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WEST MUSGRAVE COMPLEX — NEW GEOLOGICAL INSIGHTS FROM RECENT MAPPING, GEOCHRONOLOGY, AND GEOCHEMICAL STUDIES

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

NGAANYATJARRA
COUNCIL (Aboriginal Corporation)

GEOLOGICAL SURVEY · WESTERN AUSTRALIA

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The west Musgrave Complex — new geological insights from recent mapping, geochronology, and geochemical studies

by

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

Abstract

The Geological Survey of Western Australia's west Musgrave mapping project has provided new insights into the geological evolution of the western part of the Meso- to Neoproterozoic Musgrave Complex (west Musgrave Complex), in central Australia. Locally exposed basement rocks in the eastern part of the Musgrave Complex are possibly as old as c. 1600 Ma, but oldest exposed rocks in the west Musgrave Complex are gneisses of sedimentary, volcaniclastic, and volcanic origin with maximum depositional ages of between c. 1360 and c. 1307 Ma. These form the newly defined Wirku Metamorphics. Their zircon age spectra include additional detrital peaks between c. 3200 and c. 1410 Ma and can be used to divide outcrop of the Wirku Metamorphics into at least four geographically separate zones.

Granites with crystallization ages between c. 1336 and c. 1293 Ma are the most voluminous felsic component in the southwestern part of the west Musgrave Complex. They belong to the newly defined Wankanki Supersuite and are a product of the Mount West Orogeny. Volcanic equivalents are present, and detritus of this age contributed to units within the Wirku Metamorphics. The Wankanki Supersuite comprises calc-alkaline, I-type granites and differs in this respect from all other granites in the west Musgrave Complex.

The Musgravian Orogeny is dated between 1219 and 1155 Ma and involved intense deformation and widespread high-grade crustal reworking that included the production of the voluminous A-type granites of the Pitjantjatjara Supersuite. The Pitjantjatjara Supersuite granites fall into two distinct age groups: an older group reflecting magmatism and metamorphism between c. 1219 and 1200 Ma (early Musgravian Orogeny), and a younger group reflecting magmatism and metamorphism between c. 1190 and 1155 Ma (late Musgravian Orogeny). The distribution of these granites and those of the Wankanki Supersuite is essentially antithetic — granites of the Pitjantjatjara Supersuite are most abundant in the northeast of the west Musgrave Complex, but only form small plutons and dykes in the southwest.

The Warakurna Supersuite groups all igneous rocks thought to related to the c. 1075 Ma Giles Event. Layered mafic–ultramafic intrusions that form the west-northwest spine of the west Musgrave Complex have a minimum age of c. 1078 Ma, but might be as old as the latest Musgravian Orogeny (c. 1170 Ma). Unlayered gabbro intrudes the layered intrusions, forming a regionally extensive feature offset by sinistral movement along late west-trending faults. Comagmatic leucogranite is dated at between c. 1075 and c. 1078 Ma, which defines a period of mafic and felsic magmatism, upright folding, and northwest to north-northwest trending shearing. Like the Pitjantjatjara Supersuite, the Giles Event granites show strongly developed A-type compositional characteristics.

Volcanic and sedimentary rocks of the Tollu Group (as originally defined) form part of the regionally extensive Bentley Supergroup. This group is now subdivided into the (lower) Kunmarnara Group and the overlying redefined Tollu Group because layered mafic–ultramafic intrusions, likely to be c. 1078 Ma, or older, were locally emplaced into the Kunmarnara Group but feeder dykes to the volcanic rocks in the upper part of the group cut the layered intrusions. A dacite from the upper Tollu Group yielded a preliminary age of 1026 ± 26 Ma, which is more consistent with field relationships established within the region. Thus deposition of the Kunmarnara and (redefined) Tollu Group is likely separated by a minimum of 50 m.y., and possibly up to 150 m.y. — a hiatus that saw emplacement of layered mafic–ultramafic intrusions, uplift, erosion, and possibly folding. This complex history of volcanism, emplacement of large layered mafic–ultramafic intrusions, felsic magmatism and deformation over a time period of at least 50 m.y. is more akin to the evolution of a failed intracontinental rift than a classic plume-related large igneous province.

KEYWORDS: Musgrave Complex, Mesoproterozoic, Neoproterozoic, Mount West Orogeny, Musgravian Orogeny, Giles Event, Warakurna Large Igneous Province.

Introduction

The west Musgrave Complex mapping project commenced in 2004 with the aim of providing regional 1:100 000 scale geological map coverage and supporting geophysical, geochronological, geochemical, and structural data and interpretations across the entire exposed area of the Musgrave Complex in Western Australia (referred to herein as the 'west Musgrave Complex'). The results of the project will expand on, update, and refine investigations carried out by the Geological Survey of Western Australia during the late 1960s and early 1970s, which was compiled into GSWA Bulletin 123 by Daniels (1974), and by Geoscience Australia (Bulletin 239) in the early 1990s (Glikson et al., 1996). The current project has been strongly supported and facilitated by local Traditional Owners and by the Ngaanyatjarra Council, and continues to operate under a formal Agreement as a joint GSWA – Ngaanyatjarra Council project. The project also enjoys ongoing collaboration with research staff from the Continental Evolution Research Group at the University of Adelaide and from the Centre for Exploration Targeting at the University of Western Australia.

At the end of 2008, field work had been completed on five 1:100 000 geological map sheets (Bates, Bell Rock, Blackstone, Holt, and Finlayson; Fig. 1), with map compilation complete on four of these areas (Bates, Bell Rock, Blackstone, and Holt). Regional geophysical data sets now include complete aeromagnetic and radiometric coverage (flown at 400 m line spacing) and regional gravity (collected on a 2.5 km grid). Geochronology (mostly by secondary ionization mass spectrometry (SIMS) U–Pb zircon analyses on a sensitive high-resolution ion microprobe (SHRIMP)) has been collected on more than 70 samples, and major- and trace-element geochemistry has been determined on more than 400 samples.

This Record summarizes work carried out so far and presents some preliminary interpretations. It concentrates on general age constraints and field relationships and forms an introduction to more detailed reports, including those covering geology and provenance of basement paragneiss (Evins et al., in prep), the detailed geochronology and structural evolution of the Giles Event (Evins et al., in prep.), geochemistry of mafic dykes (Howard et al., in prep.), and the geochemical evolution of the felsic crust of the west Musgrave Complex (Smithies et al., in prep.). Our geological investigations began in the areas abutting the South Australian and Northern Territory borders, and so this Record relates specifically to the eastern part of the west Musgrave Complex.

Regional geological summary

The Musgrave Complex, in central Australia, is an earliest Mesoproterozoic to Neoproterozoic belt bounded by

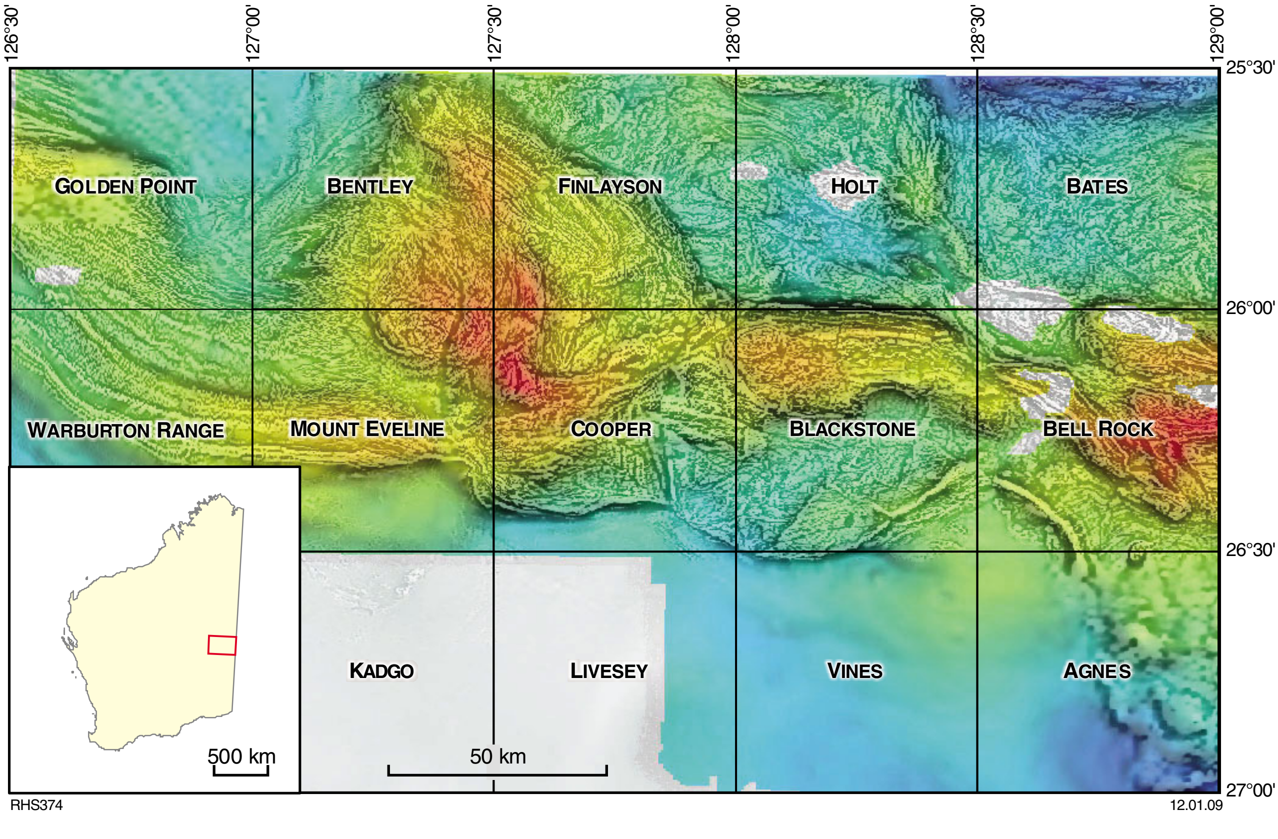

Figure 1. Map showing the location of the project area within Western Australia (inset), a combined gravity and TMI (total magnetic intensity — grey scale) image of the project area, and individual 1:100 000 map sheets. Gravity scales range from high (red) to low (blue)

