphism. The Giles intrusions have considerable potential for nickel–copper–PGE sulfide and iron–titanium–vanadium oxide mineralization.

In the Musgrave Province, granites of the Warakurna Supersuite are locally mylonitic, and these areas, plus contact zones with other lithologies, typically preserve metamorphic assemblages consistent with recrystallization at the amphibolite to granulite facies. However, these metamorphic effects are not well-developed away from such zones, where the granites typically range from fine to coarse grained, have equigranular to porphyritic igneous textures, and locally show rapakivi textures. They include hornblende- and biotite-bearing granites as well as charnockites, and have a strong A-type geochemical signature formed through high-temperature and dry crustal melting associated with mafic magmatic phases of the Warakurna Supersuite (Sun et al., 1996).

In the Musgrave region, the Bentley Supergroup has been divided into four groups, although the lower two — the Pussy Cat and Tollu Groups — may be laterally equivalent (Daniels, 1974). Three felsic volcanic–granite associations — Scamp, Palgrave, and Skirmish Hill — have also been recognized, and are apparently confined to, and define the extent of, three separate volcanic centres.

A lithologically similar sequence of volcanic, volcaniclastic, and clastic rocks lies to the north and in the footwall of the Woodroffe Thrust (between the Petermann and Bloods Ranges in both Western Australia and the Northern Territory), where it occurs unconformably beneath the basal sedimentary rocks of the Amadeus Basin. Close et al. (2003) redefined these rocks as the Tjauwata Group, incorporating and replacing the Bloods Range Beds and the Mount Harris Volcanics. Recent geochronological data (1085–1040 Ma; Edgoose et al., 2004) show that these units can be directly correlated with the Bentley Supergroup, specifically with the Tollu Group (Close et al., 2003).

To the south of the Musgrave Province, a drillhole intersected basalt beneath the basal sedimentary rock unit of the Officer Basin, which gave a K–Ar age of 1058 ± 13 Ma (Stevens and Apak, 1999); this suggests a southern extension of the Bentley Supergroup lies beneath this Neoproterozoic basin.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Mixed or Xenolith/ Inclusion Bearing	Mixed	x
Rock type 1	Igneous mafic intrusive	o
Rock type 2	Igneous felsic rock	-f
Rock code		**P_-WK-xo-f**

Geochronology

P_-WK-xo-f	*Maximum*	*Minimum*
Age (Ma)	1084 ± 9	1026 ± 26
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Edgoose et al., 2004	Kirkland et al., in prep.

Isotopic age determinations (SHRIMP U–Pb zircon and baddeleyite, K–Ar, Rb–Sr; Wingate et al., 2004 and references therein) obtained from mafic sills that intruded the Collier Basin in the Capricorn Orogen have yielded ages ranging from c. 1058 Ma to c. 1078 Ma. Basaltic rocks intersected at a depth of 1600 m in drillhole GSWA Empress 1A yielded a K–Ar age of 1058 ± 13 Ma (Stevens and Apak, 1999). Farther east, in central Australia, mafic–ultramafic rocks of the Giles Suite gave U–Pb zircon ages ranging from c. 1078 Ma to 1067 Ma (Sun et al., 1996; Glikson et al., 1996; GSWA data summarized in Evins et al., 2010).

SHRIMP U–Pb zircon ages obtained from rocks of the Bentley Supergroup range between c. 1075 and 1026 Ma (Sun et al., 1996; Glikson et al., 1996; GSWA data summarized in Evins et al., 2010); recent geochronological data (1085–1040 Ma SHRIMP U–Pb zircon and Pb–Pb zircon dates) show that the Tjauwata Group (in the southwest of the Northern Territory) can be directly correlated with the Bentley Supergroup (Close et al., 2003; Edgoose et al., 2004).

In the Northern Territory, granites of the Warakurna Supersuite form four main intrusions into the Musgrave Province, and these have been dated between 1080 and 1040 Ma (Edgoose et al., 2004). Individual granites in the west Musgrave Province have been dated (SHRIMP U–Pb zircon) to between c. 1078 and 1051 Ma (Sun et al., 1996; GSWA data summarized in Evins et al., 2010).

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Giles Suite (P_-WKg1-xo-a)

Legend narrative

Layered mafic–ultramafic intrusions; undivided

Rank	Suite
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This unit contains all of the layered mafic–ultramafic rocks of the Giles intrusions, which together form the oldest phases of the Giles Suite (Warakurna Supersuite). The unit includes large-scale troctolitic intrusions, such as Bell Rock (BELL ROCK), Blackstone (BLACKSTONE), and Jameson (FINLAYSON), and gabbroic intrusions such as the Hinckley Range (BELL ROCK), Michael Hills (BELL ROCK), Morgan Range (HOLT), and Cavenagh Range (BLACKSTONE–COOPER) intrusions. It also forms smaller-scale, more ultramafic intrusions, such as the Wart (BELL ROCK), Wingellina Hills (BELL ROCK), Latitude Hills (BELL ROCK), and Pirtiri Mulari (HOLT). The layered mafic–ultramafic intrusions of the Giles Suite have crystallization ages between c. 1078 and c. 1075 Ma.

Distribution

This mafic–ultramafic rock unit forms several large-scale intrusions such as Bell Rock (BELL ROCK), Blackstone (BLACKSTONE), Jameson (FINLAYSON), Hinckley Range (BELL ROCK), Cavenagh Range (BLACKSTONE–COOPER), and Michael Hills (BELL ROCK), plus smaller-scale intrusions such as Morgan Range (HOLT), the Wart (BELL ROCK), Wingellina Hills (BELL ROCK), Latitude Hills (BELL ROCK), and Pirntirri Mulari (HOLT).

Lithology

The unit incorporates a range of lithologies, including gabbro, troctolite, gabbronorite, olivine gabbro, olivine gabbronorite, norite, pyroxenite, and anorthosite. The Bell Rock, Blackstone, and Jameson intrusions are broadly troctolitic intrusions, whereas the Hinckley Range, Michael Hills, and Morgan Range are dominantly gabbroic intrusions. Several smaller-scale intrusions are composed of dominantly ultramafic lithologies, including the Wart, Wingellina Hills, North Hinckley Range, Latitude Hills, and Pirntirri Mulari.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Mixed or Xenolith/ Inclusion Bearing	Mixed	x
Rock type 1	Igneous mafic intrusive	o
Rock type 2	Igneous ultramafic intrusive	-a
Rock code		**P_-WKg1-xo-a**

Contact relationships

The Latitude Hills and Bell Rock intrusions are in contact with granites of the Wankanki (P_-WN-mg) and Pitjantjatjara Supersuites (P_-PJ-mg); parts of the Morgan, Blackstone, and Murray Range intrusions are in contact with early Pitjantjatjara Supersuite granite (PJ1-mg). The Blackstone and Cavenagh intrusions are overlain by the felsic volcanics of the Tollu Group (P_-TL-f), and the Bell Rock and Mount Muir intrusions are overlain by siliciclastic and mafic volcanic rocks of the Bentley Supergroup (P_-KR-xs-b). In the Hinckley Range and Murray Range, the mafic–ultramafic unit is in contact with mafic rocks of the Warakurna Supersuite (P_-WKg2-o). The Cavenagh Range and Lake Hills intrusions are in contact with granites of the Warakurna Supersuite (P_-WK-g).

Geochronology

P_-WKg1-xo-a	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite intrudes into the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-o)

Legend narrative

Mafic intrusive rock; massive or weakly layered; locally mingled with leucogranite; undivided

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This undivided mafic intrusive rock unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers or intrusions within the Blackstone Range (northern Blackstone), Cavenagh Range (western Blackstone), and in the southern part of the Blackstone map sheet. Where exposed, the unit is a medium- to coarse-grained mafic rock, and has an inferred crystallization age of c. 1075 Ma.

Distribution

This unit forms several layers within the Blackstone Range intrusion (northern Blackstone), and some layers at the northern margin of the Cavenagh intrusion (western Blackstone). To the north of the Tollu pluton and Mummawarrawarra Hill, and elsewhere on Blackstone, there are several occurrences of the unit interpreted partially or entirely using geophysical data (TMI).

Lithology

Where exposed, the unit is a fine- to coarse-grained, massive to foliated, plagioclase-porphyritic gabbro. The unit is largely interpreted from geophysical data, as it forms magnetic (TMI) lows within larger igneous bodies of higher magnetic (TMI) response.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Rock code		**P_-WKg1-o**

Contact relationships

Within the Blackstone intrusion, the unit is in contact with leucocratic troctolite (P_-WKg1-otly) and gabbro (P_-WKg1-ogjq). On the southwest side of the Blackstone intrusion, the unit is intruded by younger norite (formerly P_-WKg3-owq; now recoded as Alcurra Dolerite suite, P_-WKA-owq). In the northern part of the Cavenagh Range, the unit occurs as pods or lenses within a larger metamorphosed gabbro unit (P_-WKg1-moge). To the north of the Tollu pluton, the unit is in contact with felsic volcanics (P_-TLs-frp, P_-TLs-ftp) of the Tollu Group, and mafic volcanics of the Mummawarrawarra Basalt (P_-KRm-xmb-mo). In the southern part of the Blackstone map sheet, the unit is interpreted as intruding Wankanki metasyenogranite (P_-WN-mgrb), and rocks of the Wirku Metamorphics (P_-WM-xmh-mf).

Geochronology

P_-WKg1-o	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite intrudes into the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-oa)

Legend narrative

Medium- to coarse-grained anorthosite; massive to foliated; locally with symplectic intergrowths of clinopyroxene and plagioclase

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This anorthosite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several thin layers within the Hinckley Range, Michael Hills, Blackstone, and Bell Rock intrusions. The unit is a medium- to coarse-grained anorthosite, with cumulate to granoblastic, elongate textures where foliated. The unit has a crystallization age of c. 1075 Ma.

Distribution

This unit forms a near-vertical layer on the south side of the Bell Rock intrusion (e.g. BELL ROCK, MGA 471792E 7097858N), several discontinuous layers within the Michael Hills intrusion, and several minor layers in the Hinckley Range intrusion. At Michael Hills, this unit forms a subhorizontal layer, 10 m thick, at the summit (e.g. BELL ROCK, MGA 486228E 7102717N), which overlies leucogabbronorite (P_-WKg1-oml), plus a steeper northerly dipping lens in the south of the intrusion (e.g. BELL ROCK, MGA 497514E 7094784N) within a thicker unit of even-grained gabbro (P_-WKg1-oge).

Lithology

The unit is a medium- to coarse-grained anorthosite, with cumulate to granoblastic, elongate textures where foliated. The major minerals are plagioclase and orthopyroxene, with minor pale-green clinopyroxene, magnetite, and quartz and formed. Some pyroxene grains contain fine-grained inclusions of biotite and opaque minerals. Fine-grained magnetite is also present along grain boundaries. Where the unit is foliated, plagioclase has undulose extinction and mortar textures. Plagioclase is sericitized in places. Symplectite intergrowths of clinopyroxene and plagioclase are present at plagioclase–pyroxene margins, and seem to be associated, in places, with late magnetite.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Anorthosite	a
Rock code		**P_-WKg1-oa**

Geochronology

P_-WKg1-oa	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite intrudes into the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-oany)

Legend narrative

Medium-grained anorthosite interlayered on a cm- to m-scale with troctolite and olivine gabbronorite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine-rich anorthosite unit is a very minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming only one lens within the northern part of the Blackstone intrusion (BELL ROCK). The unit is a medium- to coarse-grained, medium to well-banded anorthosite, and has a crystallization age of c. 1075 Ma.

Distribution

Olivine-rich anorthosite forms a single lens, dipping moderately to the south, on the northern portion of the Blackstone intrusion (BLACKSTONE).

Lithology

This olivine-rich anorthosite unit is medium- to coarse-grained, and moderately to well-banded, with pyroxene-rich layers up to 1 cm thick. The unit contains plagioclase, olivine, clinopyroxene, orthopyroxene, and magnetite. Rare orthopyroxene rims are present on olivine grains.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Anorthosite	a
1st qualifier	Olivine	n
2nd qualifier	Layered/banded	y
Rock code		**P_-WKg1-oany**

Contact relationships

This olivine-rich anorthosite unit overlies the fine- to medium-grained metagabbro unit (P_-WKg1-moge) on the northern margin of the Blackstone intrusion, and is in turn overlain by the thick layer of leucocratic troctolite (P_-WKg1-otly) that forms the main body of the intrusion. The unit is intruded by several northeast-trending mafic dykes.

Geochronology

P_-WKg1-oany	Maximum	Minimum
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

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Giles Suite; subunit (P_-WKg1-oax)

Legend narrative

Medium-grained anorthosite to leucogabbroanorthosite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This anorthosite to leucogabbroanorthosite unit is a very minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming only one layer on the eastern side of the Cavenagh Range intrusion (western BLACKSTONE). The unit is composed of sheets of fine- to coarse-grained, plagioclase-porphyritic anorthosite, with plagioclase phenocrysts ranging in length from 5–8 mm, within a fine-grained and acicular-textured groundmass. The unit has a crystallization age of c. 1075 Ma.

Distribution

This anorthosite to leucogabbroanorthosite unit forms a shallowly dipping layer on the eastern side of the Cavenagh Range intrusion (western BLACKSTONE).

Lithology

This unit comprises interlayered sheets of fine- to coarse-grained plagioclase-porphyritic anorthosite, and rare leucogabbroanorthosite. Subhedral to euhedral plagioclase phenocrysts are 5–8 mm in length, and some are skeletal. Clinopyroxene is mostly interstitial, and partially replaced by chlorite. The groundmass is fine-grained and acicular textured, and the unit locally contains cognate xenoliths.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Anorthosite	a
1st qualifier	Pyroxene	x
Rock code		**P_-WKg1-oax**

Geochronology

P_-WKg1-oax	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-) and that the true intrusive period was likely to have been short.

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Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-otjy)

Legend narrative

Fine- to medium-grained leucotroctolite; well-developed cm-scale magmatic banding; locally magnetite-rich

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This layered magnetite-rich troctolite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a relatively small lens within a larger layered leucotroctolite unit (P_-WKg1-otly) on the east side of the Cavenagh Range (western BLACKSTONE). The troctolite shows centimetre-scale magmatic layering, and contains magnetite oikocrysts up to 1 cm in size. The unit has a crystallization age of 1075 Ma.

Distribution

There is one lens of this magnetite-rich troctolite unit, found within a larger leucotroctolite unit (P_-WKg1-otly) on the east side of the Cavenagh Range (western BLACKSTONE), on the south side of the Blackstone Sub-Basin. The lens strikes northwest–southeast and dips approximately 30° to the northeast.

Lithology

This unit is a fine- to medium-grained, magnetite-rich gabbro with centimetre-scale magmatic layering, which locally grades into leucogabbro containing magnetite oikocrysts up to 1 cm in size.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Troctolite	t
1st qualifier	Magnetite	j
2nd qualifier	Layered/banded	y
Rock code		**P_-WKg1-otjy**

Contact relationships

Outcrop of this unit is enclosed entirely within the leucotroctolite unit (P_-WKg1-otly).

Geochronology

P_-WKg1-otjy	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-otly)

Legend narrative

Coarse-grained leucotroctolite; layered; cumulate texture with glomeroporphyritic olivine commonly enclosed in orthopyroxene

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This layered leucotroctolite unit is a major component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming layers within the central portion of the Bell Rock (BELL ROCK), Blackstone (BLACKSTONE), and Jameson (FINLAYSON) intrusions. The leucotroctolite is interlayered with anorthosite, olivine gabbro, olivine-rich troctolite, gabbro, and gabbronorite. The unit is a coarse-grained layered leucotroctolite, and has an inferred intrusive age of c. 1075 Ma.

Distribution

This unit forms steeply dipping layers in the central portion of the Bell Rock intrusion (BELL ROCK). The layers of leucotroctolite are young and dip to the southwest, and form the dominant lithology within this intrusion. The main leucotroctolite zone overlies olivine gabbro, and structurally overlies both gabbronorite and gabbro to the northwest. In outcrop, the leucotroctolite commonly contains layers of glomeroporphyritic-textured olivine, which show broad cross-bedding that suggests younging to the southwest. On the south side of the Bell Rock intrusion (e.g. BELL ROCK, MGA 472541E 7098459N), the contact between this leucotroctolite and an olivine-rich troctolite (P_-WKgl-otn) is sheared.

Lithology

The troctolite is cumulate-textured, containing glomeroporphyritic olivine in places. The amounts of plagioclase and olivine vary, but minor orthopyroxene, magnetite, and accessory biotite contents are consistently low. Orthopyroxene commonly partially or entirely encloses olivine, but is rarely seen on weathered surfaces. Interstitial magnetite symplectites are common, as are magnetite inclusions that occur along pyroxene cleavage planes.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Troctolite	t
1st qualifier	Leuco-	l
2nd qualifier	Layered/banded	y
Rock code		**P_-WKg1-otly**

Geochronology

P_-WKg1-otly	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-otn)

Legend narrative

Olivine-rich troctolite; olivine poikilitic to granoblastic texture; contains up to 70% olivine; locally foliated

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine-rich troctolite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming layers up to 200 m thick within the Bell Rock and Blackstone intrusions. The troctolite is interlayered with a layered leucotroctolite. The unit is olivine poikilitic to granoblastic textured, and has an inferred crystallization age of c. 1075 Ma.

Distribution

This unit forms one near-vertical layer, up to 200 m thick, on the southwestern side of the Bell Rock intrusion (Bell Rock). It also forms several layers within the Blackstone intrusion. It has a red-brown weathered colour, which distinguishes it from the units it is in contact with. The distribution of olivine grains varies through the thickness of the layer, the more concentrated areas being on the northeast side of the layer, suggesting that way-up is to the southwest. The margin has a tectonic fabric, and magnesite is present in places.

Lithology

This olivine-rich, cumulate-textured troctolite is medium grained, and composed of olivine (70%), plagioclase (28%), clinopyroxene (2%), and accessory magnetite. Olivine locally shows a poikilitic to granoblastic texture. The rock shows a weak foliation close to the basal contact.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Troctolite	t
1st qualifier	Olivine	n
Rock code		**P_-WKg1-otn**

Contact relationships

This unit overlies a thick unit of coarse-grained leucotroctolite (P_-WKg1-otly) to the north of its outcrop, and is in turn overlain by a thinner unit of the same leucotroctolite to the south.

Geochronology

P_-WKg1-otn	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-og)

Legend narrative

Medium-grained, even-textured gabbro; locally olivine porphyritic

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming part of several intrusions, including North Hinckley Range, Wingellina Hills, Latitude Hills, the Wart, Bell Rock (all on BELL ROCK), and Morgan Range (HOLT). The unit is a medium- to coarse-grained layered gabbro, and has an inferred intrusive age of c. 1075 Ma.

Distribution

This unit forms several steeply dipping layers in the North Hinckley Range and Wingellina Hills intrusions, also forming parts of the Latitude Hills intrusion, the Wart, the eastern portion of the Bell Rock intrusion, the western margin of Mount West, and is the dominant lithology found in the Morgan Range.

Lithology

The unit is a layered, medium- to coarse-grained, equigranular gabbro. It contains primary plagioclase, clinopyroxene, orthopyroxene, olivine, and magnetite. Clinopyroxene is commonly enclosed in orthopyroxene. In the foliated gabbro, biotite inclusions are common within pyroxene. Local metamorphic textures include plagioclase coronas formed on olivine grains.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
Rock code		**P_-WKg1-og**

Contact relationships

In the Wingellina Hills and North Hinckley Range, this gabbro unit is interlayered with steeply dipping layers of poikilitic peridotite (P_-WKg1-apz), pyroxenite (P_-WKg1-ax), and olivine-rich melagabbro (P_-WKg1-ogxn). In the Bell Rock and Mount West areas, the unit is in contact with granite and gneiss of the Wankanki Supersuite (P_-WN-mgno, P_-WN-xmgn-mg). At the Wart, the unit is in contact with pyroxenite (P_-WKg1-ax); at Latitude Hills, the unit is interlayered with gabbro (P_-WKg1-ogx, P_-WKg1-ogp, P_-WKg1-ogy) and pyroxenite (P_-WKg1-ax). At the Morgan Range, the unit is interlayered with olivine gabbro (P_-WKg1-oojy), peridotite (P_-WKg1-apz), and olivine gabbronorite (P_-WKg1-ol), whereas at the margin of the intrusion it is in contact with granite hosts belonging to the Pitjantjatjara Supersuite (P_-PJ1-mgmn) and Wankanki Supersuite (P_-WN-xmfn-mh).

Geochronology

P_-WKg1-og	Maximum	Minimum
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-oge)

Legend narrative

Massive gabbro; even-grained; locally weakly metamorphosed

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This even-grained gabbro is a relatively minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), although it forms significant layers in the southern portion of the Michael Hills intrusion (Bell Rock). The unit is a pale brown, medium-grained gabbro, with an inferred age of c. 1075 Ma.

Distribution

This unit outcrops extensively on Bell Rock, forming significant parts of the southern portion of the Michael Hills layered intrusion.

Lithology

The unit is a pale brown, even-grained gabbro, with rare, thin (1–2 cm thick), igneous layering shown by pyroxene accumulation. Jointing is common along this layering. The unit is strongly foliated in the northeast of Michael Hills, towards the synform axis. The gabbro is medium grained, and contains plagioclase, orthopyroxene, clinopyroxene, magnetite (5%), and accessory biotite. The pyroxene crystals contain abundant inclusions of biotite and magnetite; magnetite is recrystallized along grain boundaries and mineral fractures. Some pyroxene grains are warped, and there is minor recrystallization of plagioclase along grain boundaries.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Even-grained/even textured/equigranular	e
Rock code		**P_-WKg1-oge**

Contact relationships

The unit is overlain by, and interleaved with, layers of anorthosite (P_-WKg1-oa) and norite (P_-WKg1-ow). This even-grained gabbro unit also contains lenses of anorthosite, and inclusions of fine-grained leucogabbronorite (P_-WKgl-omla).

Geochronology

P_-WKg1-oge	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-ogj)

Legend narrative

Fine- to coarse-grained gabbro; interstitial magnetite typically penetrates mineral fractures

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This magnetite-rich gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a major layer within both the Bell Rock (BELL ROCK) and the Murray Range (HOLT) intrusions. The unit is a medium- to coarse-grained, dominantly even-textured or equigranular, magnetite-rich gabbro. The unit has an inferred age of c. 1075 Ma.

Distribution

This unit forms a steeply southwest-dipping gabbro layer, approximately 800 m thick, on the southwest side of the Bell Rock Range (BELL ROCK); it also forms a near-vertical layer of similar thickness in the northeast portion of the Murray Range (HOLT).

Lithology

This gabbro is medium- to coarse-grained, and dominantly even-textured or equigranular. There is local small-scale igneous layering dominated by pyroxene layers of 1–2 cm thick, although no clear way-up indicators are present. Weathering surfaces are pale, but the unit has a high magnetite content that produces a relatively high magnetic susceptibility (2650–3500 x 10^{-5} SI). A weak foliation is locally developed. The rock consists of plagioclase, clinopyroxene, olivine, orthopyroxene, magnetite (up to 10%), and accessory biotite. The texture is dominantly igneous, although the texture may be partially granoblastic where deformation is more pervasive. In these areas, the gabbro contains large subhedral plagioclase laths with an interstitial granoblastic aggregate of clinopyroxene; olivine, and magnetite. Pyroxene commonly shows lamellae twinning. There is abundant rutile associated with magnetite and Fe–Ti oxide staining, and with inclusions along cleavage planes of pyroxene, and in fractures in olivine.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Magnetite	j
Rock code		**P_-WKg1-ogj**

Contact relationships

This unit overlies a thick layer of troctolite (P_-WKg1-otly), and is in turn overlain by a layer of leucogabbro of similar thickness (P_-WKg1-ogl). On the western side of the Murray Range a layer of this unit overlies olivine gabbronorite (P_-WKg1-ol), and is faulted against mylonitic amphibolite (P_-WKg2-moay).

Geochronology

P_-WKg1-ogj	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ogjq)

Legend narrative

Seriate-textured magnetite-rich gabbro; plagioclase phenocrysts and clinopyroxene or magnetite oikocrysts in a fine-grained and felsitic groundmass of plagioclase, quartz, and hornblende

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This quartz-bearing gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers and lenses within the Blackstone intrusion (BLACKSTONE). The unit is a medium-grained, locally acicular-textured, magnetite-rich gabbro, and has an inferred age of c. 1075 Ma.

Distribution

This unit forms several layers and lenses within the southern portion of the Blackstone intrusion (BLACKSTONE).

Lithology

This quartz-bearing gabbro is medium grained, and dominantly even-textured and equigranular, with a weak magmatic foliation. The gabbro contains acicular plagioclase phenocrysts, clinopyroxene oikocrysts, and magnetite oikocrysts, within a plagioclase groundmass. The unit is highly magnetite-rich (5–10%), and magnetite forms oikocrysts up to 4 mm in size. Hornblende forms rims on magnetite grains between contacts with plagioclase.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Magnetite	j
2nd qualifier	Quartz-bearing	q
Rock code		**P_-WKg1-ogjq**

Contact relationships

This quartz-bearing gabbro unit overlies a thick layer of leucocratic troctolite (P_-WKg1-otly) that forms the main body of the Blackstone intrusion, and is also interlayered with other mafic intrusive rocks of the Giles Suite (P_-WKg1-o). On the southern margin of the Blackstone intrusion, the unit is overlain by felsic volcanics (P_-TLs-frp). On the eastern side of this intrusion, this quartz-bearing gabbro is faulted against troctolite (P_-WKg1-otly); on the western side it is faulted against olivine gabbro (P_-WKg2-oob).

Geochronology

P_-WKg1-ogjq	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ogl)

Legend narrative

Medium- to coarse-grained leucogabbro; poikilitic; locally weakly metamorphosed

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This leucogabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming layers within the Bell Rock, the Wart, and the Michael Hills intrusions (BELL ROCK). The unit is a medium- to coarse-grained, poikilitic textured leucogabbro, and has an inferred age of c. 1075 Ma.

Distribution

This unit of leucogabbro forms one large, well-exposed layer on the southwest side of the Bell Rock Range (BELL ROCK). The layer dips steeply (80–85º) to the southwest and is at least 600 m in thickness. This leucogabbro also forms a layer on the western margin of the Wart (BELL ROCK), and a minor layer on the southern margin of the Michael Hills intrusion (BELL ROCK).

Lithology

At Bell Rock, the leucogabbro is medium to coarse grained and poikilitic in texture. It contains 80% plagioclase, 10% augite oikocrysts, and 10% poikilitic magnetite. Minor minerals include accessory amphibole, biotite, and chlorite. Plagioclase phenocrysts, 0.5 – 10 mm in length, are enclosed by both augite oikocrysts up to 20 mm in length, and magnetite oikocrysts up to 7 mm in length. Reaction textures include recrystallized coronas of clinopyroxene forming on augite, and recrystallized magnetite with multiple coronas of fine-grained biotite, chlorite, and plagioclase. At the Wart, the leucogabbro has slightly lower abundances of plagioclase and magnetite, greater amounts of orthopyroxene, and has suffered a higher degree of metamorphism than its equivalent at Bell Rock; for example, although some of the plagioclase poikilitic texture is preserved, much of the pyroxene has a granoblastic polygonal texture and vermicular intergrowths. In addition, magnetite is generally interstitial but has been concentrated along grain boundaries and fractures where recrystallized.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Leuco-	l
Rock code		**P_-WKg1-ogl**

Contact relationships

On the southwest side of Bell Rock Range, a layer of this unit overlies a layer of magnetite-rich gabbro (P_-WKg1-ogj), marking the top of the exposed mafic sequence. In the Wart intrusion, the unit overlies a gabbro unit (P_-WKg1-og) and also marks the top of the exposed mafic sequence. In the Michael Hills intrusion, the unit forms a narrow layer within a larger layered gabbro (P_-WKg1-ogy).

