



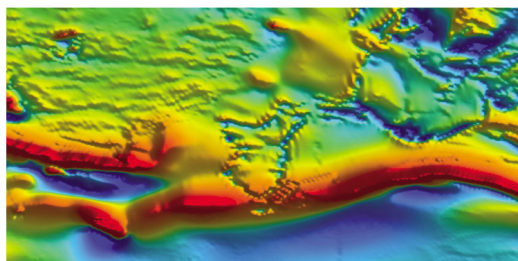
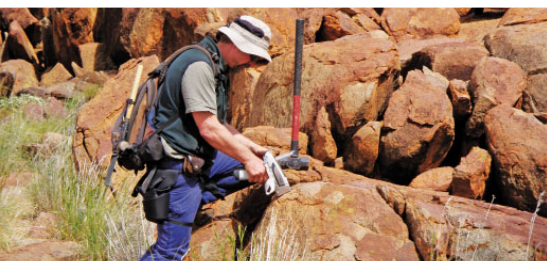
Government of **Western Australia**
Department of **Mines and Petroleum**

RECORD 2010/6

REDEFINING THE GILES EVENT WITHIN THE SETTING OF THE 1120–1020 Ma NGAANYATJARRA RIFT, WEST MUSGRAVE PROVINCE, CENTRAL AUSTRALIA

by

**PM Evins, RH Smithies, HM Howard, CL Kirkland,
MTD Wingate, and S Bodorkos**



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Perth 2010



**Geological Survey of
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Redefining the Giles Event within the setting of the 1120–1020 Ma Ngaanyatjarra Rift, west Musgrave Province, central Australia

by

**PM Evins, RH Smithies, HM Howard, CL Kirkland, MTD Wingate,
and S Bodorkos**

Abstract

New geochronology and mapping of mafic and felsic rocks of the Musgrave Province resolve a complex sequence of at least eight magmatic pulses with hiati of up to 10 m.y. during the Giles Event. The spatial and temporal distribution of these pulses is consistent with a long-lived intracontinental rift setting, referred to here as the Ngaanyatjarra Rift. This rift hosts the layered mafic–ultramafic Giles intrusions, including the giant Bell Rock–Blackstone–Finlay–Jameson intrusion. These intrusions formed before a 10-km wide mafic–felsic magmatic shear zone that marks a period of macroscopic folding, transpression, and basin inversion coeval with the c. 1075 Ma Warakurna Large Igneous Province (LIP). The extensive mafic to felsic volcanic rocks of the Tollu Group (traditionally assigned to the Giles Event) were emplaced 25–50 m.y. later than the c. 1075 Ma Warakurna LIP. The extended time period (at least 50 m.y.) of magmatism and deformation during the Giles Event precludes a single mantle plume as its sole cause. Instead, the Giles Event may be the result of a long-lived thermal anomaly underlying the Musgrave Province since the beginning of the 1220–1120 Ma Musgrave Orogeny.

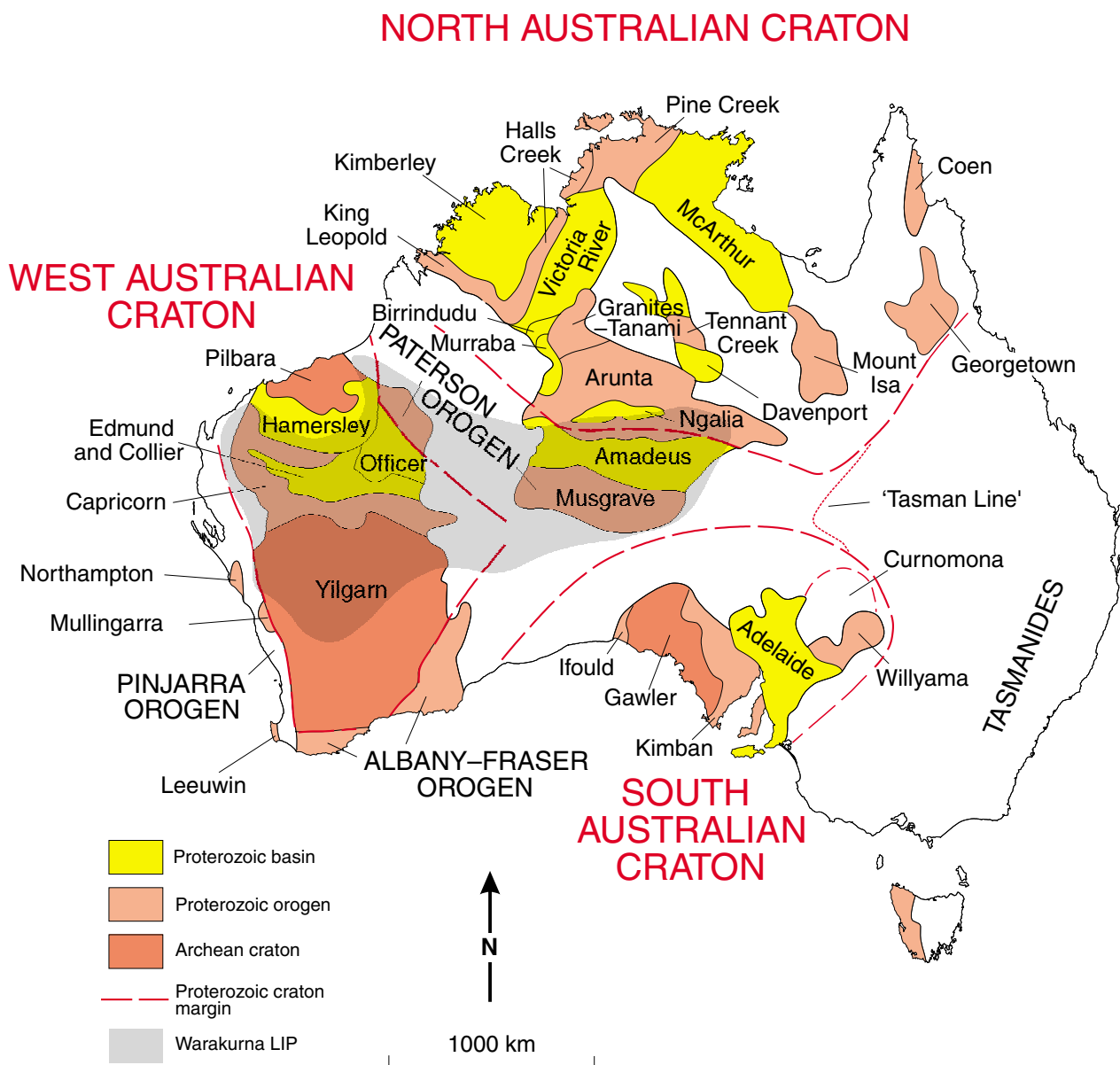
KEYWORDS: magmatism, Ngaanyatjarra Rift, mafic rocks, felsic igneous rocks, Giles Event, Musgrave Province, Western Australia

Introduction

Although the Musgrave Province lies at the convergence of Australian Proterozoic structural trends formed by the amalgamation of the North Australian, West Australian, and South Australian Cratons (Fig. 1), it remains Australia's least studied exposed Proterozoic terrane. Geological surveys have established a broad lithological framework (Daniels, 1974; Glikson et al., 1996; Edgoose et al., 2004), but the orogenic episodes that formed the Musgrave Province have not been presented in detail until recently. In 2004, the Geological Survey of Western Australia (GSWA) began a new program of geological investigation within the portion of the Musgrave Province that lies in the state of Western Australia (herein referred to as the 'west Musgrave Province'; Fig. 2). This program has provided a large and regionally extensive dataset of new geophysical, geochemical, and isotopic data, underpinned by detailed geological mapping (Fig. 3). In turn, this dataset has allowed detailed descriptions of the 1345–1293 Ma Mount West (Evins et al., in prep.) and

1220–1120 Ma Musgrave Orogenies (Smithies et al., 2010). This Record focuses on a later orogeny, the Giles Event, and its relevance to the Warakurna Large Igneous Province (LIP).

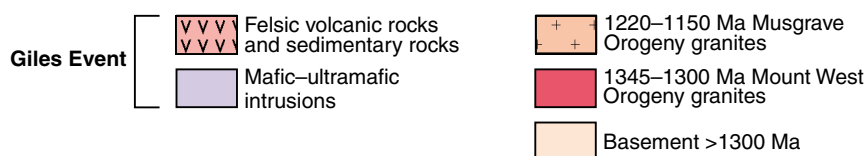
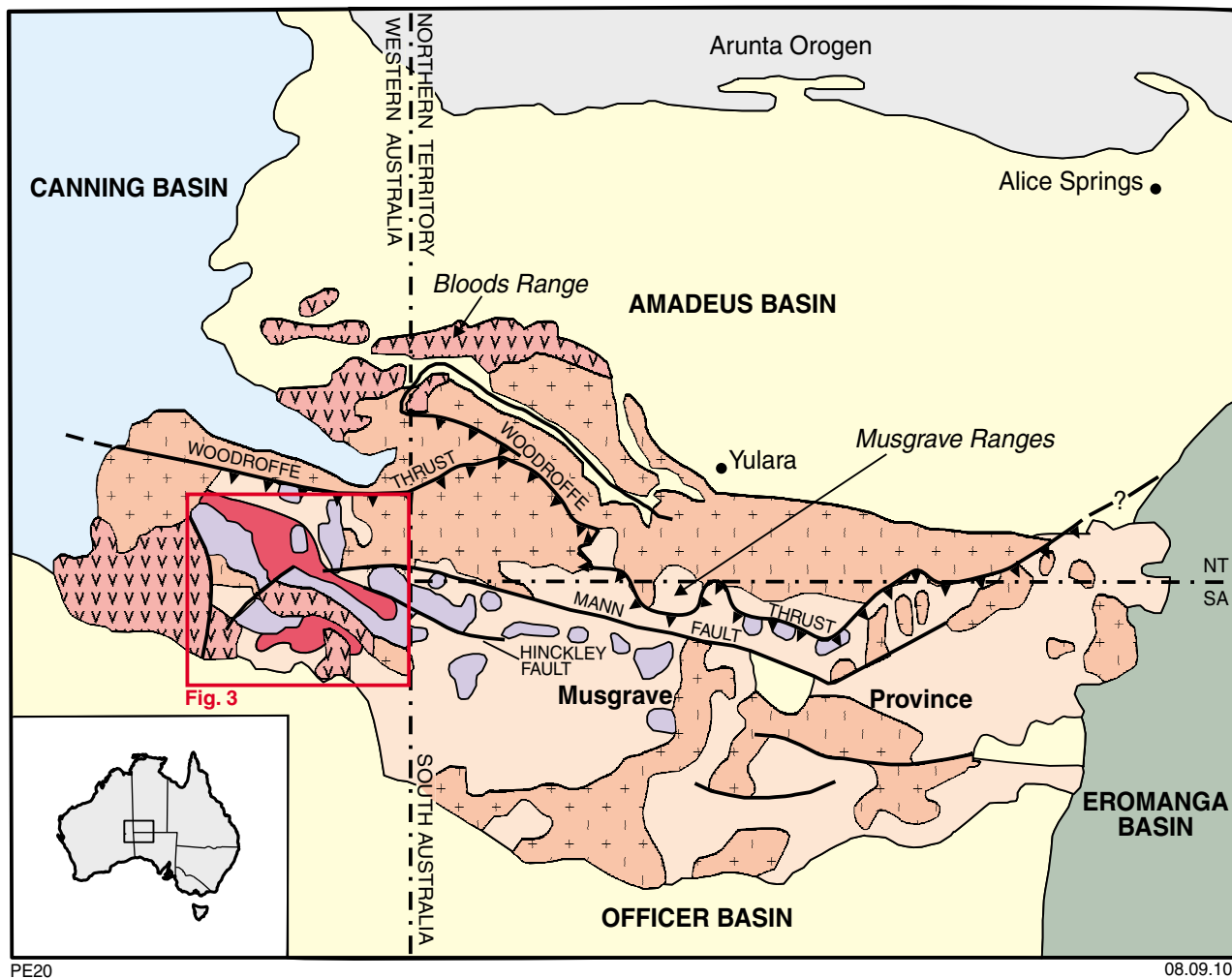
The Warakurna LIP (Wingate et al., 2004; Morris and Pirajno, 2005) outcrops across approximately 1.5 million km² of central to far western Australia (Figs 1 and 2). Rocks in this supersuite include sill complexes and dykes in the Paleoproterozoic Earahedy Basin, the Mesoproterozoic Edmund and Neoproterozoic Collier Basins (Bangemall Supergroup), and the Capricorn Orogen (Fig. 4), with sensitive high-resolution ion microprobe (SHRIMP) ages ranging from c. 1058 Ma to c. 1078 (obtained using U–Pb zircon and baddeleyite, K–Ar, and Rb–Sr analyses; Wingate et al., 2004, and references therein). The Collier and Edmund sill complex alone is estimated to cover an area of about 143 000 km², has individual sills up to 100 m thick, and is traceable for more than 60 km (Fig. 4). Farther east, drilling has intersected 1058 ± 13 Ma (K–Ar whole rock analysis;



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Figure 1. Map of Australia highlighting the boundaries of the North Australian, South Australian, and West Australian Cratons and their stitching orogens. Modified from Myers et al. (1996). Grey area shows known extent of the Warakurna Large Igneous Province.



100 km

Figure 2. Generalized geology of the Musgrave Province after Edgoose et al. (2004). Locations mentioned in the text are labelled. The Tjauwata Group, Puntitjata Rhyolite, Rowley Granophyre, and Walu Granite lie in the western Bloods Range. The Angatja, Michell Nob, and Nulchara granites lie in the Musgrave Ranges.

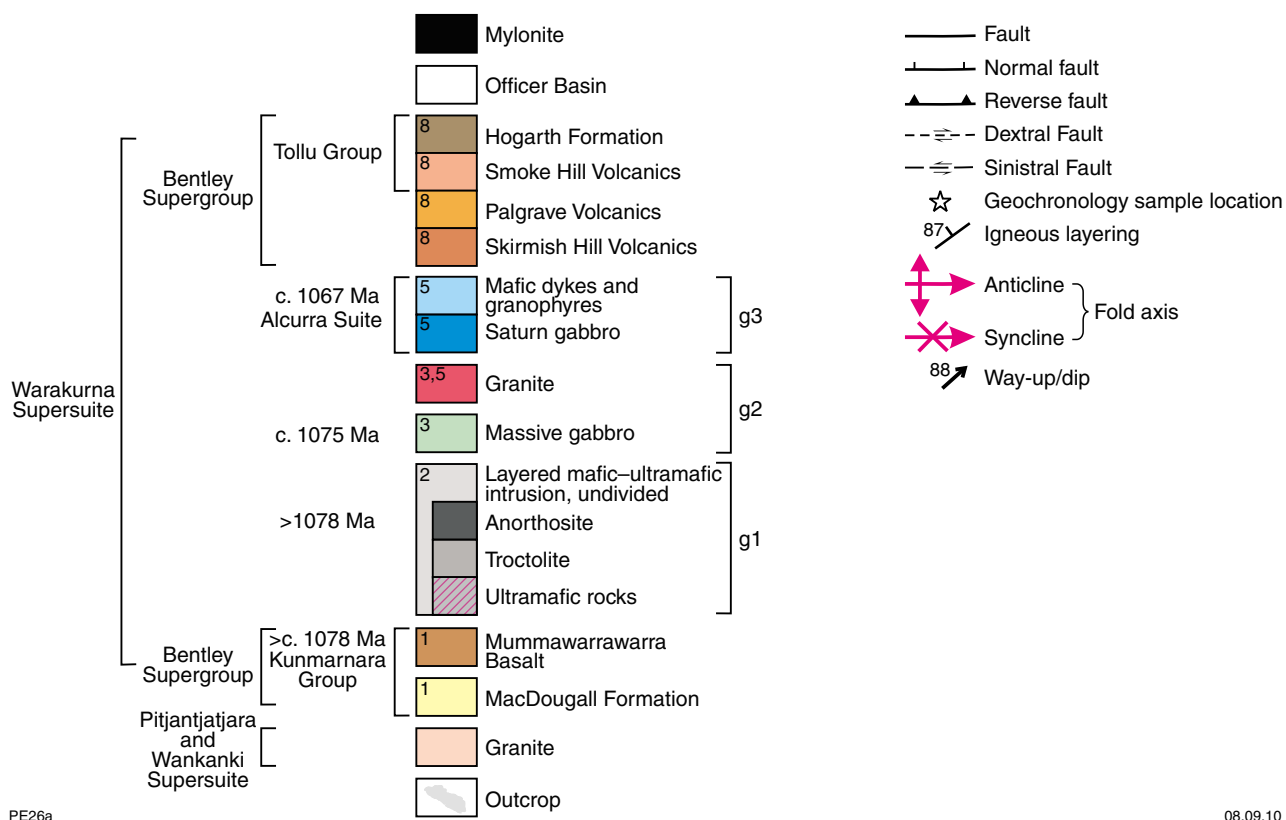


Figure 3. Geological map of the eastern portion of the west Musgrave Province, covering the BATES, BELL ROCK, HOLT, BLACKSTONE, FINLAYSON, and COOPER 1:100 000 Geological Series map sheets, with emphasis on units associated with the Giles Event. Geological Survey of Western Australia and Geoscience Australia geochronology sample localities are labelled. Boxes define areas represented in Figures 8, 12, 14, and 15. Numbers (1–8) in legend boxes refer to phases of magmatism.

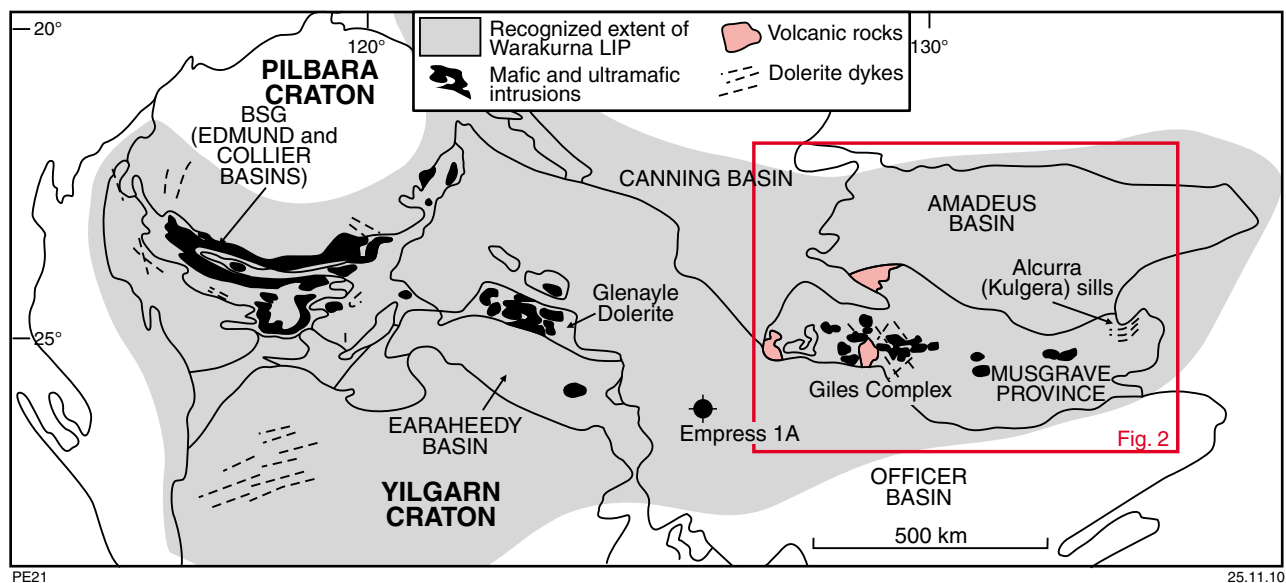


Figure 4. Spatial extent of the Warakurna Large Igneous Province (after Wingate et al., 2004). Intrusions mentioned in the text are labelled.

Stevens and Apak, 1999) basalt buried by sedimentary rocks of the Officer Basin. The Musgrave Province includes the easternmost and best exposed portion of the Warakurna LIP in Western Australia. All rocks previously thought to have formed during Warakurna LIP magmatism (Warakurna Supersuite and Bentley Supergroup) have been collectively grouped together as part of the Giles Event (Table 1).

