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PROVENANCE OF THE 1340–1270 Ma RAMARAMA BASIN IN THE WEST MUSGRAVE PROVINCE, CENTRAL AUSTRALIA

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

NGAANYATJARRA COUNCIL (Aboriginal Corporation)

Geological Survey of Western Australia

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Cover photograph: Detrital zircon grains from a gneiss (GSWA 194433) of the Cohn Hill – Mount Blythe area. Zircons from this sample underwent partial to near complete radiogenic–Pb loss duing a 1156 Ma metamorphic event, which also caused new zircon rim growth.

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Provenance of the 1340–1270 Ma Ramarama Basin in the west Musgrave Province, Central Australia

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Abstract

The Ramarama Basin is the oldest exposed basement of the west Musgrave Province. The basin comprises calc-alkaline volcanic and intrusive rocks of the 1345–1293 Ma Wankanki Supersuite interleaved with paragneisses of the Wirku Metamorphics. Most of the paragneisses had sedimentary precursors that were deposited between c. 1340 and 1300 Ma, in environments proximal to a possible volcanic arc (represented by the Wankanki Supersuite) or in the proximal portions of submarine fans adjacent to this arc. Wankanki Supersuite magmatism is restricted to the central and southwestern portions of the west Musgrave Province.

Detrital zircon age spectra from samples of Wirku Metamorphics and the ages of inherited zircons from younger intrusive rocks reveal younging trends within newly defined, northwest-trending geographic–tectonic zones. Dominant detrital and inherited-zircon age components range from c. 1570 Ma in the northeast to c. 1520 Ma in the centre to c. 1330 Ma in the southwest. Detrital zircons with Archean ages similar to those in the Yilgarn Craton are present to the southeast. A younger stratigraphic level of the Wirku Metamorphics, with maximum depositional ages as young as c. 1250 Ma, is restricted to western regions of the central domain, although it is dominated by 1400–1500 Ma detrital zircons.

Although igneous rocks older than 1345 Ma are rare in the west Musgrave Province, the presence of early Mesoproterozoic basement is implied by the abundance of detrital and inherited zircons of this age. The Nd- and Hf-isotopic evolution of nearly all rocks in the Musgrave Province indicates the presence of juvenile early Mesoproterozoic basement along with a minor Archean component beneath the current exposure level. Rare exposures of c. 1550 Ma orthogneiss elsewhere confirm the presence of basement of this age. However, the tectonic setting of this basement is poorly constrained.

The Ramarama Basin is interpreted as part of a relatively juvenile calc-alkaline magmatic arc (Wankanki Supersuite) with compositional similarities to Andean-style continental arcs. Constraints from this study are consistent with formation of the Ramarama Basin above a north-dipping subduction zone between the North and South Australian Cratons from c. 1340 to 1300 Ma.

Introduction

The Musgrave Province lies at the junction of the North, South, and West Australian Cratons (Fig. 1). As such, this triple-point is thought to mark the Mesoproterozoic amalgamation of those cratons and highlights that the Musgrave Province is one of the most important keys to the reconstruction of Proterozoic Australia. The magmatic rocks in the Musgrave Province are significantly younger than those in the Australian cratons. However, the basement of the Musgrave Province holds clues, in the form of detrital and inherited zircons, to the timing of amalgamation of Proterozoic Australia.

Geological surveys have established a broad lithological framework for the Musgrave Province (Daniels, 1974; Glikson et al., 1996; Edgoose et al., 2004), and provided a foundation for later targeted studies. These studies (PhD theses of Gray, 1971, Maboko, 1988, and Camacho, 1997) focused on Rb–Sr isotope systematics, regional geochronology, and the Petermann Orogeny, respectively. However, they did not emphasize the role of the Musgrave Province within a wider Proterozoic evolutionary context. The studies by White et al (1999), Wade et al. (2006, 2008), and Aitken and Betts (2008) highlighted temporal links to other Proterozoic terranes. Until recently, however, the regionally extensive geochemical, isotopic, and geochronological datasets necessary to further chronicle the tectonic evolution of this region have been lacking.