Geochronology

P_-WKg1-ogl	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of both granite and gabbro of 1075 ± 1 Ma (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ogn)

Legend narrative

Medium-grained olivine-bearing gabbro

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine-rich gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming one large intrusive body approximately 10 km southwest of the Bell Rock Range. The unit is a medium-grained, granophyric-textured, olivine-rich gabbro, and has an inferred age of c. 1075 Ma.

Distribution

This unit of olivine-rich gabbro forms one large intrusive body, approximately 10 km southwest of the Bell Rock Range (BELL ROCK and BLACKSTONE).

Lithology

This olivine-rich gabbro is medium to coarse grained, and granophyric and ophitic textured. It contains plagioclase, clinopyroxene oikocrysts up to 1 cm, and subhedral olivine. Clinopyroxene oikocrysts enclose both olivine and plagioclase.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Olivine	n
Rock code		**P_-WKg1-ogn**

Contact relationships

This intrusive body of olivine-rich gabbro is overlain by the Mummawarrawarra Basalt (P_-KRm-bbg).

Geochronology

P_-WKg1-ogn	Maximum	Minimum
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

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References

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Giles Suite; subunit (P_-WKg1-ogp)

Legend narrative

Medium-grained porphyritic gabbro; phenocrysts of orthopyroxene up to 6 mm

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This porphyritic gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming moderately to steeply dipping, north-trending layers on the northern side of Latitude Hill (BELL ROCK). The unit contains large euhedral orthopyroxene phenocrysts within a fine- to medium-grained intergranular groundmass of clinopyroxene, orthopyroxene, plagioclase, and opaque minerals. The unit has an inferred age of c. 1075 Ma.

Distribution

This unit forms two moderately to steeply dipping, north-trending layers on the northern side of Latitude Hill, in the southeastern area of BELL ROCK. Exposure of both layers is truncated by faults.

Lithology

This unit contains 10–15% large (up to 6 mm in length) euhedral orthopyroxene phenocrysts within a fine- to medium-grained intergranular groundmass. The groundmass contains clinopyroxene, orthopyroxene, plagioclase, accessory biotite, and opaque minerals. Clinopyroxene shows both simple and lamellae twinning. Warping and recrystallization is common in some plagioclase and pyroxene grains.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Porphyritic	p
Rock code		**P_-WKg1-ogp**

Contact relationships

This porphyritic gabbro unit forms two layers, approximately 50 m in width, in contact with gabbro (P_-WKg1-og) and melagabbro (P_-WKg1-ogx) layers of the Latitude Hill intrusion.

Geochronology

P_-WKg1-ogp	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ogx)

Legend narrative

Medium-grained intergranular to subophitic melagabbro

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This melagabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers within the Latitude Hills intrusion. The unit is a medium-grained, intergranular to subophitic melagabbro, and has an inferred age of c. 1075 Ma.

Distribution

This lithology forms several north-trending layers within the Latitude Hills intrusion (e.g. Bell Rock, MGA 492226E 7092258N). The melagabbro layers dip 50–80º to the west, and vary from 50–200 m thick. The layers are bounded by northwest-trending faults, and are displaced in a dextral sense by a fault of similar orientation. The large-scale layers of this lithology are interlayered with large layers of gabbro and pyroxenite. Where layering is on a centimetre scale, e.g. in the main body of Latitude Hills, this lithology forms a component of the layered gabbro (P_-WKgl-ogy).

Lithology

This melagabbro is medium grained, and intergranular to subophitic in texture. Major minerals are 65% augite, 30% plagioclase, and 5% orthopyroxene. Augite phenocrysts contain accessory amounts of biotite and opaque mineral inclusions, particularly along cleavage planes. Plagioclase and augite mutually enclose one another; augite generally partially encloses plagioclase, and tends to be wholly enclosed within the larger plagioclase phenocrysts, although smaller interstitial plagioclase is common.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Pyroxene	x
Rock code		**P_-WKg1-ogx**

Geochronology

P_-WKg1-ogx	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

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Giles Suite; subunit (P_-WKg1-ogxn)

Legend narrative

Olivine-porphyritic melagabbro; weakly metamorphosed

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine-porphyritic melagabbro is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming the dominant lithology in the North Hinckley Range. The unit is a medium-grained, olivine-porphyritic melagabbro with varied olivine content, and has an inferred age of c. 1075 Ma.

Distribution

This unit of olivine-porphyritic melagabbro forms the dominant lithology in the North Hinckley Range (Bell Rock), including several layers of melagabbro that dip 60–70º to the southwest. In the North Hinckley Range, the melagabbro layer overlies layers of poikilitic peridotite (P_-WKgl-apz) and pyroxenite (P_-WKgl-z). Within the melagabbro layer, the olivine content decreases up-sequence, eventually grading into a gabbro unit (P_-WKgl-og) towards the southwest.

Lithology

This medium-grained olivine-porphyritic gabbro contains a major mineral assemblage of 40–50% plagioclase, 40–50% clinopyroxene, 10% olivine, and an accessory opaque mineral phase. The texture is dominantly igneous, but becomes increasingly metamorphosed and deformed towards a shear zone on the south side of the North Hinckley Range. Where deformed, this unit is weakly foliated, and contains warped, elongate plagioclase crystals with undulose extinction. Recrystallized plagioclase phenocrysts, and more commonly pyroxene, show a granoblastic polygonal texture. Pyroxene phenocrysts are commonly altered to chlorite, but contain inclusions of biotite where fresh. Interstitial vermicular chlorite (after pyroxene) and plagioclase intergrowths are both present. Iddingsite and Fe-oxides are present in olivine along internal fractures and grain margins. Reaction textures include coronas of cloudy pink plagioclase forming on olivine.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Pyroxene	x
2nd qualifier	Olivine	n
Rock code		**P_-WKg1-ogxn**

Contact relationships

In the North Hinckley Range, the melagabbro layer overlies layers of poikilitic peridotite (P_-WKgl-apz) and pyroxenite (P_-WKgl-z). Within this layer, the olivine content decreases up-sequence, eventually grading into a gabbro unit (P_-WKgl-og) towards the southwest.

Geochronology

P_-WKg1-ogxn	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ogy)

Legend narrative

Gabbro; mm- and cm-scale layering of pyroxenite to anorthosite compositions; locally metamorphosed

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This layered gabbro unit is a component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a substantial portion of the Hinckley Range and Latitude Hills intrusions (BELL ROCK). The unit is a gabbro with millimetre- to centimetre-scale layering varying in composition between pyroxenite and anorthosite, and has an inferred age of c. 1075 Ma.

Distribution

This layered gabbro unit forms a substantial portion of the Hinckley Range and Latitude Hills intrusions (BELL ROCK). In the Hinckley Range, the unit dips 20–55° to the north, and is interlayered with anorthosite (layers 10 m wide). In the Latitude Hills region, the unit dips approximately 40º to the west, and is interlayered with pyroxenite.

Lithology

This unit comprises medium- to coarse-grained layered gabbro, with millimetre- to centimetre-scale layering varying in composition between pyroxenite and anorthosite. It has an intergranular to granoblastic texture containing plagioclase, clinopyroxene, orthopyroxene, and ilmenite. The unit is cut by abundant pseudotachylite veins.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Layered/banded	y
Rock code		**P_-WKg1-ogy**

Contact relationships

In the Hinckley Range, the layered gabbro is in contact with a biotite gabbro layer (P_-WKg2-ogb) to the south, whereas the northern margin is in faulted contact with the southern part of the North Hinckley Range. To the west, the unit is in contact with a gabbro that is variably mixed and mingled with granite (P_-WKg2-xog-g). In the Hinckley Range, the unit is also dissected by abundant dykes of the Kullal Dyke Suite (P_-KL-od).

Geochronology

P_-WKg1-ogy	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

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Giles Suite; subunit (P_-WKg1-ogz)

Legend narrative

Massive, weakly metamorphosed gabbro; well-developed ophitic to subophitic texture with oikocrysts up to 1 cm

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This ophitic gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a steeply dipping lens within the central portion of the Bell Rock intrusion (Bell Rock). The unit is massive to weakly layered and coarse grained, containing plagioclase, clinopyroxene, orthopyroxene, olivine, and interstitial magnetite. Clinopyroxene oikocrysts up to 1 cm in size commonly enclose plagioclase and olivine grains. The unit has an inferred age of c. 1075 Ma.

Distribution

This unit forms a northwest-trending lens within the central part of the Bell Rock intrusion.

Lithology

This ophitic gabbro unit is coarse grained, and contains plagioclase, clinopyroxene, orthopyroxene, olivine, and interstitial magnetite. Magnetite inclusions are present in pyroxene; clinopyroxene oikocrysts up to 1 cm in size commonly enclose plagioclase and olivine grains. This ophitic gabbro is commonly massive, although some portions show igneous layering defined by pyroxene-rich layers. This unit is commonly crosscut by pseudotachylite veins.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Ophitic	z
Rock code		**P_-WKg1-ogz**

Contact relationships

This ophitic gabbro forms a lens within the dominant leucocratic troctolite (P_-WKg1-otly) lithology of the Bell Rock intrusion.

Geochronology

P_-WKg1-ogz	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-occ)

Legend narrative

Medium-grained clinopyroxene melagabbro; intergranular to adcumulate texture

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This clinopyroxene melagabbro is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a layer, approximately 100 m thick, within the ultramafic layered intrusion known as 'the Wart', in the southern part of BELL ROCK. The clinopyroxene melagabbro is interlayered with clinopyroxenite. The unit is a medium-grained, intergranular to adcumulate-textured, clinopyroxene melagabbro, and has an inferred intrusive age of c. 1075 Ma.

Distribution

This lithology forms a near-vertical, north–south striking layer within the Wart intrusion (e.g. BELL ROCK, MGA 484798E 7094344N). The melagabbro layer is approximately 100 m thick, and lenses out towards the northern end of the intrusion. It is truncated by a fault to the south.

Lithology

The melagabbro is medium-grained, with an intergranular to adcumulate texture. The major mineral assemblage consists of approximately 70% lamellar twinned augite, 20% plagioclase, and 10% orthopyroxene. Very minor iron-staining occurs along some grain boundaries. Although the texture is dominantly igneous, some plagioclase phenocrysts show recrystallization and undulose extinction.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Clinopyroxene-gabbro	c
1st qualifier	Clinopyroxene	c
Rock code		**P_-WKg1-occ**

Geochronology

P_-WKg1-occ	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of both granite and gabbro of 1075 ± 1 Ma (Evins et al., 2010), within error of to the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-ol)

Legend narrative

Medium-grained, leucocratic olivine gabbronorite; locally with lesser troctolite, gabbronorite, olivine gabbro, and olivine norite; locally with centimetre- to metre-scale layers and lenses of fine-grained leucocratic olivine gabbronorite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine gabbronorite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers in the Murray Range (southern HOLT) and Cavenagh Range intrusions (western BLACKSTONE), and a single lens within the Blackstone intrusion (northern BLACKSTONE). In the Murray Range intrusion, the olivine gabbronorite unit contains inclusions of fine-grained gabbro. The olivine gabbro unit is a medium- to coarse-grained, massive to weakly layered olivine gabbronorite, locally with large orthopyroxene oikocrysts containing plagioclase chadacrysts. The unit has an inferred intrusion age of c. 1075 Ma.

Distribution

This olivine gabbronorite forms several layers within the Murray Range intrusion (southern HOLT), a lens within the Blackstone intrusion (northern BLACKSTONE), several layers in the Cavenagh Range intrusion (western BLACKSTONE), and a small part of the Morgan Range (northeastern HOLT).

Lithology

The unit is a medium- to coarse-grained, massive to weakly layered olivine gabbronorite, containing plagioclase, clinopyroxene, orthopyroxene, olivine, magnetite (as exsolved blebs in clinopyroxene and as a late interstitial phase), and trace secondary biotite. Large orthopyroxene oikocrysts containing plagioclase chadacrysts occur locally. Clinopyroxene grains contain abundant magnetite along exsolution planes. Orthopyroxene has clinopyroxene exsolution lamellae, and is likely inverted pigeonite. Within the Murray Range intrusion, the olivine gabbronorite unit contains inclusions of fine-grained gabbro.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbronorite	l
Rock code		**P_-WKg1-ol**

Contact relationships

In the southern part of the Murray Range intrusion, the unit is in contact with ophitic gabbro (P_-WKg1-ogz) and metaleucogranite (P_-PJ2-mgsi). In the northern part of the same intrusion (Butterfly Hill), the unit is in contact with layers of layered olivine gabbronorite (P_-WKg1-oly), olivine-rich troctolite (P_-WKg1-otn), and magnetite-rich gabbro (P_-WKg1-ogj). At the margins of the Murray Range layered intrusion to the north, the olivine gabbronorite unit is in contact with granite of the Pitjantjatjara Supersuite (P_-PJ-mgrs and P_-PJ-mg). Within the Blackstone intrusion, the unit forms a lens in the more dominant troctolite units (P_-WKg1-otly and P_-WKg1-otn). At the eastern margin of the Cavenagh intrusion, the unit is in contact with older units of Wankanki granite (P_-WN-mgrb and P_-WN-mgmo), Mummawarrawarra Basalt (P_-KRm-bbg), and Warakurna granite (P_-WK-gkhc). In the Morgan Range, the unit occupies a fold hinge, and is in contact with poikilitic peridotite (P_-WKg1-apz) and gabbro (P_-WKg1-og).

Geochronology

P_-WKg1-ol	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-ola)

Legend narrative

Fine-grained, locally well-layered leucocratic olivine gabbronorite, gabbronorite, and olivine gabbro; locally developed granoblastic texture induced by subsequent mafic magma injections

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This fine-grained olivine gabbronorite is a relatively minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers within the Cavenagh Range intrusion (western BLACKSTONE), where it is interlayered with a medium-grained olivine gabbronorite (P_-WKg1-ol). The unit is fine-grained, locally layered, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This fine-grained olivine gabbronorite unit forms several layers of the Cavenagh Range intrusion, on Mount Morphett (western BLACKSTONE). The unit is interlayered with, and forms inclusions within, the medium-grained olivine gabbronorite unit (P_-WKg1-ol); although the fine-grained olivine gabbronorite also contains inclusions of the medium-grained olivine gabbronorite unit.

Lithology

This fine-grained olivine gabbronorite locally contains plagioclase phenocrysts 2–3 mm in size, abundant pyroxene oikocrysts up to 1 cm, and well-developed millimetre-scale layering. The mineral assemblage includes plagioclase, orthopyroxene, clinopyroxene, and olivine, with minor magnetite and accessory biotite. Pyroxene symplectites are common.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbronorite	l
1st qualifier	Fine-grained	a
Rock code		**P_-WKg1-ola**

Contact relationships

In the Cavenagh Range intrusion, the olivine gabbronorite unit is interlayered with the medium-grained olivine gabbronorite unit (P_-WKg1-ol). On the east side of this range, the olivine gabbronorite unit is in faulted contact with Mummawarrawarra Basalt (P_-KRm-bbg); the unit is overlain by the same basalt to the north. This fine-grained olivine gabbronorite unit is also cut by a dolerite dyke trending 010º.

Geochronology

P_-WKg1-ola	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-om)

Legend narrative

Medium- to coarse-grained gabbronorite; equigranular; massive to weakly layered; locally foliated

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This gabbronorite is a relatively minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers within the Michael Hills intrusion and a minor layer in the Bell Rock intrusion (Bell Rock). The gabbronorite is medium-grained, massive to foliated, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This unit forms several layers within the Michael Hills intrusion and one layer in the Bell Rock intrusion. On Bell Rock, this unit is unmetamorphosed except where deformed by shear zones and large-scale folding. It is well-exposed on the northern side of Michael Hills, where it underlies the main leucogabbronorite unit (P_-WKg1-oml); in this area, the unit is approximately 400 m thick, and in faulted contact with gneissic granite of the Wankanki Supersuite (P_-WN-mgno). On the southern side, the thickness is generally similar, although where the eastern end of the layered intrusion is warped, it dips more steeply and the apparent thickness is less.

Lithology

This gabbronorite is medium-grained, and contains plagioclase, orthopyroxene, and clinopyroxene, with minor magnetite and accessory biotite. Pyroxene contains inclusions of biotite and magnetite. Fine-grained magnetite grains have crystallized along grain boundaries and mineral fractures. Some orthopyroxene grains also contain likely relict clinopyroxene, suggesting a degree of metamorphism; however, much of this orthopyroxene appears to be primary.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbronorite	m
Rock code		**P_-WKg1-om**

Geochronology

P_-WKg1-om	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

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Giles Suite; subunit (P_-WKg1-oml)

Legend narrative

Medium-to coarse-grained leucogabbronorite; equigranular; massive to layered on cm-scale; locally weakly foliated

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This leucogabbronorite unit is a component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming the main component of the Michael Hills intrusion on BELL ROCK. The unit is a medium to coarsegrained, intergranular textured leucogabbronorite, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This unit is the main lithological component of Michael Hills, forming a large, shallowly dipping, synformal layer in the centre of the intrusion. It is mineralogically layered, and shows upwards-fining structures (e.g. BELL ROCK, MGA 486130E 7103156N). In places, it contains large (up to 2 cm) magnetite clusters, fine-grained magnetite seams, and pyroxene-rich layers.

Lithology

The leucogabbronorite is medium to coarse grained, with an intergranular texture. Major minerals are plagioclase, orthopyroxene, clinopyroxene, and magnetite, with accessory biotite. Pyroxene phenocrysts contain a high proportion of fine-grained biotite and magnetite inclusions, which occur commonly along cleavage planes. Fine-grained magnetite is also common along grain boundaries.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbronorite	m
1st qualifier	Leuco-	l
Rock code		**P_-WKg1-oml**

Contact relationships

To the north, this unit overlies gabbronorite (P_-WKg1-om); to the south it is in contact with a lens of layered gabbronorite. It is overlain by layered gabbronorite (P_-WKgl-ogy) and anorthosite (P_-WKgl-oa).

Geochronology

P_-WKg1-oml	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-omal)

Legend narrative

Fine-grained, even-textured leucogabbronorite; forms sills, dykes, and xenoliths

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This fine-grained leucogabbronorite is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming dykes, sills, and xenoliths within the Bell Rock, Michael Hills, and Hinckley Range intrusions. The unit is a fine-grained, intergranular to poikilitic textured leucogabbronorite, and has an inferred intrusive age of c. 1075 Ma.

Distribution

This unit forms several narrow sills or dykes within the Bell Rock, Michael Hills, and Hinckley Range intrusions on BELL ROCK. In places, the coarser-grained country rocks back-veins the fine-grained leucogabbronorite sills, suggesting emplacement at a late magmatic stage (Glikson et al., 1996). There is also a quenched leucogabbronorite dyke, 1 m wide, exposed on the south side of Michael Hills (e.g. BELL ROCK, MGA 485631E 7101310N).

Lithology

This lithology consists of fine-grained, intergranular to poikilitic textured leucogabbronorite sills, xenoliths, and quenched dykes. Although the texture is dominantly igneous, minor metamorphic recrystallization is evident in places. The fine-grained leucogabbronorite contains plagioclase, clinopyroxene, orthopyroxene, and magnetite, with accessory biotite. Plagioclase is poikilitic (enclosing smaller pyroxene crystals), and commonly shows undulose extinction and minor sericitization. Inclusions of magnetite and biotite are occasionally present along cleavage planes in pyroxene.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbronorite	m
1st qualifier	Fine-grained	a
2nd qualifier	Leuco-	l
Rock code		**P_-WKg1-omal**

Geochronology

P_-WKg1-omal	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-omy)

Legend narrative

Fine-grained gabbronorite; weakly laminated; abundant magnetite oikocrysts up to 2 cm

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This laminated gabbronorite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several thin layers within the Michael Hills intrusion (Bell Rock). The unit is a fine to medium grained, cumulate-textured gabbronorite, with an inferred intrusive age of c. 1075 Ma.

Distribution

This laminated gabbronorite unit forms several thin, subhorizontal layers, up to 20 m thick, within the Michael Hills intrusion (eastern Bell Rock). Approximately 4.8 km south of the Michael Hills summit, the unit overlies gabbronorite (P_-WKg1-om), and is in turn overlain by even-grained gabbro (P_-WKg1-oge). To the west of this locality, this unit forms a layer dipping approximately 30º to the north that is in faulted contact with the main leucogabbronorite (P_-WKg1-oml). Layering in this laminated gabbronorite unit is defined by horizons dominated either by magnetite (layers to several millimetres thick) or pyroxene (layers to 1 cm thick).

Lithology

This gabbronorite is a fine to medium grained, cumulate to poikilitic textured rock. The major minerals are plagioclase, orthopyroxene, clinopyroxene, and magnetite, with accessory biotite. Magnetite and biotite inclusions are common along the cleavage planes of pyroxene phenocrysts. Plagioclase often encloses, or partially encloses, both orthopyroxene and clinopyroxene grains.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbronorite	m
1st qualifier	Layered/banded	y
Rock code		**P_-WKg1-omy**

Geochronology

P_-WKg1-omy	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-oo)

Legend narrative

Fine- to medium-grained olivine gabbro; massive to weakly foliated; locally shows cm-scale mineralogical banding

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine gabbro is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming intrusive bodies in the Lake Hills area (BELL ROCK) and within the northern part of the Murray Range (HOLT). It is a medium- to coarse-grained, equigranular to ophitic, olivine gabbro with local magmatic layering, and has an inferred intrusive age of c. 1075 Ma.

Distribution

This olivine gabbro unit forms a small intrusive body near Lake Hills (BELL ROCK), also forming a narrow layer in the northern part of the Murray Range (HOLT).

Lithology

This unit is a medium- to coarse-grained, equigranular to ophitic, olivine gabbro, containing pyroxene oikocrysts up to 7 mm in size. Olivine grains are rimmed by orthopyroxene, and are included within plagioclase and clinopyroxene. The unit is typically massive, but locally shows weak magmatic layering on the scale of 5–10 m.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbro	o
Rock code		P_-WKg1-oo

Contact relationships

In the Murray Range, the olivine gabbro unit is in contact with other units of the Warakurna Supersuite, specifically, porphyritic to seriate-textured syenogranite (P_-WK-grl) to the east, and younger magnetite-rich gabbro (P_-WKg2-ogj) to the west. In the Lake Hills area, the olivine gabbro unit is in contact with porphyritic to seriate-textured syenogranite (P_-WK-grl).

Geochronology

P_-WKg1-oo	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

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Giles Suite; subunit (P_-WKg1-ooj)

Legend narrative

Medium-grained olivine gabbro; magnetite aggregates up to 5 mm

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This magnetite-rich olivine gabbro is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming lenses or layers within both the Bell Rock (BELL ROCK) and Finlay intrusions (FINLAYSON). The unit is a medium- to coarse-grained, adcumulate-textured, magnetite-rich olivine gabbro, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This unit forms a small, steeply dipping lens at the northwestern end of the Bell Rock intrusion (BELL ROCK). Several layers of this lithology also occur within the Finlay intrusion (FINLAYSON).

Lithology

The unit is a medium- to coarse-grained, magnetite-rich olivine gabbro, containing aggregates of magnetite up to 5 mm in size. It has an adcumulate texture, is plagioclase-rich, and has interstitial clinopyroxene forming oikocrysts. Olivine crystals are elongate, enclose plagioclase grains, and are in turn commonly enclosed in pyroxene.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbro	o
1st qualifier	Magnetite	j
Rock code		**P_-WKg1-ooj**

Contact relationships

In the Bell Rock intrusion, this unit forms a lens within a layer of layered leucotroctolite (P_-WKg1-otly). Within the Finlay intrusion, this magnetite-rich olivine gabbro is interlayered with olivine-rich gabbro (P_-WKg1-ogn) and olivine gabbronorite (P_-WKg1-ol).

Geochronology

P_-WKg1-ooj	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-oojy)

Legend narrative

Olivine gabbro; magnetite-rich layers 1–2 m thick

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This layered olivine gabbro unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a thin layer within the Bell Rock intrusion (BELL ROCK and HOLT), and an interpreted layer within the layered intrusion at Mount Muir (HOLT). The unit is a medium- to coarse-grained olivine gabbro, interlayered with 1–2 m scale layers of magnetite-rich gabbro. It has an inferred intrusive age of c. 1075 Ma.

Distribution

This unit forms a narrow, steeply dipping layer within the northern portion of the Bell Rock intrusion (BELL ROCK and HOLT), and also occurs as an interpreted layer within the layered intrusion at Mount Muir (HOLT).

Lithology

The unit is a medium- to coarse-grained olivine gabbro interlayered with 1–2 m scale layers of magnetite-rich gabbro. Locally, the unit contains veins and stringers of magnetite, as well as blocks of magnetite up to 5 cm in size. The magnetite-rich gabbro contains lobate and brecciated plagioclase crystals and plagioclase–clinopyroxene inclusions up to 1 cm in size, within a matrix of opaque minerals.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbro	o
1st qualifier	Magnetite	j
2nd qualifier	Layered/banded	y
Rock code		**P_-WKg1-oojy**

Geochronology

P_-WKg1-oojy	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

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References

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Kirkland, CL, Wingate, MTD and Smithies, RH 2011a, 194762: leucogabbro, Mount Finlayson; Geochronology Record 966: Geological Survey of Western Australia, 4p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Giles Suite; subunit (P_-WKg1-ow)

Legend narrative

Coarse-grained, massive to foliated norite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This norite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming one layer within the Michael Hills intrusion (BELL ROCK). The unit is a coarse-grained equigranular norite, with an inferred intrusion age of c. 1075 Ma.

Distribution

This unit is confined to BELL ROCK, where it forms one thin layer within the Michael Hills intrusion (e.g. BELL ROCK, MGA 490260E 7097432N). The norite layer is truncated by a major fault at the western end of this intrusion.

Lithology

This norite is coarse-grained with an equigranular texture. It contains mainly plagioclase and lamellae-twinned orthopyroxene, although inclusions of fine-grained biotite and opaque minerals are common along cleavage planes of pyroxene, and magnetite is commonly recrystallized along grain boundaries. Some pyroxene crystals show warping, and there is minor evidence of plagioclase recrystallization.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Norite	w
Rock code		**P_-WKg1-ow**

Contact relationships

To the north of the Michael Hills intrusion, this norite is overlain by a layer of gabbronorite (P_-WKg1-om), and the unit in turn overlies a thicker unit of massive gabbro (P_-WKg1-oge) to the south. The norite unit is dissected by sheets of fine-grained leucogabbronorite (P_-WKgl-omla), and by a series of northwest-trending faults and mafic dykes, some of the latter belonging to the Gairdner Dolerite. The norite layer is truncated by a major fault at the western end of its exposure.

Geochronology

P_-WKg1-ow	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

Kirkland, CL, Wingate, MTD and Smithies, RH 2011a, 194762: leucogabbro, Mount Finlayson; Geochronology Record 966: Geological Survey of Western Australia, 4p.

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Giles Suite; subunit (P_-WKg1-owc)

Legend narrative

Medium- to coarse-grained norite and lesser gabbronorite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This norite and lesser gabbronorite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a layer, approximately 10 m thick, within the east portion of the layered intrusion at Mount Morphett (BLACKSTONE). The norite is interlayered with fine-grained leucogabbronorite, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This lithology forms a layer within a layered intrusion on the east side of Mount Morphett (e.g. BLACKSTONE, MGA 400491E 7094432N). This layer dips approximately 10° to the west, overlies leucocratic olivine gabbronorite (P_-WKg1-ol), and lies within a larger layer of fine-grained leucocratic gabbronorite (P_-WKg1-ola).

Lithology

This unit consists of medium- to coarse-grained norite and lesser gabbronorite.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous mafic intrusive	o
Lithname	Norite	w
1st qualifier	Clinopyroxene	c
Rock code		**P_-WKg1-owc**

Geochronology

P_-WKg1-owc	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

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Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Giles Suite; subunit (P_-WKg1-moge)

Legend narrative

Fine- to medium-grained metagabbro and metagabbronorite; well-developed granoblastic texture caused by later mafic magma injections; locally interlayered with leucocratic olivine gabbronorite, olivine gabbro, and olivine norite

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This metagabbro and metagabbronorite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a layer on the north side of the Cavenagh Range (western Blackstone). The unit is dominated by fine- to medium-grained, magnetite-rich, even-textured metagabbro, but is locally granophyric to acicular, or shows weak magmatic layering. It has an inferred intrusion age of c. 1075 Ma.