Rocks produced during the Giles Event have traditionally (Daniels, 1974; Edgoose et al., 2004) been interpreted as a bimodal series, subdivided into the Warakurna Supersuite, consisting of layered mafic–ultramafic intrusions (Giles intrusions), massive gabbros, mafic dykes (Alcurra Dolerite) and rare granitic rocks, and the Bentley Supergroup, dominated by felsic volcanic rocks (Fig. 2). These rocks were thought to relate to a single thermal pulse — the Giles Event — produced by a mantle plume, which (based on the size and extent of the Giles intrusions) was thought to have impacted the lithosphere beneath the Musgrave Province (Morris and Pirajno, 2005).

The Giles Event was contemporaneous with several major tectonothermal events elsewhere in the world, such as the Umkondo–Grunhognia LIP in southern Africa and Antarctica (Hanson et al., 2004), and the Mid-Continent Rift System in North America (Ojakangas et al., 2001). Mafic–ultramafic intrusions and flood basalts are associated with these events. The Bahia dyke swarm in Brazil, the Southwestern USA Diabase province, and the Laanila–Kautokeino event in the Fennoscandian Shield are also broadly coeval with the Giles Event (Ernst and Buchan, 2001).

However, the rocks previously assigned to the Giles Event reveal a complex cycle of magmatism and deformation, rather than a simple, single tectonothermal event. This punctuated series of events persisted over a period of up to 50 m.y. The temporal framework for understanding the Giles Event provided in this study, therefore, has important implications for the extent and amount of magmatism associated with the Warakurna LIP. Along with structural data, the framework also provides constraints on the mechanisms responsible for magmatism at that time. These results contrast with the relatively short-lived and simple geological history expected with the impact of a single mantle plume in an intracontinental setting. Although impact of a mantle plume may have initiated the Giles Event, the event continued as a long-lived failed rift, herein named the Ngaanyatjarra Rift (pronounced Narngd-da-djarra).

Regional geology

Geographic subdivisions

The Mesoproterozoic to Neoproterozoic Musgrave Province is an 800 by 350 km, east-trending belt surrounded by Neoproterozoic to Paleozoic basins (Fig. 1). Camacho (1989) separated the Musgrave Province into the granulite facies Fregon Domain south of the Woodroffe Thrust, and the Mulga Park Domain to the north (Fig. 2). The south-dipping Woodroffe Thrust juxtaposes near-

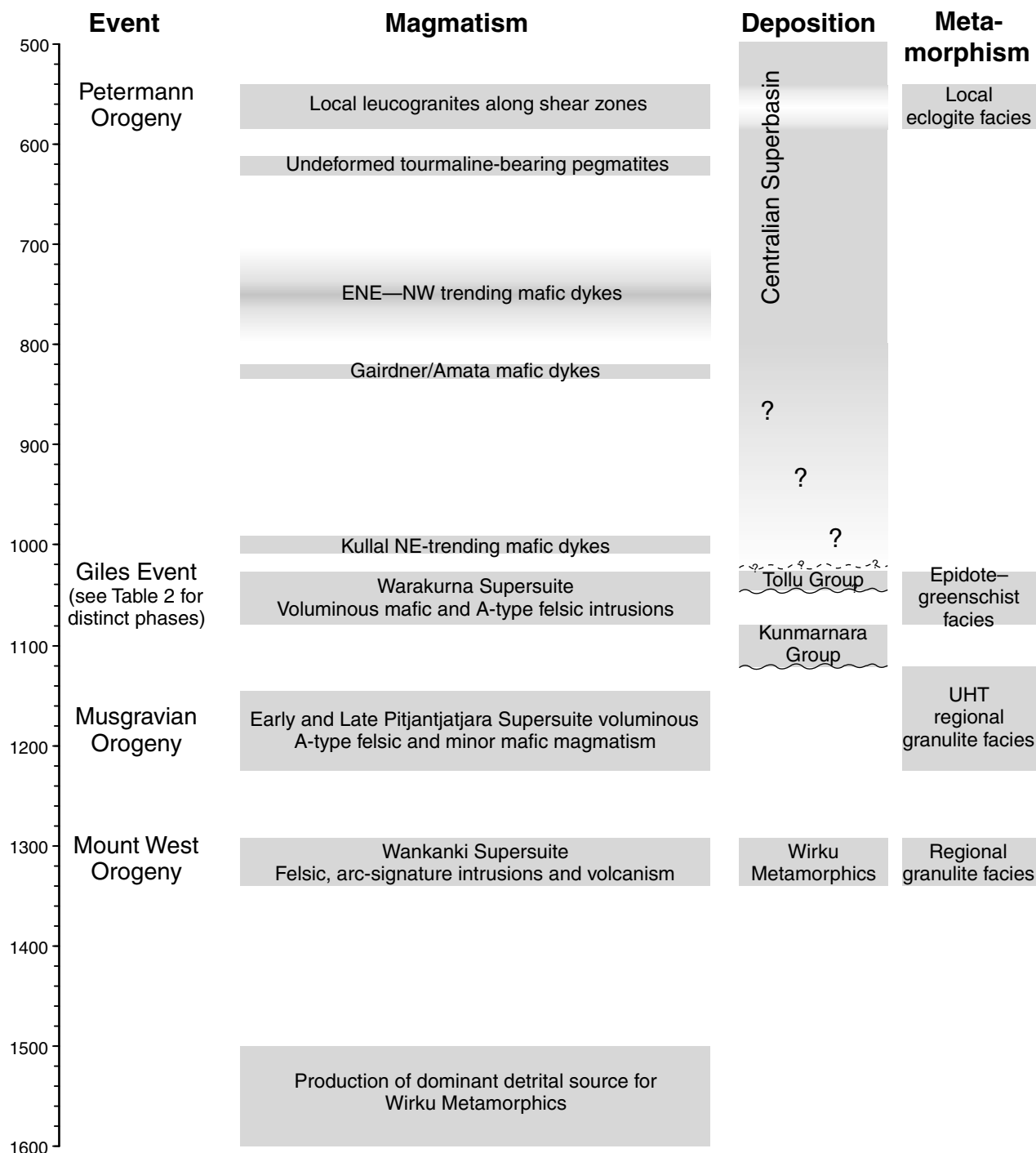
eclogite facies crust of the Fregon Domain against amphibolite facies crust of the Mulga Park Domain.

The Fregon Domain of the west Musgrave Province has been recently subdivided into three main geographic and geological zones; from northeast to southwest these are the Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, and Mamutjarra Zone (Fig. 3; Smithies et al., 2009a). The Walpa Pulka Zone is dominated by c. 1220–1150 Ma granite plutons of the Pitjantjatjara Supersuite emplaced during the Musgrave Orogeny. It contains high-pressure metamorphic assemblages preserved by rapid exhumation along east- and northwest-trending shear zones during the c. 550 Ma Petermann Orogeny (Scrimgeour and Close, 1999; Camacho et al., 1997; Raimondo et al., 2009). The Tjuni Purlka Tectonic Zone is a broad deformation zone that extends in a northwesterly direction across the west Musgrave Province (Fig. 3). Its boundaries were the locus for rifting and magmatism during the Giles Event. The earliest stage of rifting in the Ngaanyatjarra Rift, and subsequent emplacement of giant, layered troctolite–gabbro intrusions, follow 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 (Evins et al., in press). The Mamutjarra Zone is dominated by c. 1345–1293 Ma calc-alkaline granites related to the Mount West Orogeny. The effects of the Petermann Orogeny in this zone are minimal. Smithies et al. (2009a) provide a recent summary of the geological evolution of the west Musgrave Province, which is chronologically summarized in Table 1.

Orogenic events preceding the Giles Event

The Ramarama Basin

Rocks of the Ramarama Basin are the oldest exposed units in the west Musgrave Province. They occur as metre- to kilometre-scale rafts of composite banded gneiss in granite. Locally, these rocks form a significant component of the west Musgrave Province (Gray, 1971, 1978; Stewart, 1995; Evins et al., 2009, in prep.; Howard et al., 2009a,b; Smithies et al., 2009a,b). They are found in all three of the geographic zones defined above, and are thought to include intrusive components as old as c. 1600 Ma, as well as sedimentary and volcanosedimentary gneisses (Gray, 1971, 1978; Gray and Compston, 1978; Maboko et al., 1991; Major and Connor, 1993; Camacho and Fanning, 1995; Camacho, 1997; Edgoose et al., 2004; Wade et al., 2006). In the west Musgrave Province, paragneisses are dominated by metamorphosed arkosic and psammitic units formally defined as the Wirku Metamorphics. Interlayered volcanic gneisses are part of the Wankanki Supersuite (Smithies et al., 2009a). In the eastern parts of the Musgrave Province, all of the gneisses are grouped into the Birksgate Complex. Some gneisses from the eastern part of the Musgrave Province are thought to have a granitic protolith with crystallization ages as old as 1590 ± 25 Ma (Edgoose et al., 2004). However, Evins et al. (in press) have demonstrated that, in most cases, older ages from this part of the Musgrave Province reflect detrital zircon components in paragneisses now assigned

Table 1. Geochronological summary of tectonic events affecting the west Musgrave Province, summarized from Smithies et al. (2008), and some clarifications of stratigraphic nomenclature.

Warakurna Large Igneous Province — area covering a large part of Western Australia that contains c. 1075 Ma mafic sills, and minor mafic and felsic volcanic rocks (Wingate et al., 2004). Only Phase 3 of the Giles Event is coeval with, and therefore related to, the Warakurna Large Igneous Province.

Warakurna Supersuite — all magmatic rocks formed during the Giles Event in the west Musgrave Province
Bentley Supergroup — sedimentary and volcanic succession deposited during the Giles Event. Defined by Daniels (1974) but now split into the Kunmarnara Group (Phase 1 in this study) and Tollu Group (Phase 8 in this study)

Giles Event — the tectonic event that formed the Ngaanyatjarra Rift (Phases 1–8 in this study)

Ngaanyatjarra Rift — the physical manifestation of the Giles Event that includes magmatism of the Warakurna Supersuite and volcanic and sedimentary rocks of the Kunmarnara Group and Tollu Group.

Giles Intrusions — Large mafic–ultramafic intrusions (Phase 2 in this study) that form prominent hills in the Musgrave

to the Wirku Metamorphics. Together, these supracrustal gneisses are the main components of the Ramarama Basin, which formed between the North Australian and South Australian Cratons from c. 1345 to 1300 Ma, but possibly as recently as 1270 Ma (Evins et al., in prep.).

The spectrum of detrital zircon ages in the Wirku Metamorphics varies from region to region. In the Walpa Pulka Zone paragneisses, detrital zircon ages are concentrated between 1650 and 1500 Ma with a main peak at c. 1570 Ma. Detrital zircons with ages <1360 Ma are virtually absent, as are granites related to the Mount West Orogeny. Nevertheless, the youngest detrital zircon components in the Walpa Pulka Zone indicate maximum depositional ages between c. 1360 and 1307 Ma. Most paragneisses in the Tjuni Purlka Tectonic Zone contain detrital zircon ages between 1560 and 1470 Ma with a main peak at c. 1520 Ma. This distribution of ages is 50 m.y. younger than those in the Walpa Pulka Zone. Furthermore, significant components between c. 1360 and 1310 Ma are present in the Tjuni Purlka Zone, which are absent from the Walpa Pulka Zone. The youngest detrital zircon components in the Tjuni Purlka Tectonic Zone indicate maximum depositional ages between c. 1270 and 1250 Ma. Paragneisses in the Latitude Hills area are more pelitic and contain several prominent detrital zircon age peaks between c. 3200 and 2630 Ma, and between 1790 and 1590 Ma.

In the western part of the Mamutjarra Zone, the Wirku Metamorphics are dominated by banded to laminated, pelitic to psammitic paragneiss. In the east of this zone, the rocks are dominantly psammitic, compositionally very similar to granites related to the Mount West Orogeny, and are likely derived from volcanic or volcanoclastic protoliths. These rocks preserve very few detrital zircons, but show a virtually unimodal zircon age component best interpreted as reflecting volcanic deposition during the c. 1345–1293 Ma Mount West Orogeny (Evins et al., in prep.). The paragneisses assigned to the Wirku Metamorphics in the different zones likely represent slightly different tectonostratigraphic packages within a single depositional basin (the Ramarama Basin) that evolved between c. 1360 and c. 1270 Ma. Development of this basin was concomitant with the intrusion of felsic magmas of the Wankanki Supersuite during the c. 1345–1293 Ma Mount West Orogeny (Smithies et al., 2009a).

The Mount West Orogeny and the Wankanki Supersuite

Gray (1971), Sun et al. (1996), and White (1997) identified isolated outcrops of c. 1345–1293 Ma felsic gneiss in the central part of the Tjuni Purlka Tectonic Zone. Intrusive rocks of this age are now known to form a significant component within the zone, and also represent the most voluminous >1100 Ma magmatic component of the Mamutjarra Zone (Fig. 3; Howard et al., 2009b; Smithies et al., 2009a,b; Evins et al., 2009). The crystallization age range of these rocks is from c. 1345 to c. 1293 Ma (White et al., 1999; Smithies et al., 2009a; Fig. 5). Howard et al. (2009b) grouped these granitic and volcanic rocks into the Wankanki Supersuite and named the crustal event that

produced them the Mount West Orogeny. Rocks from the Wankanki Supersuite range from moderately foliated porphyritic granites, to layered felsic gneisses showing incipient to advanced migmatization. Several fine-grained, gneissic varieties of the Wankanki Supersuite have been interpreted as having volcanic protoliths (Evins et al., in prep.). These units are interleaved with, and form part of, the Ramarama Basin described above.

The Musgrave Orogeny and the Pitjantjatjara Supersuite

The Musgrave Orogeny involved the generation of enormous amounts of granitic magma to form the Pitjantjatjara Supersuite, which covers roughly half of the entire Musgrave Province (Fig. 2). These rocks, typically K-feldspar porphyritic granites, form large composite plutonic bodies that make up the majority of the Walpa Pulka Zone, as well as forming smaller plutons and dykes in the Tjuni Purlka Tectonic Zone and Mamutjarra Zone (Fig. 3). Where preserved, the primary mineralogy of these granites is anhydrous (quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene) suggesting that many are charnockites (Smithies et al., 2010). A unique group of Pitjantjatjara Supersuite granites is restricted to the Tjuni Purlka Tectonic Zone and comprises locally schlieric biotite–orthopyroxene leucogranites. Static and dynamic recrystallization is locally responsible for weak to mylonitic foliations, and the retrogression of pyroxene to hornblende, actinolite, and biotite in all granites of the Pitjantjatjara Supersuite.

Pitjantjatjara Supersuite magmatism was accompanied by intense deformation and widespread ultra high temperature metamorphism during the Musgrave Orogeny. This orogeny is unique among ultra high temperature belts around the world for its longevity and tectonic setting. Temperatures greater than 900°C were maintained in the middle to lower crust for over 100 m.y. (c. 1220–1120 Ma) in an intracontinental setting (Fig. 5; Smithies et al., 2010). The pre-Musgrave Orogeny crustal architecture, characterized by the relatively thin crust of the Musgrave Province sandwiched between the thicker, Archean-cored West, North, and South Australian Cratons, likely channelled heat and material under the Musgrave Province for an extended period (Fig. 6).

Orogenic events post-dating the Giles Event

Following the Giles Event, magmatism was limited to mafic dykes and rare pegmatites emplaced at c. 1000 Ma (age based on a garnet-bearing aplite dyke; GSWA 183597; Kirkland written comm., 2010), mafic dykes at c. 800 Ma (Gairdner and Amata dykes), and c. 620 Ma tourmaline-bearing pegmatites (GSWA 187175; Kirkland written comm., 2010). Together, these intrusions are volumetrically minor.

The Musgrave Province was again deformed during the c. 550 Ma intracratonic Petermann Orogeny when high-pressure granulites and near-eclogite facies rocks were

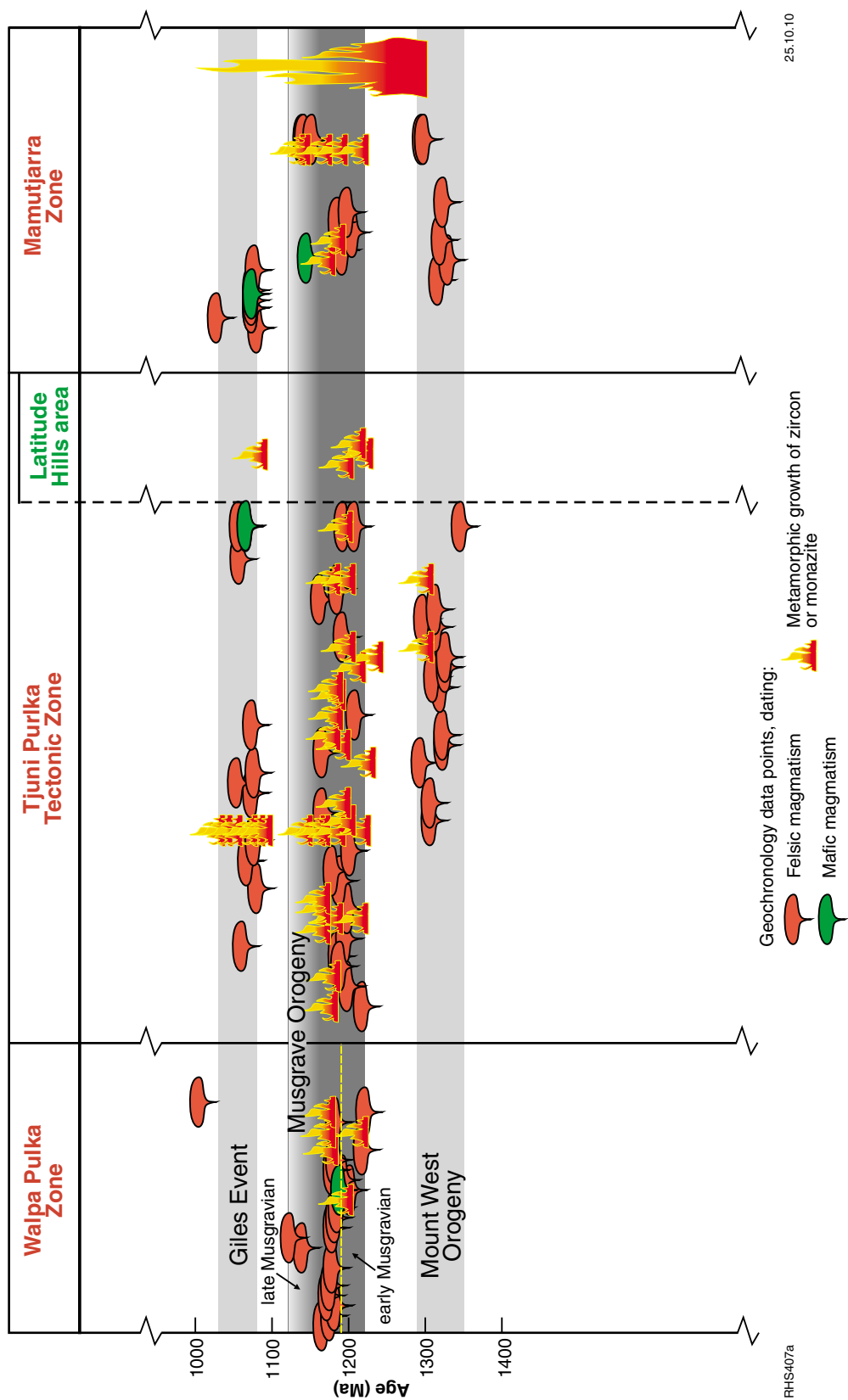


Figure 5. Time-space plot showing all GSWA SHRIMP (U–Pb) zircon ages from the west Musgrave Province (after Smithies et al., 2010). Errors on individual ages fall within the size of the individual icons.