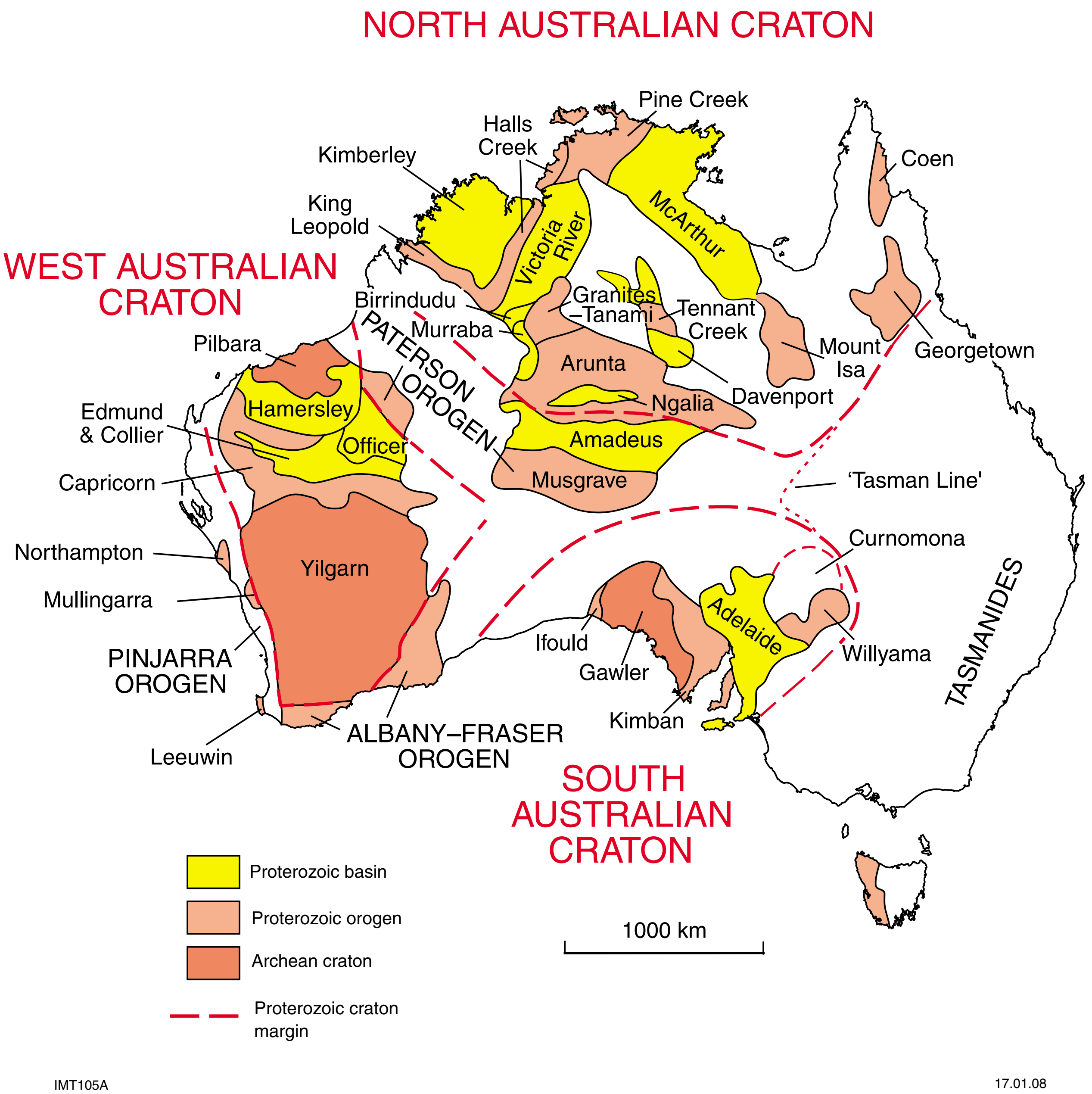

Figure 2. Location of the Musgrave Complex with respect to the North, South and West Australian Cratons (modified from Myers et al., 1996)

Neoproterozoic to Palaeozoic basins, and is expressed on geophysical images as an east-trending anomaly up to 800 km long and 350 km wide. While this region probably represents the least studied of Australia's exposed Proterozoic terrain, it lies at the convergence of three Proterozoic structural trends formed by the amalgamation of the North, West and South Australian Cratons (Fig. 2), and accordingly is one of the most important regions in terms of paleogeographic reconstructions of Proterozoic Australia.

A coincidence of intrusive and metamorphic events at 1330–1300 Ma and 1220–1160 Ma provides a late Mesoproterozoic link between the complex and the Albany–Fraser Orogen, along the southern margin of the West Australian Craton (e.g. Myers et al., 1996; White et al., 1999; Fitzsimons, 2003). At some stage in its evolution, the complex also likely formed the southeastern part of the Paterson Orogen (Fig. 2), a 2000 km long Paleoproterozoic to Neoproterozoic belt in western to central Australia that connects under Phanerozoic cover with the Musgrave Complex via a prominent gravity-high known as the Anketell Regional Gravity Ridge (Fraser, 1976).

The age and nature of the basement through which the late Mesoproterozoic granite suites intruded is poorly constrained. It is thought to have included intrusive components as old as c. 1600 Ma and banded gneiss considered to comprise protoliths of mainly volcanic,

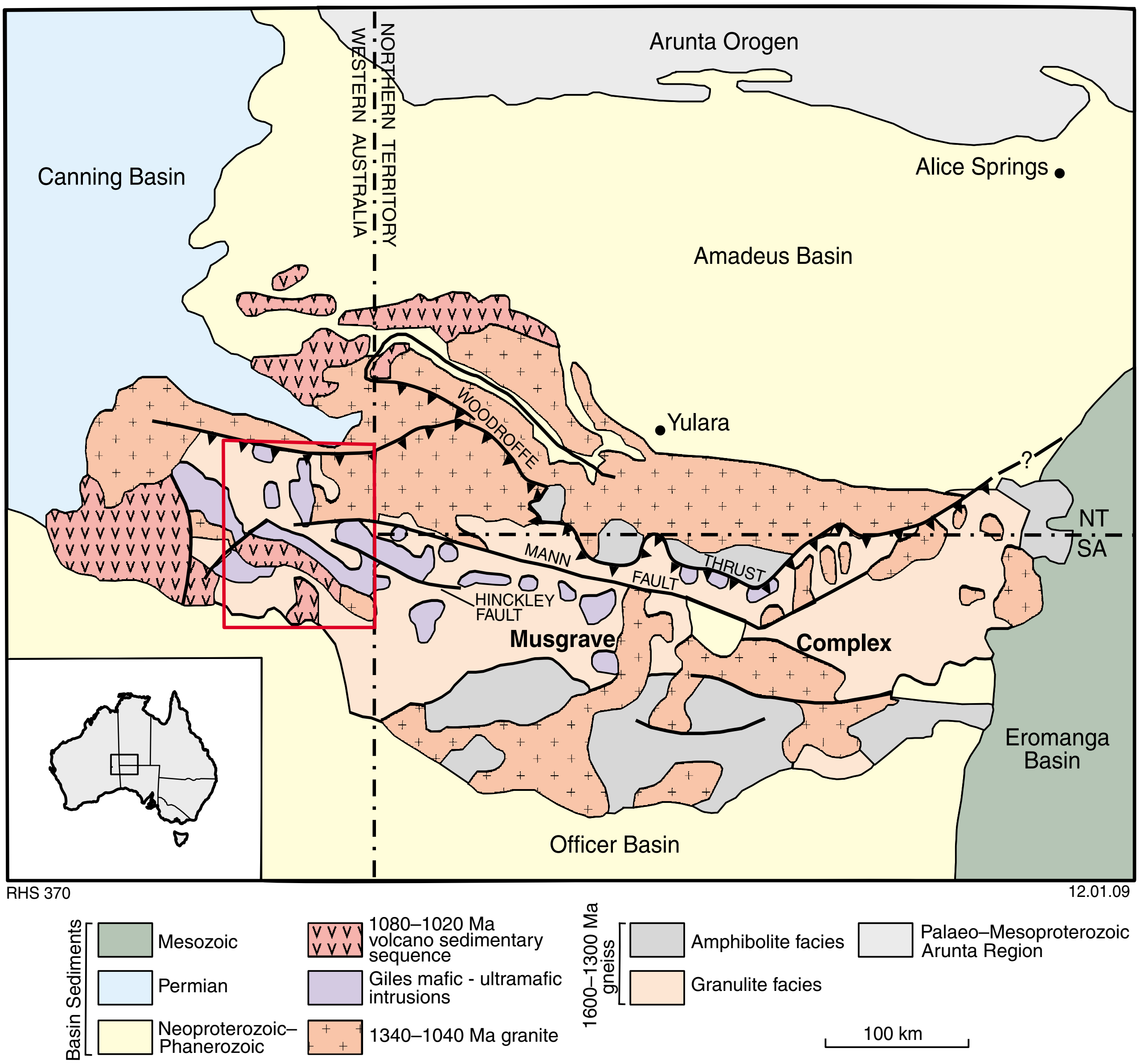

Figure 3. Regional geological sketch of the Musgrave Complex (Modified from Glikson et al, 1996 and Edgoose, et al. 2004). The red box shows the area covered in detail in Figure 4

volcaniclastic, and sedimentary origins (Gray, 1971, 1978; Gray and Compston, 1978; Maboko et al., 1991; Major and Conor, 1993; Camacho and Fanning, 1995; Edgoose et al., 2004).

Later intrusion and extrusion of voluminous mafic to felsic magmas, including the Giles layered mafic–ultramafic intrusions, into this high-grade terrain occurred during the c. 1075 Ma Giles Event (Fig. 3). The age of this event broadly coincides with the assembly of Rodinia (e.g. Cawood, 2005). The Giles Event has been interpreted as the result of a mantle plume (Wingate et al., 2004; Morris and Pirajno, 2005), but sporadic continuation of igneous activity to c. 1040 Ma (Edgoose et al., 2004) may suggest the event reflects a more complex geodynamic setting.

The complex was again deformed during the c. 550 Ma Petermann Orogeny, which coincides with the global Pan-African period of plate reorganization that marks the assembly of Gondwana (e.g. Cawood and Buchan, 2007). In the west Musgrave region, this orogeny appears to have been essentially intracratonic, with the production of very little new crust. High pressure granulites and near-eclogite facies rocks are thought to have been exhumed in a transpressional, crustal-scale, flower structure, over and into rocks of the Neoproterozoic basins (Camacho, 1997; Edgoose et al., 2004) to the north and south of the Musgrave Complex (Fig. 3).

Regional geology — new insights

Basement rocks

Major and Conor (1993) grouped all rocks formed prior to, and metamorphosed during, the 1225–1150 Ma Musgravian Orogeny into the Birksgate Complex. Several studies, however, have attempted to separate these rocks into distinct age groups (Gray, 1971, 1978; Sun and Sheraton, 1992; Camacho and Fanning, 1995; Sun et al, 1996; Camacho, 1997; White et al., 1999; Edgoose et al., 2004; Howard et al., 2006, 2007; Wade et al., 2005; Wade et al., 2006).

Gneissic rocks metamorphosed during the Musgravian Orogeny form a major component of the west Musgrave Complex (Stewart 1995; Edgoose et al., 2004; Howard et al., 2006, 2007), although the formation age of the protolith(s) remains unclear. Gray (1971, 1978) and Gray and Compston (1978) recognized a package of banded composite gneiss at Mount Aloysius (northwestern part of BELL ROCK) that extends to the Mann Ranges (on the Northern Territory – South Australia border, approximately 20 km east of the border with Western Australia; Fig. 4) with an Rb–Sr isotopic age of c. 1550 Ma. According to these authors, protoliths to the gneisses were supracrustal rocks dominated by volcanic material deposited at c. 1550 Ma, and were strongly metamorphosed at c. 1200 Ma. Maboko et al. (1991), Camacho and Fanning (1995) and Edgoose et al., (2004) also identified c. 1600–1540 Ma ages in zircon U–Pb data from gneissic rocks in the eastern part of the Musgrave Complex. These gneisses are thought to be locally dominated by material derived from volcanic, volcaniclastic, and clastic protoliths (Major and Conor, 1993; Edgoose et al., 2004). In some cases, however, the gneisses contained relatively simple zircon age populations that were interpreted as reflecting the age of crystallization of a granitic protolith component (Camacho and Fanning, 1995; Edgoose et al., 2004) as 1590 ± 25 Ma (Edgoose et al., 2004). However, our data show no indication that intrusive or extrusive felsic material older than c. 1400 Ma is exposed in the west Musgrave Complex, which appears to differ significantly from the eastern parts of the complex.