Distribution

This metagabbro and metagabbronorite unit forms a layer on the north side of the Cavenagh Range, dipping 40° to the northeast.

Lithology

This unit is a fine- to medium-grained and magnetite-rich metagabbro and metagabbronorite. The texture is generally equigranular and even-textured, but locally granophyric to acicular, and with magnetite oikocrysts in places. The mineral assemblage contains plagioclase, clinopyroxene, orthopyroxene, olivine, magnetite, and hornblende. Quartz–magnetite intergrowths are common, and magnetite inclusions are present both in pyroxenes and along fractures within olivine. The unit is commonly massive, but has weak magmatic layering, locally defined by varying proportions of magnetite. Large extents of this unit are silicified and epidotized along fracture sets trending 140°.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro	g
1st qualifier	–	
2nd qualifier	Granofels/hornfels	e
Rock code		**P_-WKg1-moge**

Contact relationships

This metagabbro and metagabbronorite unit is overlain by olivine gabbronorite (P_-WKg1-ol) and porphyritic rhyolite (P_-TLs-frp) to the north of the Cavenagh Range intrusion, and is in faulted contact with olivine gabbronorite (P_-WKg1-ol) to the south.

Geochronology

P_-WKg1-moge	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

Kirkland, CL, Wingate, MTD and Smithies, RH 2011a, 194762: leucogabbro, Mount Finlayson; Geochronology Record 966: Geological Survey of Western Australia, 4p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

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Giles Suite; subunit (P_-WKg1-momq)

Legend narrative

Strongly silicified medium-grained olivine gabbronorite and olivine gabbro

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This metagabbronorite is a very minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming a single layer on the northeast side of the Cavenagh Range (western BLACKSTONE). The metagabbronorite is medium-grained, strongly silicified and fractured, and acicular to granophyric. This unit is likely the silicified equivalent of the olivine gabbronorite unit (P_-WKg1-ola), and has an inferred intrusion age of c. 1075 Ma.

Distribution

This metagabbronorite unit forms a single, relatively minor layer on the northeast side of the Cavenagh Range intrusion (e.g. BLACKSTONE, MGA 402108E 7103762N).

Lithology

The unit is a medium-grained, strongly silicified and fractured, acicular to granophyric metagabbronorite, likely the silicified equivalent of the olivine gabbronorite unit (P_-WKg1-ola).

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro norite	m
1st qualifier	–	
2nd qualifier	Quartzose; silicified	q
Rock code		**P_-WKg1-momq**

Contact relationships

On the northeast side of the Cavenagh Range, this metagabbronorite layer overlies the fine-grained olivine gabbronorite unit (P_-WKg1-ola); on the range's north side, the unit is in contact with trachytic felsic volcanic rocks (P_-TLs-ftpz), and in faulted contact with olivine gabbronorite (P_-WKg1-ol).

Geochronology

P_-WKg1-momq	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

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Giles Suite; subunit (P_-WKg1-moty)

Legend narrative

Mylonitic leucotroctolite; layered protolith

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This mylonitic leucotroctolite is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming in shear zones that crosscut the layered leucotroctolite unit (P_-WKg1-otly) within the central portion of the Bell Rock, Blackstone, and Jameson intrusions. The unit is a fine-grained ultramylonitic to protomylonitic leucotroctolite, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This unit forms along shear zones that crosscut the steeply dipping layers of the layered leucotroctolite (P_-WKg1-otly) on the southern margin of the Bell Rock, Blackstone, and Jameson intrusions.

Lithology

This mylonitic leucotroctolite is mostly an ultramylonite, but grades to protomylonite at the shear zone margins. It contains plagioclase, olivine, orthopyroxene, magnetite, and accessory biotite.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metatroctolite	t
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-WKg1-moty**

Geochronology

P_-WKg1-moty	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Giles Suite; subunit (P_-WKg1-mosy)

Legend narrative

Mylonite derived from mafic intrusive rock

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This mylonitic mafic rock is a very minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), occupying shear zones in the Bell Rock and Blackstone intrusions. The unit is a fine-grained, strongly foliated ultramylonite; the protolith is inferred to have an intrusive age of c. 1075 Ma.

Distribution

This mylonitic mafic rock forms within two northwest-trending shear zones in the eastern end of the Bell Rock intrusion (BELL ROCK). An additional minor lens occurs at the widest part of a north-northwesterly trending shear zone that crosscuts the eastern part of the Blackstone intrusion (BLACKSTONE).

Lithology

This mylonitic mafic rock is an ultramylonite 100–150 m in width. The protolith for the westernmost of the two shear zones was most likely troctolite; the protolith for the eastern shear zone is mostly undeterminable, but at least locally includes granite (Wankanki Supersuite).

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Mafic schist derived from intrusive rock	s
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-WKg1-mosy**

Contact relationships

In the Bell Rock intrusion, this unit is in contact with the eastern margin of the leucocratic troctolite (P_-WKg1-otly); it also forms two shear zones on either side of the gabbronorite unit (P_-WKg1-om), and on the western margin of the gabbro unit (P_-WKg1-og) in the eastern part of the Bell Rock intrusion. The northern part of the most easterly contact is with Wankanki Supersuite granite (P_WN-mg).

Geochronology

P_-WKg1-mosy	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

References

Evins, PM, Smithies, RH, Howard, HM, Kirkland, CL, Wingate, MTD and Bodorkos, S 2010, Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia: Geological Survey of Western Australia, Record 2010/6, 36p.

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Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

Smithies, RH, Howard, HM, Evins, PM, Kirkland, CL, Bodorkos, S and Wingate, MTD 2009, West Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies: Geological Survey of Western Australia, Record 2008/19, 20p.

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Giles Suite; subunit (P_-WKg1-apz)

Legend narrative

Poikilitic peridotite; olivine orthocumulate with poikilitic clinopyroxene and interstitial plagioclase

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This poikilitic peridotite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKgl-xo-a), forming several narrow layers within the North Hinckley Range (Bell Rock), Morgan Range (Holt), and Pirntirri Mulari (Holt) intrusions. The unit is an olivine orthocumulate with poikilitic clinopyroxene and interstitial plagioclase, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This unit forms several near-vertical layers within the North Hinckley Range (Bell Rock), Morgan Range (Holt), and Pirntirri Mulari (Holt) intrusions. A good example of this peridotite can be observed in the North Hinckley Range (e.g. Bell Rock, MGA 499248E 7115607N), where several layers, 10–20 m wide, dip 60–70º to the southwest.

Lithology

This unit is a cumulate-textured poikilitic peridotite, composed of orthocumulate textured olivine, poikilitic clinopyroxene, and plagioclase grains that are entirely interstitial to clinopyroxene. Clinopyroxene oikocrysts are 1–7 cm in length.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous ultramafic intrusive	a
Lithname	Pyroxene peridotite	p
1st qualifier	Ophitic	z
Rock code		**P_-WKg1-apz**

Contact relationships

This lithology forms several layers in the well-layered North Hinckley Range intrusion; here, the peridotite layer usually overlies a massive pyroxenite layer (20 m wide), and is in turn overlain by thicker (~100 m) olivine-porphyritic melagabbro layers. It is interpreted to lie near the base of each of these magmatic sequences.

Geochronology

P_-WKg1-apz	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on Finlayson) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-ax)

Legend narrative

Massive pyroxenite; locally weakly metamorphosed; adcumulate to poikilitic texture

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This massive pyroxenite is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several narrow layers, approximately 10 m thick, within ultramafic layered intrusions such as the Wart, Latitude Hills, and North Hinckley Range. The pyroxenite is interlayered with gabbro, melagabbro, layered gabbro, and peridotite. The unit is a medium- to coarse-grained adcumulate-textured pyroxenite, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This lithology forms several near-vertical, north–south striking layers in the central part of the Wart intrusion, and several narrow layers within both the Latitude Hills and North Hinckley Range (BELL ROCK) intrusions. A good example of this lithology can be observed in the North Hinckley Range (e.g. BELL ROCK, MGA 499286E 7115613N), where the pyroxenite layers mark the base of the sequence and are overlain by poikilitic peridotite. The massive pyroxenite layers are approximately 10 m thick, and discrete layers are usually distinguished from other lithologies in the sequence by their dark weathered surface.

Lithology

This lithology forms layers of medium- to coarse-grained, adcumulate textured pyroxenite containing 90% augite, 5% orthopyroxene, 3% interstitial plagioclase, and 2% olivine. Accessory biotite and opaque minerals are also present. Although the texture is dominantly adcumulate, it is poikilitic in places where occasional orthopyroxene oikocrysts, up to 10 mm in length, enclose lamellae-twinned clinopyroxene. Minor metamorphic reactions are also evident in the thin mortar textures seen on pyroxenes, and in the minor plagioclase coronas developed on olivine grains. Plagioclase shows undulose extinction in places. Accessory opaque inclusions are present in pyroxene crystals, and iron-staining occurs along grain boundaries and fractures. Olivine also shows alteration to serpentine and iddingsite.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous ultramafic intrusive	a
Lithname	Pyroxenite	x
Rock code		**P_-WKg1-ax**

Contact relationships

In the North Hinckley Range, layers of the massive pyroxenite unit mark the base of the sequence and are overlain by poikilitic peridotite; this massive pyroxenite overlies gabbro and melagabbro. In the Latitude Hills intrusion, the massive pyroxenite is interlayered with massive gabbro and layered gabbro. In the Wart intrusion, the pyroxenite is in contact with clinopyroxenite and gabbro.

Geochronology

P_-WKg1-ax	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite; subunit (P_-WKg1-axc)

Legend narrative

Medium-grained clinopyroxenite; adcumulate texture

Rank	Formation
Parent	Giles Suite (P_-WKg1-xo-a)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This clinopyroxenite unit is a minor component of the Giles intrusions of the Warakurna Supersuite (P_-WKg1-xo-a), forming several layers within the layered ultramafic Wart intrusion. The clinopyroxenite unit is interlayered with pyroxenite and clinopyroxene melagabbro. The unit is a medium- to coarse-grained adcumulate-textured clinopyroxenite, and has an inferred intrusion age of c. 1075 Ma.

Distribution

This lithology forms several near-vertical, north-striking layers within the Wart intrusion (e.g. BELL ROCK, MGA 484599E 7094372N). At the northern end of the intrusion, the clinopyroxenite layer is 75 m thick, widening to several hundred metres thick at the southern end. It is overlain to the west by pyroxenite, and contains lenses of clinopyroxene melagabbro. This layer forms the base of the sequence at the Wart, and shows intrusive contacts with the metamorphosed migmatitic leucogranite (P_-mgli-MU) on the intrusion's southeastern margin. Much of the northern part of this layer is truncated by a shear zone.

Lithology

The clinopyroxenite is medium to coarse grained, with a dominantly adcumulate texture and minor poikilitic clinopyroxene. The mineral assemblage consists of 90% clinopyroxene, 5% interstitial plagioclase, and 3% olivine with iddingsite alteration. Minor metamorphic reaction textures are evidenced by plagioclase coronas developed on olivine and clinopyroxene symplectites.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg1-
Rock type	Igneous ultramafic intrusive	a
Lithname	Pyroxenite	x
1st qualifier	Clinopyroxene	c
Rock code		**P_-WKg1-axc**

Geochronology

P_-WKg1-axc	*Maximum*	*Minimum*
Age (Ma)	1078	1075
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; Kirkland et al., 2011a,b

A sample of these layered rocks obtained from Mount Finlayson (on FINLAYSON) yielded a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011a); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for emplacement of the layered intrusions (Smithies et al., 2009). A younger phase of the Giles Suite comprises a range of massive, unlayered, gabbros (P_-WKg2-o), typically co-mingled with Warakurna Supersuite granites (P_-WK-g). Seven samples of the granite have been dated, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), within error of the inferred crystallization age of the layered mafic–ultramafic rocks. In all cases where contacts are observed, the co-mingled gabbro and granite has intruded the layered mafic–ultramafic rocks, suggesting both that the c. 1075 Ma crystallization age estimate obtained for the latter rock type is a reasonable approximation of the minimum crystallization age of the layered rocks (P_-WKg1-), and that the true intrusive period was likely to have been short.

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Giles Suite (P_-WKg2-o)

Legend narrative

Mafic intrusive rock; massive or weakly layered; locally mingled with leucogranite; undivided

Rank	Suite
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This is the parent unit for all mafic rocks, typically massive gabbro, forming the second main phase of mafic magmatism (P_-WKg2) within the Giles Suite (Warakurna Supersuite). These mafic intrusive rock units outcrop on Bell Rock, Bates, Holt, Finlayson and Blackstone. SHRIMP U–Pb zircon ages for seven Warakurna Supersuite granites (P_-WK-g) co-mingled with massive gabbros of this unit give a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro.

Distribution

This mafic intrusive rock unit, encompassing all rocks formed during the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite (Warakurna Supersuite), outcrops in a dominantly northwest–trend along, or near, the northern margin of the Tjuni Purlka Tectonic Zone, on Bell Rock, Bates, and Holt. The unit also dominates outcrop in the west Hinckley (Bell Rock) and Murray Ranges (Holt), and forms minor outcrop on Finlayson and Blackstone.

Lithology

This mafic intrusive rock unit encompasses units of several lithologies, including gabbro, olivine gabbro, metamorphosed anorthosite, metagabbro, and metagabbronorite. However, the most widespread of units grouped within this parent rock unit are non-layered, typically massive, co-mingled gabbro and granite (P_-WKg2-xog-g), and ophitic gabbro (P_-WKg2-ogz). Other units form relatively minor components of this phase of Giles magmatism. North of Amy Giles Hill and south of the west Hinckley Range, the unit is in faulted contact with undivided granites of the Pitjantjatjara Supersuite (P_PJ-mg).

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Rock code		**P_-WKg2-o**

Contact relationships

Within the Murray Range (Holt), this mafic intrusive rock unit is mostly in contact with the Wirku Metamorphics (P_WM-mh) to the east, and granites of the early Pitjantjatjara Supersuite to the west. On Bell Rock, the mafic intrusive rock is in contact with layered mafic–ultramafic components (P_-WKg1-xo-a), both in the Hinckley Range and on the north side of the Michael Hills intrusion.

Geochronology

P_-WKg2-o	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that this massive gabbro unit intrudes along the margins of the layered mafic–ultramafic intrusions, and in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbro unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; GSWA 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-og)

Legend narrative

Medium-grained, even-textured gabbro; locally olivine porphyritic

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided
Metamorphic facies	Greenschist facies: undivided

Summary

This even-textured gabbro forms rare, undeformed, kilometre-scale lenses within gabbros that dominate outcrop in the Murray Range, representing low-strain domains in the Murray Range shear zone. They are typically surrounded by finer grained, compositionally similar units (P_-WKg2-oga) that are contaminated by granitic magma (P_-WKg2-ogi and P_-WKg2-ogia), or are the retrograde equivalents of such units (e.g. amphibolites such as P_-WKg2-moay, and altered units such as P_-WKg2-ogw). The unit is generally poorly exposed, outcropping only on the small hills flanking the eastern, southern, and northwestern sides of the Murray Range.

This medium-grained, leuco- to mesocratic gabbro (and local gabbronorite) is the massive, uncontaminated, undeformed parent to several other P_-WKg2 gabbros concentrated in the Murray Range. It differs from P_-WKg1-og in that it never displays layering on the millimetre- to metre-scale. The unit locally contains sparse, ~1 cm sized pyroxene oikocrysts, round plagioclase phenocrysts, or rare biotite. The constituent pyroxene and plagioclase grains display a primary ophitic to subophitic texture, although pyroxenes are locally recrystallized to form a granoblastic fabric, leaving plagioclase laths untouched; in this respect, this gabbro differs from the always ophitic to subophitic gabbro unit (P_-WKg2-ogz). This unit was emplaced at c. 1075 Ma, based on the age of granites mingled with contaminated versions of this unit seen on Amy Giles Hill.

Distribution

This gabbro unit forms lenses, up to 2.6 km long and 0.7 km wide, within the gabbros that form the bulk of the Murray Range intrusion, on Holt. They represent low-strain domains within the 5–10 km wide, north-northwesterly trending Murray Range transpressional shear zone. They are typically surrounded by finer-grained gabbro units (P_-WKg2-oga) that are contaminated by granitic magma (P_-WKg2-ogi and P_-WKg2-ogia), or else the retrograde equivalents of such contaminated gabbros (e.g. amphibolites such as P_-WKg2-moay). The unit is generally poorly exposed, outcropping only on the small hills flanking the eastern, southern, and northwestern sides of the Murray Range.

Lithology

This medium-grained, leuco- to mesocratic gabbro (to gabbronorite) is the massive, uncontaminated, undeformed parent to several other P_-WKg2 gabbros concentrated in the Murray Range, on Holt. It differs from an earlier gabbro of the Giles Suite (P_-WKg1-og) in that it does not display millimetre- to metre-scale layering. The unit locally contains sparse pyroxene oikocrysts up to ~1 cm in size, round plagioclase phenocrysts, or rare biotite. The constituent pyroxene and plagioclase display a primary ophitic to subophitic texture, although pyroxenes are locally recrystallized to form a granoblastic fabric, leaving plagioclase laths untouched; in this respect, this gabbro unit differs from the ophitic to subophitic gabbro unit (P_-WKg2-ogz).

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite; Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
Rock code		**P_-WKg2-og**

Contact relationships

On the northwestern edge of the Murray Range, this gabbro is cut by a rapakivi granite dyke dated at 1062 ± 10 Ma (GSWA 187256, Kirkland et al., 2009a), and further west on Finlayson is cut by dykes of ophitic gabbro (formerly P_-WKg3-odp; now recoded as Alcurra Dolerite suite, P_-WKA-odp) dated at 1067 ± 8 Ma (GSWA 194354, Kirkland et al., 2009b; Howard et al., 2009).

Geochronology

P_-WKg2-o	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock).

At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-oga)

Legend narrative

Massive to strongly foliated, fine-grained leucogabbro to leucogabbronorite; ophitic to subophitic texture with granoblastic interstitial pyroxene; locally associated with chill margins; locally mylonitic; locally epidotized

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided

Summary

This fine-grained, leuco- to mesocratic gabbro and gabbronorite occurs mainly as a chilled-margin phase, at a scale of 1–10 m, within other gabbros (P_-WKg2-og and P_-WKg2-ogz) in the Murray Range intrusion (eastern Holt), rarely forming mappable units. It is the protolith of several other similar gabbros contaminated by granitic magma (P_-WKg2-ogia), or else the retrogressed equivalents of such contaminated gabbros (e.g. the amphibolite unit P_-WKg2-moay, and strongly altered unit P_-WKg2-ogaw). It differs from a gabbro related to the earliest phase of the Giles Suite (P_-WKg1-og) in that it is finer-grained, and never displays millimetre- to metre-scale layering. This unit was emplaced at c. 1075 Ma, based on the age of granites mingled with contaminated versions of this unit observed on Amy Giles Hill.

Distribution

This fine-grained gabbro occurs mainly as a chilled-margin phase, at a scale of 1–10 m, within other gabbros (P_-WKg2-og and P_-WKg2-ogz) in the Murray Range intrusion (eastern Holt), rarely forming mappable units. Where contaminated by contemporaneous granite, the resulting unit (P_-WKg2-ogia) forms a much larger, exposed portion of the Murray Range intrusion. This fine-grained, uncontaminated gabbro also forms a chilled-margin phase (of P_-WKg2-og and P_-WKg2-ogz) within the southern and northwestern parts of the Murray Range. Here, the gabbro is also interpreted to underlie a 7 km long, north-trending area, 5 km north of the Murray Range. The unit is generally poorly exposed, outcropping only on the edges of a large hill on the northwest side of the Murray Range, and on a small hill near the southern edge of the Murray Range.

Lithology

This fine-grained, leuco- to mesocratic gabbro and gabbronorite is composed of pyroxene and plagioclase locally within a primary ophitic to subophitic texture, although the pyroxenes are typically recrystallized to form a granoblastic fabric, leaving plagioclase laths untouched; in this respect, this gabbro differs from the ophitic to subophitic gabbro unit (P_-WKg2-ogz). The fine-grained gabbro usually displays a foliation, and is locally mylonitic. Its finer grain size and tendency to acquire a foliation also differentiates it from its coarser-grained, undeformed equivalent, P_-WKg2-og.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Fine-grained	a
Rock code		**P_-WKg2-oga**

Contact relationships

On the northwestern edge of the Murray Range, this gabbro is cut by a rapakivi granite dyke dated at 1062 ± 10 Ma (GSWA 187256, Kirkland et al., 2009a), and further west on Finlayson is cut by dykes of ophitic gabbro (formerly P_-WKg3-odp; now recoded as Alcurra Dolerite suite, P_-WKA-odp) dated at 1067 ± 8 Ma (GSWA 194354, Kirkland et al., 2009b; Howard et al., 2009).

Geochronology

P_-WKg2-oga	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-ogb)

Legend narrative

Fine- to medium-grained biotite-bearing gabbro; locally interleaved with granite

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This biotite-bearing gabbro unit forms a minor component in the second main phase of mafic magmatism (P_-WKg2) of the Giles Suite. The unit outcrops on BELL ROCK, along the southern margin of the Hinckley Range intrusion; to the south of this area, it is in contact with metamonzogranite (P_-PJ1-mgmu) of the early Pitjantjatjara Supersuite. The biotite-bearing gabbro unit has not been directly dated, but SHRIMP U–Pb zircon ages obtained for Giles Suite granites (P_-WK-g), which are mingled with massive gabbros of the same suite (P_-WKg2-ogz and P_-WKg2-og-a), suggest an age of c. 1075 Ma.

Distribution

This biotite-bearing gabbro unit outcrops extensively along the southern margin of the Hinckley Range (BELL ROCK).

Lithology

Rocks of this biotite-bearing gabbro unit are fine to medium grained, and partly dynamically recrystallized. The mineral assemblage includes plagioclase, quartz, biotite, and clinopyroxene. There are green hornblende aggregates forming coronas on clinopyroxene grains, and Fe–Ti oxides are associated with, and commonly enclose, biotite. There are local overprints of red-brown biotite forming at the expense of pyroxene and/or ilmenite. Irregular blebs of pyrrhotite and chalcopyrite are also present.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Biotite	b
Rock code		**P_-WKg2-ogb**

Contact relationships

This biotite-bearing gabbro is in contact with the layered gabbro unit (P_-WKg1-ogy) of the layered mafic–ultramafic Hinckley intrusion to the north of the outcrop area, and with the augen metamonzogranite (P_-PJ1-mgmu) to the south. The unit is cut by southeast-trending syenogranite dykes (P_-WK-grl), and displaced most commonly by minor dextral faults.

Geochronology

P_-WKg2-ogb	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

References

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Giles Suite; subunit (P_-WKg2-ogj)

Legend narrative

Magnetite-rich gabbro; ophitic to subophitic texture; locally biotite-rich and mixed and mingled with leucogranite

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided

Summary

This gabbro, together with its less magnetite-rich counterpart (P_-WKg2-ogz), forms well-exposed, elongate intrusions, parallel to the north-trending Murray Range shear zone (eastern HOLT). The unit is sinistrally displaced at the west-trending Walu Fault, where it forms large, poorly exposed, intrusions that have been amphibolitized or epidotized, intruded by quartz veins, and rotated parallel to the fault. Generally, this unit is a massive, medium-grained gabbro, with an ophitic texture of pyroxene and plagioclase, and containing abundant, millimetre-sized, magnetite phenocrysts. Locally, the unit contains olivine, orthopyroxene phenocrysts, and stringers or xenoliths of coeval granite.

Distribution

This gabbro, together with its less magnetite-rich counterpart (P_-WKg2-ogz), makes up a significant portion of the northern Murray Range (eastern HOLT), the area where it is best exposed. The unit generally forms intrusions, up to 8 km long and 1 km wide, parallel to the north-trending Murray Range shear zone. On the northern and western sides of the Murray Range, it intrudes mylonitic granite of the Pitjantjatjara Supersuite (P_-PJ1-mgry). At the northern border of HOLT, it is sinistrally displaced along the west-trending Walu Fault; here the gabbro forms poorly exposed intrusions, up to 45 km^2 in size, which have been epidotized, intruded by quartz veins, and rotated parallel to the fault. Locally, the gabbro is cut by coeval, leucogranite dykes (P_-WK-grl), up to 100 m wide.

Lithology

This massive, typically medium-grained gabbro differs from most other gabbro units related to the second major phase of Giles Suite mafic magmatism (P_-WKg2) in that it is not recrystallized, and is only slightly contaminated by coeval Warakurna Supersuite granites. The unit displays a well-developed ophitic to subophitic texture of pyroxene and cloudy plagioclase laths, but locally contains up to 10% fine-grained, round olivine crystals. The rock also contains 5% subhedral to euhedral, millimetre-sized magnetite phenocrysts with biotite rims. Locally, orthopyroxene (up to 20%) may form sparse oikocrysts, up to 1 cm in size. Augite is locally retrogressed along shear zones and cleavage planes to a dark- to brown-green amphibole, and the entire unit may be cut by networks of epidotized ultramylonites up to 1 m wide, particularly near the Walu Fault. The gabbro locally contains xenolithic granite stringers adjacent to leucogranite dykes (P_-WK-grl). Several generations of these dykes cut the gabbro, some having cuspate margins implying that the two units are coeval.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Magnetite	j
Rock code		**P_-WKg2-ogj**

Contact relationships

This gabbro occurs as xenoliths with cuspate margins in, and is cut by, a coeval, leucogranite dyke (P_-WK-grl), particularly in the northwestern corner of the Murray Range.

Geochronology

P_-WKg2-ogj	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Giles Suite; subunit (P_-WKg2-ogz)

Legend narrative

Massive, weakly metamorphosed gabbro; well-developed ophitic to subophitic texture with oikocrysts up to 1 cm; locally epidotized and cut by abundant quartz and pegmatite veins

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided

Summary

This gabbro dominates outcrop in the northern part of the Murray Range shear zone (eastern HOLT), where, together with its magnetite-rich counterpart (P_-WKg2-ogj), it covers an area of nearly 150 km^2; in this area it hosts kilometre-scale inclusions of older, layered gabbro from the earlier stage of the Giles Suite (P_-WKg1), plus inclusions of Pitjantjatjara Supersuite granite (P_-PJ-mg). It also forms as fault-bounded blocks, 2–4 km wide, covering an area of 15 km^2 along the western side of the Murray Range shear zone. This massive, typically medium-grained gabbro differs from most other gabbro units related to the second main phase of mafic Giles Suite magmatism (P_-WKg2) in that it is not metamorphosed nor contaminated by coeval granite of the Warakurna Supersuite. The rocks of this unit typically display a well-developed ophitic to subophitic texture.

Distribution

This gabbro dominates outcrop in the northern part of the Murray Range shear zone (eastern HOLT), where, together with its magnetite-rich counterpart (P_-WKg2-ogj), it covers an area of nearly 150 km^2; in this area the unit hosts kilometre-scale inclusions of older, layered gabbro from the earlier stage of the Giles Suite (P_-WKg1-ogj and P_-WKg1-oo), plus inclusions of Pitjantjatjara Supersuite granite (P_-PJ-mg). The gabbro also forms as fault-bounded blocks, 2–4 km wide, covering an area of 15 km^2 along the western side of the Murray Range shear zone. These blocks represent the best exposed examples of this unit, comprising the northern two-thirds of Butterfly Hill (central-eastern HOLT) and the western flank of Amy Giles Hill (southeastern HOLT). In these areas, the gabbro is locally intruded by coeval mylonitic leucogranite dykes (P_-WK-mgry), up to 100 m wide. Two poorly exposed, northwest-trending lenses of this gabbro, up to 9 km long, intrude late Pitjantjatjara Supersuite granite (P_-PJ2-mgrg) to the west of the Murray Range shear zone. On the western half of the HOLT map sheet, the unit is represented by several 1–10 km^2, poorly exposed or unexposed, partially fault-bound intrusions.