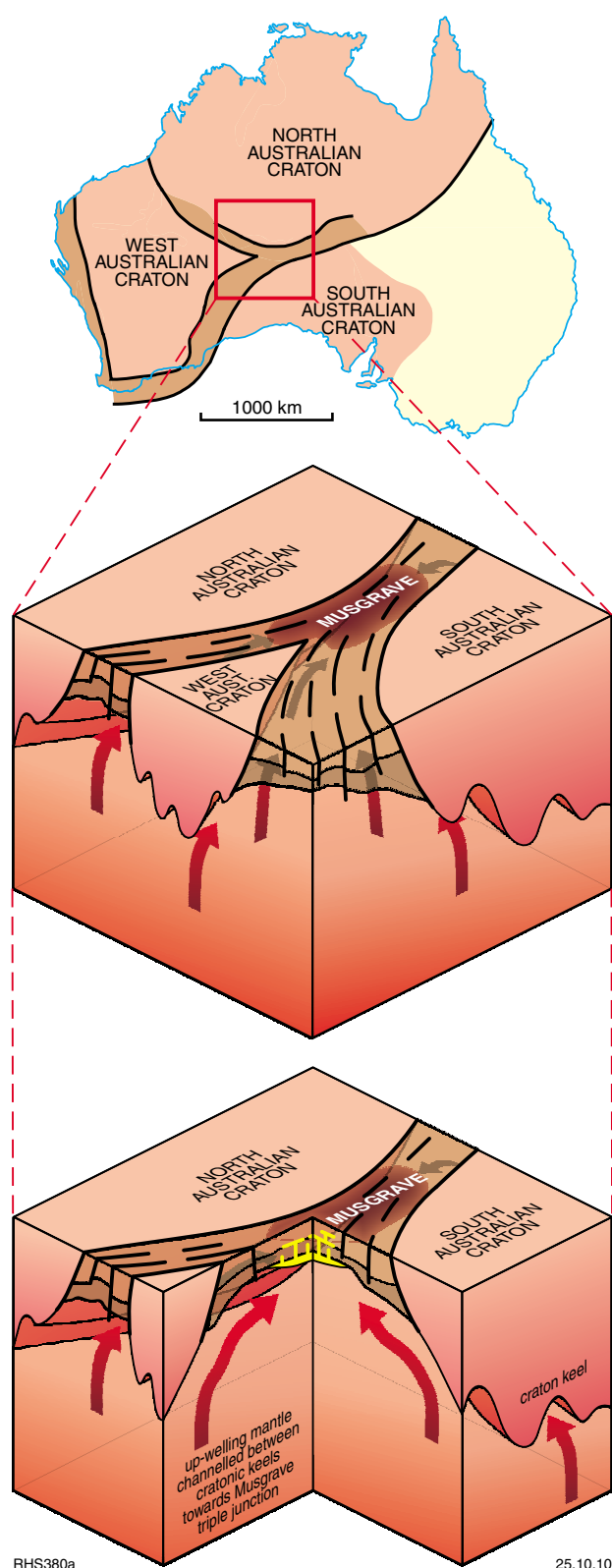


Figure 6. Block diagrams showing the influence of crustal blocks on the tectonothermal evolution during the Musgrave Orogeny (after Smithies et al., 2010).

exhumed in a wedge between the Woodroffe Thrust to the north and the Tjuni Purlka Tectonic Zone to the south (Camacho et al., 1997; Edgoose et al., 2004), in a process that involved intracontinental channel flow (Raimondo et al., 2009). Granitic rocks formed during the Giles Event are conspicuously absent from this wedge, although mafic dykes are present (Howard et al., 2009a). Later, brittle deformation events are recorded by the east-trending Mann Fault, which has sinistrally displaced the Tjuni Purlka Tectonic Zone by approximately 30 km. The Petermann Orogeny appears to have involved very little production of new crust. It coincides with the global period of plate reorganization that marks the final assembly of Gondwana (Collins and Pisarevsky, 2005).

Previous studies

The Giles intrusions have attracted particular attention due to their large size and significant economic potential for Ni–Cu and PGE mineralization; however, studies have mostly 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. Felsic magmatism and extrusive packages have mostly been discussed within the context of explanatory notes from state mapping projects in Western Australia (Daniels, 1974) and the Northern Territory (Close et al., 2003a). Gray (1971, 1978) investigated relationships between the intrusions and volcanic rocks, whereas Giles (1981) studied the geochemistry of the volcanic rocks. Smaller, Ni–Cu-mineralized dykes and intrusions have recently been the focus of detailed studies by Howard et al. (2009c) and Seat (2008).

Magmatic and tectonic stages of the Giles Event

The Giles Event, Ngaanyatjarra Rift, and Warakurna Supersuite

The Giles Event encompasses the intrusion and extrusion of voluminous mafic to felsic magmas in the Musgrave Province from >1078 to c. 1026 Ma (Table 2). It is responsible for the formation of a long-lived, failed intracontinental rift called the Ngaanyatjarra Rift (Evins et al., in press), which is almost entirely contained within the Western Australian portion of the Musgrave Province. We have identified at least eight phases of magmatism and deformation that can be attributed to this event, and these are described below. Igneous rocks formed during the Giles Event are grouped within the Warakurna Supersuite; a component of this supersuite (defined by magmatism at c. 1075 Ma) is also a component of the more spatially extensive Warakurna LIP (Wingate et al., 2004; Morris

and Pirajno, 2005), which extends west of the Musgrave Province to occupy a significant proportion of Western Australia (Fig. 4).

Three main phases of mafic intrusion have been recognized for the Giles Event. Giant, layered mafic–ultramafic bodies (Giles intrusions) intruded the boundary between the Tjuni Purlka Tectonic and Mamutjarra Zones (Fig. 3) between c. 1120 Ma and 1078 Ma (Smithies et al., 2009a). The largest of these was dissected into the Bell Rock, Blackstone, Finlay, and Jameson Ranges by later faulting, but initially occupied a volume of nearly 50 000 km³. This earliest phase of the Warakurna Supersuite is represented on GSWA maps with a g1 code suffix (P_WKg1).

Large bodies of massive, unlayered gabbro emplaced at c. 1075 Ma (Table 2) form a near-continuous feature focused along the synmagmatic shear zones marking the northeastern boundary of the Tjuni Purlka Tectonic Zone in the Murray Range (Fig. 3). They are locally characterized by extensive zones of co-mingling with felsic magmas, and bear a g2 code suffix (P_WKg2) on GSWA maps. Mafic and felsic magmatism continued to be channelled along the boundaries of the Tjuni Purlka Tectonic Zone until the eruption of Tollu Group felsic lavas at c. 1075 to 1026 Ma (Table 2). In the Tjuni Purlka Tectonic Zone and the Mamutjarra Zone, felsic intrusions related to this later magmatism range from dykes and sheets to plutons up to 12 km in diameter, and were emplaced between c. 1075 and c. 1062 Ma (Table 2).

Mafic intrusions related to this later magmatism include dolerite dykes, ferro-diorites, and ferro-gabbros of the Alcurra Suite, which are dated at c. 1072–1068 Ma, and are locally associated with Cu mineralization (Howard et al., 2009c). This stage of mafic magmatism is represented on GSWA maps with a g3 code suffix (P_WKg3).

Extrusive magmatism that occurred during the Giles Event was originally assigned to the Bentley Supergroup (Daniels, 1974; Edgoose et al., 2004). Smithies et al. (2009a,b) split the Tollu Group of the Bentley Supergroup into a basal rift succession of pebbly sandstones (MacDougall Formation) and basalt (Mummawarrawarra Basalt) called the Kunmarnara Group, and a redefined Tollu Group comprising felsic and mafic volcanic units including the Smoke Hills Volcanics and Hogarth Formation. These two groups within the Bentley Supergroup bracket emplacement of the ≥6 intrusive phases of the Warakurna Supersuite, depicted on GSWA maps as P_WKg1 to P_WKg3.

In the west Musgrave Province, rocks formed during the Giles Event are mainly restricted to the area within, and to the southwest of, the Tjuni Purlka Tectonic Zone (Fig. 3). The geological evolution of these rocks is outlined chronologically below. All reported U–Pb ages are tabulated in Table 2, together with references. Tera–Wasserburg concordia diagrams for Geological Survey of Western Australia (GSWA) geochronology dates are shown in Figure 7, and are available online at <<http://www.dmp.wa.gov.au/geochron>>. There are a few 10–100 m wide dolerite and gabbro dykes in the Walpa Pulka Zone. They do not differ significantly from the

massive gabbros described below (and are interpreted to be of a similar age), except that many contain garnet with pyroxene symplectite coronae as a result of high-pressure metamorphism during the Petermann Orogeny. They are not discussed further.

Kunmarnara Group (Phase 1)

Division of the Tollu Group

The oldest units associated with the Giles Event are the sedimentary and dominantly mafic volcanic rocks at the base of the regionally extensive Bentley Supergroup (Daniels, 1974), which in the eastern part of the west Musgrave Province was assigned by Daniels (1974) to the Tollu Group (Fig. 3). Here, Daniels (1974) defined the stratigraphy of the Tollu Group as 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 mafic to intermediate lavas of the Hogarth Formation. The Smoke Hill Volcanics and the Hogarth Formation occupy the core of the Blackstone syncline described below, whereas the MacDougall Formation and the Mummawarrawarra Basalt are mainly restricted to outcrops south of this syncline and as thin units along the base of the Blackstone and Finlay–Jameson intrusions (Daniels, 1974; Evins et al., 2009, in press). Nowhere are they exposed as a continuous sequence.

Gray (1971) considered the Giles intrusions to be significantly older than the Tollu Group. However, a date of 1078 ± 5 Ma (Sun et al., 1996) from an outcrop of rhyolite previously mapped as the Smoke Hill Volcanics (Daniels, 1974) lead to the suggestion that they were co-magmatic with the layered mafic–ultramafic Giles intrusions (e.g. Compston and Nesbitt, 1967; Glikson, 1995; Glikson et al., 1996). Re-examination of that outcrop indicated that the rock is a fine- to medium-grained leucogranite, petrographically and texturally identical to c. 1075 Ma leucogranites described below. Furthermore, decimetre- to kilometre-scale xenoliths of Mummawarrawarra Basalt occur in the basal portions of the Blackstone and Finlay–Jameson layered mafic intrusions (Fig. 8), indicating that the Giles intrusions were actually emplaced within, or at the top of, the Mummawarrawarra Basalt (Daniels, 1974; Smithies et al., 2009a).

These relationships require a significant time gap between deposition of the Mummawarrawarra Basalt and eruption of the Smoke Hill Volcanics. During this gap, the layered Giles intrusions were emplaced, uplifted, and eroded. We have accordingly subdivided the Tollu Group, as defined by Daniels (1974), into the Kunmarnara Group (comprising the MacDougall Formation and Mummawarrawarra Basalt) and the overlying Tollu Group (redefined to include the Smoke Hill Volcanics and Hogarth Formation) (Evins et al., 2009; Howard et al., 2009b; Smithies et al., 2009a,b). The Kunmarnara Group and Tollu Group bracket most of the newly defined Giles Event, based on the new age data and crosscutting relative timing relationships presented in this study.

Table 2. All existing U–Pb zircon ages associated with the Giles Event(s) subdivided into the phases described in the text

Sample no.	Easting	Northing	Sample description uncertainty	Age Ma \pm 95% description	n; MSWD; zircon	Geochronology comments	Ref.
BR97CJE73	525452	7269400	Unfoliated, medium- to fine-grained Walu leucogranite. Green biotite, rare hornblende; epidote and quartz patches and veins. Intrudes Mount Harris Basalt.	1084 \pm 9	na	–	7
Phase 3 — syntectonic gabbro and granite, and felsic volcanic rocks							
91988053	473425	7118330	Recrystallized biotite gabbro. nore.	1075 \pm 1	MSWD = 0.84	–	–
174589	451114	7133869	K-feldspar porphyritic (1 cm) granite dyke mingled with sheets of gabbro at Amy Giles Hill.	1073 \pm 5	6; NA; r, o	–	2
M2a	517278	7116021	Assimilated granite in marginal gabbro to the Erawara intrusion.	1074 \pm 3	27; 0.79; h, o	–	9
				1075 \pm 14	4; 0.9	Four analyses from 2 embayed zircon grains.	3
185509	471391	7120896	Medium-grained foliated leucogranite that forms veins and patches that migrate into boudin necks.	1075 \pm 3	20; 1.3; h	–	10
174761	473626	7116039	Weakly foliated K-feldspar porphyritic granite with locally abundant biotite-rich schlieren.	1075 \pm 7	17; 0.77; Oz	One 1210 Ma xenocryst.	11
91988005	458263	7104889	Cuts sample 174589 and intrudes along the Hincley Range macroscopic fold axial plane. Massive fine- to medium-grained leucogranite locally containing cognate microgranite xenoliths to 5 cm.	1078 \pm 5	35; NA; s, r, o	–	2
91989313B	477572	7091980	Leucogranitic pegmatite sill in the Bell Rock intrusion at Boundary Peak.	–	–	–	–
BR98DFC429	551843	7261231	Rowley Granophyre; plagioclase, K-feldspar, and quartz phenocrysts in a medium- to coarse-grained quartz and feldspar groundmass of quartz and feldspar. Mafic minerals include biotite, chlorite, and opaques. Abundant granophyric intergrowths between quartz and alkali feldspar; cut by Alcurra Dolerite.	1078 \pm 3	26; NA; p, o	~4000 ppm U.	2
BR97CJE153	540600	7274480	Punitijata Rhyolite extrusive equivalent of the Rowley Granophyre.	1075 \pm 2	–	Pb–Pb Kober.	7
190256	421981	7186055	Well foliated rhyolite with rare plagioclase phenocrysts up to 3 mm; 3% muscovite and 2% opaques; phenocrysts rich in muscovite inclusions; dissected by numerous quartz and epidote veins.	1074 \pm 4	18; 1.4; p, c-b, o, i	Concordia age; inclusions of quartz and feldspar.	1
183847	439840	7079281	Massive, coarse- to medium-grained Skirmish Hill syenite.	1078 \pm 4	26; 0.94	Weighted mean 207- corrected $^{206}\text{Pb}/^{238}\text{U}$ age.	1
Phase 4 — post-macroscopic folding plutons							
183474	467560	7071861	Massive, unmetamorphosed, hornblende–biotite South Hill syenogranite.	1073 \pm 2	MSWD = 0.39	–	–
				1072 \pm 8	30; 1.5; o,z	Weighted mean 207-corrected $^{206}\text{Pb}/^{238}\text{U}$ age.	12
185583	435796	7100732	Massive, medium- to fine-grained, porphyritic Tolu Granite; Tabular, euhedral, perthite phenocrysts up to 2 cm = 10–15% of the rock. Rare rapakivi texture; up to 1 cm biotite clots (with associated zircon) can make up 10% of the rock.	1073 \pm 6	30; 2.2	One 1176 Ma xenocryst.	16
PR96DFC535	619081	7126639	Ellipsoidal, elongate, pale blue K-feldspar porphyritic Angatja hornblende granite; aggregates of hornblende and fine garnet, biotite, and secondary hornblende make up 20–25% of the rock and define a foliation.	1071 \pm 5	–	Pb evaporation.	5
MP1	773300	7121300	Mylonitic (Petermann-aged fabric) Michell Nob Granite; up to 3 cm subrounded microcline and perthite phenocrysts wrapped by granoblastic fabric. Mafic assemblage of biotite, blue-green hornblende, sphene, garnet and epidote. Plagioclase contains small euhedral inclusions of epidote. Intrudes Michael Nob Granite.	1068 \pm 13	3; 0.5; l, p, c, o-z, i	Weighted mean 207-corrected $^{206}\text{Pb}/^{238}\text{U}$ age. Inclusions of opaque oxides, apatite and fluid.	3
Phase 5 — mafic intrusions, felsic dykes, and mineralization							
91988064	488738	7108828	Porphyritic clinopyroxene–biotite rapakivi feldspar porphyritic granite dyke.	1068 \pm 3	MSWD = 0.33	–	–
1018-097 and 70-019	na	na	Gabbroite co-magmatic with orthomagmatic Ni–Cu–PGE mineralization at the Nebo–Babel deposit.	1068 \pm 6	32; NA; p, c, o	Upper intercept age.	13
				1068 \pm 4	42; 1.17; p, c, o	–	–

94354	354869	7163642	NE-trending coarse-grained gabbro dyke cutting the Finlay–Jameson intrusion. Ophitic 'dual' texture of subhedral to euhedral plagioclase laths with interstitial pyroxene, trace olivine and opaques (1%). Pyroxene is partially to completely replaced by blue-green sodic amphibole). Plagioclase is sericitized and chrysocolla (Cu alteration) is associated with the dyke.	1067 ± 8	20; 1.8; s, c, z	Concordia age; fragments of larger grains.	14
J0197	na	na	Saturn Gabbro.	1072 ± 8	–	Baddeleyite; 13 to 56 ppm U.	8
Phase 6 — mingled gabbro and granite, felsic dykes, and felsic volcanic rocks							
91988094	490142	7103735	Centre of a 130 m wide leucogabbro dyke.	1062 ± 4	MSWD = 0.14	–	–
187256	436323	7160678	Undeformed, fine to medium-grained, grey, leucocratic syenogranite with 1 cm K-feldspar phenocrysts. 1% each of hornblende, clinopyroxene, and orthopyroxene. Feldspar recrystallization along phenocryst margins give a pseudotachyite appearance. Some phenocrysts fractured with recrystallized infill.	1058 ± 14	27; NA; r, c	Upper intercept age.	–
194454	465893	7127906	Undeformed, fine- to medium-grained gabbro contaminated by whips of granite; taken from a low-strain domain within the Mann Fault; up to 5 mm euhedral, bent plagioclase laths in a groundmass of recrystallized clinopyroxene occasionally altered to biotite; 1 mm rounded orthopyroxene surrounded by recrystallized clinopyroxene and opaques; rare 1 cm plagioclase glomerocrysts.	1062 ± 10	17; 1.2; l-e, o	Large equant high U, and smaller elongate low U.	17
				1066 ± 9	15; 1.4; p, c-b, z	Weighted mean 207-corrected ²⁰⁶ Pb/ ²³⁸ U age. Th/U = 1.3 – 2.6.	1
O94/57F	659750	7208450	Rhyolite diast from Mount Currie conglomerate.	1062 ± 6	–	Kober Pb evaporation.	6
Phase 7 — granite and felsic volcanic rocks							
W-129	na	na	Undeformed granite truncated by the Davenport Shear Zone.	1048 ± 6	MSWD = 0.33	–	–
				1047 ± 12	15; 1.16; r-p, c, o-z	26–59 ppm U; Th/U 1.3 – 2.1, low common Pb.	4
W-147b	na	na	Mylonitic granite equivalent of sample W-129.	1050 ± 18	24; 1.07; p, o-z	11–44 ppm U; Th/U 1.5 – 2.6, low common Pb.	4
91988059	474029	7116448	Porphyritic hornblende-biotite granite dyke.	1052 ± 11	18; NA; s, r, o, i	–	2
MP21	774900	7120900	Heterogeneous, medium to coarse-grained blue-green to dark-green Nulchara Charnockite with rapakivi feldspar phenocrysts up to 5 cm and mafic clots of clinopyroxene, orthopyroxene, and hornblende.	1044 ± 10	15; 1.2; e, p, c, z	Weighted averages of 207-corrected ²⁰⁶ Pb/ ²³⁸ U* IDTIMS U–Pb zircon. Some zircons embayed.	15
PR96IRS623	506380	7221500	Wankari Volcanics — Porphyritic rhyolite with rare epidotized and amygdaloidal mafic volcanics.	1051 ± 22	NA; NA; l, p, b, o-z, i	Inclusions include rutile apatite and sulfides.	5
Phase 8 — Tollu Group							
187177	436662	7116045	Plagioclase-phryic dacite from the Smoke Hill Volcanics.	1026 ± 26	6; NA; r, c-b, o	Ten xenocrysts = 1782 – 1150 Ma; 2 concordant dates of 356 ± 6 and 518 ± 10 Ma.	1

NOTES: Light grey shading highlights volcanic rocks. Ages are weighted averages of ²⁰⁷Pb/²³⁵Pb SHRIMP U–Pb zircon analyses unless otherwise indicated.