Oldest exposed rocks — Wirku Metamorphics

In the west Musgrave Complex most rocks older than c. 1330 Ma are gneisses. All of these older rocks are of sedimentary and lesser volcaniclastic and volcanic origin based on locally continuous meter-scale layering, centimetre- and millimetre-scale banding, the presence of pelitic, arkosic (Fig. 5) and quartzitic interlayers, and on their complex zircon age spectra (e.g. GSWA 187289, 185591, 185592, 183466 — GSWA preliminary data).

Based on grain size, continuity of banding, and on composition a dominantly felsic volcanic origin has been proposed for gneisses of the Mann Range (Gray, 1978; Scrimgeour et al., 1999; Wade et al., 2006). Their radiogenic Nd-isotopic composition, coupled with arc-like geochemistry, has been used to infer their production as juvenile crust in a subduction setting (Glikson et al., 1996; Edgoose et al., 2004; Wade et al., 2006) at c. 1600–1550 Ma. However, age distribution patterns for zircon populations call into question this interpretation for lithologically and isotopically similar packages of rocks in the northern part of the west Musgrave Complex (including Mount Aloysius). These packages include supracrustal units containing age distribution patterns for detrital zircon with persistent peaks (see below and Evins et al., in prep) that indicate a maximum depositional age of c. 1360 Ma. Intrusive contacts with granites of the Wankanki Supersuite (i.e rock of the Mount West Orogeny — Fig. 6 and see below) provide a minimum depositional age of 1336–1293 Ma.

Wade et al (2005) showed that the far eastern Musgrave Complex includes a sequence of supracrustal gneisses derived from c. 1490–1400 Ma sources, which was deposited after c. 1400 Ma. Our data from paragneisses in the west Musgrave Complex suggests that sediments were deposited over a wide region between c. 1360 and 1307 Ma, prior to and coincident with intrusion by granites of the 1336–1293 Ma Wankanki Supersuite. We refer to these gneisses as the Wirku Metamorphics (includes all rocks in the west Musgrave Complex formerly grouped into the Birksgate, Wirku, or Pity Palya Metamorphics).

The age spectra for detrital zircons in the Wirku Metamorphics define at least four geographically separate groups (BATES region, Tjuni Purlka Tectonic Zone, Latitude Hills area and the southern BLACKSTONE region — see detrital age spectra in Fig. 6a and geographical regions shown in Fig. 7). Paragneisses in the northeastern part of the west Musgrave Complex (BATES region) are dominated by age peaks at c. 1560, 1530, and 1470 Ma with several younger peaks between 1410 and 1310 Ma.

A broad zone of extensive, multi-generational, strike- and dip-slip faulting extends in a northwest direction across the west Musgrave Complex and is referred here to as the Tjuni Purlka Tectonic Zone (Fig. 7). This zone contains some of the largest exposures of paragneisses in the entire Musgrave Complex, some of which occur as kilometre-scale rafts in granite. These paragneisses are mostly dominated by detrital zircon age peaks at 1510 and 1410 Ma (slightly younger than the old peaks in the paragneisses to the northeast; Fig. 6a) and have a significantly greater proportion of younger ages between c. 1360 and 1310 Ma compared to supracrustal paragneisses on BATES. However, there is significant local variation in detrital age spectra which likely reflects either the inclusion of tectonic fragments from neighbouring areas or more than one detrital zircon provinance.

Supracrustal gneisses forming basement in the southeastern part of the west Musgrave Complex (Latitude Hills area; Fig. 7) differ markedly from those to the north in that they contain several prominent detrital zircon age peaks between c. 3200 and 2630 Ma and between 1790 and 1590 Ma (Fig. 6a). They also have a correspondingly much less radiogenic Nd isotopic composition, with an ε_{Nd} range of about -12 to -15 compared to a range of +3 to -3 for the paragneisses in the BATES region and a range of -2 to -5 for paragneisses from the Tjuni Purlka Tectonic Zone.

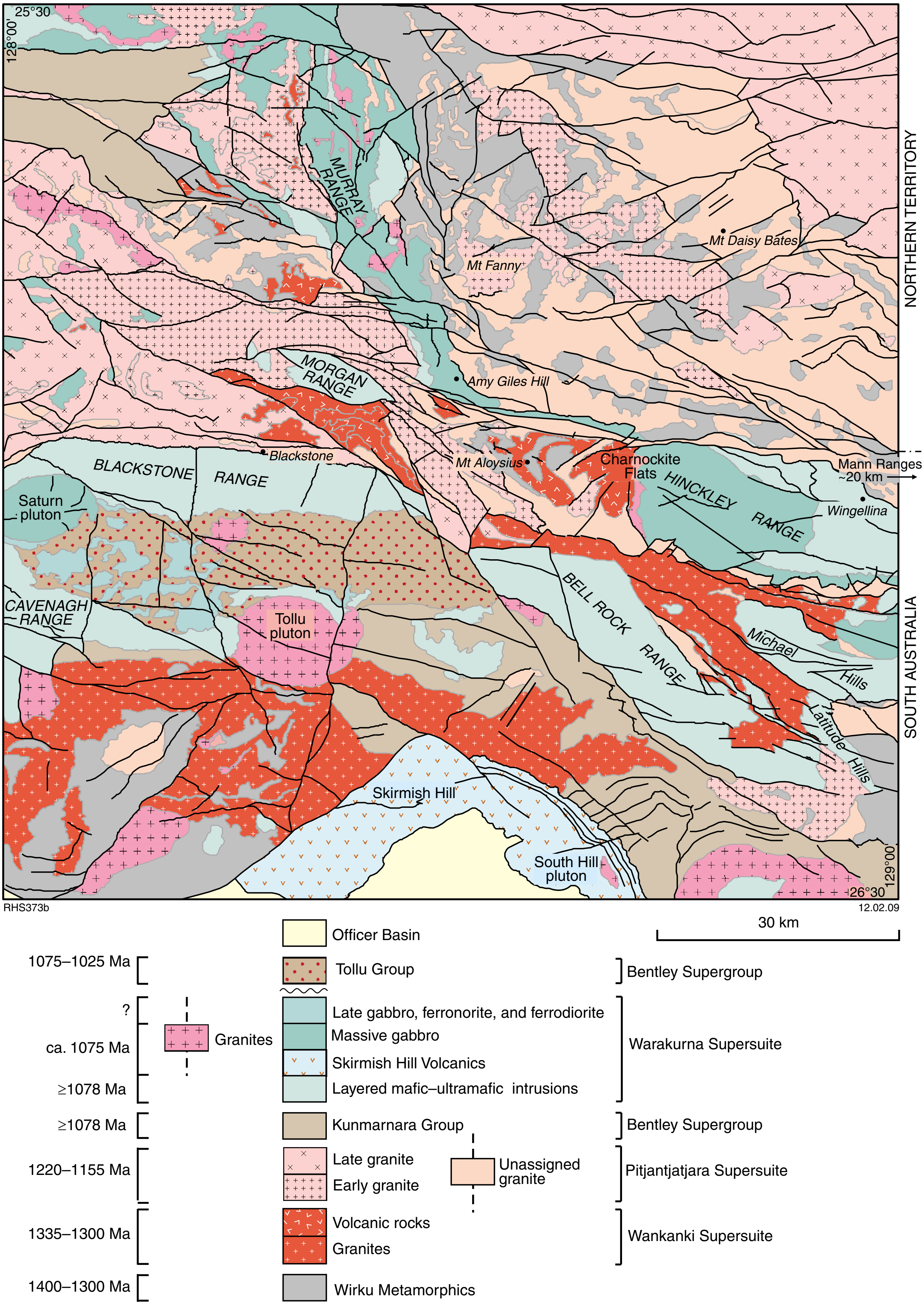

Figure 4. Interpreted bedrock geology map of the eastern portion of the west Musgrave Complex

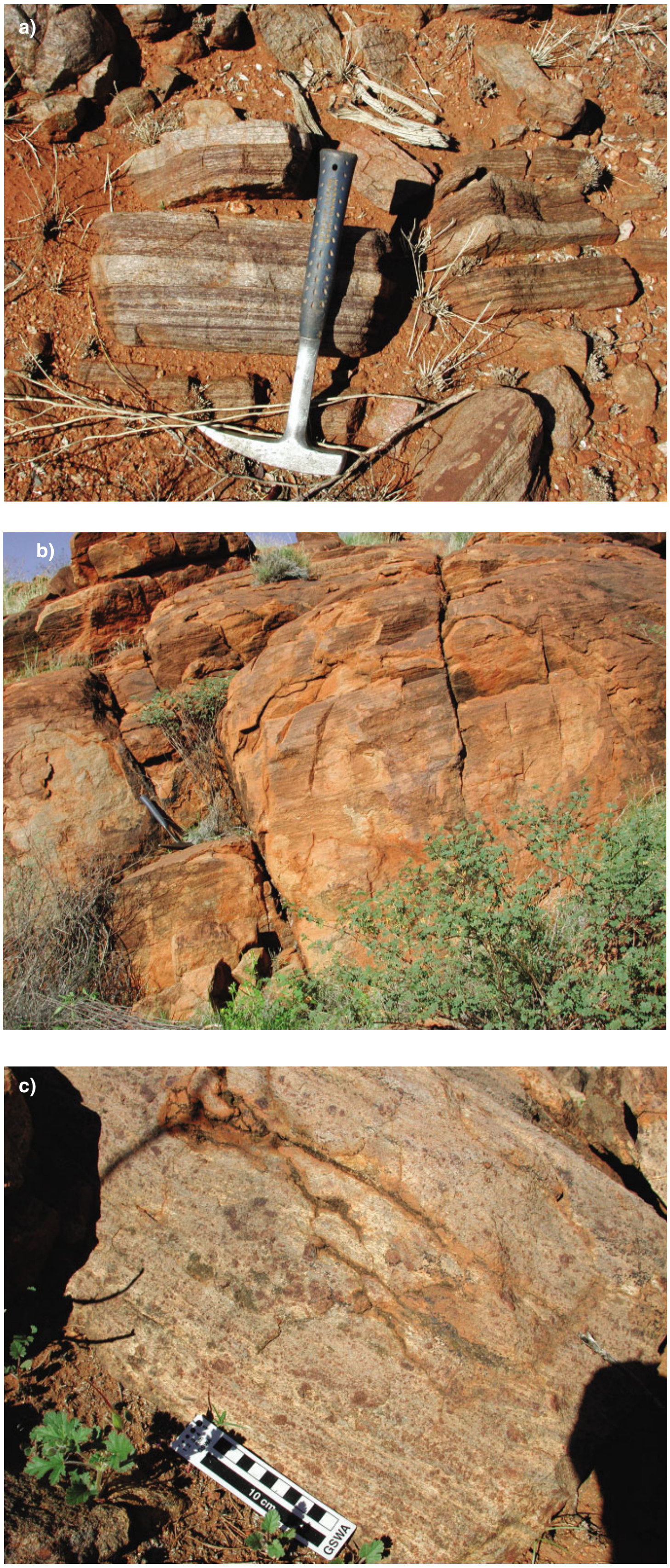

Figure 5. Outcrop photographs of the Wirku Metamorphics: a) thinly interlayered arkosic metasandstone (Latitude Hills area — Bell Rock); b) laminated arkosic metasandstone (southern Holt); c) pelitic (garnet–sillimanite–hercynite–cordierite) gneiss (Latitude Hills area — Bell Rock)