Lithology

This massive, typically medium-grained gabbro differs from most other gabbro units related to the second major phase of mafic Giles Suite magmatism (P_-WKg2) in that it is not metamorphosed, nor contaminated by coeval Warakurna Supersuite granites. The unit is composed of orthopyroxene, elongate, anhedral augite, and anhedral, interlocking, stubby plagioclase laths. Interstitial opaque minerals have thin biotite rims, and generally make up less than 2% of the rock. Trace opaque minerals are locally present along pyroxene cleavage planes. Olivine (up to 5%) and orthopyroxene (up to 20%) may locally form sparse phenocrysts up to 1 cm in size. In the northern Murray Range shear zone and on western HOLT, augite is locally retrogressed along cleavage planes to a dark- to brown-green amphibole.

This gabbro typically displays a well-developed ophitic to subophitic texture. Locally, it shows the same recrystallization texture seen in fine-grained (P_-WKg2-oga) and contaminated gabbros (P_-WKg2-ogia) elsewhere in the Murray Range shear zone, in which mafic minerals form a granoblastic foam texture, but plagioclase grains are left untouched. Near Butterfly Hill, the gabbro may contain xenolithic granite stringers adjacent to mylonitic, leucogranite dykes (P_-WK-mgry). At Amy Giles Hill and in the northern Murray Range shear zone, this unit displays faint layering, possibly representing primary magmatic layering.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Gabbro	g
1st qualifier	Ophitic	z
Rock code		**P_-WKg2-ogz**

Contact relationships

On the northwestern edge of the Murray Range, this gabbro intrudes into an Early Pitjantjatjara Supersuite granite, and is cut by a rapakivi granite dyke dated at 1062 ± 10 Ma (GSWA 187256, Kirkland et al., 2009a); further west on FINLAYSON, the unit is also cut by dykes of ophitic gabbro (formerly P_-WKg3-odp; now Alcurra Dolerite suite, P_-WKA-odp) dated at 1067 ± 8 Ma (GSWA 194354, Kirkland et al., 2009b).

Geochronology

P_-WKg2-ogz	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for the layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-oob)

Legend narrative

Olivine gabbro; typically contains biotite and magnetite oikocrysts; massive to weakly flow banded

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This unit of olivine gabbro with magnetite oikocrysts represents the sole outcropping lithology within the concentrically zoned 'Saturn intrusion', a prominent elliptical aeromagnetic anomaly, approximately 10 km in diameter, in the northwest of BLACKSTONE. The rock is a massive, leucocratic, has magnetite oikocrysts up to 1 cm in size, and ranges in composition from olivine gabbro to olivine gabbronorite. Although included within the second phase of Giles magmatism (P_-WKg2), the geochemistry of this rock is transitional to rocks of the Alcurra Dolerite suite (P_-WKA-, formerly P_-WKg3).

Distribution

This olivine gabbro with magnetite oikocrysts forms several small, scattered outcrops in the northwest of BLACKSTONE (centred on MGA 404200E 7117100N), between Cavenagh Range and the western end of Blackstone Range. These outcrops form the only surface exposure of a prominent, concentrically zoned, elliptical aeromagnetic anomaly approximately 10 km in diameter, referred to as the 'Saturn intrusion'.

Lithology

This olivine gabbro is a massive, leucocratic rock, with prominent magnetite oikocrysts up to 1 cm in size that form up to 5% of the rock. Within the oikocrysts, magnetite forms a semicontinuous interstitial network between plagioclase crystals, and is itself commonly partially rimmed by biotite. Plagioclase forms 65–75% of the rock, whereas mafic minerals (other than magnetite) form 20–30%. Olivine (typically <8%) occurs as rounded inclusions, typically within orthopyroxene. Clinopyroxene either forms discrete anhedral crystals locally rimming orthopyroxene, or is an exsolution intergrowth in orthopyroxene. The abundance of clinopyroxene exceeds that of orthopyroxene, and the rocks range from olivine gabbro to olivine gabbronorite.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbro	o
1st qualifier	Biotite	b
Rock code		**P_-WKg2-oob**

Geochronology

P_-WKg2-oob	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Isotopic
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

Although included within the second phase of Giles magmatism (P_-WKg2), the geochemistry of the olivine gabbro unit is transitional to rocks of the Alcurra Dolerite suite (P_-WKA-, formerly P_-WKg3; Howard et al., 2009). A direct date of 1072 ± 8 Ma obtained for the 'Saturn intrusion' (Redstone Resources, written comm., 2007), whilst within error of the c. 1075 Ma age for the second main phase of Giles Suite mafic magmatism (P_-WKg2), might also reflect this transitional nature.

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Giles Suite; subunit (P_-WKg2-xog-g)

Legend narrative

Gabbro; ophitic to subophitic texture; variably mixed and mingled with leucogranite; locally foliated and mylonitic

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided

Summary

This variably mingled leucogabbro and leucogranite unit forms the major magmatic component related to the second major phase of the Giles Suite (P_-WKg2). This mingled unit outcrops on the west Hinckley Range (Bell Rock), north of the Michael Hills intrusion (Bell Rock), and on the Murray Range (Holt). The gabbro is typically contaminated by granitic material occurring as xenolithic granitic blebs, or else mingled with leucogranite to form agmatites. The boundaries between the mafic and felsic phases have cuspate or cauliform margins, indicating that neither phase was solid during emplacement.

Distribution

This medium-grained, contaminated gabbro forms the dominant lithology within the west Hinckley Range (Bell Rock), forms a small area north of the Michael Hills intrusion (Bell Rock), and dominates outcrop in the southern half of the Murray Range (Holt).

Lithology

Along with its fine-grained equivalent (P_-WKg2-xoga-g), this medium-grained, co-mingled gabbro–granite unit forms the major component of magmatism within the second phase of the Giles Suite (P_-WKg2). The gabbroic component is composed of augite, orthopyroxene, and plagioclase, locally arranged in a primary ophitic to subophitic texture. Minor biotite and fine-grained magnetite are common along grain boundaries. This gabbro is typically contaminated by granitic material in three ways: 1) by containing xenolithic granitic blebs, lenses, or curvilinear segregations, up to 5 cm in length; 2) by mingling with leucogranite to form agmatites; 3) and rarely, by mixing with granite to form hybrid magmas. In the first two cases, boundaries between the mafic and felsic phases are curvilinear, cuspate, and cauliform, indicating that neither phase was solid during emplacement; i.e. the phases were coeval. However, gabbros containing syn-magmatic-appearing granitic blebs are agmatized by the leucogranite that also forms syn-magmatic appearing boundaries with the gabbro. This indicates that granite magmatism was continuous during emplacement of the gabbro.

This unit of gabbro and intermingled granite is commonly strongly deformed. The granite blebs that contaminate the gabbro are excellent markers that usually define a moderate to strong foliation or lineation. Bleb margins appear to have remained wispy and cuspate during this deformation, suggesting that the deformation was also syn-magmatic.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Mixed or Xenolith/ Inclusion Bearing	Mixed	x
Rock type 1	Igneous mafic intrusive	o
Lithname 1	Gabbro	g
Rock type 2	Igneous granitic	-g
Rock code		**P_-WKg2-xog-g**

Contact relationships

In the west Hinckley Range, this unit is in contact with the layered gabbro (P_-WKg1-ogy) of the Hinckley intrusion to the east, and with granite of the Warakurna Supersuite (P_-WK-ggc and P_-WK-mgry) to the west. To the north of Michael Hills, the unit is in contact with gabbronorite (P_-WKg1-om and P_-WKg1-oml) layers of the Michael Hills intrusion, and Wankanki Supersuite granites (P_-WN-mgno). In the Murray Range, the unit is in contact with similarly aged mafic rock units (P_-WKg2-ogz, P_-WKg2-og, P_-WKg2-moad, P_-WKg2-moay, P_-WKg2-ogj) and its own finer-grained equivalent (P_-WKg2-xoga-g). The unit is in contact with several Warakurna Supersuite granite units (P_-WK-mgyd, P_-WK-grah, P_-WK-grl) and olivine gabbronorite (P_-WKg1-ol). The southernmost exposure of this unit intrudes rocks of the Wirku Metamorphics (P_-WM-xmfn-mf).

Geochronology

P_-WKg2-xog-g	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-xoga-g)

Legend narrative

Moderately to strongly foliated, fine- to medium-grained leucogabbro to leucogabbronorite; ophitic to subophitic texture with granoblastic interstitial pyroxene; variably mingled with leucogranite

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Epidote–amphibolite facies: undivided

Summary

Along with its medium-grained equivalent (P_-WKg2-xog-g), this fine-grained, co-mingled gabbro–granite unit forms the major magmatic component within the second main phase of the Giles Suite (P_-WKg2). It forms a large north-northwesterly trending section of the Murray Range shear zone, up to 10 km long (central-eastern HOLT), and outcrops over most of the northern half of the Murray Range; further south, the unit outcrops on the northern face of Butterfly Hill. This unit shows gradational contacts with its coarser-grained counterparts (P_-WKg2-ogi and P_-WKg2-og), and with gabbros that are uncontaminated by granite (P_-WKg2-oga). A date obtained from this unit's granitic component, at c. 1075 Ma, gives the intrusive age of both the gabbroic and granitic components.

Distribution

This fine-grained, contaminated gabbro forms a large, north-northwesterly trending section of the Murray Range shear zone, up to 10 km long (central-eastern HOLT), and outcrops over the northern half of the Murray Range. Further south, the unit outcrops on the northern face of Butterfly Hill, where it forms a zone, 500 m wide, which wraps around an inclusion of older layered gabbro (P_-WKg1-ol). The southern half of the Murray Range is dominated by the coarser-grained variety of this unit (P_-WKg2-xog-g). Near the southwestern corner of HOLT, it forms a fault-bounded, 1 km wide dyke cutting composite gneisses of the Wankanki and Pitjantjatjara Supersuites.

Lithology

Along with its medium-grained equivalent (P_-WKg2-xog-g), this fine-grained, co-mingled gabbro–granite unit forms the major magmatic component within the second main phase of the Giles Suite (P_-WKg2). The unit consists of augite, orthopyroxene, and plagioclase locally arranged in a primary ophitic to subophitic texture, although the pyroxenes are typically recrystallized to form a granoblastic fabric, leaving plagioclase laths untouched. The finer-grained, more equigranular texture distinguishes this unit from the coarser-grained variety (P_-WKg2-xog-g); this texture is interpreted as the result of autometamorphism, related to fluids associated with co-magmatic contamination by granitic magmas. Minor biotite and fine-grained magnetite are also common along grain boundaries.

This gabbro is typically contaminated by granitic material in three ways: 1) by containing xenolithic granitic blebs, lenses, or curvilinear segregations, up to 5 cm in length; 2) by mingling with leucogranite to form agmatites; 3) and rarely, by mixing with granite to form hybrid magmas. In the first two cases, boundaries between the mafic and felsic phases are curvilinear, cuspate, and cauliform, indicating that neither phase was solid during emplacement; i.e. the phases were coeval. However, gabbros containing syn-magmatic appearing granitic blebs are agmatized by the leucogranite that also forms syn-magmatic appearing boundaries with the gabbro. This indicates that granite magmatism was continuous during emplacement of the gabbro.

This unit of gabbro and intermingled granite is commonly strongly deformed. The granite blebs that contaminate the gabbro are excellent markers that usually define a moderate to strong foliation or lineation. Bleb margins appear to have remained wispy and cuspate during this deformation, suggesting that the deformation was syn-magmatic. Where the gabbro is strongly deformed but devoid of markers, it has a fine-grained, recrystallized, pyroxene-plagioclase matrix that likely recovered from earlier deformation.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Mixed or Xenolith/ Inclusion Bearing	Mixed	x
Rock type 1	Igneous mafic intrusive	o
Lithname 1	Gabbro	g
1st qualifier	Fine-grained	a
Rock type 2	Igneous granitic	-g
Rock code		**P_-WKg2-xoga-g**

Geochronology

P_-WKg2-xoga-g	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

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Giles Suite; subunit (P_-WKg2-moad)

Legend narrative

Moderately to strongly foliated amphibolite after fine- to medium-grained gabbro; strongly epidotized and cut by abundant quartz and pegmatite veins; locally mylonitic

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies: green hornblende

Summary

This altered amphibolite forms part of an alteration zone parallel to the mylonite zone that marks the eastern boundary of the Murray Range shear zone, in the central-eastern part of HOLT. It is the altered, less deformed equivalent of the rock found within that mylonite zone (P_-WKg2-moay). The protoliths to this altered amphibolite were gabbros variably contaminated by granite; the emplacement age of these protoliths is interpreted to be c. 1075 Ma, which is also the maximum age of amphibolite-facies metamorphism for this unit. The minimum age of amphibolite-facies metamorphism is also constrained by an epidotization event that replaced amphiboles within the rock, which may be as young as the Petermann Orogeny.

Distribution

This altered amphibolite forms part of an alteration zone, 3 km long and 0.5 km wide, parallel to a north-trending mylonite zone that marks the eastern boundary of the Murray Range shear zone (central-eastern HOLT). The unit is the altered, less deformed equivalent of the metagabbro found within that mylonite zone (P_-WKg2-moay).

Lithology

The protoliths to this altered amphibolite were gabbros variably contaminated by granite (P_-WKg2-xog-g, P_-WKg2-xoga-g, P_-WKg2-og, and P_-WKg2-oga). Locally, the unit is composed of fine-grained pyroxene and plagioclase domains, with sparsely interspersed granitic domains that display a blastomylonitic fabric. The variable to wholesale replacement of pyroxene grains with a granoblastic network of green amphibole, distinguishes this unit from its protolith gabbros. These amphibole domains, and millimetre-wide recrystallized granite blebs streaked out to 100:1 axial ratios, locally form a mylonitic fabric that wraps around subhedral plagioclase phenocrysts (5% of the rock). Significant magnetite (up to 10% of the rock) is found along grain boundaries. Although this metamorphic texture is locally preserved, the unit is pervasively altered to form a rock dominated by anhedral to euhedral, needle-like epidote, subhedral clinozoisite, and anhedral plagioclase. K-feldspar and some plagioclase grains in the granitic portion of this amphibolite are also replaced by epidote, and quartz is typically recrystallized. The rock is typically cut by abundant millimetre- to centimetre-scale quartz and epidote veins.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Amphibolite derived from intrusive rock	a
1st qualifier	–	
2nd qualifier	Epidote	d
Rock code		**P_-WKg2-moad**

Geochronology

P_-WKg2-moad	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

References

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Giles Suite; subunit (P_-WKg2-moay)

Legend narrative

Mylonitic amphibolite after fine- to medium-grained gabbro

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies: green hornblende

Summary

This unit lies within a moderately west-dipping and north-striking mylonite zone that marks the eastern boundary of the Murray Range shear zone (central-eastern Holt), corresponding to a prominent aeromagnetic (TMI) anomaly in that area. This gabbro is the amphibolitized and mylonitized equivalent of numerous gabbros that have been variably contaminated by granite. The emplacement age of this mylonite's protolith is interpreted to be c. 1075 Ma, which is also the maximum age of amphibolite-facies metamorphism for this unit. The minimum age of amphibolite-facies metamorphism is also constrained by an epidotization event that replaced amphiboles within the rock, which may be as young as the Petermann Orogeny.

Distribution

This gabbro unit forms within a moderately west-dipping and north-striking mylonite zone that marks the eastern boundary of the Murray Range shear zone (central-eastern Holt). It wraps around kilometre-scale, low-strain domains of relatively undeformed gabbro (P_-WKg2-og), and includes transposed mylonitic granite veins (P_-WK-mgry) up to 10 m wide. Within the outcrop area, this unit corresponds to a prominent aeromagnetic (TMI) anomaly. This gabbro unit is best exposed along the eastern edge of the Murray Range; further north, it forms the base of low hills, and is topped by undeformed gabbro (P_-WKg2-og).

Lithology

This gabbro is the amphibolitized and mylonitized equivalent of numerous gabbros variably contaminated by granite (P_-WKg2-xog-g, P_-WKg2-xoga-g, P_-WKg2-og, and P_-WKg2-oga). In most cases, the unit is composed of fine-grained pyroxene and plagioclase domains, with sparsely interspersed granitic domains; all display a blastomylonitic fabric. The pyroxene is variably replaced by green amphibole; in mylonitic amphibolites pyroxene has been completely replaced by a granoblastic network of anhedral to subhedral green-amphibole (70% of the rock), with significant magnetite (up to 10% of the rock) along grain boundaries. These amphibole domains, plus millimetre-wide recrystallized granite blebs streaked out to 100:1 axial ratios, form the mylonitic fabric that wraps around subhedral plagioclase phenocrysts (5% of the rock). The mylonite is locally epidotized.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Amphibolite derived from intrusive rock	a
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-WKg2-moay**

Geochronology

P_-WKg2-moay	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

References

Bodorkos, S and Wingate, MTD 2008, 174589: quartz syenite dyke, Amy Giles Hill; Geochronology Record 715: Geological Survey of Western Australia, 4p.

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Giles Suite; subunit (P_-WKg2-mog)

Legend narrative

Fine- to medium-grained metagabbro; granoblastic texture; locally foliated

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies

Summary

This metagabbro unit forms a minor magmatic component related to the second main phase (P_-WKg2) of the Giles Suite. The unit outcrops on BELL ROCK, where it represents granite-free portions either within, or at the margins of, the more extensive mingled gabbro and granite unit (P_-WKg2-xog-g). The unit has not been directly dated, but SHRIMP U–Pb zircon ages, obtained from granites mingled with the massive gabbros of the second major phase of the Giles Suite (P_-WKg2-ogz and P_-WKg2-og-a), suggest an intrusive age of c. 1075 Ma.

Distribution

This metagabbro unit outcrops as two small intrusions within a relatively small area on eastern edge of BELL ROCK, where it represents portions either within, or at the margins of, the more extensive mingled gabbro and granite unit (P_-WKg2-xog-g).

Lithology

This metagabbro is fine to medium grained, strongly foliated, and has a granoblastic texture. The mineral assemblage includes plagioclase, perthitic feldspar, clinopyroxene, orthopyroxene, and ilmenite, with secondary biotite and chlorite. Fine-grained ilmenite penetrates the microfractures and grain boundaries of pyroxene crystals. There are occasional rounded intergrowths of chlorite, biotite, quartz, and opaque minerals; biotite inclusions occur along pyroxene cleavage planes.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro	g
Rock code		**P_-WKg2-mog**

Geochronology

P_-WKg2-mog	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma. The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, felsic volcanism, macroscopic folding, and crustal-scale shearing (Smithies et al., 2009).

References

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Giles Suite; subunit (P_-WKg2-mogy)

Legend narrative

Mylonite derived from gabbro or from mixed and mingled gabbro and leucogranite

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies

Summary

This mylonitic metagabbro unit forms a minor magmatic component related to the second major phase (P_-WKg2) of the Giles Suite. The unit outcrops on BELL ROCK, where it represents parts of the metagabbro (P_-WKg2-mog) or mingled gabbro and granite (P_-WKg2-xog-g) units altered by mylonitic deformation. On HOLT, the unit represents the variable deformation and amphibolitization of ophitic gabbro (P_-WKg2-ogz). Field relationships suggest that this deformation is part of the Giles Event. Neither this unit nor its protolith have been directly dated, but SHRIMP U–Pb zircon ages from granites, mingled with massive gabbros of the second major Giles Suite phase (P_-WKg2-ogz and P_-WKg2-og-a), suggest an intrusive age of c. 1075 Ma.

Distribution

This mylonitic metagabbro outcrops in several places on both BELL ROCK and HOLT. On BELL ROCK, the unit forms an ultramylonite zone approximately 2 km to the south of a hill named ‘The Bald One’ (at BELL ROCK, MGA 495900E 7100416N), and also outcrops to the east of Mount Aloysius (at BELL ROCK, MGA 471927E 7121337N). In the central-eastern parts of HOLT, the unit forms on the eastern side of a layered mafic–ultramafic intrusion related to the first major phase (P_-WKg1) of the Giles Suite.

Lithology

This mylonitic metagabbro unit, as seen south of The Bald One, is an ultramylonite zone within metagabbro (P_-WKg2-mog). The deformation is most likely related to a synform to the north, which folds the eastern end of the Michael Hills intrusion, and is therefore related to the Giles Event. To the east of Mount Aloysius, the mylonitic metagabbro unit represents deformation of the mingled gabbro and granite (P_-WKg2-xog-g) unit, and shows a gneissic fabric in places. In the central-eastern parts of HOLT, the unit is a variably mylonitized metagabbro.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro	g
1st qualifier	–	
2nd qualifier	Mylonitic	y
Rock code		**P_-WKg2-mogy**

Geochronology

P_-WKg2-o	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; GSWA 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern BATES) and on the western edge of the Hinckley Range (BELL ROCK). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, together giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

The ages listed above define a very narrow time interval of concomitant intrusion of massive gabbro, multi-phase intrusion of leucogranites, macroscopic folding, and also the crustal-scale shearing (Smithies et al., 2009) to which the mylonitic metagabbro unit likely relates.

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Kirkland, CL, Wingate, MTD and Smithies, RH 2011a, 194762: leucogabbro, Mount Finlayson; Geochronology Record 966: Geological Survey of Western Australia, 4p.

Kirkland, CL, Wingate, MTD and Evins, PM 2011b, 194763: gabbro, Jamieson Range; Geochronology Record 964: Geological Survey of Western Australia, 5p.

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Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Giles Suite; subunit (P_-WKg2-mom)

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Giles Suite	WKg2-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro norite	m
Rock code		**P_-WKg2-mom**

Legend narrative

Coarse- to medium-grained metagabbronorite; orthopyroxene–clinopyroxene and labradorite (antiperthite, where metamorphosed); locally minor sulfide disseminations

Rank	Formation
Parent	Giles Suite (P_-WKg2-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Amphibolite facies

Summary

This metagabbronorite unit forms a minor magmatic component related to the second major phase (P_-WKg2) of the Giles Suite. The unit outcrops on Bates, where it intrudes undivided granite (P_-PJ-mg), and metagranodiorite to metamorphosed quartz monzodiorite (P_-PJ1-mggo), both of the Pitjantjatjara Supersuite. The unit has not been directly dated, but SHRIMP U–Pb zircon ages from granites, mingled with the massive gabbros of the second major Giles Suite phase (P_-WKg2-ogz and P_-WKg2-og-a), suggest an intrusive age of c. 1075 Ma.

Distribution

This metagabbronorite units outcrops as three dyke-like intrusions within a relatively small area on south-central Bates.

Lithology

This metagabbronorite is massive, coarse-grained, and has a subophitic texture. The mineral assemblage consists of plagioclase (optically determined andesine–labradorite, $An_{50–56}$), clinopyroxene, orthopyroxene, and olivine, with secondary biotite, quartz, and chlorite. Plagioclase laths are up to 5 mm in length; orthopyroxene is rimmed by granular clinopyroxene, and where present olivine is rimmed with orthopyroxene. Accessory ilmenite, pyrrhotite, pyrite, and chalcopyrite are also present. Sulfide blebs are locally associated with ilmenite, or else infill fractures in pyroxene crystals. Ilmenite has inclusions of green spinel, and coronas of reddish-brown biotite. There are also irregular patches of quartz and chlorite intergrowths.

Contact relationships

This metagabbronorite intruded into undivided granite (P_-PJ-mg), and metagranodiorite to metamorphosed quartz monzodiorite (P_-PJ1-mggo), both of the Pitjantjatjara Supersuite.

Geochronology

P_-WKg2-o	*Maximum*	*Minimum*
Age (Ma)	1078	1074
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010;	Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010

Field relationships suggest that gabbros related to the second major phase of mafic magmatism (P_-WKg2) of the Giles Suite intruded along, and into, the margins of the earlier layered mafic–ultramafic intrusions of the Giles Suite; in all cases where contacts are observed, the massive gabbros clearly post-date emplacement of the layered intrusions. The minimum age for these layered intrusions (and therefore the maximum age of the massive gabbros) is c. 1075 Ma (Sun et al., 1996; Smithies et al., 2009; Evins et al., 2010; GSWA 194762, Kirkland et al., 2011a; and 194763, Kirkland et al., 2011b). The emplacement age of the massive gabbros unit is also constrained by the ages of granites (for example, GSWA 174761, Kirkland et al., 2008a; and 185509, Kirkland et al., 2008b) that crosscut, are crosscut by, and locally mingled with, the gabbro. Examples of such relationships are seen on Amy Giles Hill (southwestern Bates) and on the western edge of the Hinckley Range (Bell Rock). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589, Bodorkos and Wingate, 2008) is co-mingled with gabbro. On the western edge of the Hinckley Range, co-mingled gabbro and granite is macroscopically folded and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761, Kirkland et al., 2008a) axial planar to that fold; further west, a syn-mylonitic leucogranite, dated at 1075 ± 3 Ma (GSWA 185509, Kirkland et al., 2008b), occupies boudin necks in a northwest-trending mylonite. Seven granite samples, showing textural evidence of synchronous intrusion with gabbro, have been dated in total, giving a weighted average crystallization age of 1075 ± 1 Ma for both granite and gabbro (Evins et al., 2010), with a potential range from c. 1078 to c. 1074 Ma.

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Bentley Supergroup (P_-BE-xs-f)

Legend narrative

Undivided; sandstone, siltstone, and felsic volcanic and volcaniclastic rocks; minor mafic volcanic rocks

Rank	Supergroup
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	Metasedimentary rocks of the Wirku Metamorphics (P_-WM-mh) (erosional); meta-igneous rocks of the Wankanki Supersuite (P_-WN-mg) (erosional); meta-igneous rocks of the Pitjantjatjara Supersuite (P_-PJ-mg) (erosional); layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional)
Maximum thickness	>10 000 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

The Bentley Supergroup was initially proposed by Daniels (1974) to include weakly to moderately deformed and metamorphosed bimodal volcanic and volcaniclastic rocks, and fine- to coarse-grained sedimentary rocks, which unconformably overlie the high-grade metamorphic rocks of the Musgrave Province. These rocks are the same age as both the mafic–ultramafic Giles intrusions, and the granites that intruded the Musgrave Province during the c. 1085 to 1040 Ma Giles Event. Together, these intrusive and extrusive rocks all form components of the Warakurna Supersuite. Daniels (1974) divided the stratigraphy of the Bentley Supergroup into four main units — the Pussy Cat, Tollu, Cassidy, and Mission Groups. Outcrop of the Tollu Group is almost entirely restricted to the east-trending, synclinal structure (Blackstone syncline) located south of Blackstone Community (the Blackstone Sub-Basin), whereas the other groups are restricted to the area extending north of Barrow Range and as far west as the Warburton area.

Distribution

The Mesoproterozoic Bentley Supergroup (Daniels, 1974) comprises weakly to moderately deformed and metamorphosed bimodal volcanic and volcaniclastic rocks, plus fine- to coarse-grained sedimentary rocks including chert, siliciclastic rocks, and stromatolite-bearing carbonate rocks. The Bentley Supergroup unconformably overlies high-grade metamorphic rocks of the Musgrave Province, mainly in the Mamutjarra Zone. This unit outcrops mainly in the region extending between Warburton to the west, and Barrow Range (approximately 40 km southwest of Jameson Community) to the east, with small outliers also found immediately south of the Blackstone Range (the Blackstone Sub-Basin on BLACKSTONE, south of Blackstone Community), around Skirmish Hill (southeast corner of BLACKSTONE), and south of the Bell Rock Range (on BELL ROCK). The largest of these outliers (the Blackstone Sub-Basin) outcrops within the Blackstone syncline immediately south of the Blackstone Range; this area also defines the outcrop extent of the Tollu Group. To the south of the Blackstone syncline, units of pebble sandstone and conglomerate (MacDougall Formation), and amygdaloidal basalt and andesite (Mummawarrawarra Basalt), originally viewed as the basal portion of the Tollu Group (Daniels, 1974), were subsequently found to form a separate unit (the Kunmarnara Group) unconformably underlying the Tollu Group (Smithies et al., 2009). The Kunmarnara Group is well exposed at MacDougall Bluff (southeastern BLACKSTONE) and at Mount Blyth (central COOPER).