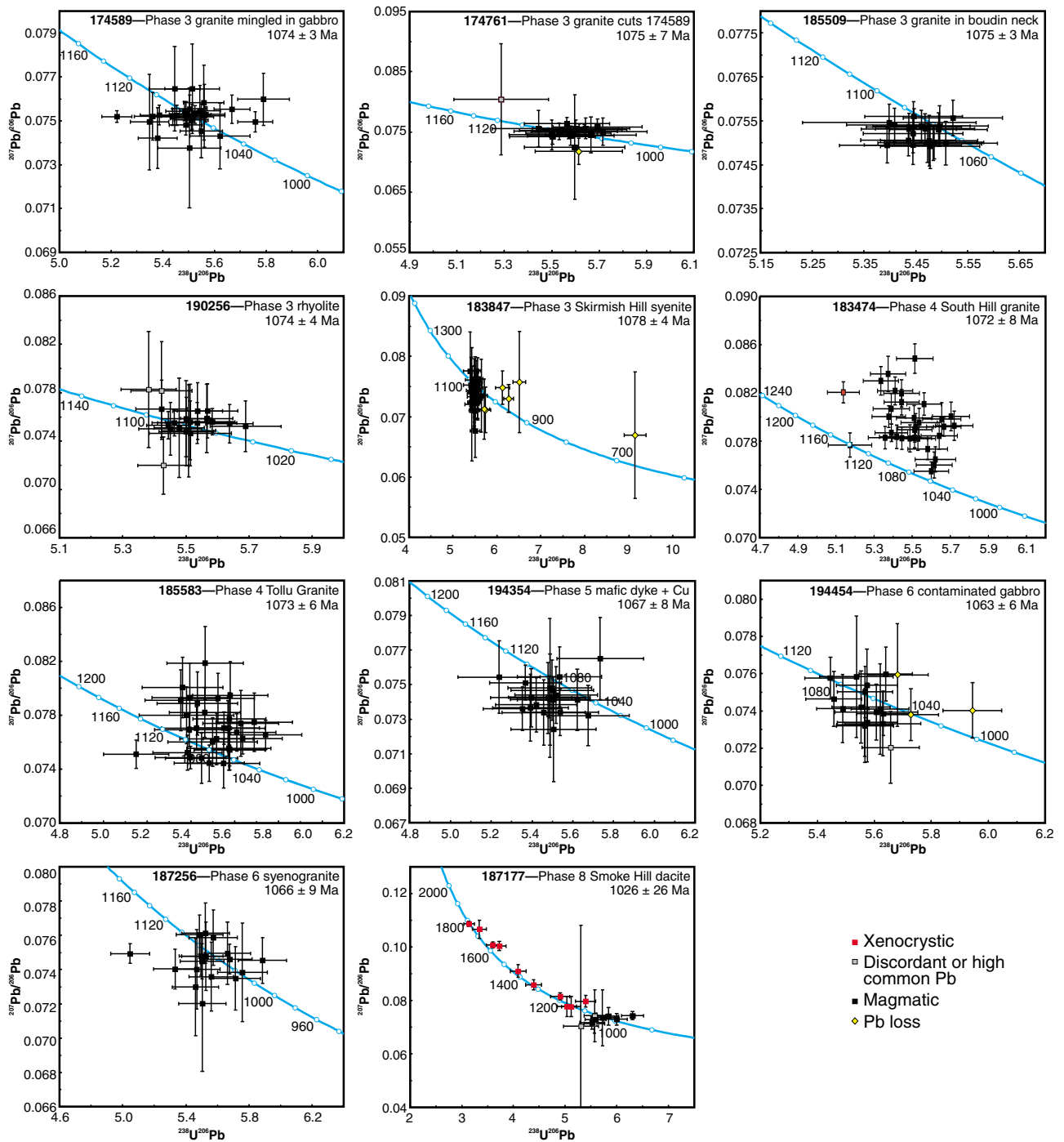
Zircon description abbreviations

l elongate
s stubby
e equant
r rounded
p prismatic
c colourless

References

1 GSWA geochronology Record — <<http://www.dmp.wa.gov.au/geochron>>
2 Sun et al., 1996
3 Camacho, 1997
4 Camacho and McDougall, 1997
5 Scrimgeour et al., 1999
6 Young et al., 2002

7 Close et al., 2003b
8 Redstone Resources, written comm., 2007
9 Bodorkos and Wingate, 2008
10 Kirkland et al., 2008b
11 Kirkland et al., 2008a
12 Kirkland et al., 2008c
13 Seat, 2008
14 Howard et al., 2009c
15 Camacho, pers. comm.
16 Kirkland et al., 2009a
17 Kirkland et al., 2009b



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Figure 7. U-Pb analytical data for zircons from GSWA samples of magmatic Giles Event(s) rocks in the west Musgrave Province. Error bars are 2σ . Ages refer to magmatic zircons only; details are available in the related GSWA Geochronology Records, available online at <http://www.dmp.wa.gov.au/geochron>.

Distribution of the Kunmarnara Group

The Kunmarnara Group is mainly exposed along the northwest-trending, northeastern boundary of the Mamutjarra Zone (Fig. 3). The northern portion of this unit is a 3–5 km wide, 100 km long, west- to northwest-striking, gently to moderately south-southwest dipping belt that runs along the northern side of the Finlay and Blackstone ranges (Fig. 8), where it forms the northern margin of the Ngaanyatjarra Rift. The Kunmarnara Group continues to the south on BELL ROCK* as a 10 km wide, northwest-trending, shallow regional syncline. The 2 km wide, west-trending southern limb is exposed further west on BLACKSTONE, where the syncline is cored by younger units of the Tollu Group. This southern limb continues west to underlie c. 80 km² of the Mount Blyth area (central COOPER) where the Kunmarnara Group and its external and internal contacts are well exposed (Fig. 3). Metamorphosed equivalents of the Kunmarnara Group are interpreted to form west-northwesterly trending, upright folds within a 38 km long and 10 km wide, fault-bounded block that straddles the border between the northern portions of the FINLAYSON and HOLT map sheets.

MacDougall Formation

The MacDougall Formation and its derivatives typically form low sandy outcrops and linear ridges in dune country. In lower lying areas, it forms saprolitic or limonitic ferricrete mounds and may underlie plains with abundant quartz colluvium sourced from its vein quartz pebbles. Fine- to coarse-grained, muddy to arkosic, poorly sorted sandstones and matrix-supported conglomerates of the MacDougall Formation (P₁-KRd-sg) are preserved in the Blackstone syncline and at Mount Blyth. Local cross-bedding suggests a depositional system that flowed away from the area between these two exposures (Daniels, 1974). At MacDougall Bluff, the formation unconformably overlies granites of the Wankanki Supersuite. At Mount Blyth, a 350 m thick succession of 1–10 m cross-bedded quartz-pebble conglomerate and poorly sorted coarse sandstone (Fig. 9a) of the MacDougall Formation rests unconformably on mylonitic, granulite facies paragneisses of the Wirku Metamorphics.

Elsewhere, the MacDougall Formation is metamorphosed to greenschist–amphibolite facies (P₁-KRd-mxsm), and mylonitized (P₁-KRd-mxym) along the northern margin of the Ngaanyatjarra Rift, where 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 clastic rocks described above, and their stratigraphic position with respect to the Giles intrusions, indicates they are the high-grade metamorphosed equivalents of the MacDougall Formation sedimentary rocks found to the south. Approaching some of the layered mafic–ultramafic intrusions, small 1 mm diameter garnets are wrapped by a dextral-normal C–S fabric defined by muscovite (C-planes) and recrystallized quartz (S-planes). This relationship suggests

the sedimentary rocks were deformed before emplacement of the Giles intrusions. However, the opposite relationship can be seen where it is mylonitized at its basal contact, which is indicative of later faulting along this anisotropy. The unconformity between the MacDougall Formation and its basement (usually Wankanki or Pitjantjatjara Supersuite granites) was a locus for deformation, and its original form is largely destroyed by the development of mylonite and ultramylonite zones tens of metres wide that are best preserved along the eastern side of the Finlay Range.

Other lithologies within the MacDougall Formation range from quartzite to meta-arkose to phyllite depending on muscovite and feldspar content. All of these rocks are rich in quartz (up to 70%) and muscovite (10–30%). Magnetite and zircon are common accessory minerals. Up to 1 cm wide, discontinuous, magnetite-rich (up to 35%) bands are locally present. An overwhelming majority of pebbles in the MacDougall Formation are vein quartz. The source of this vein quartz remains enigmatic as quartz veins are not abundant in the basement. On the contrary, quartz veins commonly crosscut the MacDougall Formation, and are most abundant in regions of the west Musgrave Province where the Kunmarnara Group outcrops (Evins et al., 2009).

Detrital zircon geochronology

Detrital zircon age spectra from three widely spaced (separated by >80 km along strike) samples of the MacDougall Formation (GSWA samples 190233, 190292, 194420; Kirkland written comm., 2010) provide little insight into the source of the vein quartz pebbles. The majority of concordant detrital zircons from these samples are derived from the Pitjantjatjara Supersuite (72% in 190233, 57% in 194420, and 46% in sample 190292). They form an age peak at c. 1170 Ma (Fig. 10). The remaining concordant detrital dates span age ranges similar to Wirku Metamorphics detritus. Sample 190233 is the only one of the samples located within the Tjuni Purlka Tectonic Zone. Its pre-Musgrave Orogeny (>1220 Ma) detrital zircon spectrum is similar to Wirku Metamorphics detrital zircon spectra from the Tjuni Purlka Tectonic Zone, in that it is dominated by a main 1520 Ma peak with subsidiary peaks at 1480 Ma and c. 1320 Ma, indicating detritus representative of Wankanki Supersuite provenance. The detrital zircon spectra of the other two samples (190292 and 194420), located in the Mamutjarra Zone, are remarkably similar, even though they are on opposite sides of the Ngaanyatjarra Rift (compare Figs 3 and 8). They contain significant detrital age components at c. 1520, 1580, and 1610 Ma, as well as detritus representative of Wankanki Supersuite provenance (Fig. 10). Apart from the presence of Wankanki Supersuite detritus, the detrital spectra of these last two samples more strongly resemble Wirku Metamorphics spectra from the distant Walpa Pulka Zone. This supports the conclusion by Smithies et al. (2009a) that the fundamental differences between the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone pre-date both the Petermann Orogeny and the Giles Event. The most likely reason for vein-quartz pebble concentration in the MacDougall Formation is the preferential preservation of rare vein quartz after extended weathering of the Musgravian basement, before the onset of rifting during

* Capitalized names refer to GSWA 1:100 000 Geological Series map sheets.

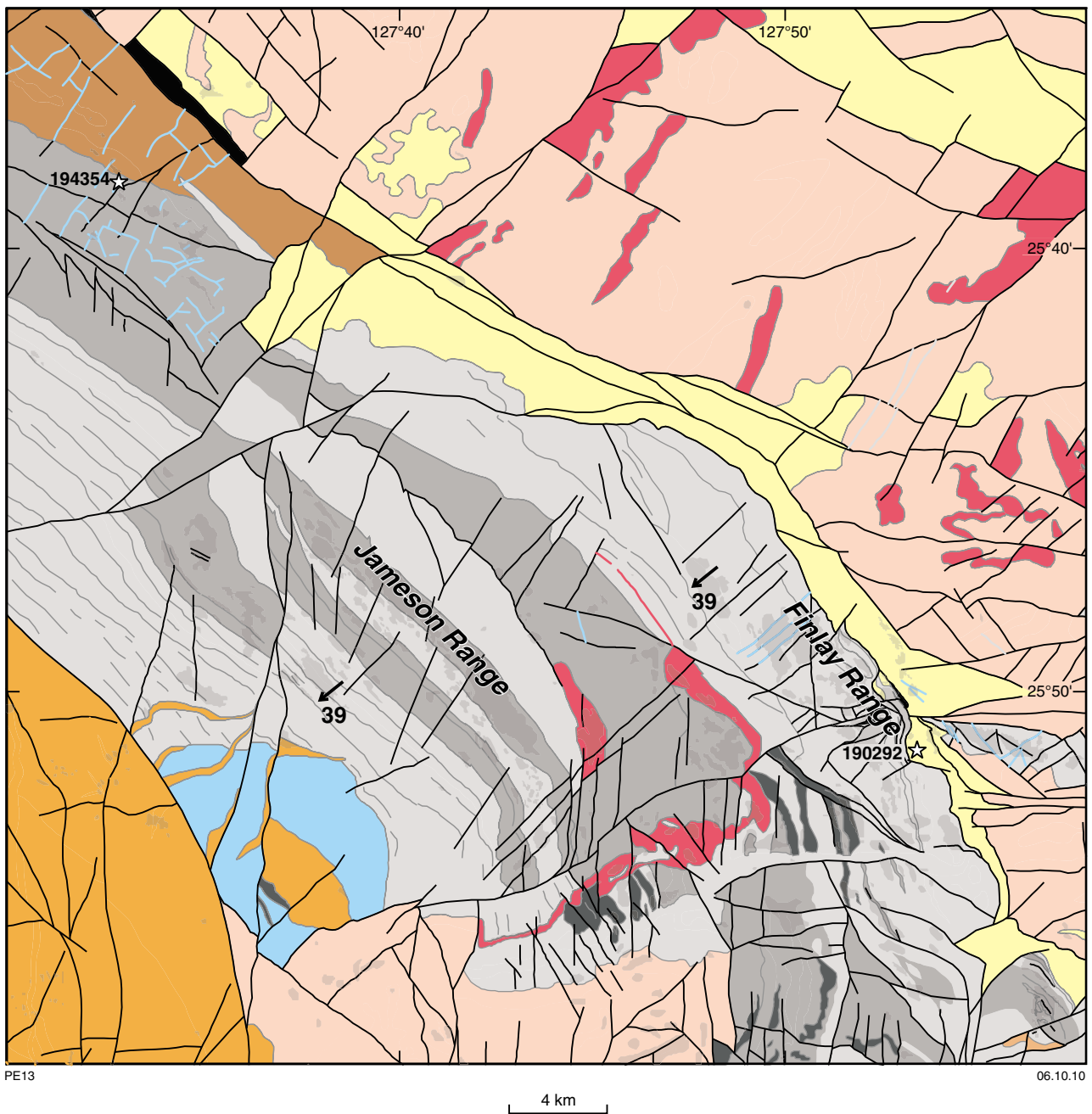
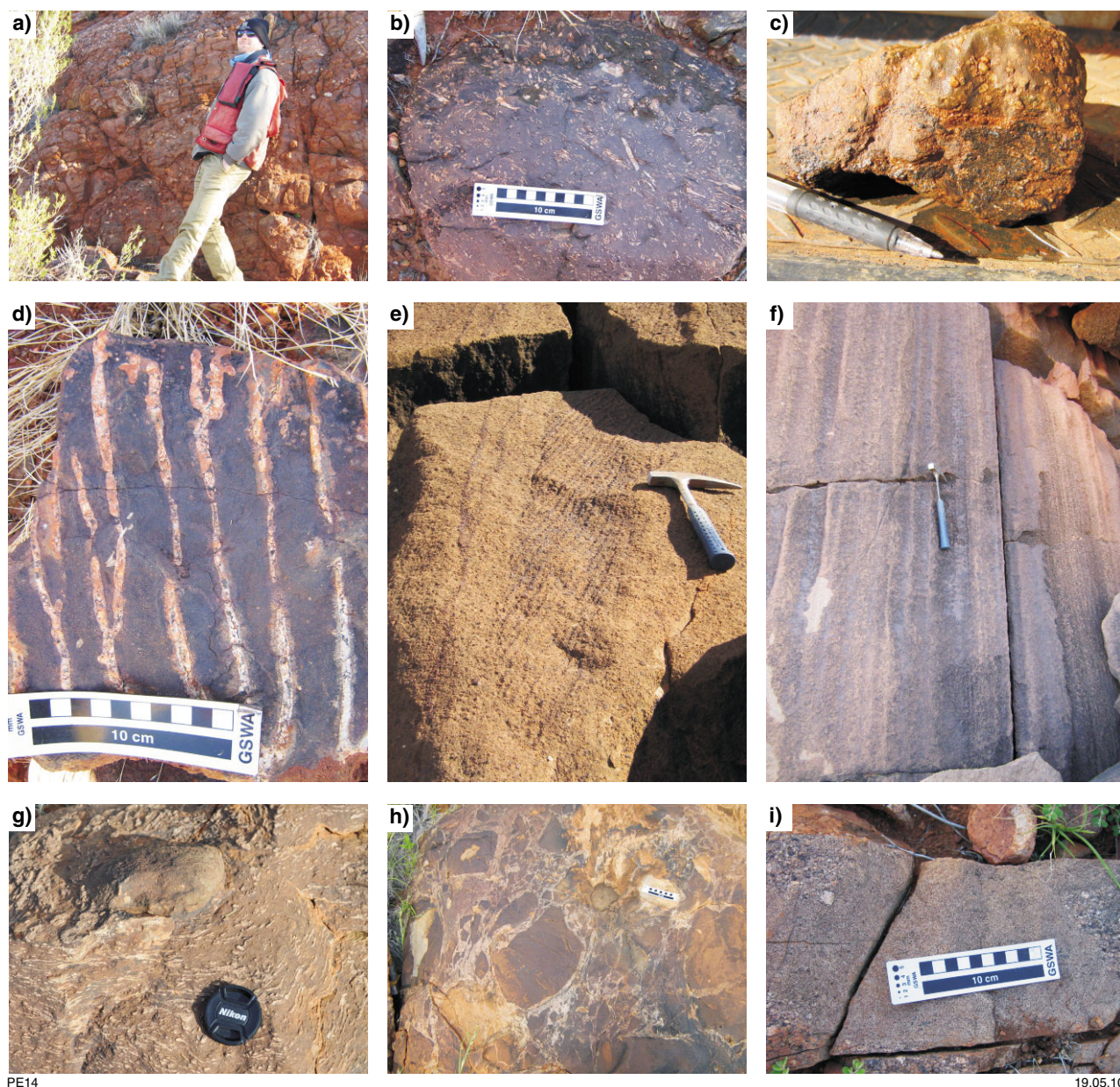


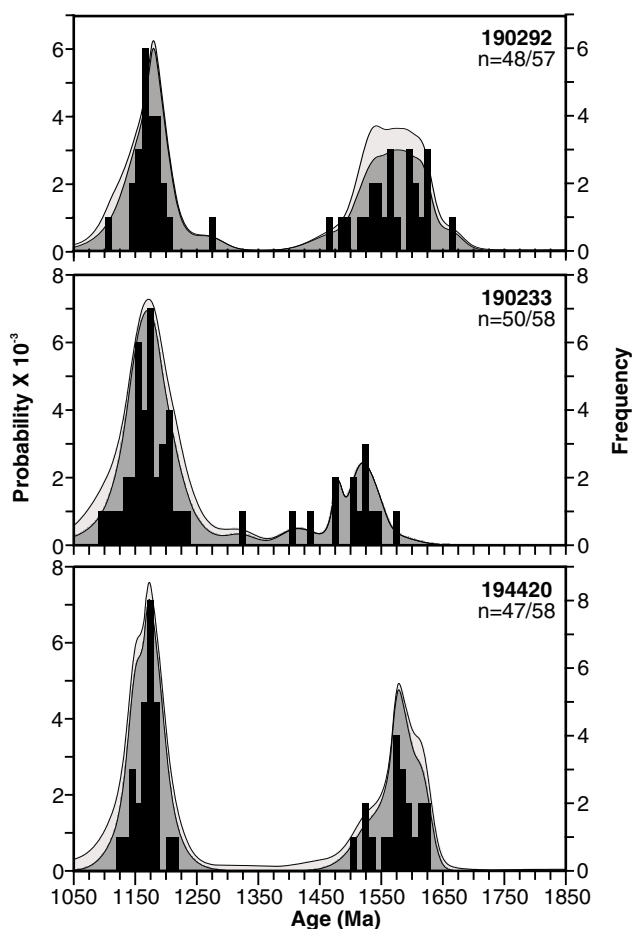
Figure 8. Geological map of the Finlay-Jameson intrusion and surrounds (see Fig. 3 for legend)



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Figure 9. Photographs of rocks from the early stages (pre-g1, g1, and g2) of the Ngaanyatjarra Rift: a) typical example of MacDougall Formation conglomerate; b) xenoliths of mylonitic Wirku Metamorphics in a Mummawarrawarra sill; c) xenolith of epidote facies amygdular Mummawarrawarra Basalt in the basal magnetite-rich, olivine gabbro layer of the Finlay–Jameson Phase 2 layered mafic intrusion; d) pipe vesicles in Mummawarrawarra Basalt; e) a xenolith of centimetre-scale layered olivine gabbro within more uniform olivine gabbro layered at a scale of tens of metres. Both gabbros are part of the Ilurpa layered mafic intrusion and display the internal complexity and multitude of phases seen in each Phase 2 intrusion; f) cumulate layering in the Ilurpa intrusion; g) round, Phase 2 layered gabbro xenolith, in Phase 3 gabbro contaminated with co-magmatic granitic blebs; h) leucogranite mingled with gabbro to form an agmatite; i) mixed porphyritic granite and gabbro form a hybrid magma with remnant K-feldspar phenocrysts near its margins.