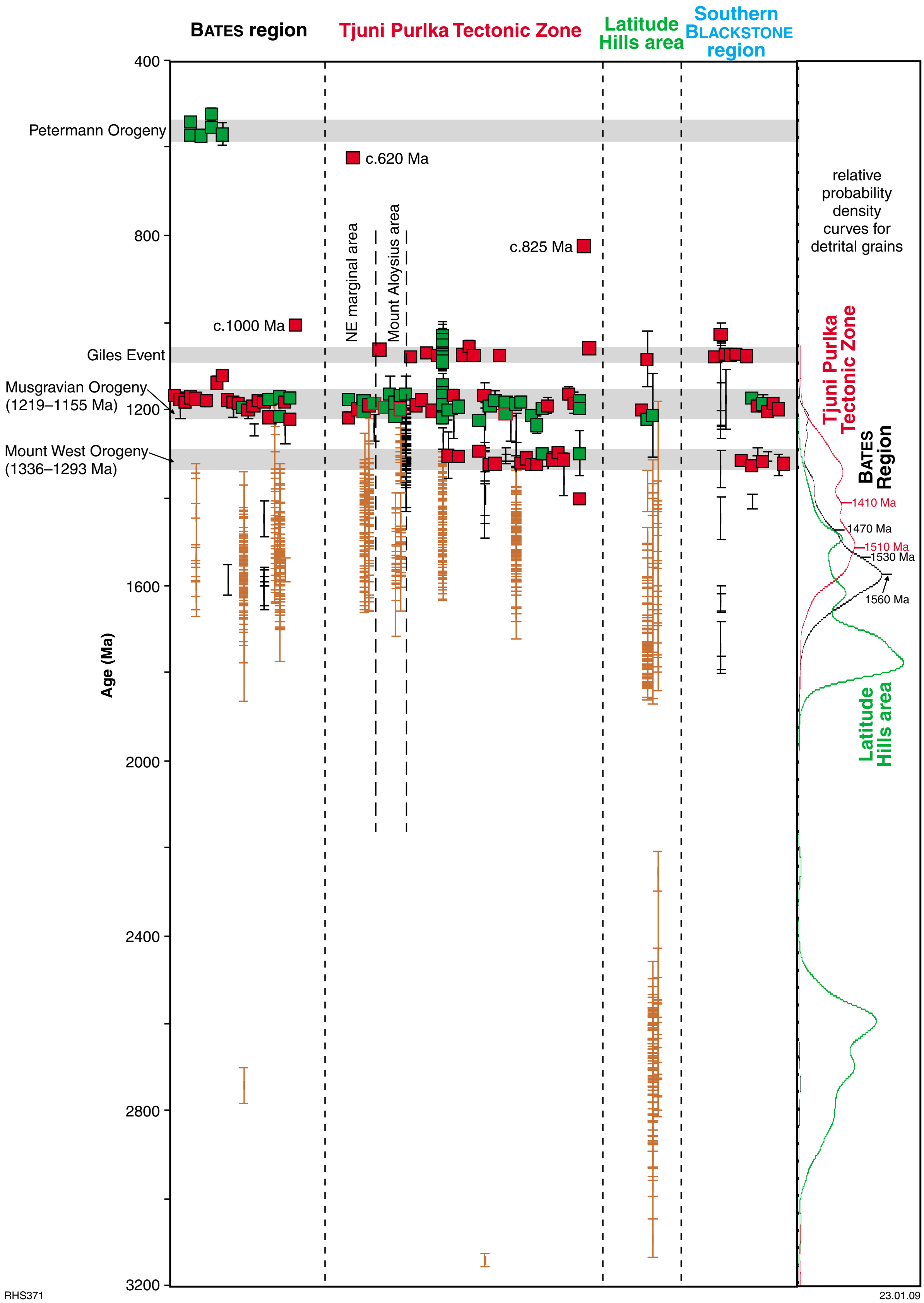

Figure 6. **a) Time-space plot of SIMS (U–Pb) zircon ages; b) the c. 1120–1345 Ma time bracket in detail showing Late and Early Musgravian Orogeny subdivisions as well as an apparently distinct young (c. 1160–1165 Ma) thermal event within the Late Musgravian Orogeny. Red squares denotes igneous crystallization; green squares denote an age interpreted as metamorphic; green square with red boarder denotes an age interpreted as local migmatization; unfilled (no squares) black error bars denote inheritance; unfilled brown error bars denote detrital ages. Source: GSWA(2008)**

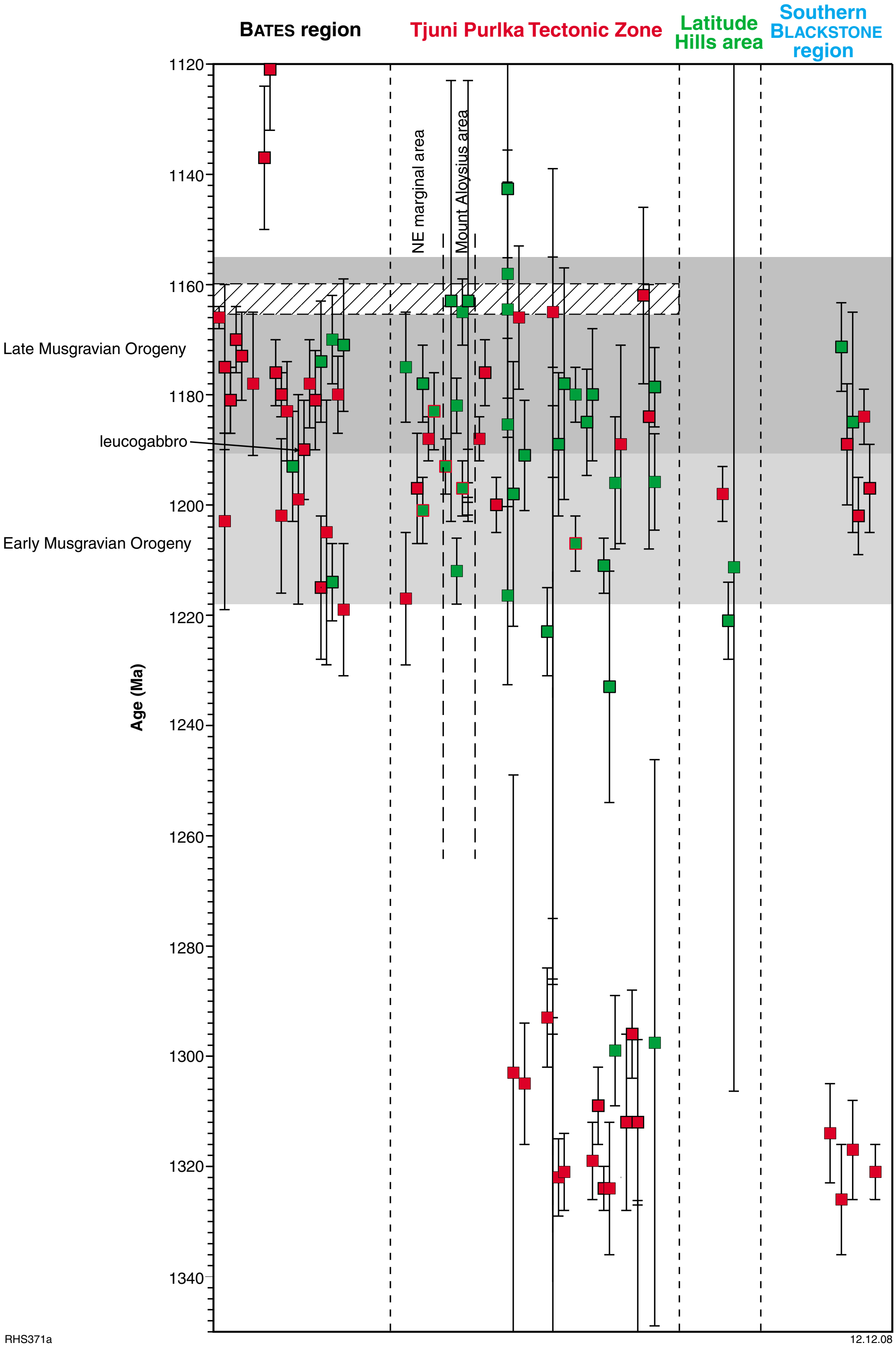
BATES region
Tjuni Purlka Tectonic Zone
Latitude Hills area
Southern BLACKSTONE region
NE marginal area
Mount Aloysius area
Late Musgravian Orogeny
leucogabbro
Early Musgravian Orogeny
Age (Ma)
1120
1140
1160
1180
1200
1220
1240
1260
1280
1300
1320
1340
RHS371a
12.12.08

Figure 6b

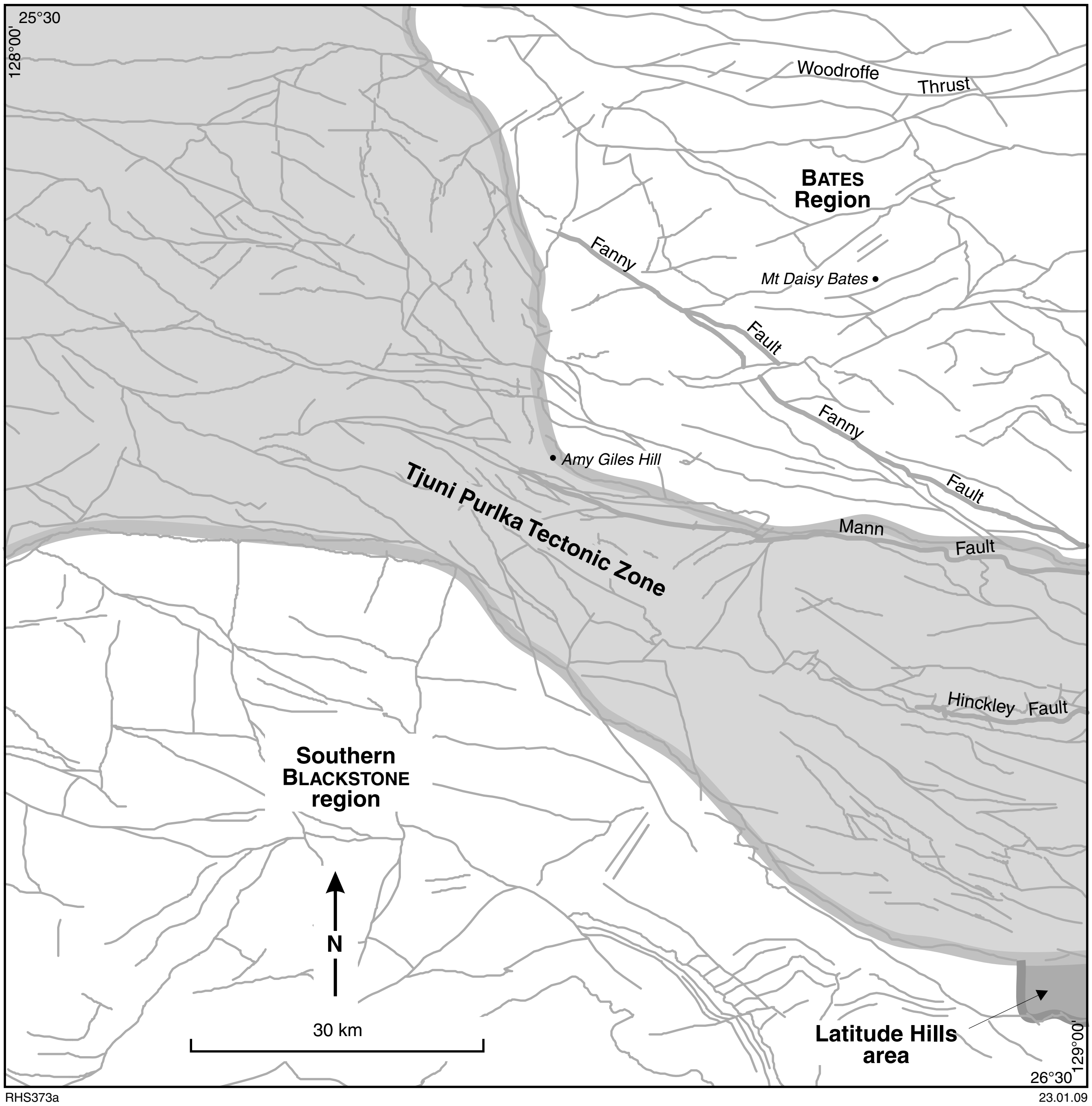

Figure 7. Major faults and tectonic regions of the eastern portion of the west Musgrave Complex