Although outcrop of the Tollu Group is almost entirely restricted to an east-trending, synclinal structure (Blackstone syncline), the unit most likely extends eastwards under cover onto the western edge of BLACKSTONE. Recent mapping on COOPER also suggests that the Tollu and Kunmarnara Groups may extend under cover to the west-southwest, possibly providing a direct link with more extensive Bentley Supergroup units (the Pussy Cat, Cassidy, and Mission Groups), exposed within the Talbot Sub-Basin in the Mount Palgrave – Barrow Range region (MOUNT EVELINE). Rocks of the Kunmarnara Group are also exposed adjacent to, and to the north of, the Hinckley intrusion (FINLAYSON), and within the Tjuni Purlka Tectonic Zone in the north of HOLT and the south of GUNBARREL.

A lithologically similar sequence of volcanic, volcaniclastic, and clastic rocks lies to the north of this region, within the footwall of the Woodroffe Thrust (between the Petermann and Bloods Ranges in both Western Australia and the Northern Territory), and unconformably beneath the basal sedimentary rocks of the Amadeus Basin. Close et al. (2003) redefined these rocks as the Tjauwata Group by combining and replacing the Bloods Range Beds and the Mount Harris Volcanics. Recent geochronological data (1085–1040 Ma; Edgoose et al., 2004) show that this group can be directly correlated with the Bentley Supergroup. To the south of the Musgrave Province, a drillhole (GSWA Empress 1) intersected basalt beneath the basal sedimentary rock unit of the Officer Basin, which gave a K–Ar age of 1058 ± 13 Ma (Stevens and Apak, 1999). This occurrence suggests that the Bentley Supergroup extends south beneath this Neoproterozoic basin.

Lithology

Daniels (1974) divided the stratigraphy of the Bentley Supergroup into four main units — the Pussy Cat, Tollu, Cassidy, and Mission Groups. Outcrop of the Tollu Group is almost entirely restricted to an east-trending, synclinal structure (Blackstone syncline) south of BLACKSTONE, whereas the other groups are restricted to the region between Warburton to the west and the Barrow Range to the east. In addition, Daniels (1974) recognized three regions dominated by felsic volcanic rocks, but also intruded by subvolcanic granite, called the Scamp, Palgrave, and Skirmish Hill associations (Daniels, 1974).

The Tollu Group has been subdivided subsequent to its original definition by Daniels (1974). To the south of the Blackstone syncline, units of pebble sandstone and conglomerate (MacDougall Formation), and amygdaloidal basalt and andesite (Mummawarrawarra Basalt), originally viewed as the basal portion of the Tollu Group (Daniels, 1974), were subsequently found to form a separate group (the Kunmarnara Group) unconformably underlying the Tollu Group (Smithies et al., 2009). The redefined Tollu Group now consists of the basal Smoke Hill Volcanics and overlying Hogarth Formation (Daniels, 1974; Smithies et al., 2009). The Smoke Hill Volcanics is dominated by porphyritic rhyolite and dacite, occurring as lavas, sills, and cryptodomes. Volcaniclastic deposits are locally common, and include breccia-sandstone and laminated sandstones to siltstones. Some volcaniclastic units are interpreted as rheoignimbrites. Intrusive and extrusive rocks are locally flow-banded, amygdaloidal, or spherulitic. Lavas also show hyaloclastite breccias, indicating subaqueous deposition. The overlying Hogarth Formation comprises andesitic to trachytic lava flows. The dominant unit is a variolitic, andesitic to trachytic lava, but acicular- and comb-textured andesitic to trachytic lavas also occur. Volcaniclastic rocks, including pebble breccias, laminated volcanic siltstones, and subordinate sandstones, are interbedded with the lavas near the base of the formation, and porphyritic aphanitic rhyolite and lesser dacite lavas often occur at the top of the formation.

Daniels (1974) suggested that the Tollu and Pussy Cat Groups are lateral equivalents. The Pussy Cat Group includes the lower dacitic to rhyolitic Kathleen Ignimbrite, which is intercalated with, and overlain by, the basalts and felsic to mafic volcaniclastic rocks of the Glyde Formation. However, geochemical data obtained by GSWA do not support a correlation between the Tollu and Pussy Cat Group.

The Cassidy Group is a bimodal volcanic sequence comprising (listed from base upwards) the Wururu Rhyolite, Gombugurra Rhyolite (including minor volcanosedimentary rocks and basalt), Gurgadi Basalt, Thomas Rhyolite, Warubuyu Basalt, Hilda Rhyolite, and Miller Basalt (Daniels, 1974).

The overlying Mission Group is a more diverse sequence, including a significant proportion of volcaniclastic and clastic rocks (Daniels, 1974). From the base upwards, this unit consists of the Gamminah Conglomerate, Frank Scott Formation (stromatolitic dolomite, siltstone, chert, and sandstone), Lilian Formation (shale, basalt, chert, conglomerate, and rare dolomite), and Milesia Formation (basalt and fine- to coarse-grained siliciclastic sedimentary rocks).

Age code	Proterozoic	P_-
Stratigraphic code	Bentley Supergroup	BE-
Mixed or xenolith/ inclusion bearing	Mixed	x
Rock type 1	Sedimentary siliciclastic	s
Rock type 2	Igneous felsic volcanic	-f
Rock code		**P_-BE-xs-f**

Contact relationships

Contacts between rocks of the Bentley Supergroup and those of the underlying Musgrave Province are either unconformable or faulted. In the area between Jameson and Warburton, Daniels (1974) suggested that the contacts between the Cassidy Group and the Scamp volcanic association, and between these units and the Palgrave volcanic association, were major faults, defining the boundaries of separate calderas. However, more recent mapping suggests that all of these rocks most likely comprise a single stratigraphic pile, with the Cassidy Group conformably overlying the rocks of the Scamp volcanic association, and this combined pile being at least partly laterally equivalent to the rocks of the Palgrave volcanic association (Werner and Howard, 2010).

Rocks of the redefined Tollu Group directly overlie layered mafic intrusive rocks from the earliest magmatic phase of the Giles Suite (P_-WKg1). The mafic intrusive rocks of the Giles Suite intrude rocks of the Kunmarnara Group, and basalt inclusions can be seen in the basalt units of many of the layered and unlayered Giles intrusions. Where the volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the layered mafic Blackstone intrusion (P_-WKg1-o), the depositional layering in the volcanic rocks parallels igneous layering in the intrusion. There is no evidence for a faulted contact between the intrusion and the volcanic rocks. In addition, dykes that are geochemically identical to lavas in the Hogarth Formation cut the layering in the mafic Cavenagh intrusion (P_-WKg1-o) to the south. These relationships indicate a significant time gap between deposition of the Kunmarnara Group (which pre-dates, and were intruded by, P_-WKg1 layered mafic intrusions) and eruption of the Smoke Hill Volcanics. During that time gap, the layered mafic–ultramafic intrusions were emplaced within the Mummawarrawarra Basalt (Kunmarnara Group), and the whole package was uplifted, eroded, and possibly folded. The rocks of the Tollu Group also unconformably overlie rocks of the Musgrave Province’s Mamutjarra Zone.

Geochronology

P_-BE-xs-f	*Maximum*	*Minimum*
Age (Ma)	1078	1026 ± 26
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Isotopic
References	Smithies et al., 2009	Kirkland et al., 2010

Rocks of the Bentley Supergroup were dated as 1060 ± 140 Ma (based on a Rb–Sr isochron; Compston and Nesbitt, 1967) and, more recently, as 1078 ± 5 Ma (SHRIMP U–Pb zircon) by Sun et al. (1996), confirming suggestions made by Daniels (1974) that these rocks are broadly the same age as the mafic–ultramafic Giles intrusions (P_-WKg1- and P_-WKg2-). Recent geochronological data obtained from the Tjauwata Group in the southwest of the Northern Territory (1085–1040 Ma; Edgoose et al., 2004) show that this unit can be directly correlated with the Bentley Supergroup, and specifically with the Tollu Group (Close et al., 2003).

Layered mafic intrusive rocks (P_-WKg1-) of the Giles Suite were emplaced within the Mummawarrawarra Basalt of the Kunmarnara Group, and at the base of the Bentley Supergroup. A sample obtained from these layered rocks yields a magmatic crystallization age of 1076 ± 7 Ma (GSWA 194762, Kirkland et al., 2011); Sun et al. (1996) obtained an age of 1078 ± 3 Ma from a granitic layer within the layered Bell Rock intrusion. Hence, an age range of 1078–1075 Ma can be inferred for these layered intrusions, which can also be interpreted as a minimum age of deposition for the basalt unit (Smithies et al., 2009). The maximum age of deposition is constrained by the youngest detrital zircon population (1172 ± 8 Ma, Evins et al., 2010) from rocks of the MacDougall Formation, which forms the base of the Kunmarnara Group.

Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite (Smoke Hill Volcanics). Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock was in fact a fine- to medium-grained leucogranite, petrographically and texturally identical to c. 1075 Ma leucogranites of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill, gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), which was interpreted as the igneous crystallization age of the upper part of the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite dated by Kirkland et al. (2010) represents a subvolcanic sill younger than the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or younger units); this date now provides a minimum crystallization age for the Tollu Group.

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Tollu Group (P_-TL-f)

Legend narrative

Undivided; rhyolitic and basaltic volcanic rocks; conglomerate and sandstone

Rank	Group
Parent	Bentley Supergroup (P_-BE-xs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Maximum thickness	4200 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

Outcrop of the Tollu Group is almost entirely restricted to Blackstone (Blackstone Sub-Basin), where the rocks are sporadically exposed within a major, east-trending synclinal structure (Blackstone syncline), bounded to the north by the Blackstone Range and to the south by granitic and gneissic basement. The Blackstone syncline extends eastwards under cover onto the western edge of Bell Rock, and may also extend under cover to the west-southwest, possibly providing a direct link with other Bentley Supergroup units exposed within the Mount Palgrave – Barrow Range region (Mount Eveline). The rocks of the Tollu Group unconformably overlie rocks of the Musgrave Province, mainly within the Mamutjarra Zone. The group comprises two formations: the rhyolitic and dacitic volcanic and volcaniclastic rocks, breccia-sandstones, and laminated sandstones to siltstones of the Smoke Hill Volcanics; and andesitic to trachyitic lava flows, pebble breccias, and laminated volcanic siltstones and subordinate sandstones of the overlying Hogarth Formation. The base of the Tollu Group rests directly on c. 1075 Ma rocks belonging to the layered mafic–ultramafic intrusions (Blackstone and Cavenagh intrusions; P_-WKg1) of the Giles Suite (Warakurna Supersuite), which were uplifted and eroded prior to deposition of the Tollu Group between c. 1072 and c. 1026 Ma.

Distribution

Outcrop of the Tollu Group is almost entirely restricted to the east-trending, synclinal structure (Blackstone syncline) defining the preserved extent of the Blackstone Sub-Basin in the north of Blackstone, but probably extends eastwards under cover onto the western edge of Bell Rock. Recent mapping on Cooper also suggests that the Tollu Group may extend under cover to the west-southwest, possibly providing a direct link between the Blackstone Sub-Basin and other units of the Bentley Supergroup exposed within the Mount Palgrave – Barrow Range region (Mount Eveline).

Lithology

The Tollu Group has been subdivided into the Smoke Hill Volcanics and overlying Hogarth Formation (Daniels, 1974; Smithies et al., 2009). The Smoke Hill Volcanics is dominated by porphyritic rhyolite and dacite, occurring as lavas, sills, and cryptodomes. Volcaniclastic deposits are locally common, and include breccia-sandstone and laminated sandstones to siltstones. Some volcaniclastic units are interpreted as rheoignimbrites. Intrusive and extrusive rocks are locally flow-banded, amygdaloidal, or spherulitic; lavas also show hyaloclastite breccias, indicating subaqueous deposition.

The overlying Hogarth Formation comprises andesitic to trachyitic lava flows. The dominant unit consists of variolitic andesitic to trachyitic lava, but acicular- and comb-textured andesitic to trachyitic lavas also occur. Volcaniclastic rocks, including pebble breccia, laminated volcanic siltstones, and subordinate sandstones are interbedded with lavas near the base of the formation, and porphyritic aphanitic rhyolite and lesser dacite lavas often occur at the top of the formation.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group	TL-
Rock type	Igneous felsic volcanic	f
Rock code		**P_-TL-f**

Contact relationships

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the layered, mafic, Blackstone intrusion (P_-WKg1-o); depositional layering in these volcanic rocks parallels igneous layering in the intrusion, and there is no evidence for a faulted contact between the intrusion and the volcanic rocks. In addition, dykes geochemically identical to lavas seen in the Hogarth Formation cut the layering within the layered mafic Cavenagh intrusion (P_-WKg1-o) to the south. These relationships indicate a significant time gap between the deposition of the Kunmarnara Group (which pre-dates, and was intruded by, P_-WKg1 layered mafic intrusions) and the eruption of the Smoke Hill Volcanics. During that time gap, the layered mafic–ultramafic intrusions were emplaced within the Mummawarrawarra Basalt (Kunmarnara Group), and the whole package was uplifted, eroded, and possibly folded. The rocks of the Tollu Group unconformably overlie rocks of the Musgrave Province's Mamutjarra Zone.

Geochronology

P_-TL-f	*Maximum*	*Minimum*
Age (Ma)	1073 ± 7	1026 ± 26
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Coleman et al., 2010b	Kirkland et al., 2010

Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion (P_-WKg1). Dating of a vitric dacite sample collected from the upper part of the Smoke Hill Volcanics, and on the northern limb of the Blackstone syncline (on BLACKSTONE), gave a crystallization age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010). However, a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, and similar rocks to the west (COOPER and FINLAYSON), have been dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). This requires at least some rocks within the Smoke Hill Volcanics to have been deposited before c. 1067 Ma. Indeed, two rhyolite samples obtained from around Mount Jane (northeastern BLACKSTONE) in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill younger than the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or younger units), and instead provides a minimum crystallization age for the whole Tollu Group. Regardless, there must have been a hiatus between emplacement of the Blackstone intrusion and deposition of the Tollu Group, with an intervening period of major uplift and erosion for the layered mafic intrusion.

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SMOKE HILL VOLCANICS (P_-TLs-f)

Legend narrative

Undivided; rhyolitic and basaltic volcanic rocks; conglomerate and sandstone

Rank	Formation
Parent	Tollu Group (P_-TL-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Maximum thickness	3000 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

The Smoke Hill Volcanics forms the lowermost unit of the Tollu Group, and is conformably overlain by the Hogarth Formation. It is exposed on BLACKSTONE within the major, east-trending synclinal structure (Blackstone syncline), bounded to the north by the Blackstone Range and to the south by granitic and gneissic basement. This unit is dominated by porphyritic rhyolite and dacite, occurring as lavas, sills, and cryptodomes. Volcaniclastic deposits are common locally, and include rheoignimbrite, breccia-sandstone, and laminated sandstones to siltstones and volcaniclastic conglomerate. The rocks unconformably overlie the layered mafic Blackstone intrusion, which is related to the earliest mafic magmatic stage of the Giles Suite (P_-WKg1). Deposition of the Smoke Hill Volcanics is constrained to between c. 1075 and c. 1026 Ma.

Distribution

The main exposure of the Smoke Hill Volcanics is on BLACKSTONE within the major, east-trending synclinal structure (Blackstone syncline), bounded to the north by the Blackstone Range and to the south by granitic and gneissic basement. The unit probably extends eastwards under cover onto the western edge of BELL ROCK. Recent mapping on COOPER also suggests that units of the Tollu Group may extend under cover to the west-southwest, possibly providing a direct link with other Bentley Supergroup units, exposed within the Mount Palgrave – Barrow Range region (MOUNT EVELINE).

Lithology

The Smoke Hill Volcanics forms the lowermost unit of the Tollu Group. It is dominated by porphyritic rhyolite and dacite, occurring as lavas, sills, and cryptodomes. The complete compositional range of magmas extends from andesite to trachyte. Volcaniclastic deposits are locally common, and include breccia-sandstone, and laminated sandstones to siltstones and volcaniclastic conglomerate. Some volcaniclastic units are interpreted as rheoignimbrite. Intrusive and extrusive rocks are locally flow-banded, amygdaloidal, or spherulitic. Lavas also show hyaloclastite breccias, indicating local subaqueous deposition.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Rock code		**P_-TLs-f**

Contact relationships

Rocks of the Smoke Hill Volcanics unconformably overlie rocks of the Musgrave Province's Mamutjarra Zone. Volcanic rocks at the base of the Smoke Hill Volcanics directly overlie the layered, mafic Blackstone intrusion (P_-WKg1-o); depositional layering in the volcanic rocks parallels igneous layering in the intrusion, and there is no evidence for a faulted contact between the intrusion and the volcanic rocks. These relationships indicate a significant time gap between the emplacement of layered mafic intrusions (P_-WKg1) and the Kunmarnara Group (which underlies the Tollu Group), and eruption of the Smoke Hill Volcanics. During this time gap, the layered mafic–ultramafic intrusions and the Kunmarnara Group were uplifted, eroded, and possibly folded.

Geochronology

P_-TLs-f	*Maximum*	*Minimum*
Age (Ma)	1073 ± 7	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Age constraints on the Smoke Hill Volcanics have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion (P_-WKg1). A vitric dacite sampled to the south of the Blackstone Range and north of Smoke Hill (central BLACKSTONE), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), which was interpreted as the igneous crystallization age of lavas (or subvolcanic sills) of the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples of the Smoke Hill Volcanics (P_-TLs-frp) recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite P_-WKA; previously coded P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded into the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or to an event that post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010a, 191728: rhyolite, Mount Jane, Geochronology Record 917: Geological Survey of Western Australia, 4p.

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frc)

Legend narrative

Felsic volcaniclastic conglomerate; subangular to subrounded poorly-sorted clasts up to 1 m dominated by aphanitic feldspar-porphyritic dacite to rhyolite, with lesser granite, gabbro and basalt; typically matrix supported

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This felsic volcaniclastic conglomerate unit forms a minor component of the Smoke Hill Volcanics, found in the Blackstone syncline on northern BLACKSTONE. It occurs as lenses within the porphyritic and aphanitic dacite to rhyolite unit that dominates this area, but rarely forms discrete, mappable units. The conglomerate comprises subangular to subrounded, poorly-sorted clasts up to 1 m in size, supported in a dark, aphanitic, volcanic matrix. Clasts are dominated by aphanitic, feldspar porphyritic dacite to rhyolite, but also include lithologies from stratigraphically lower levels in the Blackstone syncline. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This felsic volcaniclastic conglomerate unit occurs as lenses within the porphyritic and aphanitic dacite to rhyolite unit that dominates the northern BLACKSTONE area, but only forms discrete, mappable units in the area approximately 11 km to the southeast of the mafic Saturn intrusion (northwest BLACKSTONE).

Lithology

This felsic volcaniclastic conglomerate comprises subangular to subrounded, poorly-sorted clasts, supported in a dark, aphanitic, volcanic matrix. Clasts are up to 1 m in size, but are typically smaller than ~20 cm; aphanitic feldspar-porphyritic dacite to rhyolite dominates the clast population, although granite, gabbro, layered gabbronorite, and basalt also occur. All of these clasts are similar to lithologies that outcrop nearby and at stratigraphically lower levels in the Blackstone syncline, and are thus inferred to underlie the present conglomerate. Hence, the basalt clasts are likely derived from the underlying Mummawarrawarra Basalt, whereas the gabbros and gabbronorites are likely derived from the mafic layered Blackstone intrusion. This felsic volcaniclastic conglomerate unit is therefore interpreted to form one of the stratigraphically lowest (oldest) units in the Smoke Hill Volcanics.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic conglomerate	c
Rock code		**P_-TLs-frc**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered, mafic, Blackstone intrusion (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-); they are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frc	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This felsic volcaniclastic conglomerate unit has not been dated directly, so the depositional age range is inferred through the dating of other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central BLACKSTONE), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite P_-WKA; previously coded P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frlz)

Legend narrative

Silicified laminated volcanic siltstone

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This silicified laminated volcanic siltstone unit is a minor component of the Smoke Hill Volcanics, forming a small, east-trending outcrop south of the Blackstone Range and west of Barnard Rocks, on BLACKSTONE. It consists mainly of highly siliceous siltstone with subordinate sandstone, and is likely to be an ash deposit. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This silicified laminated volcanic siltstone unit forms a small, east-trending outcrop on BLACKSTONE, south of the Blackstone Range and west of Barnard Rocks.

Lithology

This silicified laminated volcanic unit consists mainly of highly siliceous siltstone, with subordinate amounts of sandstone. The siltstone layers show persistent, 1–2 mm scale laminations, and are likely to be ash deposits. Associated sandstones and fragmental units are likewise interpreted to be felsic volcaniclastic deposits.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic siltstone/mudstone	l
2nd qualifier	Silicified	z
Rock code		**P_-TLs-frlz**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-); the unit is in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frlz	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This silicified laminated volcanic siltstone unit (P_-TLs-frlz) has not been dated directly, so the depositional age range is inferred based on dating of other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill, gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded into the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frp)

Legend narrative

Porphyritic rhyolite and lesser dacite as lavas and subvolcanic sills and cryptodomes; includes up to 10% subhedral to euhedral microcline phenocrysts up to 6 mm; locally laminated, flow banded, amygdaloidal or spherulitic

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This porphyritic rhyolite and lesser dacite unit is the most voluminous component of the Smoke Hill Volcanics, forming widespread but patchy outcrop within the Blackstone syncline to the south of the Blackstone Range, on BLACKSTONE. This unit consists primarily of porphyritic rhyolite and lesser dacite, occurring as lavas and subvolcanic sills and cryptodomes, associated with local metre- to decametre-scale layers or lenses of volcaniclastic breccias, conglomerates, sandstones, and tuffaceous siltstones. The porphyritic rocks locally show millimetre-scale flow-banding, which was commonly deformed and folded during magma flow. They also contain locally abundant ~1 mm sized spherulites and rarer 1–3 mm quartz-filled amygdales, show perlitic fractures, and include rare hyaloclastite breccias that indicate subaqueous deposition. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This porphyritic rhyolite and lesser dacite unit is the most voluminous component of the Smoke Hill Volcanics, forming widespread but patchy outcrop within the Blackstone syncline to the south of the Blackstone Range, on BLACKSTONE.

Lithology

This unit consists primarily of porphyritic rhyolite and lesser dacite, occurring as lavas and subvolcanic sills and cryptodomes, associated with local metre- to decametre-scale layers or lenses of volcaniclastic breccias, conglomerates, sandstones, and tuffaceous siltstones. The porphyritic rocks locally show millimetre-scale flow-banding, which was commonly deformed and folded during magma flow. The unit also contains locally abundant ~1 mm sized spherulites and rarer 1–3 mm quartz-filled amygdales, and show perlitic fractures. Individual bed thicknesses are difficult to estimate, and evidence for an extrusive origin is rare; however, this evidence is provided by interlayered volcanosedimentary or volcaniclastic units, including hyaloclastite layers that indicate subaqueous deposition.

Stratigraphically, the unit overlies acicular-textured trachyitic and subordinate dacitic and rhyolitic rocks (possibly subvolcanic sills), which locally form the base of the Tollu Group. However, in the western part of the Blackstone syncline, the porphyritic aphanitic unit directly overlies the layered, mafic Blackstone and Cavenagh intrusions.

At Barnard Rocks (MGA 424400E 7114100N), the volcanic rocks are hornfelsed in proximity to an intruding granite pluton, but otherwise shows no evidence for metamorphism higher than the greenschist facies. The rocks are typically only weakly deformed, but locally show a well-developed fracture cleavage, which is axial planar to east-trending, open folds. At one locality (WAROX site RHSMUG000999), egg-box interference fold patterns occur with north-northeasterly axial planar foliation imposed on the early east-trending axial planar foliation.

The porphyritic rocks are typically very fine grained and porphyritic, having a weakly to moderately foliated felsitic groundmass that is holocrystalline, hypidiomorphic to allotriomorphic, and seriate textured. The groundmass comprises feldspar, quartz, and 10–20% mafic minerals. Mafic minerals in the groundmass are typically dominated by green to blue-green amphibole, but also include biotite and epidote. Where the tectonic foliation is better developed, biotite partially to largely replaces the amphibole. Subhedral to euhedral phenocrysts comprise up to 10% of the rock, are up to 8 mm in size, and consist mainly of microcline with lesser amounts of plagioclase. Anhedral to subhedral phenocrysts of blue-green amphibole, up to 2 mm in size, are sieved with quartz, and sometimes contain clinopyroxene cores. The amphibole also occurs as wispy clots up to 4 mm in size, which form up to 5% of some rocks. Clots or granular aggregates of titanite are up to 1mm in size, and form up to 2% of the rock.

At Mount Jane, to the south of the eastern end of the Blackstone Range, porphyritic rocks are interbedded on a metre- to decametre-scale with very fine grained, laminated, weakly porphyritic rock (GSWA 185531; WAROX site RHSMUG001015). The latter has an allotriomorphic, seriate-textured, moderately foliated matrix comprising feldspar, quartz, and ~10% mafic minerals. Mafic minerals in this rock's matrix are dominated by brown-green biotite, but also include green to blue-green amphibole, epidote, and small garnet crystals that range from (rarely) euhedral to anhedral with broken grains. Anhedral clasts are up to 8 mm in size, and consist mainly of microcline with lesser amounts of plagioclase. This rock is interpreted to be a volcaniclastic siltstone, with non-volcanic material derived, in part, from basement garnetiferous pelitic gneisses, similar to those exposed at Mount Aloysius.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Porphyritic/glomeroporphyritic	p
Rock code		**P_-TLs-frp**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion (P_-WKg1-o) of the Giles Suite, and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-), and are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frp	*Maximum*	*Minimum*
Age (Ma)	1073 ± 7	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Inferred
References	CColeman et al., 2010b	Kirkland et al., 2010

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central BLACKSTONE), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frs)

Legend narrative

Felsic volcanic breccia-sandstone; subangular to angular clasts of porphyritic dacite to rhyolite, up to 10 cm, supported in a fine-grained volcaniclastic matrix

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This felsic volcaniclastic breccia-sandstone unit forms a minor component of the Smoke Hill Volcanics in the Blackstone syncline, on northern BLACKSTONE. It occurs as several lenses within the porphyritic dacite to rhyolite unit that dominates the area. The breccia-sandstone comprises angular to subangular, poorly-sorted clasts up to 10 cm in size, supported in a fine- to medium-grained, locally welded, ash tuff volcanic matrix. Clasts are dominated by aphanitic feldspar porphyritic dacite to rhyolite. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This felsic volcaniclastic breccia-sandstone unit typically forms rare, thin (<10 m) layers within the porphyritic volcanic unit that dominates outcrop of the Smoke Hill Volcanics, only forming mappable outcrops in the southern part of the Blackstone syncline (northern BLACKSTONE), where it is interbedded with a range of other volcaniclastic units.

Lithology

This felsic volcaniclastic breccia-sandstone comprises a matrix-supported volcaniclastic breccia with a fine- to medium-grained matrix. It contains angular to subangular clasts of porphyritic dacite and spherulitic dacite, up to 10 cm in length, plus plagioclase and quartz crystals. The matrix is a quartz–feldspar ash tuff showing fiamme and evidence of welding.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic breccia-sandstone	s
Rock code		**P_-TLs-frs**

Contact relationships

This unit occurs layered within the more dominant porphyritic rhyolite and lesser dacite unit (P_-TLs-frp). Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-), and are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frs	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This felsic volcaniclastic breccia-sandstone unit has not been dated directly, so the depositional age range is inferred through the dating on other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central BLACKSTONE), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010a, 191728: rhyolite, Mount Jane, Geochronology Record 917: Geological Survey of Western Australia, 4p.

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010b, 191706: mylonitic rhyolite, Mount Maria, Geochronology Record 915: Geological Survey of Western Australia, 4p.