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 within Western Australia, herein referred to as the 'west Musgrave Province' (Fig. 2). This program has provided a large and regionally extensive dataset of new geochemical, geochronological, and isotopic data, underpinned by detailed geological mapping (Fig. 3).

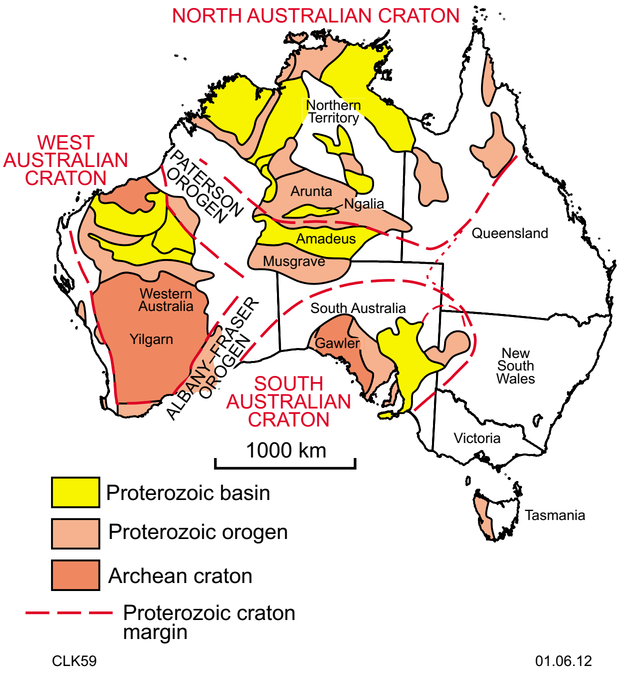

Figure 1. Location of the Musgrave Province relative to the North, South and West Australian cratons and their bounding orogens. Modified from Tyler (2005).

This Report focuses on one of the oldest rock units exposed in the west Musgrave Province: the Wirku Metamorphics and volcanic units of the Wankanki Supersuite. We present new geochronological, geochemical, and isotopic data on these units that elucidate their relationships with one another, and more importantly, their provenance. Through their provenance, we investigate the 'hidden' early Mesoproterozoic basement by combining U–Pb dating of detrital and inherited zircons. We also reassess existing data on early Mesoproterozoic basement orthogneisses throughout the entire Musgrave Province and conclude that these rocks are much more rare than generally thought. This has an important bearing on current tectonic models of the Proterozoic amalgamation of Australia by c. 1500 Ma (Wade et al. 2006, 2008; Cawood and Korsch, 2008; Payne et al., 2009). These models are based on the assumption that apparent 1600–1540 Ma orthogneisses formed in a juvenile magmatic arc that welded the North and South Australian Cratons. We define a basin (herein named the Ramarama Basin), which includes volcanic debris locally derived from what was possibly a magmatic arc between the North and South Australian Cratons during the much younger 1340–1300 Ma interval.

Regional geology

The Mesoproterozoic to Neoproterozoic Musgrave Province of central Australia is an east-trending belt about 800 km long and 350 km wide, bounded to the north and south by Neoproterozoic to Paleozoic basins (Fig. 2). Camacho (1997) separated the Musgrave Province into the Mulga Park Domain north of the Woodroffe Thrust and the granulite-facies Fregon Domain to the south (Fig. 2). The south-dipping Woodroffe Thrust juxtaposed subgranulite facies crust in the Fregon Domain against amphibolite facies crust of the Mulga Park Domain to the north (Camacho, 1997; Edgoose et al., 2004). Most rock units are difficult to correlate across this boundary. The main portion of the west Musgrave Province currently under investigation by GSWA is south of the Woodroffe Thrust and therefore lies almost entirely within the Fregon Domain (Fig. 2). This Report deals only with rocks of the Fregon Domain.