Banded felsic gneisses in the southwestern area (southern Blackstone region; Fig. 7) include fine-grained and laminated quartzofeldspathic gneiss, locally with minor interlayers of garnet- and garnet(–hercynite)-gneiss. No sample taken from this region has produced multi-modal zircon age populations. Rather, all have yielded relatively simple age populations between c. 1336 and 1315 Ma, with only a single older inherited crystal giving an age of c. 1410 Ma. We tentatively assign these rocks to the Wirku Metamorphics, suggesting that their protoliths were possibly volcaniclastic rocks directly related to the Wankanki Supersuite (see below). An alternative suggestion, however, is that these rocks represent zones of intense deformation (blastomylonites) of granites belonging to the Wankanki Supersuite. If this is the case, the deformation itself relates to a hitherto unrecognized period of local deformation between c. 1320–1200 Ma, since distinctive rafts of this banded felsic rock form xenoliths in weakly deformed granite that formed during the early Musgravian Orogeny (c. 1200 Ma; GSWA 184146 — preliminary data).

The relationship between these four groups of supracrustal rocks assigned to the Wirku Metamorphics is not yet clear. We cannot rule out the possibility that they simply represent slightly different stratigraphic packages within a single depositional basin that evolved between c. 1360 and c. 1293 Ma.

Rocks formed before c. 1360 Ma have not yet been identified in the west Musgrave Complex, but granite magmatism at 1336–1293 Ma and at 1219–1155 Ma involved melting of crustal material that was isotopically different to the exposed rocks of the Wirku Metamorphics. The bulk source for these granites has an average depleted mantle model age (T_{DM2}) of ~2000 Ma and is likely the unexposed basement to the west Musgrave Complex.

The 1336–1293 Ma Mount West Orogeny and the Wankanki Supersuite

Migmatitic gneisses with protolith ages between c. 1330 and 1300 Ma were first identified by Gray (1971), who also noted that these rocks appeared to be restricted to south of the Mann and Hinckley Faults. Gray (1978) suggested the gneissic rocks were metamorphosed volcanic rocks. However, structurally transitional contacts with foliated porphyritic monzogranites of equivalent age (Sun et al., 1996; White, 1997; White et al., 1999; Howard et al., 2007) suggest that many of these rocks were intrusive. Subsequent regional mapping of the west Musgrave Complex (Howard et al, 2007; Smithies et al., 2008; Evins et al., 2008) and geochronological data (GSWA preliminary data) shows that intrusive igneous rocks of this age form a significant component within the Tjuni Purlka Tectonic Zone and represent the most voluminous pre c. 1100 Ma magmatic component to the southwest of that zone (Fig. 4). Volcanic equivalents are tentatively identified (as part of the Wirku Metamorphics) in both the southern BLACKSTONE region and the Tjuni Purlka Tectonic Zone, and detrital zircon age studies indicate that detritus derived from rocks, or lavas, of this age contributed to units within the Wirku Metamorphics within all areas of the western Musgrave Complex except, perhaps, the Latitude Hills area (Fig. 6a). While intrusive rocks of this age are common in the southern BLACKSTONE region and the Tjuni Purlka Tectonic Zone, none are yet known from either the BATES region or the Latitude Hills area.

Howard et al. (2007) grouped these rocks into the Wankanki Supersuite and termed the crustal event that produced them the Mount West Orogeny. The crystallization age range of these rocks is from c. 1336 to c. 1293 Ma (White et al., 1999; Kirkland et al., 2008a; GSWA preliminary data), with most lying within a narrow period between c. 1326 and 1312 Ma. (Fig. 6b). In lower strain zones, the Wankanki granites are typically porphyritic granodiorites and monzogranites containing up to 15% (?primary) clinopyroxene and orthopyroxene and late (?retrograde) hornblende. The rocks are typically strongly deformed and have been metamorphosed up to granulite facies. Migmatization in the most leucocratic Wankanki granites is locally conspicuous.

Rare, laminated, orthopyroxene-bearing granulites to the south of the Cavenagh Range (southern BLACKSTONE region) are geochemically similar to the Wankanki granites and are interpreted as representing volcanic or volcaniclastic equivalents of these granites (Smithies et al., 2008). These granulites are locally interleaved (?interbedded) with minor garnet, and garnet(–hercynite) pelitic gneiss. Geochemically similar sequences of laminated, fine- to medium-grained, orthopyroxene-bearing felsic granulites also occur in the Tjuni Purlka Tectonic Zone, to the north of the Blackstone Range (Fig. 4), where they are interlayered with other supracrustal gneisses of the Wirku Metamorphics, including pelitic units. Dating of zircon from these orthopyroxene-bearing felsic granulites gives a maximum depositional age of 1319 ± 7 Ma (GSWA 180867; GSWA preliminary data) in the Tjuni Purlka Tectonic Zone north of the Blackstone Range, and 1317 ± 9 Ma (GSWA 184150; GSWA preliminary data) in the southern BLACKSTONE region. This suggests that the Tjuni Purlka Tectonic Zone and the southern BLACKSTONE region represent slightly higher crustal level equivalents of the dominantly intrusive rocks of the Wankanki Supersuite terrain exposed in the Tjuni Purlka Tectonic Zone to the north of the Latitude Hills area. Some samples of the Wirku Metamorphics from the BATES region show detrital zircon age patterns that reflect a very minor contribution from sources equivalent in age to rocks of the Wankanki Supersuite, and may reflect a sporadic volcanosedimentary contribution from distal Wankanki Supersuite felsic volcanism.

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

Throughout the west Musgrave Complex, rocks of the Wirku Metamorphics show evidence for extensive recrystallization during the Musgravian Orogeny (see below) and it is likely that this has largely destroyed metamorphic fabrics and assemblages produced during the earlier Mount West Orogeny. Within and to the south of the Tjuni Purlka Tectonic Zone, Wirku metasedimentary inclusions within Wankanki Supersuite granites contain zircons with metamorphic rims that formed during the Mount West Orogeny (White et al., 1999). Monazite growth within leucosome portions of migmatized Wirku gneisses at Cohn Hill also occurred during the Mount West Orogeny (Kelly et al., 2006). However north of the Tjuni Purlka Tectonic Zone, where Wankanki Supersuite granites have not been identified, there is no clear evidence for deformation or metamorphism during the Mount West Orogeny.

Rocks of the Wankanki Supersuite show a large range in SiO_2 from 58.95 to 76.76 wt%, although there is a gap from 60.33 to 65.79 wt%, which separates rare tonalites and granodiorites from more abundant monzogranites and syenogranites. The granites and associated volcanic units are metaluminous (ASI = 0.85 – 1.02), calc-alkaline, I-type rocks. On tectonic discrimination diagrams (Pearce et al., 1984), they consistently fall within the field for volcanic arc granites (Fig. 8) and they differ in this respect from all other granites of all ages in the west Musgrave Complex. While it is possible that the Wankanki Supersuite reflects magmatism within a continental arc, it must be noted that gabbroic rocks that might be expected to accompany felsic magmatism in such a setting have not yet been identified

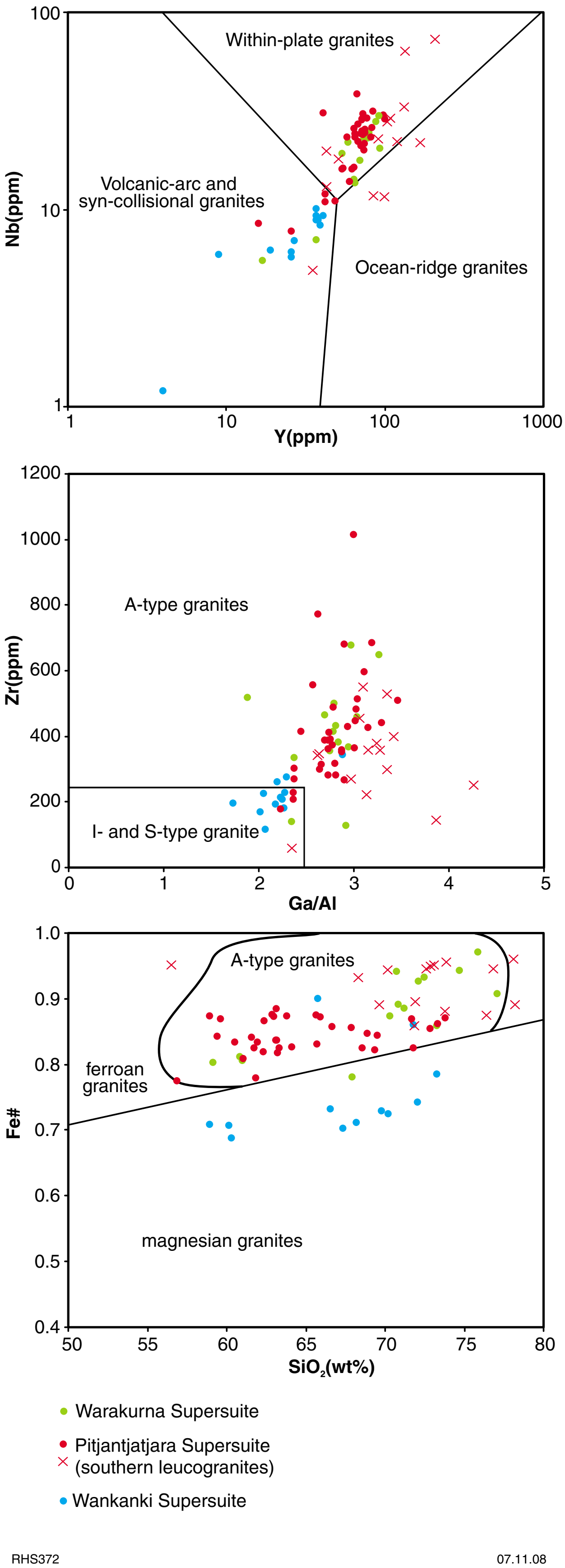

Figure 8. Tectonic and compositional discrimination diagrams showing the various granite age groups in the eastern portion of the west Musgrave Complex (see text for details)

within the supersuite and that the granites themselves derive from a source with an T_{DM} model age between c. 2000 and c. 1900 Ma.