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Figure 10. Probability density diagrams and histograms for detrital zircon U–Pb ages from three GSWA samples of the MacDougall Formation. Histograms are divided into 10 m.y. bins, and heights are normalized by frequency for direct cross-comparison between datasets. Only data $\geq 95\%$ concordant are plotted. These data are also represented by the dark grey curves. Light grey curves include all (concordant + discordant) dates. N — number of concordant / total analyses.

the Giles Event. Alternatively, the vein quartz represents hydrothermal activity immediately preceding rifting during the Giles Event.

Mummawarrawarra Basalt

The Mummawarrawarra Basalt only forms significant hills where it is unmetamorphosed, as is the case along the southern limb of the Blackstone syncline at MacDougall Buff and Mummawarrawarra Hill, and south of Mount Blyth. Elsewhere, the basalt forms low hills or rubbly mounds. The largest continuous outcrop of Mummawarrawarra Basalt is a >250 m thick sequence of amygdaloidal basaltic andesite that rests conformably on coarse sandstone of the MacDougall Formation at Mount Blyth. A 50 m wide dyke, oriented perpendicular to the base of the basalt, is composed of fine-grained

plagioclase porphyritic gabbro with abundant xenoliths of the MacDougall Formation. At the base of the basalt is a 30 m thick layer of grey, medium- to coarse-grained, volcanolithic sandstone. A geochronology sample (GSWA 194421) taken 100 m stratigraphically above this layer yielded only detrital zircon inherited from the underlying MacDougall Formation. Numerous 10 to 50 m wide dykes and sills of fine-grained plagioclase-phyric gabbro cut the MacDougall Formation below this contact, including a sill containing abundant xenoliths of mylonitic Wirku Metamorphics (Fig. 9b) that intrudes the basal unconformity of the Kunmarnara Group.

The Mummawarrawarra Basalt comprises a stack of individual 1–5 m thick flow units, which range in composition from basalt to andesite, with most being in the range of basaltic andesite. The layers range from massive and non-amygdaloidal to highly amygdaloidal (Fig. 9c), and from non-porphyritic to plagioclase-porphyritic. Pipe vesicles occur locally (Fig. 9d). In thin section, pristine 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 interstitial glassy groundmass with lobate amygdaloids (now quartz, epidote, and chlorite). More typically the Mummawarrawarra Basalt (P₋KRm-xmb-mo) contains up to 10% euhedral plagioclase phenocrysts and glomerophenocrysts up to 8 mm in size in a subophitic matrix. Macroscopically, this plagioclase-phyric microgabbro is difficult to distinguish from later plagioclase-phyric gabbros (P₋WKg3-odp) that intrude it as dykes and sills. However, in thin section, the latter show a characteristic dual texture, more abundant amphibole (sodic) and magnetite, and a larger variation in grain size. Mafic minerals in the Mummawarrawarra Basalt are variably to completely altered to actinolite or epidote, particularly adjacent to the Giles intrusions. At its highest metamorphic grade, it is slightly migmatized and forms gneiss of alternating layers dominated by fine-grained brown-green amphibole, or by coarser-grained epidote. The Mummawarrawarra Basalt is highly magnetic where it is strongly metamorphosed. More pristine varieties, where epidote alteration predominates, are not magnetic.

Potential correlatives of the Kunmarnara Group

The Tjauwata Group is a sequence of supracrustal rocks straddling the Western Australian and Northern Territory border. These rocks lie beneath the basal sedimentary rocks of the Neoproterozoic to Devonian Amadeus Basin (Maidment et al., 2007). Close et al. (2003a) tentatively correlated the KaruKali Quartzite and Mount Harris Basalt of the Tjauwata Group to the MacDougall Formation and Mummawarrawarra Basalt of the Kunmarnara Group, based on stratigraphic, geochemical, and geochronological similarities. The 1075 ± 2 Ma Puntitjata Rhyolite (Close et al., 2003b) at the top of the Tjauwata Group is younger than the 1084 ± 9 Ma Walu Granite that intrudes the Mount Harris Basalt lower in the sequence (Close et al., 2003b), possibly implying a magmatic and depositional hiatus between the Mount Harris Basalt and Puntitjata Rhyolite in the Tjauwata Group.

Age of the Kunmarnara Group

The maximum age of the Kunmarnara Group is constrained by the youngest detrital age component of c. 1172 Ma, obtained from samples of the MacDougall Formation. A 1078 ± 3 Ma leucogranite that cuts the Bell Rock intrusion (Sun et al., 1996) provides a minimum age, because extensions of this intrusion cut the Mummawarrawarra Basalt. If the Mount Harris Basalt is a correlative of the Mummawarrawarra Basalt, then the intruding 1084 ± 9 Ma Walu Granite (Close et al., 2003b) provides a slightly older minimum age for the Kunmarnara Group. Rocks of the Kunmarnara Group typically preserve a much lower (greenschist facies) metamorphic grade than demonstrably older rocks elsewhere in the west Musgrave Province. The MacDougall Formation everywhere contains a significant detrital component of zircons from the Musgrave Orogeny, and is nowhere cut by granites of the same orogeny. From these observations, we conclude that the Kunmarnara rift sequence was deposited after significant erosion of its basement.

g1 — Layered mafic–ultramafic suite (Phase 2)

Layered mafic–ultramafic intrusions, traditionally known as the Giles intrusions or Giles Complex, form at least 20 sheet-like bodies that extend 550 km along a westerly trend, across the Musgrave Province (Figs 2 and 4). These intrusions form most of the ranges in the eastern half of the west Musgrave Province, and are characterized by parallel ridges that represent layering in the intrusions and correspond to aeromagnetic and gravity highs (Fig. 11). Rocks of the layered mafic–ultramafic suite are the only ubiquitously layered mafic units in the Warakurna Supersuite.

Goode (1970), Daniels (1974), and Glikson et al. (1996) studied the petrography of a number of these layered intrusions, which can be broadly subdivided into ultramafic, gabbroic, or troctolitic. Ultramafic-dominated intrusions, such as Wingelinna Hills, Latitude Hills, Kalka, the Wart, and Pirntirri Mulari, are layered at scales of centimetres to hundreds of metres, and contain olivine-rich orthocumulates with plagioclase as a late poikilitic or intercumulus phase. The gabbroic dominated intrusions, such as Michael Hills, Cavanagh, and Ilurpa, show well-developed centimetre-scale layering, and display numerous way-up indicators including grading and cross-bedding (Fig. 9e). They are composed of olivine–orthopyroxene–clinopyroxene–plagioclase adcumulates. Troctolitic bodies, such as the Bell Rock, Blackstone, and Jameson ranges, are dominated by olivine–plagioclase(–orthopyroxene–magnetite) adcumulates, and layered on the scale of tens to hundreds of metres.

Size of intrusions

Glikson et al. (1996) classified each of the Giles intrusions as distinct sill complexes, with the exception of the Bell Rock and Blackstone ranges, which they implied from stratigraphic correlation to have a thickness

of ~5 km. However, the combined Finlay–Jameson intrusion (Fig. 8) represents a nearly complete, 9 km thick stratigraphic succession through the layered mafic suite, with gabbroic adcumulates at the bottom grading upwards into leucogabbros then troctolites and leucotroctolites. On the regional scale, Glikson et al. (1996) claimed that Giles intrusions become more felsic from north to south, citing the concentration of ultramafic intrusions (Kalka, Wingelinna Hills, and Ewarara) north of the gabbroic Michael Hills intrusion, which, in turn, is north of the troctolitic Bell Rock and Blackstone ranges (Fig. 3). However, these ultramafic intrusions are always tectonically separated from the troctolitic and gabbroic bodies by a major Petermann-age structure. Furthermore, macroscopic folding (described below) complicates their relationship.

All of the intrusions have been tilted or folded by Giles-age and later shear zones about upright axial planes and subhorizontal west- to northwest-trending fold axes (see below). Retrodeformation and unfolding of these intrusions allow the gabbroic and troctolitic Bell Rock, Blackstone, Michael Hills, Cavanagh, and Finlay–Jameson intrusions to be joined to form a single intrusion (Fig. 11). If this is the case, then this intrusion could have originally been greater than 170 km long, 25 km wide, and 10 km thick. Individual ultramafic intrusions reach a maximum thickness of 5 km in the Kalka intrusion (Goode, 1970). Recent gravity surveys in Western Australia suggest that at least some of these intrusions may be linked below the surface.

Depth of emplacement

Observations of spinel and rutile exsolution in pyroxenes, high-Al composite pyroxenes, orthopyroxene–clinopyroxene–spinel coronas over olivines in contact with plagioclase, and early crystallization of orthopyroxene prompted Goode (1970) to propose that the Kalka, Ewarara, and Teizi layered ultramafic intrusions of the central Musgrave Province were emplaced at depths between 35 and 40 km. However, many of these textures were also observed in later, c. 800 Ma, mafic dykes, where they were linked to the c. 550 Ma Petermann Orogeny (Clarke and Powell, 1991; Camacho, 1997; Scrimgeour and Close, 1999). These textures do not occur in the Mount Davies layered mafic intrusion (Goode, 1970), separated from the Kalka intrusion by the Wingelinna Fault, a major Petermann-age structure. Layered ultramafic–mafic intrusions with Petermann-aged high-pressure assemblages are restricted to a corridor of rocks exhumed during the Petermann Orogeny and bounded to the south by the Wingelinna Fault.

Inclusions of the Mummawarrawarra Basalt near the bottom of the Finlay–Jameson intrusion (Fig. 9c) provide the best constraints on the depth at which g1 layered mafic–ultramafic intrusions were emplaced. Mafic minerals in these inclusions are variably to completely altered to actinolite or epidote, making it unlikely that emplacement of the c. 10 km thick, g1 intrusion cited above was at depths considerably greater than c. 15 km. In addition, the low metamorphic grade of wall rocks adjacent to these intrusions suggests they were shielded

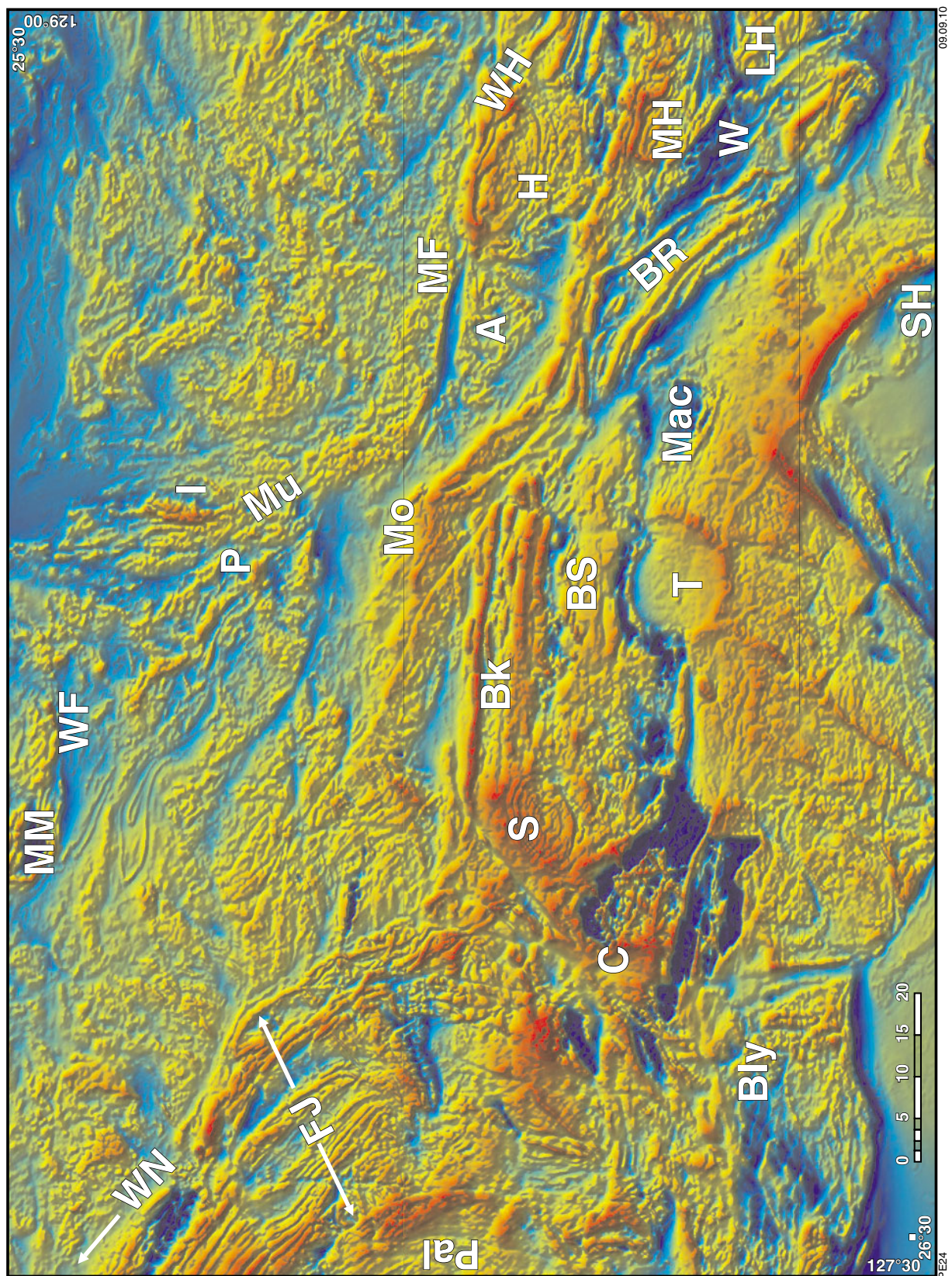


Figure 11. Total magnetic intensity map of the west Musgrave Province (corresponding to the same area presented in Figure 3). Geological features in the text are labelled as follows: WN — Wanarn, MM — Mount Muir, FJ — Finlay-Jameson intrusion, I — Ilurpa intrusion, P — Pirntirri Mulari intrusion, C — Cavanagh intrusion, S — Saturn intrusion, T — Tollu intrusion, Mu — Murray Range, Mo — Morgan Range, Bk — Blackstone intrusion, A — Mount Aloysius, SH — South Hill, WH — Wingelinna Hills, H — Hinckley Range, MH — Michael Hills, BR — Bell Rock intrusion, W — the Wart intrusion, LH — Latitude Hills, Pal — Palgrave Complex, Mac — MacDougall Bluff, Bly — Mount Blyth, MF — Mann Fault, WF — Walu Fault, BS — Blackstone syncline.

from significant thermal effects by a first stage of quenched sills. Subsequent phases of sill injection inflated the intrusions to their current size.

Age

Sun et al. (1996) obtained a U–Pb zircon date of 1078 ± 3 Ma from a granophyric leucogranite thought to form part of the layering in the Bell Rock intrusion. However, this date is identical to the age of locally common felsic dykes (see Phase 3 below) that elsewhere clearly truncate g1 layering. These dykes are co-magmatic with massive g2 gabbros that also engulf the layered intrusions. No granitic or pegmatitic granophyric rocks have been identified within the Bell Rock Range, and even the most evolved rocks from the Bell Rock Range contain zirconium concentrations less than 50 ppm. We conclude that the 1078 ± 3 Ma date represents a minimum age for emplacement of the layered intrusion. The maximum age for emplacement of the g1 layered intrusions is poorly constrained by the age of the Kunmarnara Group.

g2 — Mafic–felsic magmatic shear zone, macroscopic folding, and post-tectonic plutons (Phases 3–4)

Phase 3 — Syntectonic gabbro and granite, and felsic volcanic rocks

There is a clear distinction between the g1 (Phase 2) layered mafic–ultramafic Giles intrusions and the g2 unlayered gabbros that intrude and locally engulf them (Fig. 9g). The latter dominate the Murray and West Hinckley ranges (Evins et al., 2009; Howard et al., 2009b), together forming a near-continuous zone of g2 unlayered gabbro up to 10 km wide along the northern margin of the Tjuni Purlka Tectonic Zone (Figs 3 and 12). This feature is named the Murray Range Shear Zone, which is cut by later (Petermann-age) east-trending faults (Figs 3 and 11). The most notable offsets are 30 km of sinistral displacement along the Mann Fault, and 5 to 10 km of sinistral oblique displacement along the Walu Fault.

Gabbro

The unlayered mafic rocks are fine- to medium-grained, leuco- to mesocratic gabbro and gabbro-norite. They are mainly composed of orthopyroxene, elongate and anhedral augite, and anhedral, interlocking, stubby plagioclase laths. Interstitial opaques have thin biotite rims and generally make up less than 2% of the rock. Trace amounts of opaque oxide minerals are locally present along the pyroxene cleavage planes. Undeformed varieties display a well-developed ophitic to subophitic texture. In finer grained varieties, pyroxenes are typically recrystallized to form a granoblastic fabric, leaving plagioclase laths untouched. This is interpreted to be the result of autometamorphism related to fluids associated with co-magmatic contamination by granitic magmas.

Locally, orthopyroxene (up to 20%), olivine (up to 5%), or plagioclase may form up to 1 cm phenocrysts or oikocrysts. Near the Walu Fault, augite is locally retrogressed to a dark-green to brown-green amphibole along cleavage planes. The gabbros occur as both non-magnetic and magnetic types; the latter is characterized by abundant interstitial magnetite.

Contaminated gabbro

The gabbros are typically contaminated by granitic material at three scales: 1) on a fine scale, as xenolithic granitic blebs, lenses, or curvilinear segregations up to 5 cm in length; 2) on a larger scale, where they are mingled with leucogranite to form agmatites; and 3) on a large scale, where they are mixed with granite to form rare hybrid magmas (Fig. 9g–i). Curvilinear, cusped, and cauliflower boundaries between the mafic and felsic phases indicate that neither phase was solid during emplacement (i.e. the phases were coeval). However, gabbro containing granitic blebs with lobate synmagmatic margins is agmatized by leucogranite that also forms synmagmatic boundaries with the gabbro. Therefore, emplacement of the gabbro was accompanied by continuous granite magmatism over a short time frame. In this scenario, the granite that formed xenolithic blebs was still hot when the gabbro was emplaced, which was also still ductile when more leucogranite intruded.

Granite

The leucogranites that contaminate and cut the gabbros described above are typically hornblende- and biotite-bearing, equigranular to porphyritic, quartz syenites, syenogranites, and lesser monzogranites. They contain local rapakivi feldspar phenocrysts when forming more homogenous sheets greater than 100 m wide. These leucogranites show A-type compositional characteristics (Smithies et al., 2009a) similar in most respects to the early and late Musgravian leucogranites within the Tjuni Purlka Tectonic Zone. They are ferroan and alkali-calcic and fall into the A-type field of Whalen et al. (1987) and Frost et al. (2001), and into the within-plate granite field on the tectonic discrimination diagrams of Pearce et al. (1984). Compared to most of the Pitjantjatjara magmas at similar silica values, these granites are significantly enriched in rare earth elements (REE) and high field strength elements (HFSE).