Three orogenic crust-building episodes are responsible for the formation of the west Musgrave Province between 1345 and 1020 Ma (Fig. 4). An older, 1600–1500 Ma basement is documented elsewhere in the Musgrave Province (Maboko et al., 1991; Camacho, 1997; Edgoose et al., 2004, Wade et al., 2006), although it is not exposed in the west Musgrave Province. The 1345–1293 Ma Mount West Orogeny (Howard et al., 2006) encompasses intrusion of dominantly felsic, I-type magmas of the Wankanki Supersuite and deposition of volcanic to clastic precursors of the Wirku Metamorphics, which filled the Ramarama Basin. Nearly half the present exposure of the Musgrave Province was formed during the 1220–1120 Ma Musgrave Orogeny, when granites and minor mafic rocks of the 1220–1150 Ma Pitjantjatjara Supersuite were emplaced in an intracontinental setting and at ultra-high-temperature metamorphic conditions that prevailed until at least 1120 Ma (Smithies et al., 2009a). The 1080–1030 Ma Giles Event marks the formation of the Ngaanyatjarra Rift (Evins et al., 2010). The Ngaanyatjarra Rift contains basal supracrustal units (the Kunmarnara Group) intruded or overlain by various mafic and felsic magmatic rocks of the Warakurna Supersuite.

The west Musgrave Province has recently been subdivided into three distinct tectonic zones, from northeast to southwest: the Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, and Mamutjarra Zone (Smithies et al., 2009a). The Tjuni Purlka Tectonic Zone is a broad zone of multi-generational (c. 1220, 1075, and 550 Ma) shearing that extends in a northwest direction across the west Musgrave Province (Fig. 3). Its boundaries were the locus for mafic and felsic magmatism during the 1080–1030 Ma Giles Event. The earliest stage of rifting in the Ngaanyatjarra Rift and subsequent emplacement of giant layered troctolite–gabbronorite–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 Walpa Pulka Zone to the north (Fig. 3), is a deep-crustal domain dominated by 1220–1150 Ma granite plutons of the Pitjantjatjara Supersuite that were emplaced during the Musgrave Orogeny. This zone contains high-pressure metamorphic assemblages preserved by rapid exhumation along east- and northwest-trending mylonitic and migmatitic shear zones related to the c. 550 Ma Petermann Orogeny (Scrimgeour and Close, 1999; Camacho et al., 1997; Raimondo et al., 2009). South of the Tjuni Purlka Tectonic Zone, the Mamutjarra Zone (Fig. 3) is dominated by 1345–1293 Ma calc-alkaline granites related to the Mount West Orogeny. The effects of the Petermann Orogeny in