The 1219–1155 Ma Musgravian Orogeny and the Pitjantjatjara Supersuite

The Musgravian Orogeny involved intense deformation and widespread amphibolite to granulite facies crustal reworking, including the production of voluminous felsic magmas, and was broadly coincident with the global Grenvillian Event (Edgoose et al., 2004). Edgoose et al., (2004) place the orogeny between c. 1200 and 1160 Ma, and group syn- to post-tectonic granite magmas into the 1190–1130 Ma Pitjantjatjara Supersuite. Recent dating from the west Musgrave Complex (Bodorkos et al., 2008a–e; Bodorkos and Wingate, 2008a; Kirkland 2008 b–d; Howard et al., 2006, 2007) requires minor modifications to these age brackets. This is the oldest orogenic event to have clearly affected all areas of the western Musgrave Complex.

Rocks of the Pitjantjatjara Supersuite (Musgravian Orogeny) have all been metamorphosed at granulite facies and range from statically recrystallized unfoliated rocks, to strongly foliated and mylonitized rocks. Where low-strain zones preserve primary igneous textures, these are typically seriate to porphyritic. Rounded rapakivi-textured feldspar phenocrysts, up to 5 cm in size, are locally preserved; thus these units can be classified as rapakivi granites according to the definition of Haapala and Rämö (1992). The rocks also retain evidence of primary orthopyroxene–clinopyroxene(–biotite) mineralogy and on that basis can also be classified as metamorphosed charnockites (e.g. Frost and Frost, 2008).

A compilation of new U–Pb SIMS (SHRIMP) dates on zircons broadly within or close to the 1220–1150 Ma age range, includes both ages interpreted to reflect crystallization of the granite magma, and ages on zircon rims, including zircons from migmatites, that are interpreted to reflect metamorphic growth. On Bates, the combined age populations can be divided into two distinct age groups: an older group reflecting magmatism and metamorphism between c. 1219 and 1200 Ma, and a younger group reflecting magmatism and metamorphism between c. 1190 and 1155 Ma (Fig. 6b). These two groups bracket events that are here referred to as 'early Musgravian Orogeny' and 'late Musgravian Orogeny' respectively. The oldest early Musgravian Orogeny granite so far identified is dated at 1219 ± 12 Ma (GSWA 174737; Bodorkos et al., 2008d) and was foliated before or during intrusion and metamorphism by late Musgravian Orogeny leucogranite magmatism at 1180 ± 6 Ma (GSWA 174736; Bodorkos et al., 2008c). The youngest late Musgravian Orogeny granite from the Bates region has been dated at 1164 ± 10 Ma (GSWA 183509; GSWA preliminary data) and is an unfoliated (post-tectonic) leucogranite dyke that cuts a late Musgravian Orogeny foliation.

Granites of the Pitjantjatjara Supersuite dominate outcrop in the Bates region (Fig. 4). Rare leucogabbro was also intruded during the late Musgravian Orogeny at 1190 ± 7 Ma (GSWA 174594; GSWA preliminary data), suggesting at least some juvenile crust addition during the Musgravian Orogeny, either at the end of the early Musgravian Orogeny or at the beginning of the late Musgravian Orogeny. Based on the intrusive age of granites, the Bates region can be broadly divided into two areas that parallel the northwest-trending Fanny Fault. Early Musgravian Orogeny granites are restricted to the western area (Fig. 4), and range in composition from quartz monzodiorite and granodiorite to monzogranite. Late Musgravian Orogeny granites, which form as much as 65% of the total Musgravian Orogeny magmatism in this region, form the eastern area and range in composition from monzogranite to syenogranite. The late Musgravian Orogeny granites can be further subdivided, on the basis of slight but persistent trace element differences, into two suites that form northwest-trending outcrop patterns, although this more likely reflects a late structural control, rather than a geographic trend in source distribution. Both early and late Musgravian Orogeny granites are intruded and locally engulfed by schlieric leucogranites which form sheet-like bodies and which are themselves a product of local late Musgravian Orogeny anatexis.

In the Tjuni Purlka Tectonic Zone, a slight distinction between the early and late Musgravian Orogeny can be made in the ages of granite magmatism, but not in terms of metamorphic ages (Fig. 6b). Here, rocks of the Wankanki Supersuite and Wirku Metamorphics appear to have been metamorphosed (including anatexis) almost continuously from c. 1219 to c. 1175 Ma. What appears to be a discrete and very late magmatic and metamorphic event also affects the zone, particularly in the southeast, between c. 1165 and 1160 Ma (outlined box in Fig. 6b) overlapping in time with the latest part of the late Musgravian Orogeny in the Bates region. The more continuous distribution of metamorphic ages within the Tjuni Purlka Tectonic Zone suggests that this zone was tectonically active throughout the entire Musgravian Orogeny, and indicates that much of the deformation that actually defines the zone is itself related to the Musgravian Orogeny.

Granites of the Pitjantjatjara Supersuite are significantly less abundant within the Tjuni Purlka Tectonic Zone than they are in the Bates region (Fig. 4). In addition, large plutonic bodies that characterize the Bates region are very rare in the Tjuni Purlka Tectonic Zone. Those large plutons that do occur, lie in the northeastern part of the zone, are early Musgravian Orogeny in age, and possibly reflect tectonic inclusions of rocks from the Bates region (immediately to the east). Most other Pitjantjatjara Supersuite granites within the Tjuni Purlka Tectonic Zone form dykes or small bodies and sheets of leucogranite, and are geochemically distinct from the granites of the Bates region (see below). In the southeastern part of the Tjuni Purlka Tectonic Zone, Musgravian Orogeny granites lie within two structural corridors that separate rocks of the Wankanki Supersuite from later mafic intrusions. A northern, east-trending, structural corridor is dominated by early Musgravian Orogeny K-feldspar porphyritic leucocratic rocks in the monzogranitic to syenogranitic range, whereas a southern, northwest-trending corridor is dominated by petrographically similar late Musgravian Orogeny rocks. Large areas of the northwestern part of the Tjuni Purlka Tectonic Zone are interpreted to also comprise networks of these leucogranites which vein and engulf older rocks of the Wirku Metamorphics and Wankanki Supersuite (e.g. Evins et al., 2008).

In the area south of Latitude Hills, an early Musgravian Orogeny mesocratic orthopyroxene- and clinopyroxene-rich charnockitic intrusion, dated at 1198 ± 5 Ma (GSWA 185590; preliminary data), sporadically outcrops over ~25 km^2. This forms the largest single intrusion of Musgravian Orogeny granite found south of the Tjuni Purlka Tectonic Zone in the west Musgrave Complex. It contains a single hypersolvus feldspar phase which forms subhedral phenocrysts up to ~1 cm size, and locally comprises up to 40% of the rock.

As a group, granites of the Pitjantjatjara Supersuite are readily distinguished geochemically from the Wankanki Supersuite granites. Both are metaluminous and cover a similar range in silica, but compared to the Wankanki Supersuite granites, the Pitjantjatjara Supersuite granites at equivalent silica concentrations have lower Al_2O_3, CaO, Na_2O, ASI, Sr, MgO, and $Mg^\#$ (mol $Mg^{2+}/(Mg^{2+}$+ total Fe as Fe^{2+})), and higher K_2O, TiO_2, Fe_2O_3, P_2O_5, Pb, Rb, REE, and HFSE. Many granites of the Pitjantjatjara Supersuite are broadly charnockitic in the sense proposed by Frost and Frost (2008). These authors stress that orthopyroxene-bearing granites, as a group (i.e. charnockite-series rocks), have no specific compositional type, parentage, or tectonic environment, other than one that allows emplacement of relatively dry and hot magmas. In the terminology of Frost et al. (2001), all of the Pitjantjatjara Supersuite magmas are ferroan, and range from alkali-calcic to calc-alkaline. In contrast to the Wankanki Supersuite granites, these fall into the within-plate granite field (Fig. 8) on the tectonic discrimination diagrams of Pearce et al. (1984), and the A-type fields of Whalen et al. (1987) and Frost et al. (2001). The leucogranites (early and late) within the Tjuni Purlka Tectonic Zone, in particular, have very strongly developed A-type compositional characteristics and, compared with the other Pitjantjatjara Supersuite magmas at a similar silica value, are strongly enriched in HFSE and REE (particularly the HREE). Other than these southern leucogranites, the Pitjantjatjara Supersuite magmas show very close compositional similarities to a range of Ti- and P-rich charnockitic intrusive and extrusive rocks described by Kilpatrick and Ellis (1992) from a range of Proterozoic to Palaeozoic terrains. These rocks are now generally regarded as part of the A-type spectrum (e.g. Bonin, 2007; Frost and Frost, 2008) and retain a primary mineralogy that reflects extremely high crystallization temperatures, in some cases greater than 1000°C.

The Giles Event and the Warakurna Supersuite

All igneous rocks related to the c. 1075 Ma Giles Event are grouped into the Warakurna Supersuite. The supersuite crops out across approximately 1.5 million km^2 of central and western Australia, forming the Warakurna large igneous province (Wingate et al., 2004; Morris and

Pirajno, 2005). Included in this supersuite are layered mafic–ultramafic intrusions (Giles intrusions), mafic dykes, granites, and possibly remnants of bimodal volcanics (basalt and rhyolite) that intrude and unconformably overlie the Musgrave Complex. In the west Musgrave Complex, felsic rocks and large mafic intrusions attributed to the c. 1075 Ma Giles Event are mainly restricted in outcrop to the area within and to the southwest of the Tjuni Purlka Tectonic Zone (Figs 4 and 7). To the northeast, the only intrusions aged the same as the Giles Event are 10–50 m wide dolerite and gabbro dykes. In addition, instead of having a relatively short-lived and simple geological history, in the west Musgrave Complex at least, it now appears that extensive deformation accompanied a very complicated magmatic history (Evins et al., 2007, 2008), and that magmatism historically attributed to the Giles Event occurred as punctuated events over a period as long as 60 m.y.

Layered mafic–ultramafic intrusions

A clear distinction needs to be made between the layered mafic–ultramafic 'Giles intrusions', and the massive gabbro bodies that intrude them. The layered mafic–ultramafic intrusions form the west to west-northwest spine of the west Musgrave Complex (Fig. 4). The petrography of a number of these layered intrusions has been studied in detail by Daniels (1974) and Glikson et al., (1996), and they can be subdivided into those that are either broadly troctolitic (e.g. Bell Rock, Blackstone), peridotitic (e.g. Wingellina), or gabbroic (e.g. Michael Hills). The preserved thickness of the layered bodies reaches a maximum of ~10 km in the Jameson area, but the present outcrop extent clearly understates the original size of some of the intrusions. The Blackstone intrusion, for example, is actually the exposed northern limb of an upright west-trending structural syncline, and relicts of the southern limb are sporadically exposed approximately 20 km to the south, immediately north of the Cavenagh intrusion. It is also likely that the troctolitic Bell Rock, Blackstone, and Jameson-Finlay intrusions are tectonically dislocated parts of a single intrusion. If this is the case, then this intrusion could have originally been greater than 170 km long, 25 km wide, and 10 km thick.

The age of the layered Giles intrusions is poorly constrained. Sun et al. (1996) obtained a U–Pb zircon age of 1078 ± 3 Ma from a granophyric leucogranite thought to form part of the layering in the Bell Rock intrusion. This date, however, is identical to the age of locally common felsic dykes that elsewhere clearly truncate that layering and that were comagmatic with massive gabbros that also engulf the layered intrusions. We identified no granitic or pegmatitic granophyric rocks within the Bell Rock Range and no sample taken from there had Zr concentrations greater than 50 ppm. It is possible that the leucogranite from the Bell Rock intrusion is a localized sill, and that the 1078 ± 3 Ma date represents a *minimum* age for emplacement of the layered intrusion. If this is the case, then the maximum age constraint on the layered intrusions is a latest Musgravian Orogeny age of c. 1170 Ma, similar to the estimates of Gray (1971).