Deformation

Both the gabbro and granite are commonly strongly deformed. The granite blebs that contaminate the gabbro are excellent markers that may be streaked out to 100:1 axial ratios, defining a moderate to strong foliation or lineation (Fig. 9g). Preserved wispy and cusped margins of elongated blebs indicate that the deformation was synmagmatic. Where the gabbro is strongly deformed but devoid of markers, it has a fine-grained pyroxene–plagioclase matrix that likely recrystallized after earlier deformation. Mylonitic versions of g2 contaminated gabbros typically have suffered partial to complete replacement of pyroxene with a granoblastic network

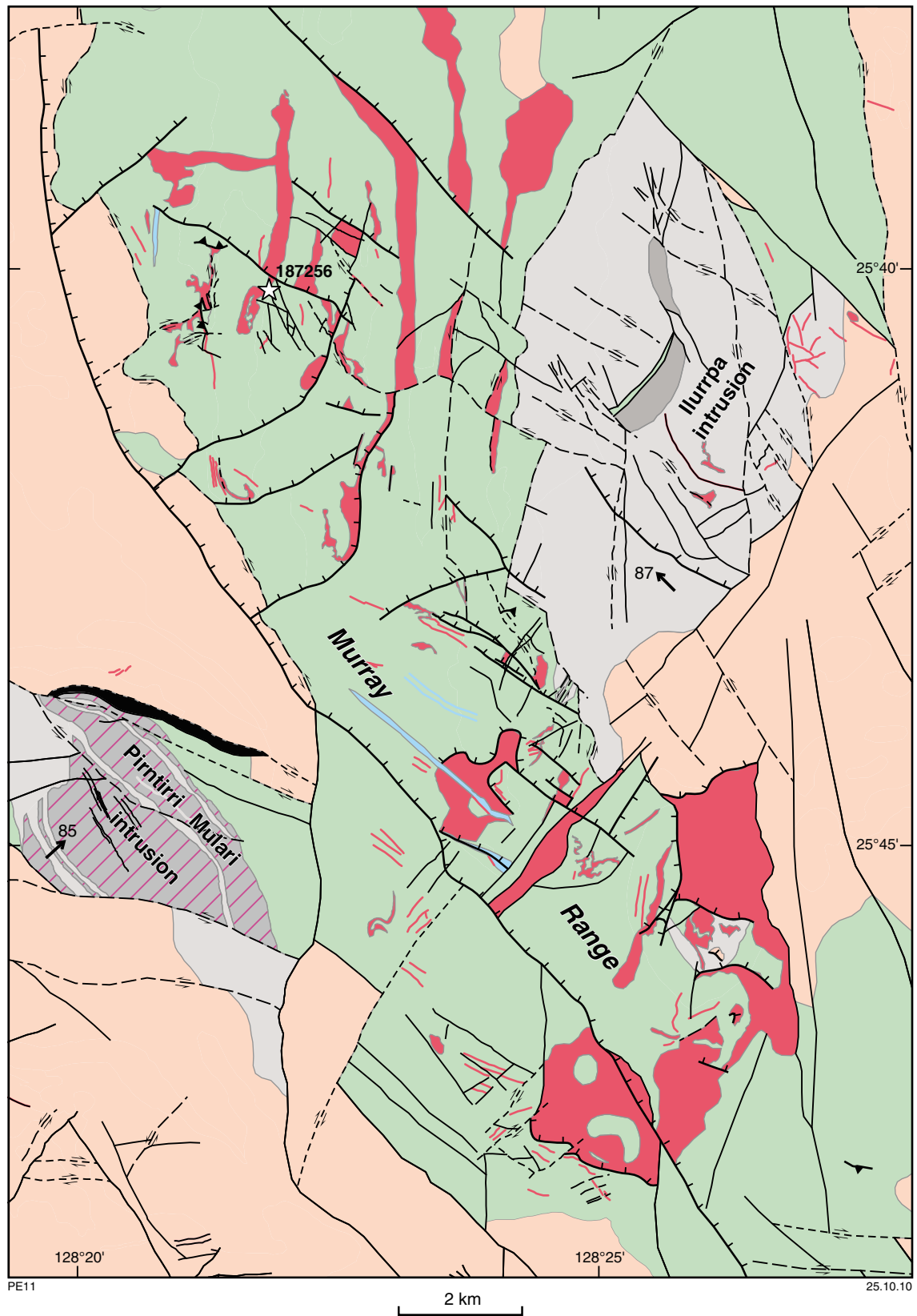


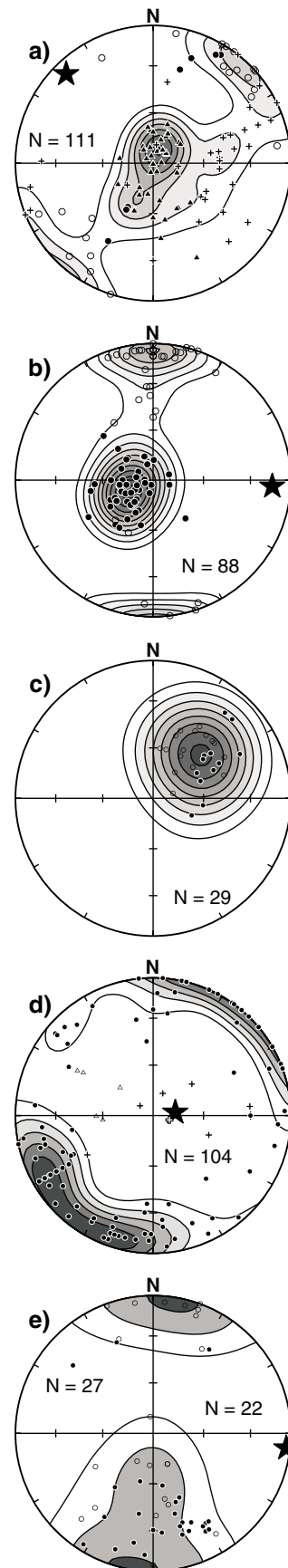
Figure 12. Geological map of the central portion of the Murray Range Shear Zone (see Fig. 3 for legend)

of green amphibole. Locally, amphibole domains and mm-wide recrystallized granite blebs form a mylonitic fabric that wraps around small (up to 2 mm) subhedral plagioclase phenocrysts (5% of the rock). Significant magnetite (up to 10% of the rock) is found along grain boundaries. Although this amphibolite texture is locally preserved, the unit is pervasively altered to a composition dominated by anhedral to euhedral, elongate epidote–subhedral clinozoisite–anhedral plagioclase. K-feldspar and some plagioclase components of the granitic portion of the amphibolite are also replaced by epidote, and quartz is typically recrystallized. The rock is typically cut by abundant mm- to cm-scale quartz and epidote veins; in places it resembles a breccia. This type of epidote alteration is associated with mylonitization or the emplacement of later ophitic gabbros (P₂-Wkg3-odp) that crosscut the g₂ gabbro.

Macroscopic folding

Layering in the Wingelina Hills, Michael Hills, Latitude Hills, and Bell Rock intrusions is folded about a common, shallowly northwest-plunging axis (Fig. 13a; dip direction/dip 316°/11°, 50% girdle, 67% cylindricity). The ultramafic Wingelina Hills intrusion is separated from layered gabbros and anorthosites just south of Wingelina Hills by an east-trending fault (Fig. 14) that traces the fold axis of the Wingelina syncline (116°/04°, 90° interlimb angle). Layering in the gabbroic Michael Hills intrusion to the south is generally shallow and defines a broad (130° interlimb angle), upright syncline (Fig. 14). Gabbroic and ultramafic layers of the Latitude Hills intrusion further south are folded into a syncline–anticline–syncline trio that verges and tightens (interlimb angles change from 100° to 60° to 35°) to the southwest (Fig. 14). The

Figure 13. Lower hemisphere, equal-area projections of igneous layering from Phase 2 and Phase 3 intrusions. All contours are drawn at 3σ intervals: a) igneous layering, plotted as poles, in the Wingelina Hills (filled circles), Michael Hills (triangles), Latitude Hills (crosses), and Bell Rock (open circles) intrusions is folded about a common shallowly northwest-plunging axis (star); b) igneous layering in the Blackstone (open circles) and Cavanagh (filled circles) intrusions is folded about a subhorizontal east-trending axis (star); c) the Finlay (filled circles)–Jameson (open circles) intrusion shows little variation in the orientation of igneous layering; d) tectonic foliations and igneous layering in the Phase 3 Hinckley Range are macroscopically folded about a steep axis (star). Mesoscopic fold axes (crosses) on the Hinckley Range are also generally steep. Macroscopic fold axes on nearby Mount Aloysius (triangles) plunge between Phase 2 macroscopic fold axes and the Hinckley fold axis; e) bedding in the Tollu Group (open circles) is folded into a syncline about a subhorizontal east-trending axis (star) nearly parallel to that of the syncline defined by igneous layering in the Blackstone and Cavanagh intrusions. An axial planar subsolidus foliation (filled circles) is prominent in the core of the syncline.



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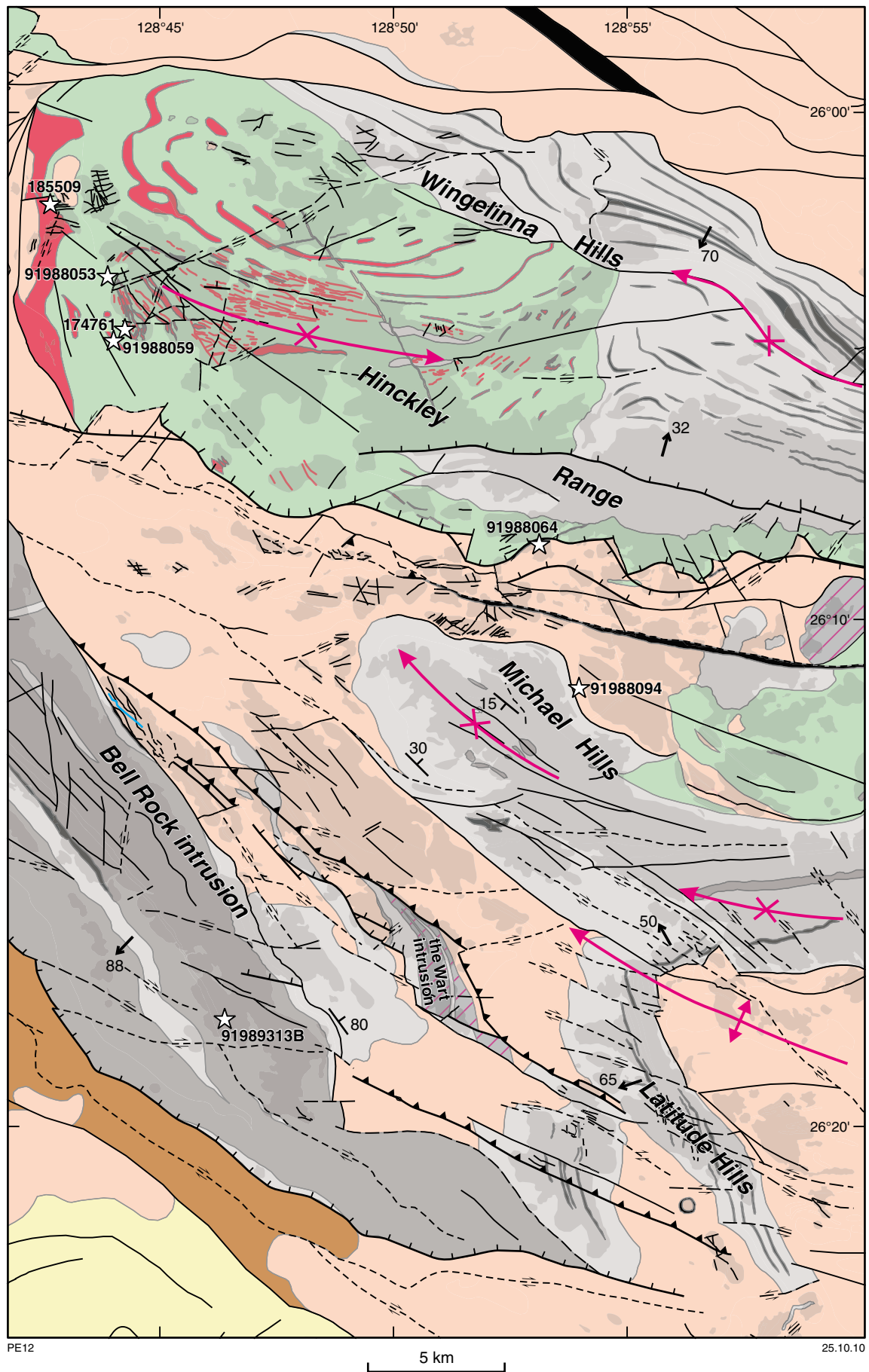


Figure 14. Geological map of the Wingelinna– Michael Hills–Latitude Hills fold train (see Fig. 3 for legend)

troctolitic Bell Rock intrusion represents the subvertical southwesternmost limb (average orientation of Bell Rock layering is $043^{\circ}/88^{\circ}$) of this fold train. The Morgan Range intrusion is also folded into an upright syncline about a northwest-trending axis ($130/35^{\circ}$, 20° interlimb angle). Remnants of a layered intrusion within the Murray Range are folded into a synform about a steep northwest-trending axis ($330^{\circ}/75^{\circ}$).

Layering in the Blackstone intrusion becomes progressively shallower from its eastern edge (dipping 81° to the south) to its western edge (dipping 45° south). The Blackstone Range is the exposed northern limb of an upright west-plunging syncline. Relicts of the shallow northeast-dipping ($034^{\circ}/34^{\circ}$) southern limb are sporadically exposed approximately 20 km to the south. The Cavanagh intrusion is horizontally layered and forms a broad (135° interlimb angle) anticline portion of a syncline–anticline–syncline trio (Fig. 15). A syncline at the southern margin of the Cavanagh intrusion is partially exposed. Together, these intrusions are folded about a common west-plunging subhorizontal fold axis (Fig. 13b; $093^{\circ}/14^{\circ}$, 73% girdle, 90% cylindricity).

Other smaller ultramafic intrusions show consistent, subvertical, northwest-trending layering as in the Wart and Pirntirri Mulari intrusions ($61^{\circ}/85^{\circ}$). Layering in the Finlay–Jameson intrusion dips consistently to the southwest ($225^{\circ}/39^{\circ}$; Fig. 13c). The Ilurpa intrusion is a notable exception in that its subvertical layering trends northeast ($335^{\circ}/87^{\circ}$). This is likely due to the clockwise rotation of the entire intrusion during sinistral shearing in the Murray Range Shear Zone.

The open interlimb angles of these folds, and steepening of layering in intrusions adjacent to regional scale faults, permits the suggestion that they might have been emplaced as synformal or antiformal lopoliths or laccoliths that later sagged or were rotated along these faults. However, the lack of major synmagmatic disruption to internal layering, and the consistency of fold axis orientations within the individual Wingelina Hills–Michael Hills–Latitude Hills–Bell Rock and Blackstone–Cavanagh fold trains, favours an interpretation as macroscopic, tectonic folds. Similarity in character (subhorizontal axes, 90 – 130° interlimb angles, 5–15 km wavelengths) between the two fold trains suggests they are of the same generation, with the fold axes slightly rotated about a subvertical axis.

In the West Hinckley Range, locally mingled and foliated g2 gabbros and larger granite dykes define a steeply plunging synform ($056^{\circ}/81^{\circ}$, 79% girdle, 75% cylindricity) with an east-trending, subvertical axial plane (Fig. 14). Although this axial plane is similarly oriented to macroscopic fold axial planes for the g1 layered mafic–ultramafic suite, the plunge of the axis is much steeper (Fig. 13d). The axis of the macroscopic antiform of Mount Aloysius (Stewart, 1995) plunges at intermediate angles between the shallow macroscopic fold axes in g1 intrusions and the steep West Hinckley Range fold axis. These differences in macroscopic fold plunges are likely due to a combination of: 1) the initial orientation of layering before folding (subhorizontal for the g1 layered mafic–ultramafic suite, and subvertical for g2 Hinckley Range gabbros and granites and previously folded

Mount Aloysius layering); 2) the rheological response of different lithologies (very rigid layered intrusions and rigid basement gneisses, versus soft, syntectonic, mingled gabbros) to the same deformation event; and 3) rotation of fold axes into younger structures, such as the Mann Fault just north of the Hinckley Range and Mount Aloysius. The orientations of the northwesterly to west-northwesterly trending macroscopic folds and sinistral-oblique transpressional Murray Range Shear Zone imply a period of northeast-directed compression and possible basin inversion during Phase 3 of the Ngaanyatjarra Rift (Fig. 16).

The unknown age of the g1 layered mafic–ultramafic suite, coupled with the difference in macroscopic fold plunges between g1 and g2 gabbros, hinders constraints on the age of macroscopic folding. For the g1 layered mafic–ultramafic suite, folding must be younger than the youngest (c. 1170 Ma) wall-rocks to the intrusions, and older than the undeformed Saturn gabbro (1072 ± 8 Ma — Redstone Resources, written comm., 2007) and Tollu granite (1073 ± 6 Ma — GSWA 185583; Kirkland et al., 2009a; Fig. 3) plutons that crosscut the northern and southern limbs of the Blackstone syncline. Macroscopic folding of g2 gabbros and coeval granite dykes is tightly constrained by a 1074 ± 3 Ma (GSWA 174589; Bodorkos and Wingate, 2008) macroscopically folded granite, and a crosscutting 1075 ± 7 Ma (GSWA 174761; Kirkland et al., 2008a) granite dyke that is axial planar to the macroscopic folding.

The Smoke Hill Volcanics are folded about the same c. 1075 Ma axis as the Blackstone syncline (compare Fig. 13b and 13e). They contain an axially planar subsolidus fabric implying deformation occurred after their deposition along similar strain axes to the 1075 Ma Blackstone syncline. However, the age of the Smoke Hill Volcanics (1026 ± 26 Ma — GSWA 187177; Kirkland written comm., 2010) is younger than the folding responsible for the Blackstone syncline (Fig. 3). Several east-trending sinistral faults are parallel to the axial plane of the Smoke Hill Volcanics syncline. It is possible that the faults formed during Petermann-age deformation partitioning into the Tollu Group, as it was wedged between rigid limbs of the Cavanagh and Blackstone intrusions.