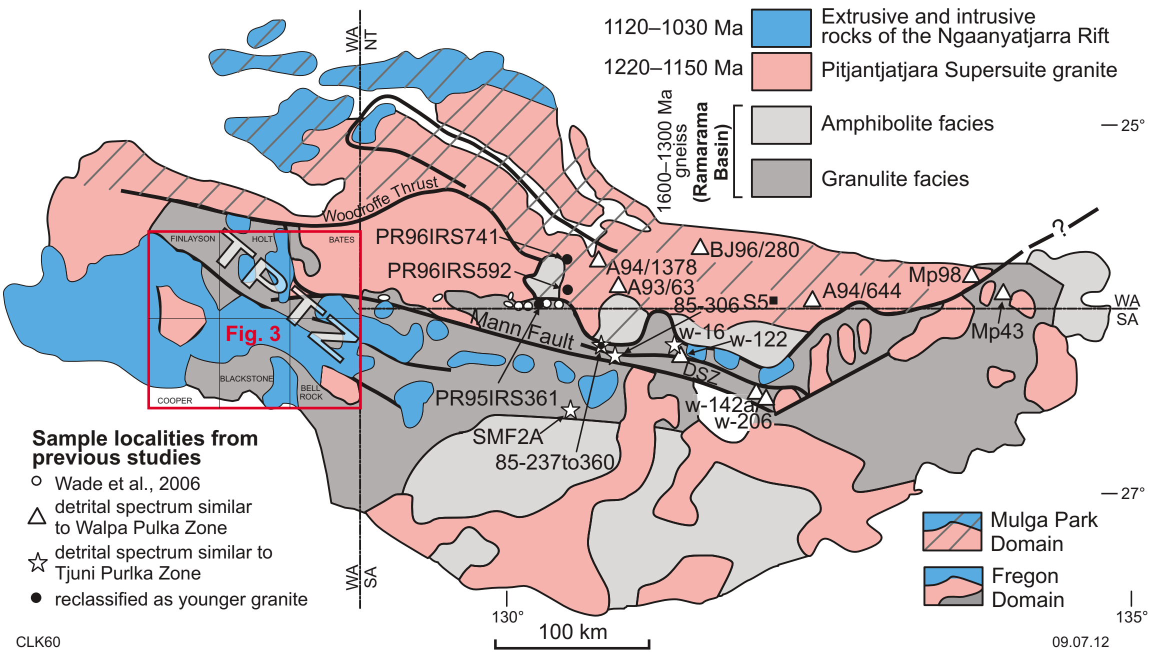

Figure 2. Simplified geological map of the Musgrave Province (after Edgoose et al., 2004) with sample localities from previous workers. DSZ = Davenport Shear Zone. TPTZ = Tjuni Purlka Tectonic Zone.