Massive gabbro and leucogranite

Bodies and dykes of massive, unlayered, gabbro locally intrude and engulf the layered intrusions (Fig. 4). These are particularly well exposed in the Murray Range, the West Hinckley Range and immediately northeast of the Michael Hills intrusion. Together, these gabbro bodies parallel the main northwest structural trend of the west Musgrave Complex, as a near-continuous feature locally offset by sinistral movement along west-trending faults, including the Mann Fault (Fig. 4) last activated during the Petermann Orogeny.

Leucogranite intrudes as dykes and also forms larger pluton-scale bodies such as the Tollu pluton, a circular intrusion to the south of Blackstone Range, which is ~12 km in diameter (Fig. 4). The granites are typically hornblende- and biotite-bearing, equigranular to porphyritic, quartz syenites, syenogranites, and lesser monzogranites and locally show well-developed rapakivi textures. Abundant leucogranite veins and dykes are spatially and temporally associated with the massive gabbros (Fig. 9). A leucogranite showing well-developed mixing and co-mingling textures with gabbro at Amy Giles Hill (Howard et al., 2006) has been dated at 1074 ± 3 Ma (Bodorkos and Wingate, 2008b). In the West Hinckley Range, locally mingled gabbro forms a km-scale fold with a steep northwest-trending axial plane intruded by syn-deformational leucogranite (including syn-magmatic mylonites; Howard et al., 2006) dated at 1075 ± 7 Ma (Kirkland et al., 2008e). Syn-mylonitic leucogranite has pooled into boudan necks in a northwest-trending mylonite immediately south of Charnockite Flats, and has been dated at 1075 ± 2 Ma (Kirkland et al., 2008f). These data effectively define a very narrow period of intrusion of massive gabbro, multi-phase intrusion of leucogranites, northwest-directed folding, and northwest-trending shearing, and confirm earlier suggestions by Clarke et al. (1995) that substantial deformation occurred during the Giles Event in the west Musgrave Complex. Granophyre forming part of the Skirmish Hill Volcanics, a felsic-dominated bimodal volcanic sequence in the far south of the west Musgrave Complex, has been dated at 1076 ± 6 Ma (GSWA 183847 — preliminary data). This sequence is possibly the surface expression of the c. 1075 Ma intrusions found to the north.

To the south of the Blackstone and Bell Rock intrusions (i.e Blackstone and Bell Rock Ranges) three large plutons (two leucogranite and one a concentrically zoned gabbro body) intruded during the Giles Event, lie on a northwest trend (Fig. 4). These intrusions include the 1072 ± 8 Ma (Kirkland et al., 2008g) South Hill pluton, the 1073 ± 6 Ma (GSWA 185583 — preliminary data) Tollu pluton, and the 1072 ± 8 Ma Saturn pluton (Redstone Resources, 2007, written comm.). These aligned bodies indicate structurally controlled contemporaneous intrusion of mafic and felsic magmas essentially coeval with the c. 1075 Ma event described above.

Granites related to the c. 1075 Ma Giles Event, and temporally associated with the massive gabbros, show strongly developed A-type compositional characteristic (Sheraton and Sun, 1995), similar in most respects to the early and late Musgravian Orogeny leucogranites that lie

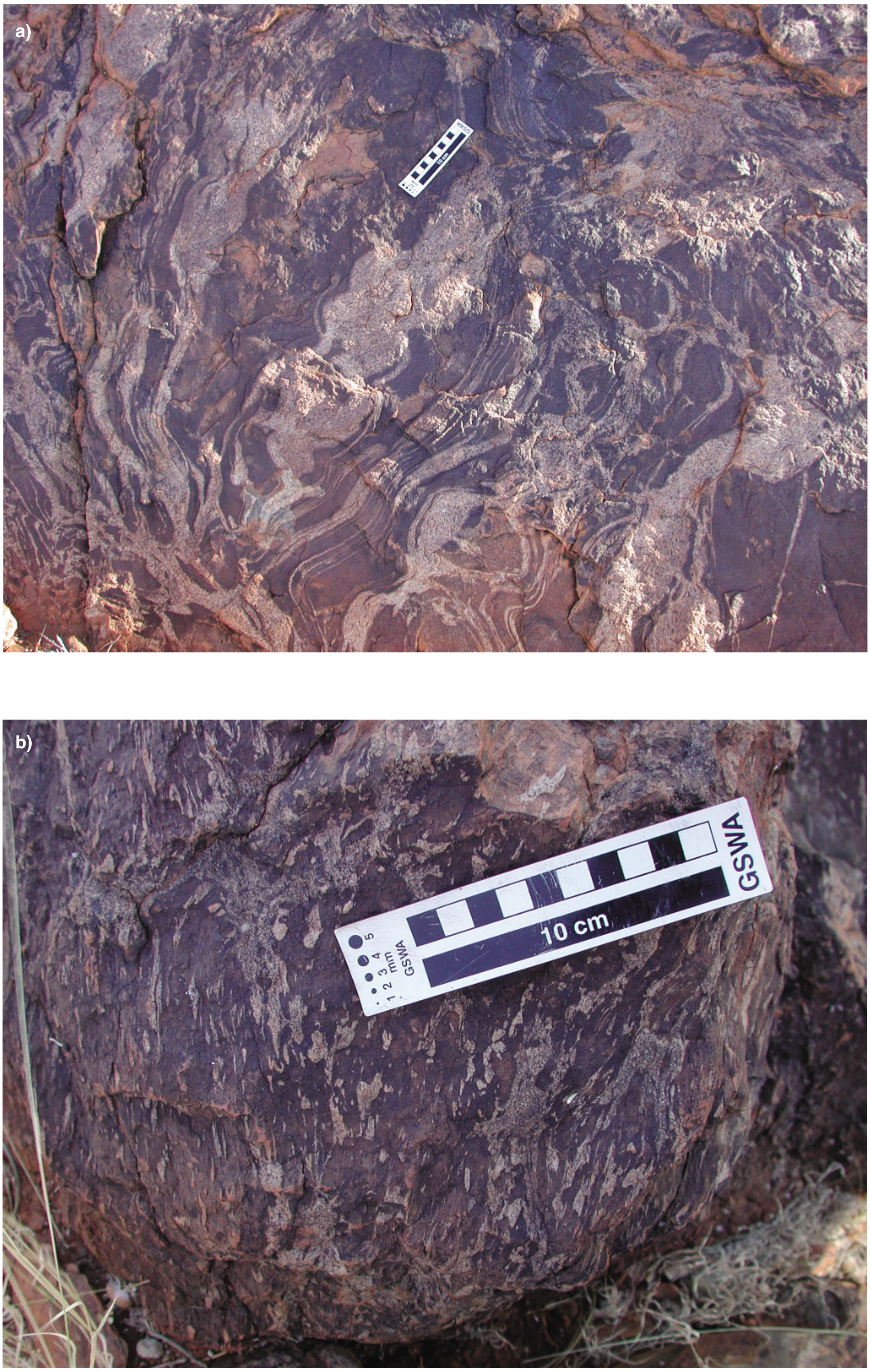

Figure 9. Magma mingling relationships and synmagmatic shear zones related to the Giles Event: a) agmatitic injection migmatite produced through intrusion of granite into largely solidified gabbro (North Hinckley Range — northern BELL ROCK); b) mingling of granitic and gabbroic magmas — note the cuspate margins that indicate magma–magma boundaries, as well as areas where felsic veins clearly cross cut the gabbro (Mount Finlayson — southeastern FINLAYSON)

within the Tjuni Purlka Tectonic Zone. They are ferroan and alkali-calcic and fall into the within-plate granite field (Fig. 8) on the tectonic discrimination diagrams of Pearce et al. (1984), and the A-type fields of Whalen et al. (1987), and Frost et al. (2001). Like the Musgravian Orogeny leucogranites, the Giles Event granites are significantly enriched in REE and HFSE compared to most of the Pitjantjatjara Supersuite magmas at similar silica values.

Bentley Supergroup

Felsic and mafic volcanic and volcaniclastic rocks and interlayered sedimentary rocks form the regionally extensive Bentley Supergroup (Daniels, 1974), which is expressed in the eastern part of the west Musgrave Complex as the Tollu Group (Daniels, 1974). As a result of our mapping and new age determinations, we have excised some rocks from the Tollu Group and placed them in the Kunmarnara Group (see below). Dating of the volcanic rocks has lead to the suggestion that they are comagmatic with the layered mafic–ultramafic Giles intrusion bodies and the granites (e.g. Compston and Nesbitt, 1967; Daniels, 1974; Glikson, et al., 1995; 1996), although such a relationship was disputed by Gray (1971), who considered the mafic rocks of the Giles intrusions to be significantly older than those of the Tollu Group.

The stratigraphy of the Tollu Group, as originally defined and described by Daniels (1971), included basal sandstones, pebbly sandstones, and conglomerates of the MacDougall Formation overlain by amygdaloidal basalts of the Mummawarrawarra Basalt. The basalts were, in turn, overlain by felsic lavas of the Smoke Hill Volcanics and then by basic to intermediate lavas of the Hogarth Formation. The Smoke Hill Volcanics and the Hogarth Formation only outcrop south of the Blackstone intrusion, within the core of an upright, west-trending, structural syncline, of which the Blackstone intrusion forms the northern limb. The MacDougall Formation and the Mummawarrawarra Basalt are mainly restricted to outcrops south of the poorly exposed southern limb of that syncline. As noted by Daniels (1974), however, xenoliths of Mummawarrawarra Basalt occur in the northern (basal) portions of the Blackstone and Jameson intrusions and to the north of the Hinckley intrusion, and indicate that the layered mafic–ultramafic intrusions were actually emplaced within, or at the top of, the Mummawarrawarra Basalt.

Volcanic rocks of the Smoke Hill Volcanics directly overlie the Blackstone intrusion, and depositional layering in the volcanic rocks parallels igneous layering in the intrusion. There is no evidence for a faulted contact between the intrusion and the volcanic rocks. In addition, dykes that are geochemically identical to the Hoggarth Formation cut the layering in the Cavenagh intrusion, to the south. These relationships indicate a significant time gap between deposition of the Mummawarrawarra Basalt and eruption of the Smoke Hill Volcanics. During that time gap, the layered mafic–ultramafic intrusions were emplaced within the Mummawarrawarra Basalt and the whole package was uplifted, eroded, and possibly folded before deposition of the Smoke Hill Volcanics and Hogarth Formation.

Age constraints on the Smoke Hill Volcanics (and the Tollu Group in general) have hinged on a 1078 ± 5 Ma date obtained by Glikson et al., (1996), from an outcrop previously mapped as rhyolite (Daniels, et al.,1970). Re-examination of that outcrop (in 2008) indicated that the rock was, in fact, a fine- to medium-grained leucogranite, petrographically and texturally identical to c. 1075 Ma leucogranites described above. However, vitric dacite sampled to the south of the Blackstone Range and north of Smoke Hill has yielded a preliminary age of 1026 ± 26 Ma (GSWA 187177 — preliminary data). This age is much more consistent with field relationships established within the region. Given that the Mummawarrawarra Basalt has to be older than c. 1078 Ma (the minimum age of the layered mafic–ultramafic intrusions), deposition of the basalt unit and of the overlying felsic volcanic rocks are separated by possibly more than 50 m.y. We have accordingly split the previously defined Tollu Group into the Kunmarnara Group (MacDougall Formation and Mummawarrawarra Basalt) and the overlying redefined Tollu Group (Smoke Hill Volcanics and Hogarth Formation; Fig. 4).