Howard, HM, Smithies, RH, Kirkland, CL, Evins, PM and Wingate, MTD 2009, Age and geochemistry of the Alcurra Suite in the western Musgrave Province and implications for orthomagmatic Ni–Cu–PGE mineralization during the Giles Event: Geological Survey of Western Australia, Record 2009/16, 16p.

Kirkland, CL, Wingate, MTD and Smithies, RH 2010, 187177: metadacite, Hogarth Well Rockhole; Geochronology Record 847: Geological Survey of Western Australia, 4p.

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frt)

Legend narrative

Felsic volcanic sandstone; locally includes layers of laminated volcanic siltstone, volcanolithic sandstone containing abundant angular felsic volcanic and volcaniclastic fragments, and volcaniclastic breccia

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This felsic volcanic sandstone unit forms a minor component of the Smoke Hill Volcanics, in the Blackstone syncline on northern Blackstone. It occurs as several lenses within the porphyritic dacite to rhyolite unit that dominates outcrop in the area. This felsic volcanic sandstone is fine to medium grained, has a banded ash matrix, and contains subrounded dacite clasts; it is locally interbedded with laminated siltstone. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This unit typically forms rare, thin (<10 m) layers within the porphyritic volcanic unit that dominates outcrop in the Smoke Hill Volcanics, only forming mappable outcrops in the southern part of the Blackstone syncline, where it is interbedded with a range of other volcaniclastic units belonging to the Smoke Hill Volcanics.

Lithology

This felsic volcanic sandstone unit is fine to medium grained, matrix supported, and dominantly poorly sorted; it is locally interbedded with laminated siltstone. The rocks of this unit contain subrounded dacite clasts, dominantly 1 cm in size but up to 5 cm, and subrounded plagioclase grains in the groundmass. It has a banded ash matrix; more obvious flow-structures and fining-upwards structures are present in the upper part of the unit. The rock is dominantly composed of alkali feldspar, plagioclase, and quartz, with accessory magnetite, pyrite, epidote, hornblende, chlorite, and biotite. Spherulitic and perlitic textures are common, and feldspars are occasionally micropoikilitic.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic sandstone (grain size equiv to tuff)	t
Rock code		**P_-TLs-frt**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-), and are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frt	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This felsic volcanic sandstone unit has not been dated directly, so the depositional age range is inferred through the dating of other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central Blackstone), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010a, 191728: rhyolite, Mount Jane, Geochronology Record 917: Geological Survey of Western Australia, 4p.

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Kirkland, CL, Wingate, MTD and Smithies, RH 2010, 187177: metadacite, Hogarth Well Rockhole; Geochronology Record 847: Geological Survey of Western Australia, 4p.

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SMOKE HILL VOLCANICS; subunit (P_-TLs-frvr)

Legend narrative

Dacitic to rhyolitic volcaniclastic rock; rheoignimbrite; abundant green-amphibole needles and well-developed felsitic texture; includes cm-scale layers containing angular autoclasts, aphanitic layers and hyaloclastite

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

Thin layers of this dacitic to rhyolitic, rheoignimbritic volcaniclastic rock (P_-TLs-frvr) form a rare component of the Smoke Hill Volcanics, within the Blackstone syncline on BLACKSTONE. This is a highly variable, fine-grained, and holocrystalline rock, comprising angular but locally embayed perthite clasts up to 7 mm, rounded quartz clasts up to 2 mm, and angular autoclasts and cognate rip-up clasts up to 1 cm in size. These clasts lie in a fine-grained, allotriomorphic matrix or groundmass, showing a seriate, felsitic to micrographyric texture. The unit includes tuff or ash layers and hyaloclastites locally. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

This unit forms a rare component of the Smoke Hill Volcanics, occurring within the Blackstone syncline on BLACKSTONE, only forming a mappable layer at a single outcrop (WAROX site RHSMUG001397) in the southwestern part of the syncline.

Lithology

This is a highly variable unit dominated by fine-grained dacitic to rhyolitic volcaniclastic rock. It is a holocrystalline rock, comprising angular but locally embayed perthite clasts up to 7 mm in size, rounded quartz clasts up to 2 mm in size, and angular autoclasts and cognate rip-up clasts up to 1 cm in size. These all lie within a fine-grained, allotriomorphic matrix or groundmass, showing a seriate, felsitic to micrographyric texture. The groundmass comprises quartz, feldspar, and abundant (up to 10%) blue-green amphibole, the latter of which ranges from needles 1–3 mm long, to more prismatic and skeletal crystals with clinopyroxene cores. The unit locally grades into a rock with medium- to coarse-grained amphibole needles, which is usually indistinguishable from the acicular-textured trachyitic to dacitic and rhyolitic unit that forms a lower stratigraphic component (possibly a subvolcanic sill) of the Smoke Hill Volcanics. This fine-grained dacitic to rhyolitic volcaniclastic unit also grades into what look like tuff or ash layers (with micro-acicular textures), and into hyaloclastite.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcaniclastic	v
2nd qualifier	Autoclastic	r
Rock code		**P_-TLs-frvr**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-), and are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-frvr	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This dacitic to rhyolitic rheoignimbritic volcaniclastic rock unit has not been dated directly, so the depositional age range is inferred through the dating of other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central BLACKSTONE), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010a, 191728: rhyolite, Mount Jane, Geochronology Record 917: Geological Survey of Western Australia, 4p.

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SMOKE HILL VOLCANICS; subunit (P_-TLs-gvh)

Legend narrative

Fine- to medium-grained granophyric granite; randomly oriented hornblende needles up to 3 cm; subvolcanic intrusions related to acicular-textured felsic volcanic rocks

Rank	Member
Parent	SMOKE HILL VOLCANICS (P_-TLs-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	HOGARTH FORMATION (P_-TLh-f) (conformable)
Underlying units	Layered mafic intrusive rocks of the Giles Suite (P_-WKg1-o) (erosional); Kunmarnara Group (P_-KR-) (erosional)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

Small outcrops of this fine- to medium-grained granophyric granite are found in the southwestern parts of the Blackstone syncline, on Blackstone. These rocks are difficult to distinguish from the felsic volcanic rocks of the Smoke Hill Volcanics that they intrude; as such they are interpreted to be the subvolcanic equivalents of those felsic volcanic rocks. The rocks of this unit are typically leucocratic, have <10% mafic minerals, are fine to medium grained, locally contain abundant country-rock xenoliths, are generally unfoliated, and have a hypidiomorphic granular to acicular texture, containing hornblende needles up to 3 cm long. These rocks were deposited between c. 1073 and c. 1026 Ma.

Distribution

Outcrop of this unit is found in the southwestern parts of the Blackstone syncline, on Blackstone, occurring as dykes within other units of the Smoke Hill Volcanics.

Lithology

Rocks of this fine- to medium-grained granophyric granite unit are difficult to distinguish from the felsic volcanic rocks of the Smoke Hill Volcanics that they intrude, and as such are interpreted to be the subvolcanic equivalents of those felsic volcanic rocks. The rocks of this unit are typically leucocratic, have <10% mafic minerals, are fine to medium grained, locally contain abundant country-rock xenoliths, are generally unfoliated, and have a hypidiomorphic granular to acicular texture. Subhedral perthite crystals form a semicontinuous framework in the rock, with intergranular patches of either granophyre or quartz–perthite(–plagioclase). The main mafic mineral is hornblende, which ranges in shape from elongate crystals to needles, and locally contains clinopyroxene cores. Amphibole needles range up to 3 cm in size, but are typically fine grained. Biotite forms anhedral to subhedral crystals, in places rimming hornblende; titanite, magnetite, apatite, and zircon are common accessory minerals.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, SMOKE HILL VOLCANICS	TLs-
Rock type	Igneous granitic	g
Lithname	Granophyre	v
1st qualifier	Hornblende	h
Rock code		**P_-TLs-gvh**

Contact relationships

Volcanic rocks of the Smoke Hill Volcanics unconformably overlie both the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1-o), and amygdaloidal basalt–andesites and conglomerates of the Kunmarnara Group (P_-KR-), and are in turn conformably overlain by volcanic and volcaniclastic rocks of the Hogarth Formation. Contact relationships between individual Smoke Hill Volcanics units are rarely preserved; most appear to be conformable, although massive to flow-banded units with no internal boundaries are common, and likely reflect subvolcanic sills or cryptodomes.

Geochronology

P_-TLs-gvh	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

This fine- to medium-grained granophyric granite unit (P_-TLs-gvh) has not been dated directly, so the intrusive age range is inferred through the dating of other Tollu Group units.

A vitric dacite, sampled south of the Blackstone Range and north of Smoke Hill (central Blackstone), gave an age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010), interpreted as the igneous crystallization age of lavas (or subvolcanic sills) belonging to the Smoke Hill Volcanics (Smithies et al., 2009). However, two rhyolite samples also from the Smoke Hill Volcanics (P_-TLs-frp), recently collected from around Mount Jane in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). These ages are consistent with the observation that a series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, are part of a geochemically homogeneous suite containing units dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill that intruded the Smoke Hill Volcanics (either belonging to the Hogarth Formation, or an event that the post-dates this formation). Therefore, this date provides a minimum crystallization age for both the Tollu Group and the Bentley Supergroup. The depositional age of the Smoke Hill Volcanics, and of the Tollu Group in general, is thus constrained to between c. 1073 and c. 1026 Ma.

References

Coleman, PM, Kirkland, CL, Wingate, MTD and Smithies, RH 2010a, 191728: rhyolite, Mount Jane, Geochronology Record 917: Geological Survey of Western Australia, 4p.

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HOGARTH FORMATION (P_-TLh-f)

Legend narrative

Andesitic to trachytic lava flows; minor interbedded volcaniclastic rocks and rhyolite and lesser dacite

Rank	Formation
Parent	Tollu Group (P_-TL-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	SMOKE HILL VOLCANICS (P_-TLs-f)
Maximum thickness	1200 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

The Hogarth Formation (Daniels, 1974) is the youngest unit of the Tollu Group, and forms scattered and poor outcrop in the core of the Blackstone syncline in the northern part of BLACKSTONE. The unit is dominated by andesitic to trachytic lava flows, but also includes interbedded volcaniclastic rocks near the base, and rhyolite and lesser dacite lavas towards the top of the formation. Rocks of the Hogarth Formation have not been dated directly; however, the depositional age range for the Tollu Group as a whole is between c. 1072 and c. 1026 Ma.

Distribution

This formation forms scattered and poor outcrop in the core of the Blackstone syncline, within the northern part of BLACKSTONE. The best exposure occurs in the area between Barnard Rocks and Smoke Hill.

Lithology

The Hogarth Formation forms the upper unit of the Tollu Group, and comprises andesitic to trachytic lava flows that can be subdivided into two locally interbedded textural varieties. The dominant variety is a variolitic andesitic to trachytic lava, with acicular- and comb-textured andesitic to trachytic lava as the rarer variant. Volcaniclastic rocks, including pebble breccias, laminated volcanic siltstones, and subordinate sandstones are interbedded with the lavas near the base of the formation; porphyritic rhyolite and subordinate dacitic lavas form at the top of the formation.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Rock code		**P_-TLh-f**

Geochronology

P_-TLh-f	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably underlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

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HOGARTH FORMATION; subunit (P_-TLh-fa)

Legend narrative

Acicular- and comb-textured andesitic to trachytic lavas; rare trachyandesite and dacite; randomly oriented, interlocking, feather-textured or comb-like needles of green–blue amphibole

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	P_-TLh-faw
Underlying units	P_-TLh-faw; P_-TLh-frn
Maximum thickness	200 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This unit of acicular- and comb-textured andesitic to trachyitic lavas forms a minor component of the Hogarth Formation, outcropping within the core of the Blackstone syncline on BLACKSTONE. They are mesocratic to melanocratic rocks in which amphibole crystals, up to 1.3 cm long, are variably needle-like, randomly oriented, interlocking, branching, skeletal, feather-textured or comb-like, and locally form tight parallel aggregates or plates.

Distribution

This unit forms lens-shaped layers, up to ~200 m thick, within the more common variolitic andesitic to trachyitic lavas of the Hogarth Formation. Three mappable outcrops of the unit are identified within the core of the Blackstone syncline on BLACKSTONE.

Lithology

These acicular- and comb-textured lavas are typically andesitic to trachyitic, but also include trachyandesite and dacite. They are mesocratic to melanocratic rocks, containing up to 50% blue-green sodic amphibole. Approximately half of this amphibole forms dendritic to needle-like crystals up to 1.3 cm in length, which are randomly oriented, interlocking, branching, in places skeletal, and are feather-textured or comb-like. Locally, these needles form tight parallel aggregates or plates. The amphibole also forms a major component of the aphanitic groundmass, occurring as elongate subhedral crystals. The groundmass is an allotriomorphic to felsitic mass of amphibole, feldspar, and quartz, with minor epidote, magnetite, titanite, and apatite.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Lithname	Andesite	a
Rock code		**P_-TLh-fa**

Geochronology

P_-TLh-fa	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), which provides a maximum age constraint on Tollu volcanism. Dating of a vitric dacite sample, collected from the upper part of the Smoke Hill Volcanics on the northern limb of the Blackstone syncline (on BLACKSTONE), gave a crystallization age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010). However, two rhyolite samples collected from around Mount Jane (northeastern BLACKSTONE) in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). A series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, and similar rocks to the west (on COOPER and FINLAYSON), have also been dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill younger than the Smoke Hill Volcanics (belonging either to the Hogarth Formation, or younger units), and instead provides a minimum crystallization age for the Tollu Group. Regardless, there must be a hiatus between emplacement of the Blackstone intrusion and deposition of the Tollu Group, with an intervening period of major uplift and erosion affecting the layered mafic intrusion.

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HOGARTH FORMATION; subunit (P_-TLh-faw)

Legend narrative

Variolitic andesitic to trachytic lavas; locally abundant plagioclase – sodic amphibole – quartz varioles in a sodic amphibole and plagioclase-rich groundmass; rare quartz amygdales; locally well-developed perlite texture

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	P_-TLh-frp (conformable)
Underlying units	P_-TLh-fa (conformable); P_-TLh-frn (conformable); P_-TLh-frp (conformable); P_-TLh-frsi (conformable); P_-TLs-frp (conformable to disconformable); Warakurna Supersuite (P_-WK-grhb) (unconformable)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This variolitic andesitic to trachyitic lava unit dominates outcrop of the Hogarth Formation, forming scattered and poor outcrop within the core of the Blackstone syncline, in the northern part of BLACKSTONE. This unit is locally interbedded with lenses of acicular- and comb-textured lavas, and with volcaniclastic rocks. The variole-rich lavas are typically andesitic to trachyitic, but also range to trachyandesite and dacite compositions. Varioles form up to 60% of some rocks, and many are also amygdaloidal.

Distribution

Rocks of this variolitic andesitic to trachyitic lava unit dominate outcrop of the Hogarth Formation, particularly in the upper stratigraphic regions. They form scattered and poor outcrop within the core of the Blackstone syncline, in the northern part of BLACKSTONE.

Lithology

These variolitic andesitic to trachyitic lavas are locally interbedded with lenses of acicular- and comb-textured lavas, and are interbedded with volcaniclastic rocks, including pebble breccias, laminated volcanic siltstones, and subordinate sandstones, near the base of the formation.

These variolitic lavas are typically andesitic to trachyitic, but extend to trachyandesite and dacite compositions. Varioles are typically 1–2 mm in size, form up to 60% of some rocks, and occur either individually or as aggregates or coalesced varioles; some are cored by subhedral crystals of perthite. Weakly variolitic or non-variolitic layers are rare; many layers are amygdaloidal, containing quartz-filled amygdales up to 1.2 cm in size (though typically <8 mm), and forming as much as 5% of the rock. Some of the rocks contain subhedral perthite and plagioclase phenocrysts and glomerophenocrysts, all up to 2 mm in size. Perlite textures are locally well developed.

The variole-rich lavas form aphanitic, mesocratic to melanocratic rocks, containing up to 50% blue-green sodic amphibole. A mass of subparallel, branching, or comb-like blue-green amphibole needles forms 60–65% of the variole space, the remainder comprising a hypocrystalline and felsitic mass of amphibole, quartz, feldspar, magnetite, and secondary epidote. Semicontinuous intervariole patches consist of melanocratic, felsitic to feathery textured blue-green amphibole (70–80%), quartz, feldspar, and magnetite.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Lithname	Andesite	a
1st qualifier	Spherulitic, variolitic, ocellar, or lithophysae-bearing	w
Rock code		**P_-TLh-faw**

Contact relationships

This variolitic andesitic to trachyitic lava unit conformably overlies other units of the Hogarth Formation (P_-TLh-fa, P_-TLh-frn, P_-TLh-frp, and P_-TLh-frsi). Contacts with units of the underlying Smoke Hill Volcanics (P_-TLs) range from conformable (upper stratigraphic parts of the Smoke Hill Volcanics) to disconformable (lower stratigraphic parts of the Smoke Hill Volcanics). In the area around Barnard Rocks, hornblende–biotite syenogranite of the Warakurna Supersuite (P_-WK-grhb) intrudes into volcanic rocks of the lower stratigraphic parts of the Smoke Hill Volcanics, and is unconformably overlain by the Hogarth Formation.

Geochronology

P_-TLh-faw	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

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HOGARTH FORMATION; subunit (P_-TLh-frn)

Legend narrative

Laminated felsic volcanic siltstone and lesser sandstone; locally shows graded bedding

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	P_-TLh-fa (conformable); P_-TLh-faw (conformable).
Underlying units	P_-TLh-frsi (conformable)
Maximum thickness	200 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This laminated volcanic siltstone unit forms a thin, discontinuous layer near the stratigraphic base of the Hogarth Formation, in the central part of the Blackstone syncline on Blackstone.

Distribution

This unit forms a discontinuous layer, up to 200 m thick, in the central part of the Blackstone syncline on Blackstone. Here, it overlies a layer of felsic volcanic pebble breccia, and forms near the stratigraphic base of the Hogarth Formation.

Lithology

This volcanic siltstone, with subordinate sandstone, is laminated on a 1–2 mm scale, and locally shows graded-bedding ranging from silt to fine sand size; grains are typically poorly sorted, and comprise angular clasts of quartz and feldspar in a matrix of (?)stilpnomelane, chlorite, magnetite (up to 20%), quartz, and feldspar.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic sandstone–siltstone	n
Rock code		**P_-TLh-frn**

Geochronology

P_-TLh-frn	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

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HOGARTH FORMATION, subunit (P_-TLh-frp)

Legend narrative

Porphyritic rhyolite and lesser dacite; includes up to 15% subhedral to euhedral microcline (and lesser plagioclase) phenocrysts up to 6 mm and lesser subhedral green–blue amphibole

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	P_-TLh-faw (conformable and intrusive)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This porphyritic rhyolite and lesser dacite unit is interpreted to form lavas and subvolcanic sills or cryptodomes at the top of the Hogarth Formation (and therefore the Tollu Group), occurring in the core of the Blackstone syncline on BLACKSTONE. Subhedral to euhedral microcline (and lesser plagioclase) phenocrysts are up to 8 mm in size, and comprise up to 15% of the rock.

Distribution

This porphyritic rhyolite and lesser dacite unit is interpreted to form the stratigraphic top of the Hogarth Formation (and therefore the Tollu Group). The unit occurs in the core of the Blackstone syncline on BLACKSTONE, where it typically forms low, rubbly outcrop.

Lithology

The rocks of this unit are typically very fine grained and porphyritic, with a moderately foliated felsitic groundmass that is holocrystalline, hypidiomorphic to allotriomorphic, and seriate textured. The groundmass comprises feldspar, quartz, and 10–20% mafic minerals. Mafic minerals in the groundmass are typically dominated by green to blue-green amphibole, but also include biotite, magnetite, and epidote. Where the tectonic foliation is better developed, biotite partially to largely replaces amphibole grains. Subhedral to euhedral phenocrysts comprise up to 15% of the rock, are up to 8 mm in size, and are mainly composed of microcline, with lesser amounts of plagioclase. Anhedral to subhedral phenocrysts of blue-green amphibole are up to 2 mm in size.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Porphyritic/glomeroporphyritic	p
Rock code		**P_-TLh-frp**

Contact relationships

This porphyritic rhyolite and lesser dacite unit of the Hogarth Formation forms lavas that overlie, and subvolcanic sills or cryptodomes within, variolitic andesitic to trachyitic lavas (P_-TLh-faw) also of the Hogarth Formation. Individual bed thickness cannot be ascertained, clear evidence for an extrusive origin is rare, and units are commonly massive. On this basis, contacts between this unit and the variolitic andesitic to trachyitic lavas are interpreted to range from conformable (depositional) to intrusive.

Geochronology

P_-TLh-frp	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), which provides a maximum age constraint on Tollu volcanism. Dating of a vitric dacite sample, collected from the upper part of the Smoke Hill Volcanics on the northern limb of the Blackstone syncline (on BLACKSTONE), gave a crystallization age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010). However, two rhyolite samples collected from around Mount Jane (northeastern BLACKSTONE) in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). A series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, and similar rocks to the west (on COOPER and FINLAYSON), have also been dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill younger than the Smoke Hill Volcanics (belonging either to the Hogarth Formation, or younger units), and instead provides a minimum crystallization age for the Tollu Group. Regardless, there must be a hiatus between emplacement of the Blackstone intrusion and deposition of the Tollu Group, with an intervening period of major uplift and erosion affecting the layered mafic intrusion.

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HOGARTH FORMATION; subunit (P_-TLh-frsi)

Legend narrative

Felsic volcanic-pebble breccia; angular to subangular rhyolitic and lesser dacitic volcanic and volcaniclastic rock fragments up to 10 cm supported in a matrix of aphanitic, magnetite-rich rhyolite

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	P_-TLh-frn (conformable)
Underlying units	P_-TLh-faw (conformable)
Maximum thickness	150 m
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This felsic volcanic pebble breccia unit forms a thin, discontinuous layer near the stratigraphic base of the Hogarth Formation, in the central part of the Blackstone syncline on Blackstone. The rocks are typically matrix-supported, but clast-supported examples are known. Clasts are mainly angular, up to 10 cm in size, and include a variety of local volcanic and volcaniclastic lithologies. The melanocratic matrix is strongly dusted with very fine grained magnetite, and contains contorted cavities that possibly reflect either hot deposition or rheomorphic flow.

Distribution

This unit forms a discontinuous layer, up to 150 m thick, within the central part of the Blackstone syncline on Blackstone, near the stratigraphic base of the Hogarth Formation. Here, it overlies a layer of variolitic andesitic to trachyitic lavas, and underlies a layer of laminated volcanic siltstone.

Lithology

Rocks of this felsic volcanic pebble breccia unit are typically melanocratic, and contain abundant magnetite. They include clast-supported examples, although typically the melanocratic aphanitic matrix sufficiently abundant to support the clasts. Clasts are angular to (less typically) subangular, up to 10 cm in size (but more commonly <2 cm), and are polymict; contributing lithologies include fine-grained volcanic siltstone to sandstone, felsitic- and acicular-textured rhyolitic volcanic rocks, Mummawarrawarra Basalt, and felsic volcanic clasts with abundant (70%) distorted and compacted patches (originally cavities or vesicles) now replaced by (?) stilpnomelane. The matrix is also rich in these contorted (?)stilpnomelane-filled ‘cavities’, and additionally includes a felsitic-textured mass of feldspar and quartz strongly dusted with very fine grained magnetite crystals. Contortion of the ‘cavities’ might be a result of hot deposition or rheomorphic flow (i.e. the rocks might be pyroclastic).

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Igneous felsic volcanic	f
Lithname	Rhyolite	r
1st qualifier	Volcanic breccia-sandstone	s
2nd qualifier	Ferruginized	i
Rock code		**P_-TLh-frsi**

Geochronology

P_-TLh-frsi	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), which provides a maximum age constraint on Tollu volcanism. Dating of a vitric dacite sample, collected from the upper part of the Smoke Hill Volcanics on the northern limb of the Blackstone syncline (on Blackstone) gave a crystallization age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010). However, two rhyolite samples collected from around Mount Jane (northeastern Blackstone) in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). A series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite suite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, and similar rocks to the west (on Cooper and Finlayson), have also been dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill younger than the Smoke Hill Volcanics (belonging either to the Hogarth Formation, or younger units), and instead provides a minimum crystallization age for the Tollu Group. Regardless, there must be a hiatus between emplacement of the Blackstone intrusion and deposition of the Tollu Group, with an intervening period of major uplift and erosion affecting the layered mafic intrusion.

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HOGARTH FORMATION; subunit (P_-TLh-mogr) formerly Giles Suite (P_-WKg3-mogr)

Legend narrative

Metamorphosed gabbro; massive with well-developed subophitic texture; extensive actinolite replacement of igneous (?)pyroxene.

Rank	Member
Parent	HOGARTH FORMATION (P_-TLh-f)
Tectonic units	Bentley Basin, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Metamorphic facies	Greenschist facies: tremolite–actinolite

Summary

This metamorphosed gabbro unit forms a layer (sill?) near the core of the Blackstone syncline on BLACKSTONE, at or near the base of the Hogarth Formation. It is typically magnetite-rich and melanocratic, with a granophyric to acicular texture formed by needle-like plagioclase crystals up to 5 mm in length. This unit is most likely related to the andesite pile (also of the Hogarth Formation) it lies within; the upper contact appears texturally transitional with these andesitic to dacitic vesicular rocks. Thus, this unit was incorrectly assigned to the P_-WKg3 Giles suite (now Alcurra Dolerite suite, P_-WKA-) on previous edition maps, but is now reassigned to the Hogarth Formation.

Distribution

This gabbro forms a layer (sill?) near the core of the Blackstone syncline on BLACKSTONE, at or near the base of the Hogarth Formation.

Lithology

This metamorphosed gabbro is typically magnetite-rich and melanocratic, with a granophyric to acicular texture formed by needle-like plagioclase crystals up to 5 mm in length. Actinolite (~35% of the rock) locally preserves cores of clinopyroxene, and is intergranular to, and subophitically encloses, plagioclase. Subhedral magnetite (~15%) is enclosed within actinolite in intergranular areas. This rock is likely related to the andesite pile (also of the Hogarth Formation) it lies within; the upper contact appears texturally transitional with these andesitic to dacitic vesicular rocks.

Age code	Proterozoic	P_-
Stratigraphic code	Tollu Group, HOGARTH FORMATION	TLh-
Rock type	Meta-igneous mafic intrusive	mo
Lithname	Metagabbro	g
1st qualifier	–	
2nd qualifier	Tremolite/actinolite	r
Rock code		**P_-TLh-mogr**

Geochronology

P_-TLh-mogr	*Maximum*	*Minimum*
Age (Ma)	1073	1026
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Coleman et al., 2010b	Kirkland et al., 2010

Rocks of the Hogarth Formation have not been dated directly, but share the same depositional age constraints as the rocks of the conformably overlying Smoke Hill Volcanics, and of the Tollu Group in general. Age constraints on the Tollu Group have previously hinged on a 1078 ± 5 Ma date obtained by Glikson et al. (1996) from an outcrop identified as rhyolite of the Smoke Hill Volcanics. Re-examination of that outcrop (Smithies et al., 2009) indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to a c. 1075 Ma leucogranite of the Warakurna Supersuite (P_-WK-g), and therefore not part of the Tollu Group.

Volcanic rocks at the base of the Tollu Group (Smoke Hill Volcanics) directly overlie the c. 1075 Ma layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), which provides a maximum age constraint on Tollu volcanism. Dating of a vitric dacite sample, collected from the upper part of the Smoke Hill Volcanics on the northern limb of the Blackstone syncline (on BLACKSTONE), gave a crystallization age of 1026 ± 26 Ma (GSWA 187177, Kirkland et al., 2010). However, two rhyolite samples collected from around Mount Jane (northeastern BLACKSTONE) in the east of the Blackstone syncline, have given ages of 1071 ± 8 Ma (GSWA 191728, Coleman et al., 2010a) and 1073 ± 7 Ma (GSWA 191706, Coleman et al., 2010b). A series of olivine gabbros, olivine norites, ferronorites, and ferrodiorites (Alcurra Dolerite, P_-WKA; previously P_-WKg3), which intruded into the Smoke Hill Volcanics in the western part of the Blackstone syncline, and similar rocks to the west (on COOPER and FINLAYSON), have also been dated at c. 1067 Ma (Seat, 2008; Howard et al., 2009). It is most likely that the 1026 ± 26 Ma dacite represents a subvolcanic sill younger than the Smoke Hill Volcanics (belonging either to the Hogarth Formation, or younger units), and instead provides a minimum crystallization age for the Tollu Group. Regardless, there must be a hiatus between emplacement of the Blackstone intrusion and deposition of the Tollu Group, with an intervening period of major uplift and erosion affecting the layered mafic intrusion.