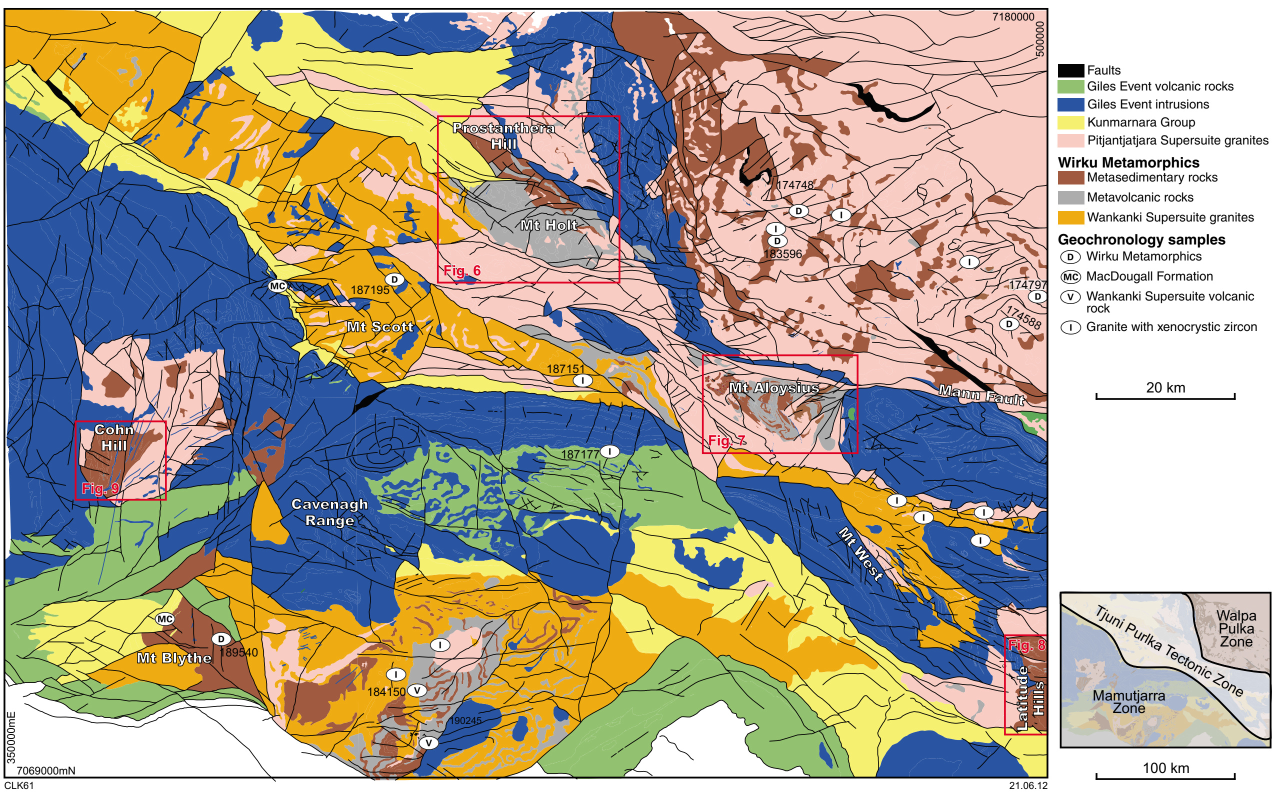

Figure 3. Geological map of parts of the west Musgrave Province, including the Bates, Bell Rock, Holt, Blackstone, Finlayson, and Cooper 1:100 000 map sheet areas. Numbers are GSWA sample numbers.

this zone are minimal. Smithies et al. (2009a) provided a recent summary of the geological evolution of the west Musgrave Province.

The basement of the Musgrave Province is thought to include intrusive components as old as c. 1600 Ma, and sedimentary and volcano-sedimentary gneisses (Gray, 1971, 1978; Gray and Compston, 1978; Maboko et al., 1991; Major and Conor, 1993; Camacho and Fanning, 1995; Camacho, 1997; Edgoose et al., 2004, Wade et al., 2006). The gneissic rocks are called the Wirku Metamorphics in the west Musgrave Province (Smithies et al., 2009a), although elsewhere they are grouped into the Birksgate Complex. The basement was intruded by felsic magmas of the Wankanki Supersuite during the 1345–1293 Ma Mount West Orogeny (Smithies et al., 2009a).

Mount West Orogeny, Wankanki Supersuite, and Ramarama Basin

Isolated outcrops of felsic gneiss with protolith ages between 1325 and 1300 Ma were identified by Gray (1971), Sun et al. (1996), and White et al. (1999) 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 form the most voluminous magmatic component older than 1100 Ma in the Mamutjarra Zone (Fig. 3; Howard et al, 2006; Smithies et al., 2009a,b; Evins et al., 2009). Crystallization ages of these rocks range from 1345 to 1293 Ma (Fig. 4; White et al., 1999; Smithies et al., 2009a), although most ages lie within a short interval between 1326 and 1312 Ma (Fig. 4). Howard et al. (2006) grouped these granitic and volcanic rocks into the Wankanki Supersuite and termed 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. Weakly metamorphosed examples preserve primary hornblende and biotite, and clinopyroxene cores within hornblende. Otherwise, the rocks are typically metamorphosed to granulite facies. We have interpreted several fine-grained, gneissic varieties of the Wankanki Supersuite as having volcanic protoliths that are interbedded with clastic precursors of the Wirku Metamorphics. Together, these volcanic units of the Wankanki Supersuite and clastic precursors of the Wirku Metamorphics filled the Ramarama Basin.

Musgrave Orogeny and Pitjantjatjara Supersuite

The Musgrave Orogeny is the oldest orogenic event to have clearly affected all areas of the west Musgrave Province. The 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 typically K-feldspar–porphyritic granites form large composite