A sequence of supracrustal rocks with a similar lithological range to the Kunmarnara and Tollu Groups forms the Tjauwata Group that straddles the Western Australian and Northern Territory border to the north, and lies unconformably beneath the basal sedimentary rocks of the Amadeus Basin. Close et al. (2003) pointed out some stratigraphic, geochemical, and geochronological similarities between the Tjauwata Group and the combined Kunmarnara and Tollu Groups (i.e. the previously defined Tollu Group). In the context of our reinterpretation of age relationships between the Mummawarrawarra Basalt and the Smoke Hill Volcanics, it is interesting to note that in the Tjauwata Group, deposition of the 1075 ± 3 Ma Puntitjata Rhyolite (possibly an age equivalent of the 1076 ± 6 Ma Skirmish Hill Volcanics rather than of the Smoke Hill Volcanics) and the 1041 ± 2 Ma Wankari Volcanics was separated by a time gap of c. 30 m.y.

The maximum age of the Kunmarnara Group is poorly constrained. These rocks are not cut by Musgravian Orogeny granites and typically preserve a much lower (greenschist facies) metamorphic grade. This low metamorphic grade indicates that the depth at which the layered mafic–ultramafic intrusions were emplaced was less than ~15 km.

In summary, it is not clear that the layered mafic–ultramafic Giles intrusions actually form part of the Warakurna Supersuite (i.e. belong to the Warakurna large igneous province or the Giles Event). Voluminous massive gabbros and leucogranites, which together intrude the layered rocks, are clearly coeval with the Giles Event, but the voluminous mafic to felsic volcanic rocks of the redefined Tollu Group probably are not.

Mafic dykes

Glikson et al. (1996) and Howard et al. (2008) divided mafic dykes that have intruded the granulites and gneisses of the Musgrave Complex into at least six suites based on combinations of their field relationships, petrography, and major, trace, and isotope geochemistry.

The oldest dykes (c.1170 Ma), which belong to the Pitjantjatjara Supersuite, are the only dykes known to pre-date the Giles Event. A metamorphosed layered leucogabbro north of the Mann Fault yielded a U–Pb SIMS (SHRIMP) zircon age of 1190 ± 7 Ma (GSWA 174594; unpublished data). Several dykes at Mount Fanny intrude, and in places appear to be interleaved with, c. 1210 Ma early Musgravian Orogeny granites of the Pitjantjatjara Supersuite but are also intruded by c. 1170 Ma late Musgravian Orogeny granite. Mafic dykes of the Pitjantjatjara Supersuite have primitive mantle normalized incompatible trace element profiles which are LREE-enriched with primitive mantle normalized La/Sm [$La/Sm_{(PM)}$] of 4.1 to 4.5 and $Gd/Yb_{(PM)}$ of 1.4 to 1.9. They also have high Th/Nb values suggesting either significant enrichment of the magma source or crustal contamination. Two Nd isotopic analyses give epsilon Nd (ε_{Nd}) values of -2.42 and -6.20 (calculated at t = 1207 Ma, their maximum age) also suggesting variable crustal contamination.

The c. 1070 Ma dykes in Western Australia are contemporaneous with the Alcurra Dolerite and Stuart Pass Dolerite in the Northern Territory and show geochemical similarities with the former. The Alcurra dykes form part of the c. 1075 Ma Giles Event and the Warakurna large igneous province (Wingate et al., 2004). In the Musgrave Complex, they intrude felsic rocks of the Pitjantjatjara Supersuite, but typically have mylonitic contacts. These mafic dykes have a distinctive ophitic texture with pyroxene oikocrysts several cm in diameter and in Western Australia are commonly oriented east-southeast and dip 40º to 60º to the south. They have MgO contents of 5.2 to 6.8 wt% and have higher TiO_2 and P_2O_5, and lower SiO_2 than mafic dykes from other dyke suites within the Musgrave Complex. They are LREE-enriched ($La/Sm_{(PM)}$ = 2.6 to 3.3, $Gd/Yb_{(PM)}$ = 1.5 to 2.0) with slight negative Nb anomalies. ε_{Nd} values range from +0.89 to -0.92 (calculated at t = 1075 Ma), inside the range of +0.1 to -1.3 for Alcurra dykes of the Northern Territory (Scrimgeour et al., 1999).

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

An un-named plagioclase-rich suite of dykes clearly post-dates the ≥1078 Ma layered Giles intrusions, but their relationship with younger mafic dyke suites is uncertain. They are northwest to north-northwest trending subophitic to ophitic dolerite dykes with 60–65% plagioclase. The dykes have flat, unfractionated, primitive mantle-normalized trace element patterns with generally slight negative Nb anomalies, and. ε_{Nd} values for the two dykes are 0.58 and -2.06, calculated at t = 1075 Ma (the maximum age of the un-named plagioclase-rich dolerites).

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

The youngest mafic dykes to intrude the Musgrave Complex are a suite of un-named LREE-depleted dykes. Their orientation varies from east-northeast to northwest. A three-point Sm–Nd age determination has yielded a 747 ± 48 Ma isochron (GSWA, unpublished data) suggesting that the rocks are either part of the ~800 Ma magmatic event which produced the Gairdner Dyke swarm and Amata Dolerite of South Australia (Zhao et al, 1994) or a slightly younger suite, possibly contemporaneous with the 755 Ma Mundine Well Dolerite Suite of northwestern Australia (Wingate and Giddings, 2000). These are medium-grained, massive, ophitic to sub-ophitic textured metagabbros that are characterized by distinctive depletions in incompatible trace elements and by high ε_{Nd} values. The LREE-depleted dykes have La/Sm ratios of 0.8 to 1.5, and flat HREE profiles (Gd/Yb = 1.3 – 1.7), compared with the other suites of dykes. They also have a slightly negative Nb anomaly and ε_{Nd} values ranging from +4.58 to +4.60.

Additional felsic magmatic events

In addition to the felsic magmatic events outlined above, at least two younger periods of felsic magmatism affected the west Musgrave Complex. A thin southwest trending undeformed garnet-bearing aplite dyke cuts Musgravian Orogeny granites immediately to the east of Mount Fanny, and has been dated at 1004 ± 8 Ma (GSWA 183597; preliminary data). This age is similar to a c. 1000 Ma Sm–Nd isochron age determined on an olivine-bearing Kullal dyke from the Musgrave Complex (Glikson et al., 1996).

A series of undeformed tourmaline-bearing pegmatites intrude massive gabbro in the Murray Range, and have been dated at 622 ± 10 Ma (GSWA 187175; preliminary data). Such igneous ages are uncommon in Western Australia, but do broadly correspond to granitic intrusion within the Telfer region of the Paterson Orogeny, in northwestern Western Australia.

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

Late tectonic subdivisions

The Musgrave Complex has previously been separated into zones with different structural and metamorphic characteristics separated by major west- and west-northwest trending faults that were last active during the c. 550 Ma Petermann Orogeny (Camacho, 1989; Edgoose et al., 1993; Camacho and Fanning, 1995). In the north, the south dipping Woodroffe Thrust (Figs 3 and 7) separates the northern amphibolite facies Mulga Park Zone from the southern granulite facies Fregon Zone. Geochemical and geochronological similarities between these zones indicate similar tectonic histories (Camacho and Fanning, 1995).

Granites formed during the Musgravian Orogeny to the north of the west-trending Mann Fault have been multiply metamorphosed at granulite facies, and the majority have been deformed within the anatomising west to west-northwest trending and shallow-dipping network of mylonites (a result of the Petermann Orogeny) that cut this part of the Musgrave Complex. In the eastern part of the west Musgrave Complex, the Fregon Zone shows a marked north–south change in the pressure of granulite-facies metamorphism. To the north, high-pressure (10–14 kbar — White and Clarke, 1997; Scrimgeour and Close, 1999) metamorphism has masked the affects of earlier (Mugravian) metamorphism and has been related to the Petermann Orogeny (Scrimgeour and Close, 1999). To the south there is little evidence of metamorphic overprints formed during the Petermann Orogeny, however evidence for high-temperature metamorphism at much lower pressure is preserved (Clarke et al., 1995). This likely relates to both the early and late Musgravian Orogeny (i.e. between c. 1225 and 1200 Ma, and between c. 1190 and 1165 Ma). In the far east of this area, the boundary separating these two metamorphic styles lies close to the west-trending and near vertical Mann Fault, and Edgoose et al. (2004) speculated that this fault may further subdivide the Fregon Zone.

The west-northwest trending Fanny Fault (Fig. 7) delineates a distinct change in pressure-sensitive assemblages across it. In contrast to rocks to the southwest of this fault, granites and mafic rocks to the northeast typically contain metamorphic garnet, and paragneiss just east of the fault locally contains prismatic kyanite. A similarly oriented fault to the south of the Mann Fault, separates those Giles layered mafic–ultramafic intrusions considered to have intruded at low to medium crustal depths (mainly in South Australia — Goode and Moore, 1975; Ballhaus and Berry, 1991; Glikson et al., 1996) from those that were intruded at higher crustal levels. The Fanny Fault parallels the Tjuni Purlka Tectonic Zone, to the southwest, across which there are also several important geological changes. The most notable changes are in the distribution of granites of both the Wankanki and Pitjantjatjara Supersuites and in detrital age distribution patterns in older paragneisses. It is also clear that northwest-trending faults were active during both Musgravian Orogeny events and have localized magmatism during the c. 1075 Ma Giles Event — this is the case for both mafic magmas (e.g. the massive gabbros of the Murray Range) and leucogranites (e.g. the syn-mylonitic leucogranites in the West Hinckley Range). It is possible that these northwest- to west-northwest trending structures underwent significant vertical reactivation during the Petermann Orogeny.

Future work

Future fieldwork will concentrate on completing outcrop mapping of the entire west Musgrave Complex, including five full 1:100 000 geological map sheets (Cooper, Bentley, Mount Eveline, Golden Point, and Warburton Range) as well as partial coverage on several map sheets peripheral to these. Much of the area still to be mapped comprises outcrop of rocks that post-date the Musgravian Orogeny — primarily those loosely attributed to the Giles Event — including extensive outcrop of metasedimentary, metavolcanic, and metavolcaniclastic rocks of the Bentley Supergroup. Dating of these units, and comparisons of those dates with age data already obtained in areas mapped so far, will provide an opportunity to clarify geochronological and geological relationships between rocks traditionally attributed to the Giles Event.

There are several significant aspects of the work carried out up to the end of 2008 that require further work, either to complete the regional geological synthesis or to address unresolved questions. This future work will include:

- a detailed structural and metamorphic synthesis of the region linked to geochronology targeted at dating deformation and metamorphism.
- a more detailed evaluation of the whole-rock geochemical data collected on the range of meta-igneous rocks of all ages, aimed at evaluating specific source regions, basement terrains and the tectonic regimes within which the magmatic events occurred.
- precise dating of specific magmatic pulses of rocks traditionally attributed to the Giles Event. This includes directly determining the age of the layered mafic–ultramafic intrusions, regarded here as being older than c. 1078 Ma, and possibly as old as the youngest rocks of the Pitjantjatjara Supersuite. Also, those intrusions that carry significant nickel, copper and, to a lesser extent, platinum-group elements need to be characterized within the regional geological, geochronological, and geochemical framework that the west Musgrave mapping project is establishing.
- recently acquired gravity data needs to be combined with the aeromagnetic data and with the detailed geological data and used to construct a three-dimensional model of the west Musgrave Complex.

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