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Alcurra Dolerite (P_-WKA-o) formerly Giles Suite (P_-WKg3-o)

Legend narrative

Dykes, sills, or plugs mainly of dolerite but also of olivine gabbro, olivine norite, ferronorite, and ferrodiorite

Rank	Suite
Parent	Warakurna Supersuite (P_-WK-xo-f
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Underlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); Kunmarnara Group (P_-KR-xs-b); Pitjantjatjara Supersuite (P_-PJ-xg-o); Wankanki Supersuite (P_-MN-mg); Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

The Alcurra Dolerite comprises basic and lesser intermediate intrusions formed at a late stage of the Giles Event, which occur as small bodies and dykes typically emplaced near the margins of, or peripheral to, older layered mafic intrusions (P_-WKg1-), and massive gabbro and co-mingled gabbro–granite intrusions (P_-WKg2-), of the Warakurna Supersuite. This suite is recognized on the Blackstone, Holt, Finlayson, and Cooper map sheets. Although previously coded P_-WKg3-, Howard et al. (2009) demonstrated a close geochemical and geochronological link between these small bodies and dykes, the dykes that form the Alcurra Dolerite dyke swarm, and the gabbros that host the orthomagmatic nickel–copper mineralization at the Nebo–Babel deposit south of the Jameson Range (Cooper). Accordingly, these authors grouped all of these rocks into a newly defined Alcurra Dolerite suite, subsequently recoded P_-WKA- (Howard et al., 2009). The unit typically includes fine- to medium-grained olivine gabbro, olivine norite, ferronorite, and ferrodiorite, and is commonly characterized by a 'dual texture', comprising a porous framework of coarse-grained crystals, and a finer-grained and locally granophyric-textured matrix. Contact relationships broadly constrain the emplacement age of this unit to between c. 1073 and c. 1026 Ma, but direct dating of these intrusions indicates a narrower intrusive period, around c. 1067 Ma.

Distribution

The basic and lesser intermediate intrusions of the Alcurra Dolerite, formed at a late stage of the Giles Event (P_-WKA-o), are found in the Blackstone syncline immediately south of the Blackstone Range (Blackstone), where small, subvolcanic intrusions occur within slightly older volcanic and volcaniclastic rocks of the Tollu Group. They also occur on Holt and Finlayson, where they form small intrusions and dykes typically emplaced near the margins of, or peripheral to, the older layered mafic intrusions of the Warakurna Supersuite. A series of northeast-trending, coarse-grained ferrogabbro dykes belonging to the Alcurra Dolerite crosscuts the northwest part of the layered Jameson intrusion; some of these dykes show extensive copper-staining (e.g. GSWA 194405; WAROX site PMEMUG001109: MGA 357797E 7161020N). Throughout parts of Blackstone and Cooper, the presence of these basic to intermediate intrusions under regolith cover can be inferred based on the coincidence of a high TMI and gravity response.

Lithology

The basic and lesser intermediate intrusions of the Alcurra Dolerite suite, formed at a late stage of the Giles Event (P_-WKA-o), typically include fine- to medium-grained olivine gabbro, olivine norite, ferronorite, and ferrodiorite. They are commonly characterized by a 'dual texture', comprising a porous framework of coarse-grained crystals (mainly euhedral to acicular plagioclase), enclosing a mineralogically identical (except for the presence of accessory quartz in granophyric intergrowths) and locally granophyric-textured, fine-grained assemblage in interstitial pockets and veins (interstitial liquid). In places, fine-grained rocks containing euhedral plagioclase phenocrysts are found, which represent rocks crystallized from the interstitial liquid that was more or less free of the components that formed the coarse-grained crystal framework.

The rocks are typified by evolved and Fe-rich tholeiitic compositions, resulting in physical properties such as a strong TMI response and high specific gravity.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Alcurra Dolerite	WKA-
Rock type	Igneous mafic intrusive	o
Rock code		**P_-WKA-o**

Contact relationships

In the Blackstone syncline (Blackstone), basic to intermediate intrusions of the Alcurra Dolerite suite have intruded into the layered, mafic, Giles intrusions (Blackstone intrusion: P_-WKg1-), and also the volcanic, volcaniclastic, and clastic rocks of the Kunmarnara and Tollu Groups. To the west-northwest on Finlayson, the marginal zones of the layered, mafic, Jameson intrusion have also been intruded by sills and northeast-trending dykes of Alcurra ferronorite. On Holt and Finlayson, these late intrusions form small bodies and dykes typically emplaced near the margins of, or peripheral to, the older layered mafic Warakurna Supersuite intrusions, presumably utilizing layering and intrusion – country rock contacts as planes of weakness. The series of northeast-trending, coarse-grained ferrogabbro dykes that crosscut the layered Jameson intrusion, and that also occur throughout the northern parts of Cooper, utilized fractures and faults related to movements likely as early as the Musgrave Orogeny.

Geochronology

P_-WKA-o	*Maximum*	*Minimum*
Age (Ma)	1068 ± 4	1067 ± 8
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Seat, 2008	Howard et al., 2009; Kirkland et al., 2009

Contact relationships broadly constrain the emplacement age of the Alcurra Dolerite intrusions to between c. 1075 Ma, the minimum age of the layered and massive mafic intrusions of the Warakurna Supersuite (i.e. P_-WKg1- and P_-WKg2-), and c. 1026 Ma, the age of the youngest component — likely a subvolcanic sill — of the Tollu Group (Smithies et al., 2009; Kirkland et al., 2010). However, two Alcurra Dolerite intrusions have also been directly dated: a granophyric-textured ferrogabbro–ferronorite (GSWA 194354) that intrudes the northwestern part of the Jameson layered intrusion (MGA 354869E 7163642N) was dated at 1067 ± 8 Ma (Howard et al., 2009; Kirkland et al., 2009); and Seat (2008) reported an age of 1068 ± 4 Ma from an intrusion in the northern part of COOPER.

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Alcurra Dolerite; subunit (P_-WKA-oon) formerly Giles Suite (P_-WKg3-oon)

Legend narrative

Olivine-rich gabbro; typically with up to 15% olivine; contains accessory biotite; massive to weakly flow banded

Rank	Formation
Parent	Alcurra Dolerite (P_-WKA-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Underlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); Kunmarnara Group (P_-KR-xs-b); Pitjantjatjara Supersuite (P_-PJ-xg-o); Wankanki Supersuite (P_-MN-mg); Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

This olivine-rich gabbro unit forms a single, east-trending outcrop in the far western part of the Blackstone syncline on Blackstone, where it lies between outcrop of the Saturn pluton (P_-WKg2-oob) and layered mafic rocks of the Cavenagh intrusion (P_-WKg1-). It is typically massive, or else shows a weak, west-trending magmatic foliation. The rocks are also leucocratic, medium-grained, and generally equigranular, with oikocrysts of clinopyroxene or magnetite up to 1 cm in size. The rocks range in composition from olivine gabbro to olivine norite.

Distribution

This olivine-rich gabbro of the Alcurra Dolerite forms a single, east-trending outcrop in the far western part of the Blackstone syncline on Blackstone, where it lies between outcrop of the Saturn pluton (P_-WKg2-oob) and layered mafic rocks of the Cavenagh intrusion (P_-WKg1-).

Lithology

This olivine-rich gabbro unit is typically massive, or else shows a weak, west-trending magmatic foliation produced by the alignment of plagioclase crystals. The rocks of this unit are leucocratic, medium-grained, and generally equigranular, with oikocrysts of clinopyroxene or magnetite up to 1 cm in size. The rocks range in composition from olivine gabbro to olivine norite.

A single thin-section obtained from samples of this unit (GSWA 185587; WAROX site RHSMUG001165) consists of an olivine norite. It contains ~60% plagioclase, with intergranular orthopyroxene (~22%) enclosing anhedral olivine (~10%). Magnetite comprises ~3% of the rock, forming as disseminated intergranular crystals or as rare oikocrysts up to 1 cm. Magnetite in oikocrysts also encloses olivine, and grows to the exclusion oforthopyroxene. Late biotite (~5%) forms along plagioclase cleavage planes, as rims to magnetite, or (rarely) as an intergranular phase.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Alcurra Dolerite	WKA-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine gabbro	o
1st qualifier	Olivine	n
Rock code		**P_-WKA-oon**

Contact relationships

This olivine-rich gabbro unit has intruded into the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), and also the volcanic, volcaniclastic, and clastic rocks of the Kunmarnara and Tollu Groups.

Geochronology

P_-WKA-oon	*Maximum*	*Minimum*
Age (Ma)	1068	1067
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Seat, 2008	Howard et al., 2009; Kirkland et al., 2009

Rocks of this olivine-rich gabbro unit have not been directly dated from their type area in the Blackstone syncline. However, contact relationships broadly constrain the emplacement age of the Alcurra Dolerite intrusions to between c. 1075 Ma, the minimum age of the layered and massive mafic intrusions of the Warakurna Supersuite (i.e. P_-WKg1- and P_-WKg2-), and c. 1026 Ma, the age of the youngest component — likely a subvolcanic sill — of the Tollu Group (Smithies et al., 2009; Kirkland et al., 2010). However, two Alcurra Dolerite intrusions have also been directly dated: a granophyric-textured ferrogabbro–ferronorite (GSWA 194354) that intrudes the northwestern part of the Jameson layered intrusion (MGA 354869E 7163642N) was dated at 1067 ± 8 Ma (Howard et al., 2009; Kirkland et al., 2009); and Seat (2008) reported an age of 1068 ± 4 Ma from an intrusion in the northern part of Cooper.

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Alcurra Dolerite; subunit (P_-WKA-orj) formerly Giles Suite (P_-WKg3-orj)

Legend narrative

Mesocratic orthopyroxene–olivine ferronorite; magnetite rich; weakly granophyric textured; locally contains minor intergranular quartz–feldspar graphic intergrowths

Rank	Formation
Parent	Alcurra Dolerite (P_-WKA-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Underlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); Kunmarnara Group (P_-KR-xs-b); Pitjantjatjara Supersuite (P_-PJ-xg-o); Wankanki Supersuite (P_-MN-mg); Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

Rocks of this mesocratic orthopyroxene–olivine ferronorite unit form a single, east-trending outcrop in the far western part of the Blackstone syncline on BLACKSTONE, where they have intruded into the c. 1075 Ma layered mafic Giles intrusions (Blackstone intrusion; P_-WKg1-), and the Tollu Group. This orthopyroxene–olivine ferronorite is interpreted as representing a chemically less evolved equivalent of the mesocratic orthopyroxene ferronorite to ferrodiorite unit also found in the Alcurra Dolerite (P_-WKA-owq).

Distribution

This mesocratic orthopyroxene–olivine ferronorite forms a single, east-trending outcrop in the far western part of the Blackstone syncline (WAROX site RHSMUG001415) on BLACKSTONE.

Lithology

This mesocratic orthopyroxene–olivine ferronorite is texturally similar to rocks of the mesocratic orthopyroxene ferronorite to ferrodiorite unit (P_-WKA-owq), which also outcrops in the Blackstone syncline region. Therefore, this orthopyroxene–olivine ferronorite is interpreted as representing a chemically less evolved equivalent of that orthopyroxene ferronorite to ferrodiorite unit.

A sample of this unit, described in thin section (185669; WAROX site RHSMUG01415), was observed to comprise two distinct domains. The first is a mass of randomly oriented plagioclase laths up to 2 mm in size, which locally includes 1–3 mm phenocrysts of olivine, with Fe-hydroxide alteration in patches and rims. Intergranular areas within this domain are mainly filled by anhedral orthopyroxene and large (1–2 mm) magnetite crystals. Magnetite also forms large stumpy to acicular skeletal grains. This domain forms stringers in, or a discontinuous network partially enclosing, the second domain. The second domain comprises a very fine grained felsitic to feather-textured or granophyric-textured assemblage of feldspar, magnetite, and quartz. Overall, the texture is interpreted to represent a semicontinuous framework of earlier-formed crystals (first domain), and quenched interstitial melt (second domain).

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Alcurra Dolerite	WKA-
Rock type	Igneous mafic intrusive	o
Lithname	Olivine norite	r
1st qualifier	Magnetite	j
Rock code		**P_-WKA-orj**

Contact relationships

Rocks of this mesocratic orthopyroxene–olivine ferronorite unit have intruded into the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), and also the volcanic, volcaniclastic, and clastic rocks of the Tollu Group.

Geochronology

P_-WKA-orj	*Maximum*	*Minimum*
Age (Ma)	1068	1067
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Seat, 2008	Howard et al., 2009; Kirkland et al., 2009

Rocks of this mesocratic orthopyroxene–olivine ferronorite unit have not been directly dated from their type area in the Blackstone syncline. However, contact relationships broadly constrain the emplacement age of the Alcurra Dolerite intrusions to between c. 1075 Ma, the minimum age of the layered and massive mafic intrusions of the Warakurna Supersuite (i.e. P_-WKg1- and P_-WKg2-), and c. 1026 Ma, the age of the youngest component — likely a subvolcanic sill — of the Tollu Group (Smithies et al., 2009; Kirkland et al., 2010). However, two Alcurra Dolerite suite intrusions have also been directly dated: a granophyric-textured ferrogabbro–ferronorite (GSWA 194354) that intrudes the northwestern part of the Jameson layered intrusion (MGA 354869E 7163642N) was dated at 1067 ± 8 Ma (Howard et al., 2009; Kirkland et al., 2009); and Seat (2008) reported an age of 1068 ± 4 Ma from an intrusion in the northern part of COOPER.

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Alcurra Dolerite; subunit (P_-WKA-owq) formerly Giles Suite (P_-WKg3-owq)

Legend narrative

Mesocratic orthopyroxene ferronorite to ferrodiorite; granophyric textured

Rank	Formation
Parent	Alcurra Dolerite (P_-WKA-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Underlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); Kunmarnara Group (P_-KR-xs-b); Pitjantjatjara Supersuite (P_-PJ-xg-o); Wankanki Supersuite (P_-MN-mg); Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

Rocks of this mesocratic orthopyroxene ferronorite to ferrodiorite unit form abundant intrusive sills and dykes within felsic volcanic country rocks, in the western part of the Blackstone syncline on BLACKSTONE. They have also intruded into the c. 1075 Ma layered mafic Giles intrusions (Blackstone intrusion; P_-WKg1-), and the Tollu Group. This mesocratic orthopyroxene ferronorite to ferrodiorite is interpreted as representing a chemically more evolved equivalent of the orthopyroxene–olivine ferronorite unit (P_-WKA-orj).

Distribution

This mesocratic orthopyroxene ferronorite to ferrodiorite forms poor outcrop, but on the basis of aeromagnetic data is interpreted to form abundant intrusive sills and dykes within felsic volcanic country rocks, in the western part of the Blackstone syncline on BLACKSTONE.

Lithology

This mesocratic orthopyroxene ferronorite to ferrodiorite typically displays a highly varied 'dual texture', formed by irregular stringers, or a semicontinuous framework, of a seriate-textured medium- to coarse grained assemblage, mixed with, or partially enclosing, a texturally and mineralogically identical fine- to medium-grained assemblage. This texture is interpreted to reflect mixing between two magmatic components, the results of pressure quenching (e.g. eruption) from these subvolcanic intrusive bodies, or both.

Rocks of this mesocratic orthopyroxene ferronorite to ferrodiorite unit are typically mesocratic, and feathery- to granophyric-textured, comprising up to ~60% seriate-textured plagioclase occurring stumpy crystals to euhedral laths or acicular crystals, and forming a locking framework. In outcrop immediately south of the Tollu Range (at WAROX site RHSMUG001021), plagioclase is pervasively sericitized. The intergranular space forms up to ~40% of the rock, and is filled mainly by anhedral, intergranular orthopyroxene with subordinate magnetite, plus fibrous aggregates of blue-green amphibole after clinopyroxene. In places where the plagioclase framework is more poorly developed, isolated stumpy plagioclase phenocrysts lie within a holocrystalline, but very fine grained, micrographic intergrowth of plagioclase, quartz, and blue-green amphibole.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Alcurra Dolerite	WKA-
Rock type	Igneous mafic intrusive	o
Lithname	Norite	w
1st qualifier	Quartz-bearing	q
Rock code		**P_-WKA-owq**

Contact relationships

Rocks of this mesocratic orthopyroxene ferronorite to ferrodiorite unit have intruded into the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), and also the volcanic, volcaniclastic, and clastic rocks of the Tollu Group.

Geochronology

P_-WKA-owq	*Maximum*	*Minimum*
Age (Ma)	1068	1067
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Seat, 2008	Howard et al., 2009; Kirkland et al., 2009

Rocks of this mesocratic orthopyroxene ferronorite to ferrodiorite unit have not been directly dated from their type area in the Blackstone syncline. However, contact relationships broadly constrain the emplacement age of the Alcurra Dolerite intrusions to between c. 1075 Ma, the minimum age of the layered and massive mafic intrusions of the Warakurna Supersuite (i.e. P_-WKg1- and P_-WKg2-), and c. 1026 Ma, the age of the youngest component — likely a subvolcanic sill — of the Tollu Group (Smithies et al., 2009; Kirkland et al., 2010). However, two Alcurra Dolerite suite intrusions have also been directly dated: a granophyric-textured ferrogabbro–ferronorite (GSWA 194354) that intrudes the northwestern part of the Jameson layered intrusion (MGA 354869E 7163642N) was dated at 1067 ± 8 Ma (Howard et al., 2009; Kirkland et al., 2009); and Seat (2008) reported an age of 1068 ± 4 Ma from an intrusion in the northern part of COOPER.

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Alcurra Dolerite, subunit (P_-WKA-owaq) formerly Giles Suite (P_-WKg3-owaq)

Legend narrative

Fine-grained, mesocratic orthopyroxene ferronorite to ferrodiorite; granophyric textured

Rank	Formation
Parent	Alcurra Dolerite (P_-WKA-o)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Overlying units	SMOKE HILL VOLCANICS (P_-TLs-f) (intrusive)
Underlying units	Giles Suite (P_-WKg1-xo-a; P_-WKg2-o); Kunmarnara Group (P_-KR-xs-b); Pitjantjatjara Supersuite (P_-PJ-xg-o); Wankanki Supersuite (P_-MN-mg); Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

This fine-grained mesocratic orthopyroxene ferronorite to ferrodiorite unit forms a single, east-trending outcrop in the western part of the Blackstone syncline on BLACKSTONE. These rocks are a finer-grained equivalent of the mesocratic orthopyroxene ferronorite to ferrodiorite unit (P_-WKA-owq), and form either as a quenched facies of that unit, or as a higher-level intrusion.

Distribution

These rocks form a single, east-trending outcrop in the western part of the Blackstone syncline, on BLACKSTONE.

Lithology

These rocks are the finer-grained equivalent of the mesocratic orthopyroxene ferronorite to ferrodiorite unit, also of the Alcurra Dolerite (P_-WKA-owq), and form either as a quenched facies of that unit, or as a higher-level intrusion.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite, Alcurra Dolerite	WKA-
Rock type	Igneous mafic intrusive	o
Lithname	Norite	w
1st qualifier	Fine-grained	a
2nd qualifier	Quartz-bearing	q
Rock code		**P_-WKA-owaq**

Contact relationships

Rocks of this fine-grained mesocratic orthopyroxene ferronorite to ferrodiorite unit have intruded into the layered mafic Blackstone intrusion of the Giles Suite (P_-WKg1), and also the volcanic, volcaniclastic, and clastic rocks of the Tollu Group.

Geochronology

P_-WKA-owaq	*Maximum*	*Minimum*
Age (Ma)	1068	1067
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Seat, 2008	Howard et al., 2009; Kirkland et al., 2009

Rocks of this ferronorite to ferrodiorite unit have not been directly dated from their type area in the Blackstone syncline. However, contact relationships broadly constrain the emplacement age of the Alcurra Dolerite intrusions to between c. 1075 Ma, the minimum age of the layered and massive mafic intrusions of the Warakurna Supersuite (i.e. P_-WKg1- and P_-WKg2-), and c. 1026 Ma, the age of the youngest component — likely a subvolcanic sill — of the Tollu Group (Smithies et al., 2009; Kirkland et al., 2010). However, two Alcurra Dolerite suite intrusions have also been directly dated: a granophyric-textured ferrogabbro–ferronorite (GSWA 194354) that intrudes the northwestern part of the Jameson layered intrusion (MGA 354869E 7163642N) was dated at 1067 ± 8 Ma (Howard et al., 2009; Kirkland et al., 2009); and Seat (2008) reported an age of 1068 ± 4 Ma from an intrusion in the northern part of COOPER.

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Warakurna Supersuite; subunit (P_-WK-g)

Legend narrative

Granite, undivided

Rank	Formation
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This unit groups all of the undivided felsic intrusive rocks assigned to the Warakurna Supersuite. In the Mamutjarra Zone, these felsic intrusive rocks typically form large plutonic bodies, whereas along the boundary between the Mamutjarra Zone and the Tjuni Purlka Tectonic Zone, and within the Tjuni Purlka Tectonic Zone itself, they generally occur as smaller dykes, veins, pods, and wispy inclusions that have intruded, have been intruded by, or have mingled and mixed with, the contemporaneous mafic Warakurna magmas. Felsic intrusive rocks of the Warakurna Supersuite are not found within the Walpa Pulka Zone. Rocks of this unit range in age between c. 1078 and c. 1062 Ma.

Distribution

Felsic rocks belonging to the Warakurna Supersuite are distributed throughout the west Musgrave Province, except the Walpa Purlka Zone. In the Mamutjarra Zone, these intrusions typically form large plutonic bodies, the best examples being the Tollu pluton south of Blackstone Range (Blackstone), and the South Hill pluton in the southwest corner of Bell Rock. Other felsic intrusions related to the Warakurna Supersuite are generally smaller, forming dykes, veins, pods, and wispy inclusions that have intruded, have been intruded by, or have mingled and mixed with, the contemporaneous mafic Warakurna magmas. Typically associated with the massive gabbro (P_-WKg2-) of the Warakurna Supersuite, these felsic rocks occur along the boundary between the Mamutjarra Zone and the Tjuni Purlka Tectonic Zone, or within the Tjuni Purlka Tectonic Zone itself.

Lithology

Granites of the Warakurna Supersuite typically range in composition from monzogranite to alkali-feldspar granite and quartz syenite. They are generally very leucocratic, and have a mafic mineralogy dominated by hornblende (commonly with clinopyroxene cores), but including biotite, clinopyroxene, and rare orthopyroxene.

Granites within the Tjuni Purlka Tectonic Zone exhibit contacts with gabbro (P_-WKg2-og) that range from clearly brittle (granite intruding solid gabbro) to clearly ductile. Three main types of contacts occur: 1) granites included as xenolithic blebs, lenses, or curvilinear segregations, up to 5 cm in length; 2) co-mingled granite and gabbro forming agmatites (see WAROX site RHSMUG500 — MGA 472977E 7119080N — in the west Hinckley Range, for spectacular examples); and 3) gabbros mixed with granite to form hybrid magmas. In the first two occurrences, boundaries between the mafic and felsic phases are curvilinear, cuspate, and cauliform, indicating that the two phases were co-magmatic. However, gabbros containing syn-magmatic granitic blebs are agmatized by the same granite, indicating that granite magmatism was continuous during emplacement of the gabbro.

Many of these granite dykes form in syn-magmatic shear zones, some containing examples where mylonitic, mixed granite–gabbros are intruded by slightly younger granites. In the west Hinckley Range, a slightly earlier generation of granite dykes is folded about a northwesterly fold axis, with younger granites then intruded along the fold axial plane; elsewhere (GSWA 185509: MGA 471391E 7120896N), the granite has pooled into boudin necks within syn-magmatic mylonite zones. The granite blebs that contaminate gabbros are excellent markers, which usually define a moderate to strong foliation or lineation. Bleb margins still remain wispy and cuspate during this deformation, also suggesting that the deformation was syn-magmatic. These granite contaminated gabbros in the Murray Range area were emplaced into a 5–10 km wide, north-northwesterly trending, subvertical, sinistral oblique shear zone. This shear zone marks the northeastern boundary of the Tjuni Purlka Tectonic Zone, and follows along an earlier (c. 1200 Ma), shallower, west-dipping reverse fault running along the western edge of the Murray Range. Within this crustal-scale, dominantly mafic shear zone, synkinematic granites intrude along shallow south-dipping to horizontal dip-slip faults, which may have accommodated shear oblique flow both during, and after, magmatism.

As a result, the ages obtained for these granites are significant in that they date not only the granite, but also the co-magmatic gabbro, and the deformation of both units (major folding and mylonitic deformation).

The observation that granites of the Warakurna Supersuite are commonly in contact with syn- to post-magmatic gabbros also belonging to the Warakurna Supersuite, clearly indicates that both the mafic and felsic magmas are utilizing the same structural intrusion pathways — mainly within, and marginal to, the Tjuni Pulka Tectonic Zone. However, granites of the Warakurna Supersuite also show clear intrusive contacts with rocks of the Wirku Metamorphics (P_-WM-mh), Wankanki Supersuite (P_-WN-mg) Pitjantjatjara Supersuite (P_-PJ-mg), and older rocks of the Warakurna Supersuite (e.g. P_-WKg1), both within, and outside of, the Tjuni Pulka Tectonic Zone.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Rock type	Igneous granitic	g
Rock code		**P_-WK-g**

Geochronology

P_-WK-g	*Maximum*	*Minimum*
Age (Ma)	1078 ± 3	1062 ± 10
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Sun et al., 1996	Kirkland et al., 2009a

Granites of the Warakurna Supersuite intruded during at least three separate stages of the Giles Event — at c. 1075, c. 1073, and c. 1062 Ma — with the full range of intrusive ages presently determined lying between c. 1078 and c. 1062 Ma. Granites that are mingled or mixed with syn-magmatic gabbros (P_-WKg2-o), and those that form syn- to post-magmatic dykes within gabbro (mostly P_-WK-grl), have been dated at six localities. Sun et al. (1996) reported an age of 1073 ± 5 Ma from a 'recrystallized gabbronorite' in the western Hinckley Range (Bell Rock), plus an age of 1078 ± 3 Ma from a sill within the Bell Rock layered mafic intrusion (Bell Rock; P_-WKg1-o), and an age of 1078 ± 5 Ma from 'rhyolite' along the western edge of the Bell Rock layered mafic intrusion (Bell Rock). A re-examination of each of these dated samples shows the dated component to be either a granite contaminant in P_-WKg2 gabbro, or else sills and dykes of granite intruded within, or marginal to, the Bell Rock layered mafic intrusion (P_-WKg1). Other dates obtained from Warakurna granites include an age of 1074 ± 3 Ma from a macroscopically folded granite dyke within gabbro at Amy Giles Hill (Bates; GSWA 174589, Bodorkos and Wingate, 2008), an age of 1075 ± 8 Ma from a northwest-trending granite dyke axial planar to macroscopically folded granite dykes within gabbro on the western Hinckley Range (Bell Rock; GSWA 174761, Kirkland et al., 2008a), and an age of 1075 ± 3 Ma from syn-mylonitic granites pooled into boudin necks in a northwest-trending mylonite to the west of the west Hinckley Range (GSWA 185509, Kirkland et al., 2008b).