Murray Range Shear Zone

Phase 3 (g2) gabbros of the Murray Range were emplaced into a 5 to 10 km wide, north-northwesterly trending, subvertical shear zone herein called the Murray Range Shear Zone (Figs 3 and 16). This crustal-scale shear zone marks the northeastern boundary of the Tjuni Purlka Tectonic Zone and is a reactivation of an earlier (c. 1200 Ma), shallower, west-dipping normal fault. The Murray Range Shear Zone is bounded by semi-continuous, north- to north-northwesterly trending sinistral-normal shear zones. Between these shear zones, massive, undeformed, uncontaminated g2 gabbros form lenses up to 2600 m long and 700 m wide, wrapped by more strongly deformed and contaminated varieties of g2 gabbro. These lenses represent low-strain blocks wrapped both by a network of steep faults that parallel the Murray Range Shear Zone boundaries, and by moderate to shallow

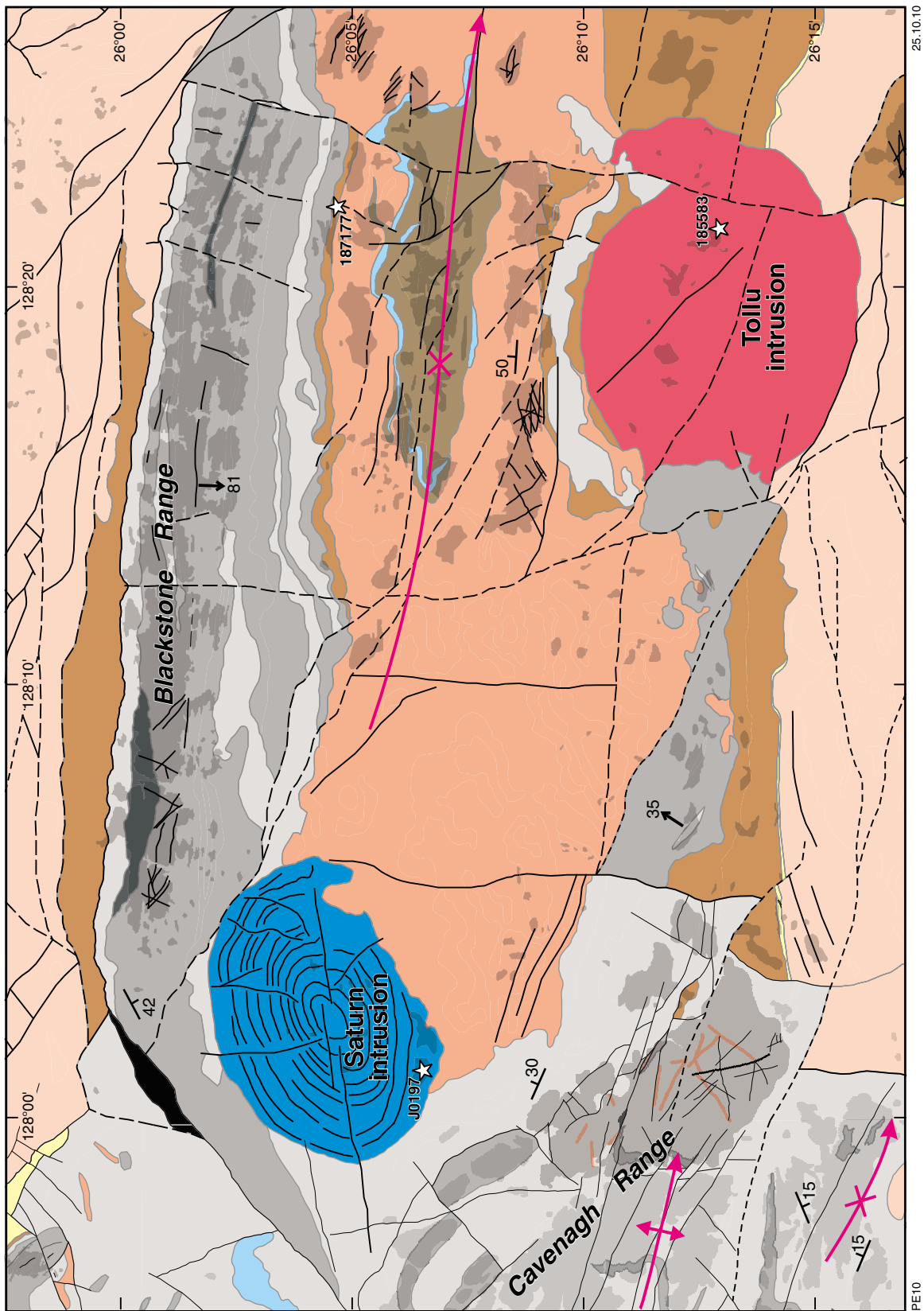


Figure 15. Geological map of the Blackstone syncline and western surrounds (see Fig. 3 for legend)

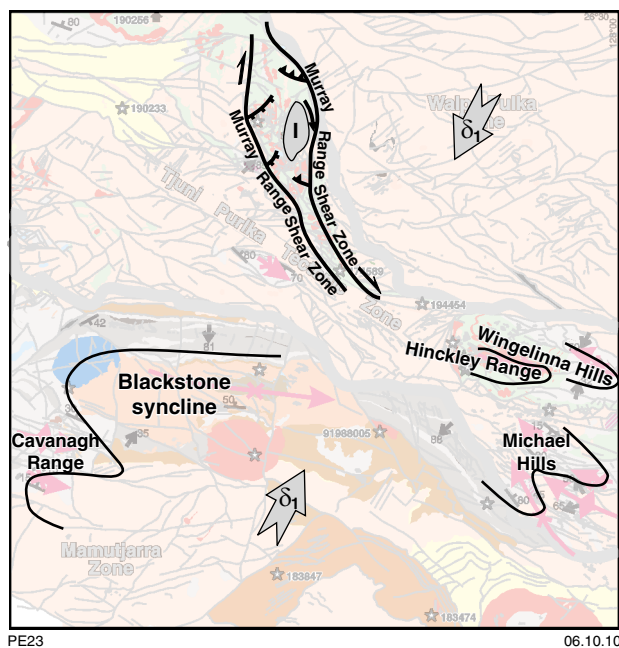


Figure 16. Kinematics of Phase 3 structures. Northeast–southwest compression folded g1 intrusions into the Blackstone syncline–Cavanagh Range fold train and Wingelina–Michael Hills–Latitude Hills fold train. The same kinematic setting formed the dextral Murray Range Shear Zone. The Illurpa intrusion (I) was rotated clockwise within the Murray Range Shear Zone.

south-dipping dip-slip faults (Fig. 12). Synkinematic, mylonitic granites are found along the majority of these faults. Locally, this fault system accommodated g2 gabbro and granitic magmatism in an extensional jog that makes up the majority of the centre of the Murray Range Shear Zone. However, on the regional scale, the kinematics of the Murray Range Shear Zone indicate dextral transpression (Fig. 16) based on the kinematics of its bounding faults, its orientation to regional, coeval macroscopic folding, and the clockwise rotation of the Illurpa intrusion.

Age of deformation and Phase 3 magmatism

The granites associated with contaminated g2 gabbros have been dated at seven localities (Table 2). Glikson et al. (1996) reported a 1073 ± 5 Ma recrystallized gabbro from the western Hinckley Range, a 1078 ± 5 Ma rhyolite thought to be part of the Smoke Hill Volcanics just west of Bell Rock, and a 1078 ± 3 Ma leucogranite thought to be part of the g1 Bell Rock layered mafic intrusion. On revisiting the latter two localities, the present authors concluded that both are g2 granites associated with northwest-trending shear zones. Camacho (1997) obtained a date of 1075 ± 14 Ma for assimilated granite from a gabbro at the margin of the g1 Ewarara layered mafic intrusion.

Five Phase 3 felsic rocks have been dated by the Geological Survey of Western Australia (Table 2). At Amy Giles Hill, a 1074 ± 3 Ma granite dyke (GSWA 174589; Bodorkos and Wingate, 2008) is macroscopically folded

and cut by a 1075 ± 7 Ma granite dyke (GSWA 174761; Kirkland et al., 2008a) that is axial planar to that fold. Further west, a synmylonitic leucogranite dated at 1075 ± 3 Ma (GSWA 185509; Kirkland et al., 2008b) occupies boudin necks in a northwest-trending mylonite. A rhyolite located on the southern edge of the GUNBARREL map sheet was dated at 1074 ± 4 Ma (GSWA 190256; Fig. 3), and may represent an extension of the Puntitjata Rhyolite from the Bloods Range into the west Musgrave Province. The Puntitjata Rhyolite, and its intrusive equivalent, the Rowley Granophyre, are located in the Bloods Range over 100 km east of sample 190256; both have been dated at 1075 ± 2 Ma (Close et al., 2003b). The Skirmish Hill Volcanics is a felsic-dominated bimodal volcanic sequence in the far south of the west Musgrave Province. Granophyre from this sequence has been dated at 1078 ± 4 Ma (GSWA 183847; Kirkland written comm., 2010; Fig. 3). The Skirmish Hill Volcanics are not strongly deformed and may be the surface expression of the granite magmatism described above.

The ages above define a very narrow time interval of concomitant intrusion of massive gabbro, multiphase leucogranite intrusion, felsic volcanism, macroscopic folding, and crustal-scale shearing. Based on the orientations of macroscopic folds and kinematics in the Murray Range Shear Zone, this magmatism and deformation occurred during regional northeast–southwest compression, which may have been responsible for the uplift and erosion of the Kunmarnara Group rocks that originally covered the g1 intrusions. No evidence for deformation and metamorphism related to the Giles Event has been found in the Musgrave Province further east (Edgoose et al., 2004), or in the Capricorn Orogen (Wingate et al., 2004).

Phase 4 — Plutons that post-date macroscopic folding

Two leucogranite plutons crosscut the above-mentioned macroscopic folds south of the Tjuni Purlka Tectonic Zone (Fig. 3). They are the 1073 ± 6 Ma Tollu pluton (GSWA 185583; Kirkland et al., 2009a; Fig. 3) and the 1072 ± 8 Ma South Hill pluton (GSWA 183474; Kirkland et al., 2008c). The Tollu pluton is a ~12 km wide, circular body that cuts the contact between basement gneisses and g1 gabbros along the southern limb of the Blackstone syncline. This intrusion is predominantly massive, medium- to coarse-grained, biotite syenogranite, typically with abundant K-feldspar phenocrysts up to 3 cm. The South Hill pluton outcrops as a ~4 km long body of massive, medium- to coarse-grained, hornblende–biotite granite. These two intrusions represent the emplacement of felsic magmas just after deformation. The overlap of their ages with c. 1075 Ma Phase 3 syntectonic magmatism imposes tight constraints on the deformation they crosscut. The duration of Phase 3 deformation must have been on the order of a million years or less.

Two granites yielded crystallization ages of c. 1070 Ma (Table 2). The 1071 ± 5 Ma Angatja intrusion (Scrimgeour et al., 1999) and 1068 ± 13 Ma Michell Nob intrusion (Camacho, 1997) are found in the eastern Mann Ranges and Mulga Park area, respectively. They are mesocratic,

K-feldspar porphyritic to rapakivi-textured, hornblende–orthopyroxene–biotite–garnet-bearing granites that were strongly deformed during the Petermann Orogeny.

g3 — Phase 5 mafic intrusions (Alcurra Suite), felsic dykes, and mineralization

The Alcurra Suite is an evolved, Fe-rich, and incompatible trace element rich suite of tholeiitic dolerite, gabbro, olivine gabbro, ferromylonite, and ferrodiorite dykes and sills. They occur in a variety of textures and settings, ranging from thin, fine-grained, actinolitized–epidotized gabbroic dykes that crosscut and amphibolitize g2 gabbros, to coarser-grained mafic dykes, to thicker granophyric dykes. In general, these crosscutting intrusions increase in abundance westwards. The geochemistry and age of the Alcurra Suite are discussed by Howard et al. (2009c).

The fine-grained variety of gabbro occurs as east- and north-trending dykes that cut the Murray Range, and northeast- and northwest-trending dyke sets that cut the Cavanagh Range and dissect some areas of the Finlay–Jameson intrusion as dykes and sills. The dykes are commonly up to 1 m wide and rarely more than 10 m wide, and are closely spaced. They are typically recrystallized, with pyroxenes invariably altered to actinolite and epidote. Their gabbroic wall-rocks are

typically amphibolitized and intruded by epidote and quartz veins (Fig. 17a). These fine-grained dykes resemble coarser-grained plagioclase-phyric basalts from central parts of the Mummawarrawarra Basalt, especially where the basalt occurs as large inclusions within the base of the g1 intrusions.

Coarse-grained mafic dykes have a distinctive dual texture of subhedral to euhedral plagioclase laths in a finer-grained plagioclase-phyric groundmass (Fig. 17b). Original pyroxene is typically altered to sodic amphibole. Two examples of these coarse-grained mafic dykes are associated with a copper-mineralized gabbro (GSWA 194354; Kirkland et al., 2009c) that cuts the Jameson Range, and a gabbro from the orthomagmatic Nebo–Babel deposit. These two dykes directly date this phase of magmatism and mineralization at 1067 ± 8 and 1068 ± 4 Ma, respectively (Howard et al., 2009c; Seat, 2008). These mafic rocks form a network of northeast-trending dykes and northwest-trending sills that intruded the northwestern portion of the Finlay–Jameson intrusion (Fig. 8) and the western portion of the Cavanagh Range. The conduits formed by the intersection of dykes and sills with west- to northwest-trending lithological boundaries are potential sites for magma mixing, and may be realistic targets for orthomagmatic mineralization. The orientation of this dyke and sill network implies that the northeast–southwest compression characteristic of Phase 3 of the Ngaanyatjarra Rift was locally active until c. 1068 Ma. By this time, the western part of the

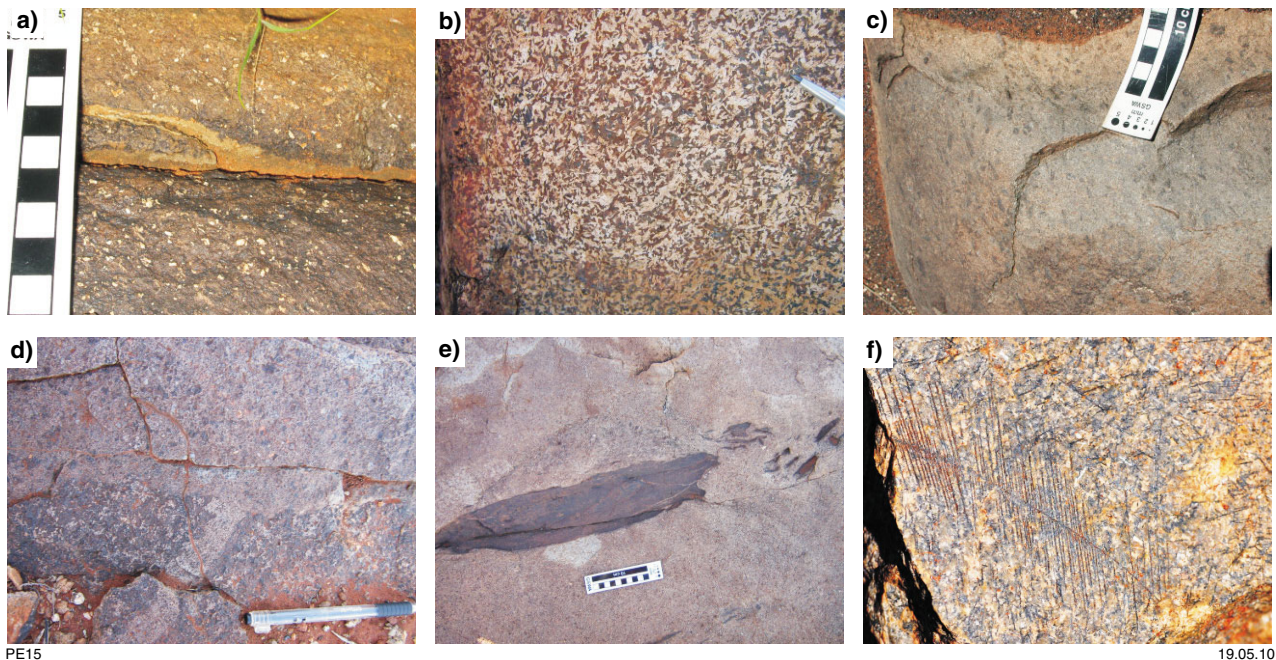


Figure 17. Field photographs of Phase 5 (g3) mafic intrusions: a) typical appearance of fine-grained gabbro dykes with white-weathering plagioclase phenocrysts; b) another type of gabbro with a distinctive dual texture of subhedral to euhedral plagioclase laths in a finer-grained plagioclase-phyric groundmass; c) fine-grained, leucocratic olivine gabbro with dark weathering plagioclase phenocrysts. This lithology cuts the southern margin of the Finlay–Jameson intrusion; d) undeformed granitic dyke (top) crosscutting a Phase 3 gabbro (note the characteristic granite blebs) and a granite dyke of intermediate age between Phase 3 and Phase 5; e) a Phase 5 gabbro enclave in fine-grained Phase 5 granite. Cuspate margins suggest the felsic magmas were extremely hot when emplaced; f) Tollu Group trachydacite with amphibole-rimmed clinopyroxene defining a comb-spinifex texture indicative of supercooling.

Ngaanyatjarra Rift was cool enough (possibly due to uplift from earlier Phase 3 basin inversion) for the emplacement of dyke networks characteristic of a brittle crustal regime.

The 1072 ± 8 Ma Saturn gabbro (Redstone Resources, written comm., 2007) is an 11 km long elliptical body that crosscuts the western side of the g1 Blackstone intrusion (Fig. 3). It comprises at least eight concentric rings of massive to weakly flow banded olivine gabbro, typically containing oikocrysts of biotite and magnetite (Smithies et al., 2009b). Geochemically, it resembles dykes of the Alcurra Suite (Howard et al., 2009c).

Two other groups of mafic intrusions are also tentatively linked to this phase of magmatism. A fine- to medium-grained, granophyric-textured, mesocratic ferrodiorite to ferrodiorite occurs as intrusions up to 60 m thick in the Blackstone syncline. Another leucocratic to mesocratic, plagioclase-glomeroporphyritic, olivine microgabbro cuts east-northeast across the southern margin of the Finlay–Jameson intrusion (Fig. 18c).

A clinopyroxene–biotite, rapakivi-textured, porphyritic granite dyke, along the southern margin of the Hinckley Range was dated at 1068 ± 6 Ma (Sun et al., 1996). This granite is compositionally and texturally similar to the Phase 3 granites described earlier, and cannot be distinguished from them either in the field or geochemically. However, because of its age similarity to the Alcurra Suite, this rapakivi granite dyke is assigned to a separate phase of magmatism that immediately postdates

the Phase 4 plutons. The age of the rapakivi granite dyke overlaps those of Phase 4 intrusions. Therefore, the dyke and Phase 4 intrusions may together represent a single protracted phase of c. 1075–1068 Ma granitic magmatism in the eastern part of the Ngaanyatjarra Rift.

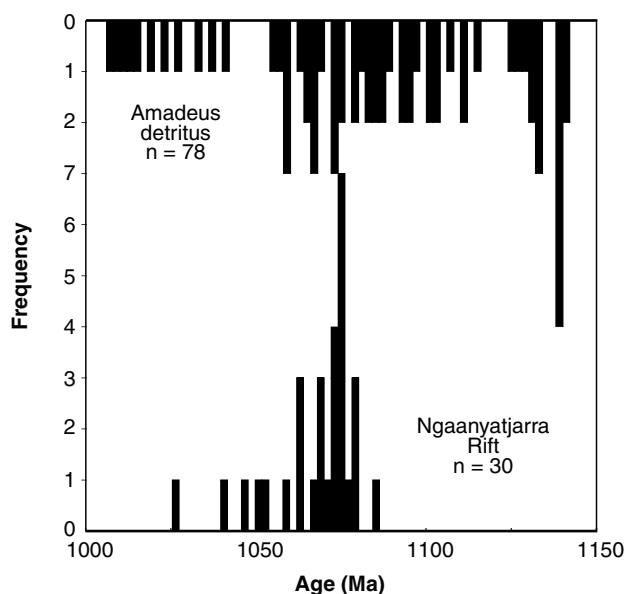
Phase 6 — Mingled gabbro and granite, felsic dykes, and felsic volcanic rocks

At the northern end of the Murray Range, a 1062 ± 10 Ma (GSWA 187256; Kirkland et al., 2009b; Fig. 3) non-deformed granitic dyke crosscuts contaminated g2 gabbros, mylonitic Phase 3 granites, and Phase 5 granites (Fig. 17d). The dyke belongs to a group of granites intruded throughout the Murray Range as 1 to 700 m wide, north-trending dykes, with greater volumes exposed in the northwestern Tjuni Purlka Tectonic Zone where they form kilometre-wide intrusions. The rocks are fine to medium grained, grey, leucocratic, equigranular to K-feldspar porphyritic syenogranites with minor amphibole, clinopyroxene, and orthopyroxene. The porphyritic variety is medium grained, and contains abundant K-feldspar phenocrysts about 1 cm across with recrystallized margins. The equigranular variety is fine grained, with clots of acicular amphibole up to 1 cm in diameter, a texture that implies a shallow level of emplacement. Both varieties contain enclaves of g2 gabbros with cusped margins, indicating either that the felsic magmas were extremely hot when emplaced, or that mafic and felsic magmatism were coeval (Fig. 17e). The latter interpretation is supported by the 1063 ± 6 Ma age of a non-deformed, medium-grained gabbro (GSWA 194454; Kirkland written comm., 2010; Fig. 3), contaminated by wisps of granite, that was sampled from a low-strain lens along the Mann Fault. The significantly younger age of this contaminated and mingled rock implies that mingling of granite and gabbro in the fashion of Phase 3 magmatism has occurred more than once. However, in this case, synmagmatic deformation is not apparent.

A rhyolite clast from the Mount Currie Conglomerate yielded a date of 1062 ± 6 Ma (Young et al., 2002). Northeast of Michael Hills, a leucogabbro dyke yielded a similar date of 1058 ± 14 Ma (Sun et al., 1996). These results are interpreted as Phase 6 magmatic ages, which are roughly 10 Ma younger than those of Phase 4 intrusions. Although within error of individual Phase 5 granite ages, they are tentatively interpreted as a separate magmatic event.