The middle phase of granite intrusions includes the 1072 ± 8 Ma (GSWA 183474, Kirkland et al., 2007) South Hill pluton (P_-WK-gmhb) in the southwestern corner of Bell Rock; and the 1073 ± 6 Ma (GSWA 185583, Kirkland et al., 2009b), circular, 12 km diameter, Tollu pluton (P_-WK-grb) that intrudes the contact between basement gneisses and layered mafic intrusions (P_-WKg1-o) south of the Blackstone Range (Blackstone).

The youngest phase of granite intrusions includes metre- to kilometre-scale north-trending dykes of hornblende–pyroxene syenogranites that intrude into gabbro within the Murray Range and throughout the northern part of the Tjuni Purlka Tectonic Zone on Holt; these were dated at 1062 ± 10 Ma (GSWA 187256, Kirkland et al., 2009a). Localized syn-magmatic intrusion of gabbro is indicated by an age of 1063 ± 6 Ma (GSWA 194454, Kirkland et al., 2011) obtained from a mingled granite–gabbro hybrid rock, sampled along the margin of the Tjuni Purlka Tectonic Zone.

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Warakurna Supersuite; subunit (P_-WK-gkh)

Legend narrative

Weakly foliated hornblende–biotite–quartz monzodiorite to granodiorite; mesocratic

Rank	Formation
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Underlying units	Wankanki Supergroup (P_-WM-mg), Wirku Metamorphics (P_-WM-mh)
Metamorphic facies	Greenschist facies: undivided

Summary

This hornblende–biotite quartz monzodiorite to granodiorite unit forms a poorly outcropping felsic component of the Warakurna Supersuite. The largest outcrops of this unit are found immediately east of a major northeast-trending fault in the southwestern part of BLACKSTONE. Here, the unit forms part of what is interpreted, based on aeromagnetic (TMI) data, to be a large (13 x 6 km), northeast-trending pluton that intruded into rocks of the Wankanki Supersuite. Another outcrop occurs approximately 9 km to the northeast, forming part of one of two thin, northeast-trending intrusions also identified using aeromagnetic data. These rocks are typically seriate-textured, medium-grained, weakly foliated to massive, and mesocratic, with a mottled texture produced by black-weathering feldspars.

Distribution

The largest exposure of this weakly foliated hornblende–biotite quartz monzodiorite to granodiorite unit is immediately east of a major northeast-trending fault in the southwestern part of BLACKSTONE. Here, the unit forms part of what is interpreted, based on aeromagnetic (TMI) data, to be a large (13 x 6 km), northeast-trending pluton that intruded into rocks of the Wankanki Supersuite. Another outcrop occurs approximately 9 km to the northeast, forming part of one of two thin, northeast-trending intrusions also identified using aeromagnetic data.

Lithology

This hornblende–biotite quartz monzodiorite to granodiorite unit comprises seriate-textured, medium-grained, weakly foliated to massive, mesocratic rocks, typically with a mottled texture produced by black-weathering feldspars. A single thin section obtained from the unit (GSWA 185659; WAROX site RHSMUG001328) consists of a quartz monzodiorite with 15–20% mafic minerals. The texture is typically igneous, although the quartz is strongly recrystallized into a granoblastic polygonal mosaic. Plagioclase is considerably more abundant than perthite; perthite locally forms large grains (phenocrysts) that enclose quartz and plagioclase. Green hornblende is the main mafic mineral, forming large, subhedral crystals, but also forms optically continuous grains that both surround quartz and plagioclase grains and fill interstitial patches. Hornblende also forms aggregates with brown biotite and opaque minerals locally; these aggregates also include kelyphitic intergrowths of biotite–quartz and hornblende–quartz.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Rock type	Igneous granitic	g
Lithname	Quartz monzodiorite	k
1st qualifier	Hornblende	h
Rock code		**P_-WK-gkh**

Geochronology

P_-WK-gkh	*Maximum*	*Minimum*
Age (Ma)	1078	1062
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996	Kirkland et al., 2009

This unit has not been dated directly, although the full range of intrusive ages determined for granites within the Warakurna Supersuite is presently between c. 1078 and c. 1062 Ma (see P_-WK-g).

References

Kirkland, CL, Wingate, MTD and Evins, P 2009, 187256: granite, Murray Range; Geochronology Record 839: Geological Survey of Western Australia, 4p.

Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Warakurna Supersuite; subunit (P_-WK-gkhc) Reassigned to Wankanki Supersuite (P_-WN-mggo)

Legend narrative

Weakly foliated hornblende–clinopyroxene–quartz monzodiorite to quartz diorite; mesocratic

Summary

This unit of weakly foliated hornblende–pyroxene quartz monzodiorite, quartz diorite, and granodiorite forms sparse, low bouldery outcrops immediately southeast and south of the layered, mafic Cavenagh Range intrusion, on the central-western part of Blackstone, and southeastern part of Cooper. These rocks are mesocratic, medium grained, and massive to weakly foliated, with a seriate to porphyritic (K-feldspar) texture. The rock contains up to 15% mafic minerals, mainly green-brown hornblende that forms large subhedral crystals, optically continuous grains that surround quartz and plagioclase, or that fill interstitial patches. Orthopyroxene is only slightly less abundant than hornblende, and is typically rimmed by hornblende; clinopyroxene is less common than both hornblende and orthopyroxene. Locally abundant, rounded mafic xenoliths, up to 6 cm in size, are possibly cognate. Due to the typically massive appearance of this rock southeast of the Cavenagh Range intrusion, in that region it was originally assigned to the Warakurna Supersuite (P_-WK-gkhc on first edition Blackstone map sheet). However, these rocks, both in this region and in the area south of the Cavenagh Range intrusion, are now known to be locally gneissic and intruded by rocks of the Pitjantjatjara Supersuite, and as such are now assigned to the Wankanki Supersuite (with which they are geochemically equivalent).

Warakurna Supersuite; subunit (P_-WK-gmhb)

Legend narrative

Medium- to coarse-grained hornblende–biotite monzogranite; massive

Rank	Formation
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This medium- to coarse-grained hornblende–biotite monzogranite unit outcrops in the south-southwestern corner of BELL ROCK, forming South Hill. It is typically unfoliated, leucocratic to mesocratic, and ranges in texture from seriate to K-feldspar porphyritic, containing euhedral phenocrysts to 1 cm. Green hornblende is the dominant mafic mineral, although biotite is locally common, forming 'books' up to 5 mm in size.

Distribution

This hornblende–biotite monzogranite outcrops in the south-southwestern corner of BELL ROCK, forming South Hill (e.g. at MGA 467500E 7072300N).

Lithology

This medium- to coarse-grained hornblende–biotite monzogranite is typically unfoliated, leucocratic to mesocratic, and ranges in texture from seriate to weakly K-feldspar porphyritic, although strongly porphyritic examples with abundant euhedral phenocrysts up to 1 cm in size occur locally. The rocks lie in the compositional range of monzogranite to syenogranite, containing 15–20% quartz, 10–30% plagioclase, and 35–55% K-feldspar (typically as microcline microperthite). Mafic minerals make up 10–15% of the rock, but can locally form up to 30% of irregular mesocratic patches. Green hornblende is the dominant mafic mineral, although biotite is locally common forming 'books' up to 5 mm in size; clinopyroxene is a minor phase, forming cores to hornblende in places.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Rock type	Igneous granitic	g
Lithname	Monzogranite	m
1st qualifier	Hornblende	h
2nd qualifier	Biotite	b
Rock code		**P_-WK-gmhb**

Contact relationships

Exposures of this unit show no contacts with any other lithology, although felsic volcanic rocks of the Bentley Supergroup outcrop approximately 1 km to the southwest.

Geochronology

P_-WK-gmhb	*Maximum*	*Minimum*
Age (Ma)	1072 ± 8	1072 ± 8
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Kirkland et al., 2007	Kirkland et al., 2007

A single sample from this medium- to coarse-grained hornblende–biotite monzogranite unit gave an intrusive age of 1072 ± 8 Ma (GSWA 183474, Kirkland et al., 2007).

References

Kirkland, CL, Wingate, MTD and Bodorkos, S 2007, 183474: hornblende syenogranite, Bell Rock; Geochronology Record 723: Geological Survey of Western Australia, 4p.

Warakurna Supersuite; subunit (P_-WK-grah)

Legend narrative

Fine-grained, leucocratic hornblende syenogranite; locally granophyric texture and with acicular or skeletal hornblende

Rank	Formation
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This fine-grained, leucocratic hornblende syenogranite unit forms linear, northerly or west-northwesterly outcrops marginal to major fault-structures, in the central-northern parts of HOLT and on southern GUNBARREL. These are fine- to medium-grained, leucocratic, seriate to porphyritic, massive rocks, with well-developed granophyric and micrographic textures, together reflecting intrusion at a high-level in the crust and rapid cooling.

Distribution

This unit forms linear, northerly or west-northwesterly outcrops marginal to major fault-structures, in the central-northern parts of HOLT and on southern GUNBARREL.

Lithology

This fine-grained, leucocratic hornblende syenogranite is a relatively minor component of the felsic units grouped within the Warakurna Supersuite. It is a fine- to medium-grained, leucocratic, seriate to porphyritic, massive rock, consisting of quartz (~35%), feldspar (~55%), sodic clinopyroxene (~3%), green amphibole (~5%), and magnetite (~2%), with accessory biotite, fluorite, epidote, rutile, and zircon. The rock has subhedral to euhedral phenocrysts of feldspar (including albitic plagioclase, perthite, and antiperthite), larger aggregates of albitic plagioclase and perthite, and complex feldspars including zoned and resorbed plagioclase itself enclosed in zoned and resorbed plagioclase or else enclosed in perthite. Subhedral crystals of strongly granophyric feldspar also occur, and these sit in a groundmass of micrographic quartz and feldspar. Magnetite forms disseminated grains throughout this groundmass. Green (sodic) clinopyroxene forms subhedral crystals, and is rimmed by deep-green to green-blue amphibole; the amphibole also occurs as needles up to 3mm in size, and as subhedral to euhedral skeletal crystals. Biotite is a rare and interstitial phase. The complex zoning and resorbtion textures seen in the feldspars are indicative of several phases of magma mixing or recharge, whereas the granophyric and micrographic textures reflect intrusion at a high-level in the crust and rapid cooling.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Rock type	Igneous granitic	g
Lithname	Syenogranite	r
1st qualifier	Fine-grained	a
2nd qualifier	Hornblende	h
Rock code		**P_-WK-grah**

Geochronology

P_-WK-grah	*Maximum*	*Minimum*
Age (Ma)	1078	1062
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Sun et al., 1996	Kirkland et al., 2009

This unit has not been dated directly, although the full range of intrusive ages determined for granites within the Warakurna Supersuite is presently between c. 1078 and c. 1062 Ma (see P_-WK-g).

References

Kirkland, CL, Wingate, MTD and Evins, P 2009, 187256: granite, Murray Range; Geochronology Record 839: Geological Survey of Western Australia, 4p.

Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Warakurna Supersuite; subunit (P_-WK-grl)

Legend narrative

Fine- to medium-grained, porphyritic to seriate-textured syenogranite; leucocratic but typically contains mafic xenoliths; locally abundant K-feldspar phenocrysts up to 1 cm; rare rapakivi texture

Rank	Formation
Parent	Warakurna Supersuite (P_-WK-xo-f)
Tectonic units	Warakurna Supersuite, PATERSON OROGEN, WESTERN AUSTRALIA
Metamorphic facies	Greenschist facies: undivided

Summary

This fine- to medium-grained porphyritic- to seriate-textured syenogranite unit of the Warakurna Supersuite is widespread as minor dykes, sheets, and pods that intrude into, and adjacent to, massive gabbros (P_-WKg2-og) also of the Warakurna Supersuite. These granites and gabbros occur most commonly along the northeastern margin of the Tjuni Purlka Tectonic Zone, but also occur in lesser amounts along the southwestern margin of the same zone. This syenogranite is typically massive to moderately foliated, leucocratic, and seriate to porphyritic, with locally abundant feldspar phenocrysts up to 8 mm in size. The unit intrudes, includes, and is co-mingled with, massive Warakurna gabbros, particularly in and near syn-magmatic mylonites. The c. 1075 Ma age obtained for these granites is significant in that it dates not only the granite, but also the co-magmatic gabbro, and the deformation of both units (major folding and mylonitic deformation).

Distribution

This unit of the Warakurna Supersuite is widespread as minor dykes, sheets, and pods that intrude into, and adjacent to, massive gabbros also of the Warakurna Supersuite. These granites and gabbros occur most commonly along the northeastern margin of the Tjuni Purlka Tectonic Zone, but also occur in lesser amounts along the southwestern margin of the same zone. As such, the granites have so far been identified on the Bates, Bell Rock, Holt, and Finlayson map sheets.

Lithology

This fine- to medium-grained syenogranite is massive to moderately foliated, leucocratic, and seriate to porphyritic, with locally abundant feldspar phenocrysts up to 8 mm in size. The unit intrudes, includes, and is co-mingled with, massive Warakurna Supersuite gabbros (P_-WKg2-og). This syenogranite forms as dykes and sheets that can be traced for many kilometres (e.g. in the west Hinckley Range), as veins, and as small pods and ‘blebs’ emplaced along foliation plains in the semi-consolidated gabbro.

These rocks show a wide variation in mineralogy, reflecting a compositional range from monzogranite to alkali-feldspar granite, although syenogranitic rocks are dominant. The rocks are composed predominantly of quartz (15–30%), weakly to strongly perthitic K-feldspar (25–65%), and plagioclase (7–20%); myrmekite is locally developed, and mafic minerals form up to 15% of the rock. Hornblende is the dominant mafic mineral, with clinopyroxene (1–6%), biotite (1–5%), and magnetite (1–2%) rarer; accessory minerals include apatite, zircon, and Fe-oxides. Textures are typically hypidiomorphic granular.

Age code	Proterozoic	P_-
Stratigraphic code	Warakurna Supersuite	WK-
Rock type	Igneous granitic	g
Lithname	Syenogranite	r
1st qualifier	Leuco-	l
Rock code		**P_-WK-grl**

Contact relationships

Contacts developed between this granite and its associated gabbro (P_-WKg2-og) range from clearly brittle (i.e. granite intruding solid gabbro) to clearly ductile. Three main types of contacts occur: 1) granites intruded as xenolithic blebs, lenses, or curvilinear segregations, up to 5 cm in length; 2) co-mingled granite and gabbro forming agmatites (see WAROX site RHSMU500 — MGA 472977E 7119080N — in the west Hinckley Range, for spectacular examples); and 3) gabbros mixed with granite to form hybrid magmas. In the first two occurrences, boundaries between the mafic and felsic phases are curvilinear, cuspate, and cauliform, indicating that neither phase was solid during emplacement, and further suggesting that the phases were coeval. However, gabbros containing syn-magmatic granitic blebs are agmatized by the same granite, indicating that granite magmatism was continuous during emplacement of the gabbro.

Many of these granite dykes are also syn-magmatic shear zones, some containing examples where mylonitic, mixed granite–gabbros are intruded by slightly younger granites. In the west Hinckley Range, a slightly earlier generation of granite dykes is folded about a northwest fold plane, with younger granites then intruded along the fold plane. Elsewhere (GSWA 185509: MGA 471391E 7120896N), the granite has pooled into boudin necks within syn-magmatic mylonite zones. The granite blebs that contaminate gabbros are excellent markers, which usually define a moderate to strong foliation or lineation. Bleb margins still remain wispy and cuspate during this deformation, also suggesting that the deformation was syn-magmatic. These granite contaminated gabbros of the Murray Range were emplaced into a 5–10 km wide, north-northwesterly trending, subvertical, sinistral oblique shear zone, which marks the northeastern boundary of the Tjuni Purlka Tectonic Zone.

The age obtained for these granites is significant in that it dates not only the granite, but also the co-magmatic gabbro, and the deformation of both units (major folding and mylonitic deformation).

Geochronology

P_-WK-grl	*Maximum*	*Minimum*
Age (Ma)	1078 ± 5	1074 ± 3
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Isotopic	Isotopic
References	Sun et al., 1996	Bodorkos and Wingate, 2008

Sun et al. (1996) reported on a 1078 ± 3 Ma crystallization age obtained from a leucogranite thought to be part of the Bell Rock layered mafic intrusion, and a 1078 ± 5 Ma crystallization age from a rhyolite thought to be part of the Smoke Hill Volcanics just southwest of Bell Rock Range. However, reanalysis of both outcrops shows them to be part of this fine- to medium-grained porphyritic- to seriate-textured syenogranite unit. Bodorkos and Wingate (2008) reported a 1074 ± 3 Ma crystallization age for a macroscopically folded granite dyke sampled from Amy Giles Hill (southwest BATES), which is cut by a 1075 ± 7 Ma granite dyke axial planar to macroscopic folding. Together, these ages define a very narrow time period that saw the intrusion of unlayered gabbros, the multi-phase intrusion of leucogranites, plus macroscopic folding and shearing.

References

Bodorkos, S and Wingate, MTD 2008, 174589: quartz syenite dyke, Amy Giles Hill; Geochronology Record 715: Geological Survey of Western Australia, 4p.

Sun, S-S, Sheraton, JW, Glikson, AY and Stewart, AJ 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 24, p. 13–15.

Gairdner Dolerite (P_-GD-od)

Age code	Proterozoic	P_-
Stratigraphic code	Gairdner Dolerite	GD-
Rock type	Igneous mafic intrusive	o
Lithname	Dolerite	d
Rock code		**P_-GD-od**

Legend narrative

Medium-grained dolerite and metadolerite; typically intergranular to subophitic; polygonal granoblastic where metamorphosed

Rank	Suite
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This dolerite unit includes all of the mafic dykes assigned to the Gairdner Dolerite (suite), which have intruded rocks of the Musgrave Province, Warakurna Supersuite, and Bentley Supergroup. These dykes have been identified at Mount Aloysius, Champ de Mars, Michael Hills, and in the Hinckley Range (Bell Rock). This dolerite unit typically forms northwest-trending dykes, 30–50 m wide, with occasional conjugate northeast-trending dykes. The dolerite is medium grained, with an intergranular to subophitic texture. Metamorphic textures evident in the Gairdner dykes most likely reflect metamorphism during the Petermann Orogeny (c. 550 to 570 Ma). The age of the Gairdner Dolerite is based on a zircon U–Pb age of 824 ± 4 Ma (Glikson et al., 1996), and a baddeleyite U–Pb age of 827 ± 6 Ma (Wingate et al., 1998), obtained from two different dykes.

Distribution

Dolerite dykes of the Gairdner Dolerite were first identified and described in South Australia (Wingate et al., 1998). In Western Australia, they occur south of the Mann Fault, intruding in Mount Aloysius, Michael Hills, Champ de Mars, and the Hinckley Range (Bell Rock).

Lithology

This dolerite unit typically forms northwest-trending dykes, 30–50 m wide. The dolerite is medium grained, with an intergranular to subophitic texture, and has plagioclase, clinopyroxene, and orthopyroxene as the major mineral phases. Minor and accessory phases include opaque minerals, green hornblende, biotite, and chlorite. Plagioclase is cloudy and shows undulose extinction. Minor hornblende replaces pyroxene, and thin rims of chlorite are present on pyroxene. Opaque phases are interstitial, forming fine-grained trails along grain boundaries, and are often disseminated through the pyroxene; accessory biotite is strongly associated with these opaque phases. The metamorphic textures evident in the Gairdner dykes most likely reflect metamorphism during the Petermann Orogeny (c. 550 to 570 Ma).

Contact relationships

Dolerite dykes of the Gairdner Dolerite crosscut numerous Giles Suite units in the Michael Hills intrusion, including gabbronorite (P_-WKg1-om), leucogabbronorite (P_-WKg1-oml), norite (P_-WKg1-ow), and gabbro (P_-WKg1-oge). At Mount Aloysius, the dykes crosscut units of the Wirku Metamorphics (P_-WM-mhig, P_-WM-mroo, and P_-WM-mtn), and granites of the Pitjantjatjara Supersuite (P_-PJ1-mgmu, P_-PJ1-jmg-md, and P_-PJ-jmg-mh). To the north of Michael Hills and at Mount Aloysius, the dykes also intrude units of the Wankanki Supersuite (P_-WN-mgno and P_-WN-xmfn-mh).

Geochronology

P_-GD-od	*Maximum*	*Minimum*
Age (Ma)	827 ± 6	824 ± 4
Age	Neoproterozoic	Neoproterozoic
Age data type	Isotopic	Isotopic
References	Wingate et al., 1998	Glikson et al., 1996

One dyke of the Gairdner Dolerite yielded a zircon U–Pb age of 824 ± 4 Ma (Glikson et al., 1996); this is similar to the baddeleyite U–Pb age of 827 ± 6 Ma obtained for a Gairdner dyke on the Stuart Shelf (Wingate et al., 1998).

References

Glikson, AY, Stewart, AT, Ballhaus, GL, Clarke, GL, Feeken, EHT, Level, JH, Sheraton, JW and Sun, S-S 1996, Geology of the western Musgrave Block, central Australia, with reference to the mafic–ultramafic Giles Complex: Australian Geological Survey Organisation, Bulletin 239, 206p.

Wingate, MTD, Campbell, IH, Compston, W and Gibson, GM 1998, Ion microprobe U–Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia: Precambrian Research, v. 87, p. 135–159.

Kullal Dyke Suite (P_-KL-od)

Legend narrative

Fine-grained olivine–plagioclase dolerite and metadolerite; typically porphyritic; granoblastic where metamorphosed

Rank	Suite
Parent	Top of lithostratigraphic order (TOL)
Tectonic units	PATERSON OROGEN, WESTERN AUSTRALIA

Summary

This dolerite unit includes all of the mafic dykes assigned to the Kullal Dyke Suite, which have intruded rocks of the Musgrave Province, Warakurna Supersuite, and Bentley Supergroup. These dykes are most commonly exposed in the Hinckley Range and Michael Hills areas of BELL ROCK, and typically consist of northeast-trending, narrow (0.5 to 5 m wide) dykes of fine-grained olivine- and plagioclase-porphyritic dolerite. Metamorphic reaction textures, such as plagioclase coronas developed on olivine grains, are common and most likely the result of metamorphism during the Petermann Orogeny (c. 550 to 570 Ma). A poorly constrained Sm–Nd mineral isochron yielded an age of c. 1000 Ma for one of the Kullal dykes (Glikson et al., 1996), which is consistent with field constraints.

Distribution

Dolerite dykes belonging to the Kullal Dyke Suite have been identified south of the Mann Fault, and are most common in the Hinckley Range and Michael Hills areas of BELL ROCK.

Derivation of name

Kullal is the local aboriginal (Pitjantjatjara) name for the west Hinckley Range, where these dykes are most abundant.

Lithology

These rocks typically form northeast-trending, narrow (0.5 – 5 m wide) dykes of fine-grained porphyritic dolerite. In the Hinckley Range, the dykes are less commonly southeast-trending (GSWA 174569: BELL ROCK, MGA 478327E 7118360N). Phenocryst of plagioclase and olivine, up to 4 mm in length, lie in a groundmass that includes plagioclase and augite, with biotite, dark-green spinel, ilmenite, pyrite, pyrrhotite, and pentlandite as minor phases. Metamorphic reaction textures, such as plagioclase coronas developed on olivine grains, are common, particularly where dykes intrude the Hinckley Range. Plagioclase is cloudy pink, with undulose extinction; olivine is altered to iddingsite, and is less commonly a dusty brown colour. The metamorphic textures evident in the Kullal dykes are most likely the result of metamorphism during the Petermann Orogeny (c. 550 to 570 Ma).

Age code	Proterozoic	P_-
Stratigraphic code	Kullal Dyke Suite	KL-
Rock type	Igneous mafic intrusive	o
Lithname	Dolerite	d
Rock code		**P_-KL-od**

Contact relationships

In the west Hinckley Range, dolerite dykes of the Kullal Dyke Suite crosscut the mixed gabbro and granite unit (P_-WKg2-xog-g) of the Warakurna Supersuite; the unit also crosscuts the layered units of gabbronorite (P_-WKg1-om) and leucogabbronorite (P_-WKg1-oml) of the Michael Hills intrusion. To the north of the Michael Hills intrusion, these dykes crosscut granites (P_-WN-mgmu) and gneissic granites (P_-WN-mgno) of the Wankanki Supersuite.

Geochronology

P_-KL-od	*Maximum*	*Minimum*
Age (Ma)	1000	1000
Age	Mesoproterozoic	Mesoproterozoic
Age data type	Inferred	Inferred
References	Glikson et al., 1996	Glikson et al., 1996

This dolerite clearly crosscuts both mafic and felsic intrusive rocks of the 1085–1040 Ma Warakurna Supersuite, and is in turn cut by the c. 825 Ma Gairdner Dyke Suite. However, a better indication of this suite's age was obtained from a poorly constrained Sm–Nd mineral isochron obtained from one of the Kullal dykes, which yielded an age of c. 1000 Ma (Glikson et al., 1996).

References

Glikson, AY, Stewart, AT, Ballhaus, GL, Clarke, GL, Feeken, EHT, Level, JH, Sheraton, JW and Sun, S-S 1996, Geology of the western Musgrave Block, central Australia, with reference to the mafic–ultramafic Giles Complex: Australian Geological Survey Organisation, Bulletin 239, 206p.

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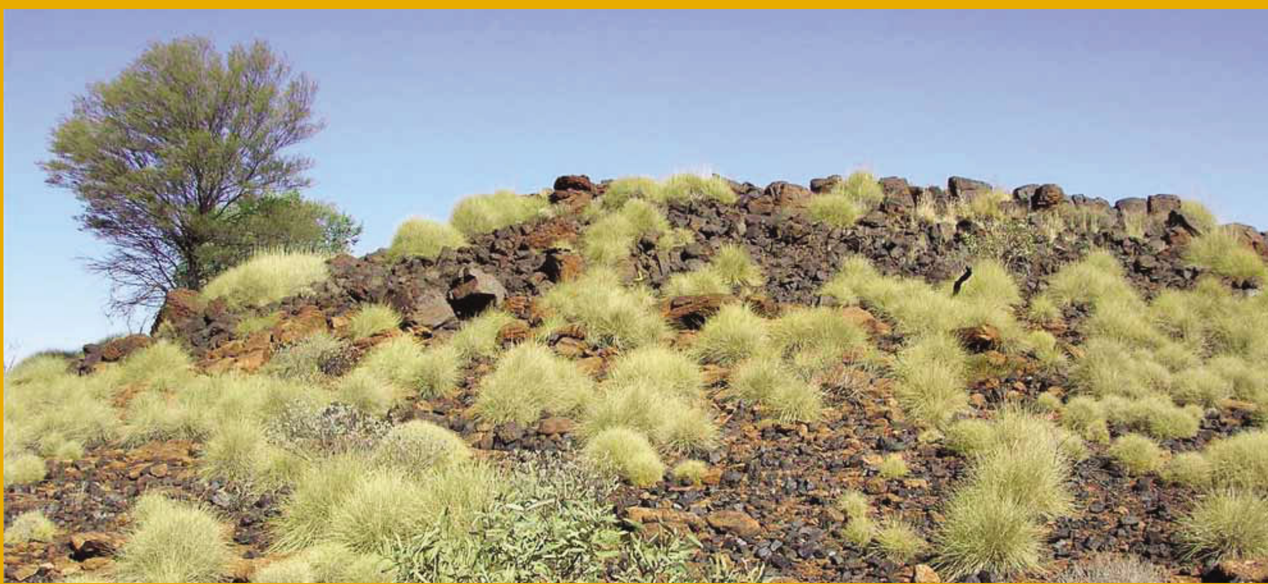
Explanatory notes for the West Musgrave Province

Straddling the border that separates Western Australia, South Australia, and the Northern Territory, the Musgrave Province also lies in the region where the major central Australian Proterozoic structural trends converge. The province has a dynamic Mesoproterozoic to Neoproterozoic history of repeated high-grade grade metamorphic events, deformation, and magmatism, and is possibly best known for the emplacement of the giant, layered mafic–ultramafic Giles intrusions. This Explanatory Notes volume summarizes the geological history of the West Australian portion of the province (the west Musgrave Province), and provides detailed descriptions of all stratigraphic units and tectonic events in the region.



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