Phase 7 — Granite and felsic volcanic rocks

Granites were emplaced in the central portions of the Musgrave Province 10 million years after Phase 6 magmatism. Five age determinations (Table 2) for this magmatic phase yield a weighted mean of 1048 ± 6 Ma. Samples of mylonitic and non-deformed porphyritic granite from the Davenport Shear Zone yield similar ages of 1047 ± 12 Ma and 1050 ± 18 Ma (Camacho, 1997).



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Figure 18. Top — histogram of all Giles-age (1000–1150 Ma) concordant detrital zircon ages from the Amadeus Basin; data from Maidment et al. (2007), and Camacho (written comm., 2008). All detrital zircon ages are U–Pb SHRIMP analyses. Bottom — age histogram for all known Giles magmatic ages presented in Table 1.

Farther west, a porphyritic hornblende–biotite granite dyke was dated by Sun et al. (1996) at 1052 ± 11 Ma. The 1044 ± 10 Ma (Camacho, written comm., 2008) Nulchara Charnockite crosscuts the Michael Nob Granite in the Mulga Park area.

This episode of granite magmatism was accompanied by volcanism (Wankari Volcanics) farther west in the Bloods Range. The Wankari Volcanics are isolated from the remainder of the Tjauwata Group stratigraphy by the Wankari Detachment Zone within the Petermann Nappe Complex, approximately 100 km north-northeast of the Hinckley Range. The Wankari Volcanics are locally amygdaloidal, fine-grained, porphyritic felsic volcanic rocks with minor interlayered mafic units. Pb–Pb dating by Kober (1987) of a single zircon from a felsic unit yielded a date of 1041 ± 2 Ma (Scrimgeour et al., 1999). Several zircons analysed by SHRIMP in the same study yielded a date of 1051 ± 22 Ma.

Phase 8 — Tollu Group

Smoke Hill Volcanics

The Tollu Group, as redefined in this Record, consists of the Smoke Hill Volcanics overlain by the Hogarth Formation. The Smoke Hill Volcanics are mainly exposed in an east-trending, 55 km long, 15 km wide zone along the centre of the Blackstone syncline (Fig. 15; Smithies et al., 2009b), with rare occurrences west of the Cavanagh Range (Evins et al., 2009). They appear to directly overlie the Blackstone intrusion, although the contact is not exposed. Depositional layering in the volcanic rocks parallels igneous layering in the Blackstone intrusion, and there is no evidence for a faulted contact between the intrusion and the volcanic rocks. However, there is sound structural and geochronological evidence (see above) that the Blackstone intrusion was at least broadly folded before deposition of the Smoke Hill Volcanics. Furthermore, at one locality a trachyte of the Smoke Hill Volcanics crosscuts an Alcurra dyke.

With an estimated thickness of 2 km, porphyritic aphanitic rhyolite and dacite is the most widespread unit in the Smoke Hill Volcanics. An acicular trachytic, and lesser dacitic and rhyolitic, sequence locally forms the base of the Tollu Group, and is the second most voluminous unit. Together, both units form subvolcanic sills and cryptodomes, or lavas with local layers or lenses of volcanoclastic breccias, conglomerates, sandstones, and tuffaceous siltstones. Spherulites, quartz-filled amygdaloids, perlitic textures, and hyaloclastite are locally abundant. Rheomorphic flow-textures are common.

Hogarth Formation

The Smoke Hill Volcanics are conformably overlain by the Hogarth Formation. The Hogarth Formation comprises andesitic to trachytic lavas with rare basalt, trachyandesite, dacite, and fine- to coarse-grained volcanoclastic rocks (Smithies et al., 2009b). Lavas are typically variolitic and amygdaloidal. They show acicular comb- or feather-textures defined by randomly oriented, interlocking

needles of green–blue amphibole (partly skeletal) in an aphanitic groundmass (Fig. 17f). The needles are typically <1 cm in length, but are locally up to 10 cm long.

Age

Vitric dacite of the Smoke Hill Volcanics, sampled between Smoke Hill and the Blackstone Range, yielded a date of 1026 ± 26 Ma (GSWA 187177; Kirkland written comm., 2010; Fig. 3). Even taking into account uncertainties, the time gap between deposition of the Kunmarnara Group (>1078 Ma) and the Tollu Group is at least 30 m.y. and possibly more than 100 m.y. During that time, the Kunmarnara Group was deformed, the g1 layered mafic–ultramafic suite was emplaced, major synmagmatic shear zones were activated, the whole package was folded, intruded by multiple generations of felsic and mafic magmas, then uplifted and eroded, before the Tollu Group was finally deposited. Interestingly, the depositional gap observed in the west Musgrave Province spans a similar time interval as the 24 m.y. gap between deposition of the Puntitjara Rhyolite (an age equivalent of the Skirmish Hill Volcanics rather than of the Smoke Hill Volcanics) and the Wankari Volcanics in the Tjauwata Group farther east (Close et al., 2003b).

Missing phases

We have compared the spectrum of ages reported in this study with all published detrital ages from Neoproterozoic sediments in the Centralian Superbasin that overlie the Musgrave Province (Fig. 18), to determine if any of the magmatic phases of the Giles Event are potentially missing from, or underrepresented in, the current exposures of the Musgrave Province. The ages of sediments belonging to the Dean Quartzite, Pinyanna Beds, Tjuninanta Beds, Winnall Beds, Ayers Rock, the Olgas, and the Lower and Upper Inindia Beds in the southern Amadeus Basin are based on work by Camacho (Camacho et al., 2002; Camacho, written comm., 2008). Maidment et al. (2007) dated more distal sediments of the Heavitree, Arumbera, Cyclops, and Goyder Formations in the northeastern Amadeus Basin, approximately 300 to 400 km northeast of the Hinckley Range. The basal unit of the Officer Basin on the southern side of the Musgrave Province has also recently been dated by GSWA (sample 189557; Kirkland written comm., 2010). Both the Amadeus and Officer Basins are part of the larger Centralian Superbasin. Stratigraphic layers younger than 500 Ma were excluded due to possible influx of ‘Pacific Gondwana’ zircon grains (Maidment et al., 2007). Detrital zircons older than c. 1140 Ma Umutju Granite (Scrimgeour et al., 1999) were not considered as they belong to the Pitjantjatjara Supersuite, which formed the basement to the Giles Event.

Sediments proximal and distal to the main Giles outcrops of the Musgraves have similar detrital zircon components, with a main peak at c. 1075 Ma and significant shoulders between 1050 and 1100 Ma (Fig. 18). The majority of igneous crystallization ages presented in this study fall within that range, and the age of 1075 Ma corresponds with the volumetric peak of felsic magmatism recorded in

this study. The presence of these ages in the sedimentary rocks of the Amadeus Basin implies that volcanic rocks or granites from Phase 3 to Phase 5 magmatism were well represented in those rocks previously overlying the present surface. There is another large peak in the Amadeus Basin detrital age data at c. 1120 Ma. The basal unit of the Officer Basin on the southern side of the Musgrave Province also contains a large detrital zircon component at c. 1134 Ma with no younger ages represented. Detrital zircons younger than 1050 Ma are sparse in all of the sediments, and make up approximately only 3% of all detrital ages within the 1000–1140 Ma range that represents potential Giles magmatism. This implies that the present exposures of the Wankari Volcanics and Tollu Group essentially represent their maximum depositional extent.

The above detrital ages, from Neoproterozoic sediments in the basins surrounding the Musgrave Province, are similar to the youngest age from the Umutju Granite (Scrimgeour et al., 1999), assigned to the latest stage of the Musgrave Orogeny, which formed the basement to the Giles Event. Metamorphism at this time is also recorded by zircon rim growth at 1127 ± 9 and 1119 ± 7 Ma from two samples of the Wirku Metamorphics in the Cohn Hill region (GSA samples 194379 and 194422, respectively; Kirkland et al., 2010; Kirkland written comm., 2010). The Centralian Superbasin detrital peak at c. 1120 Ma and g1 magmatism at c. 1075 Ma potentially constrain the deposition of the Kunmarnara Group and emplacement of g1 layered mafic–ultramafic intrusions to between c. 1135 and c. 1075 Ma.

Discussion

Although the individual ages of intrusions within Phases 3 to 7 of the Ngaanyatjarra Rift span, or overlap within, the period from 1078 to 1047 Ma, it is unlikely magmatism was continuous. The crosscutting magmatic relationships, intermittent periods of deformation, and chemical differences between some phases, detailed above, point to episodic pulses of magmatism. By taking the weighted averages of the individual ages, the age brackets can be tightened for each magmatic phase. This results in dates of 1068 ± 3 , 1062 ± 4 , and 1048 ± 6 Ma for Phases 5 through 7, respectively. Age overlap between Phase 3 (1075 ± 1 Ma) and Phase 4 (1073 ± 2 Ma) cannot presently be resolved with SHRIMP U–Pb geochronology. However, there are clear crosscutting relationships (Fig. 9g), and a significant tectonic episode of macroscopic folding and transpressional shear zone formation, between the two phases.

The Ngaanyatjarra Rift

Summary

An intracontinental setting is indicated for basement rocks to the Giles Event for at least 150 m.y. prior to this event, a setting in which the rocks have remained to the present (Smithies et al., 2009a). The sequence of events detailed above, summarized below, 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, which are folded into a 5–10 km wide syncline on the eastern side of the basin. 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. 3). 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 greater than 100 km (Fig. 3). The southern basin margin follows the southern limb of the regional Blackstone synform and continues southwest to Mount Blyth, where its basal contact is non-deformed and well exposed.

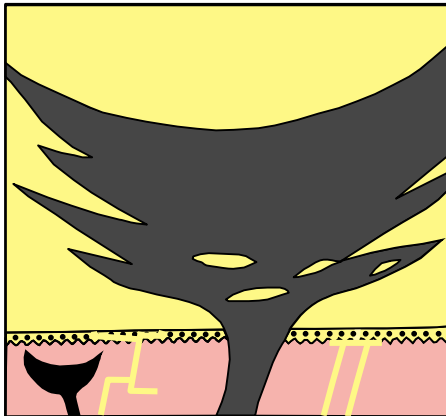
Giant g1 layered mafic–ultramafic sills (Phase 2) were then emplaced into the Mummawarrawarra Basalt. Emplacement of these sills represents an addition of c. 10 km of dense material to the upper crust (Fig. 19a). Because of the lack of high-pressure and high-temperature assemblages at the bottom of these sills, their emplacement was likely accommodated by inflation and roof uplift. These events occurred sometime between 1120 and 1075 Ma. They cannot have formed precisely at 1075 Ma (maximum age of g2 (Phase 3)), as previously thought, because mutual contacts everywhere show g2 to have intruded fully crystallized g1 rocks (Smithies et al., 2009a), although they may not be *significantly* older than g2. Therefore, it is unclear if the layered intrusions of the Giles Event are related to 1075 Ma magmatism associated with the Warakurna LIP outside of the Musgrave Province. Instead, at 1075 Ma the west Musgrave Province may have been characterized by mafic–felsic g2 magmatism focused along coeval, linear, shear zones (parallel to the Tjuni Purlka Tectonic Zone and the northern rift boundary). This g2 magmatism was concomitant with macroscopic, upright folding in a transpressional setting — events indicative of basin inversion (Fig. 16).

Deformation ceased abruptly after g2 magmatism, and was followed by the emplacement of several post-deformation Phase 4 plutons (Fig. 19b). Magmatic activity in the rift was sporadic thereafter, with four pulses (Phases 5–8) of dominantly felsic magmatism alternating with c. 10 Ma quiescent periods until c. 1040 Ma (Fig. 19c). At some point before 1040 Ma, the g1 layered mafic–ultramafic intrusions were unroofed. Major felsic magmatism began anew at c. 1030 Ma with deposition of the Tollu Group over the partially eroded Blackstone, Bell Rock, and Jameson intrusions (Fig. 19d). This likely represents the last major phase of magmatism associated with the Ngaanyatjarra Rift.

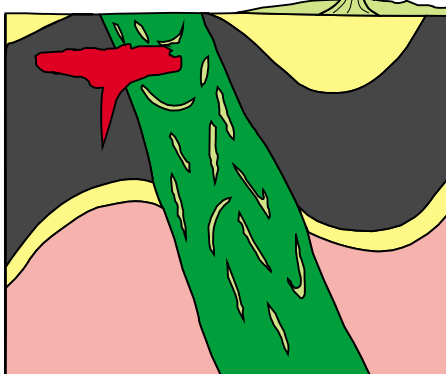
Analogues

The Ngaanyatjarra Rift is similar in many respects to the Mid-Continental Rift in North America. Both rifts were far from continental margins during their lifetime and failed to open into an ocean. Both have an episodic and complicated magmatic history that begins with basalt

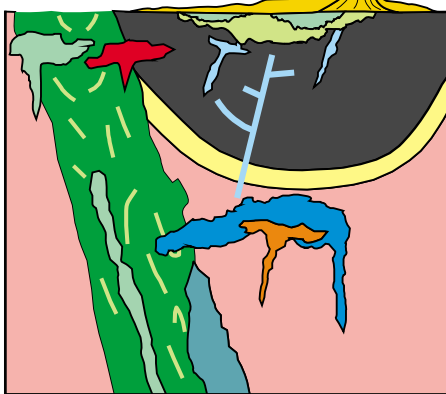
a) Phase 2: 1140–1084 Ma



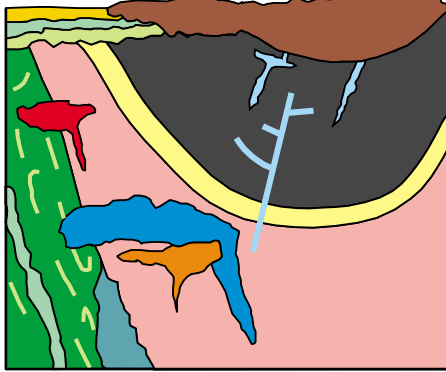
b) Phase 4: c.1073 Ma













c) Phase 7: c.1048 Ma



d) Phase 8: <1026 Ma



-  c. 1026 Ma Phase 8
Tollar Group volcanics
-  c. 1048 Ma Phase 7
Granite/felsic volcanics
-  c. 1062 Ma Phase 6
Mingled gabbro/granite + felsic volcanics
-  c. 1068 Ma Phase 5
Granite/mafic dykes + Cu–Ni mineralisation
-  c. 1073 Ma Phase 4
Granite
-  c. 1075 Ma Phase 3
Mingled gabbro/granite + felsic volcanics
-  > 1075 Ma Phase 2 layered mafic/ultramafic intrusions
-  > 1084 Ma Phase 1 Kunmarnara Group
-  MacDougall Formation/Mummawarrawarra Basalt
-  > 1150 Ma basement

5 km

Figure 19. Schematic cross sections highlighting relative timing of magmatism as snapshots after particular phases of development of the Ngaanyatjarra Rift. See text for details.

flows (1109–1107 Ma for the Mid-Continental Rift), followed by the 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 were accompanied by voluminous felsic volcanism (Green and Fitz, 1993; Vervoort et al., 2007) producing lithologies similar to those found in the Ngaanyatjarra Rift. However the Mid-Continental Rift differs from its Australian counterpart in several ways. First, major magmatism in the Mid-Continental Rift spans c. 25 m.y. as opposed to >50 m.y. for the Ngaanyatjarra Rift. Second, the Mid-Continental Rift is dominated by mafic volcanic flows (flood basalts) rather than intrusions as in the west Musgrave Province, although this may simply be the result of a deeper exposure level in the Ngaanyatjarra Rift. Third, 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 like Phase 3. Differences aside, the Mid-Continental Rift is the closest analogue to the rift described in this study and is enticingly close in age. In fact, the main magmatic events of the Mid-Continental Rift are entirely within the plausible age range of Phases 1 and 2 (analogues which dominate the Mid-Continental Rift) in the Ngaanyatjarra Rift.

Defining characteristics of the Ngaanyatjarra Rift

Although the Ngaanyatjarra Rift can be classified as an intracontinental rift, it bears a number of features that makes it unique among known rifts of this type. The tremendous size of the combined Bell Rock–Blackstone–Finlay–Jameson layered mafic intrusion rivals that of the Bushveld Complex, leaving the two in a class of their own among large, layered mafic–ultramafic intrusions. Even more unique is the Murray Range Shear Zone. We are not aware of any other synmagmatic transpressional shear zone of this size that is dominated by mafic magmatism.

The Ngaanyatjarra Rift never developed into an ocean, and the eruption of the Tollu Group appears to be the last magmatism associated with rifting. However, extension may have continued, initiating what would eventually become the Centralian Superbasin. The Townsend Quartzite overlies the Kunmarnara Group, and represents the base of the Officer Basin at the southwest edge of the Musgrave Province. It has a large detrital zircon component dated at c. 1134 Ma, which constrains its maximum depositional age. The Heavitree Quartzite, north of the Musgrave Province, is traditionally considered to be the base of the Amadeus Basin, and has a maximum depositional age of c. 1198 Ma (Kirkland et al., 2009c). Both the Townsend and Heavitree Quartzites have distinctly different provenances to the MacDougall Formation, and both have been interpreted to unconformably overlie all units formed during the Giles Event. Camacho et al. (1991) suggested that the Amadeus

Basin began as early as c. 1050 Ma, implying that formation of the Amadeus Basin may have been initiated by the Ngaanyatjarra Rift.

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

If, in future, the age of the voluminous g1 layered mafic–ultramafic intrusions is constrained to within error of g2 magmatism, then the two phases of magmatism together would represent a large volume of magma emplaced over a short time period that is coeval with the c. 1075 Ma Warakurna LIP. A mantle plume could be the heat source of such magmatism. Continental mantle plume magmatism is characterized by an early volumetric peak associated with impact of the plume head, with magmatism trailing off over a maximum period of 50 m.y. (Bryan and Ernst, 2007). However, the voluminous c. 1030 Ma Tollu Group falls just outside of this 50 m.y. maximum age range.

A local, transtensional setting seems more appropriate for the formation of the east–west trending Ngaanyatjarra Rift. This transtensional setting may have been a far-field effect from an overall, regional east–west compression, resulting from the collision of India ~1000 km to the west during the c. 1080 Ma Pinjarra Orogeny (Wilde, 1999; Fitzsimons, 2003). Zhao (2009) suggested 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. Comparable scenarios may have been the setting for the Mid-Continental Rift of North America (Van Schmus and Hinze, 1985; Ojakangas et al., 2001), and 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 c. 100 m.y. period to a minimum age of c. 1119 ± 7 Ma (Fig. 5). 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 c. 200 m.y. between c. 1220 and 1020 Ma. Smithies et al. (2010) proposed that this prolonged thermal regime 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. 6). This region of thinner crust could either channel upwelling asthenosphere in an active plume scenario, or become the locus of extension or transtension due to far-field (passive) stresses from plate boundary interactions.

Conclusions

Rocks of the Musgrave Province traditionally associated with the Giles Event can be divided into at least eight magmatic episodes, one or more of which was accompanied by intense deformation. Textural evidence and field relationships indicate that all of this magmatism occurred at relatively shallow crustal levels. The setting for this activity was a long-lived, failed intracontinental rift herein named the Ngaanyatjarra Rift.

In terms of age and tectonic setting, the Ngaanyatjarra Rift is similar to the Mid-Continental Rift of North America. In detail, though, it differs from this, and other intracontinental rifts and LIPs, in its combination of giant Bushveld-sized layered mafic-ultramafic intrusions, a crustal-scale mafic/felsic mingled magmatic shear zone, and later voluminous felsic magmatism over a >50 m.y. time span.

Although the age of some Giles Event magmatism (g2 and possibly g1) overlaps with the c. 1075 Ma Warakurna LIP, a number of magmatic pulses post-date this LIP by up to 50 million years. This long time span rules out a single mantle plume as the cause for all phases of the Giles Event. An alternative heat source for the Giles Event may be a pre-existing thermal anomaly (the c. 1220–1120 Ma ultra-high temperature Musgrave Orogeny) centred under the Musgrave Province between Archean to Paleoproterozoic cratonic keels (Smithies et al., 2010; Fig. 6). Regardless of the mechanism responsible for the initial stages of the Ngaanyatjarra Rift, extension continued due to far-field stresses from distant orogenic events.

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