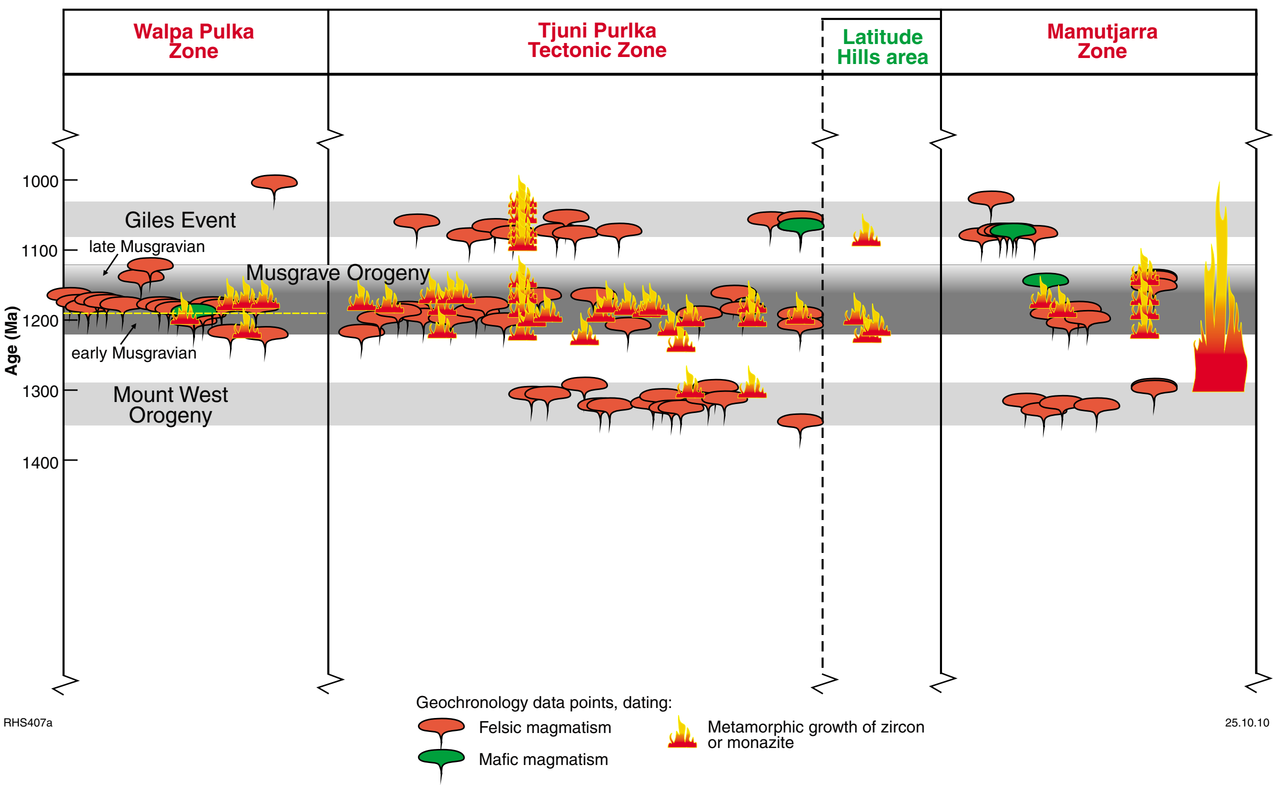

Figure 4. Time–space plot of 1400–1000 Ma magmatic and metamorphic events, based on ion microprobe (SHRIMP) U–Pb zircon ages. Sample order from left to right represents approximately northeast to southwest across the Musgrave Province (see Smithies et al., 2010 for additional information).

plutons that make up most of the Walpa Pulka Zone, and form smaller plutons and dykes within the Tjuni Purlka Tectonic and Mamutjarra Zones (Fig. 3). Where preserved, the primary mineralogy of these granites is anhydrous (quartz, plagioclase, K-feldspar, orthopyroxene, clinopyroxene, and biotite), 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 retrogression of pyroxene to hornblende, actinolite, and biotite in all granites.

Magmatism was accompanied by intense deformation and widespread ultra-high-temperature (UHT) metamorphism. Temperatures >900°C were maintained in the middle to lower crust for over 100 Ma during the 1220–1120 Ma Musgrave Orogeny (Fig. 5) in an intracontinental setting, making this orogeny unique among UHT belts around the world (Smithies et al., 2010). Smithies et al. (2010) proposed these circumstances because the pre-Musgrave Orogeny crustal architecture was characterized by relatively thin crust of the Musgrave Province between thicker Archean-cored West, North, and South Australian Cratons (Fig. 5). If this was the case, then the formation of the basement to the Musgrave Province and the Ramarama Basin played an important role in localizing younger orogenic events.

Pitjantjatjara Supersuite granites were locally metamorphosed to granulite facies during the 1080–1030 Ma Giles Event (Clarke et al., 1995) and by exhumation of the Walpa Pulka Zone (which preserves pressures up to 10–14 kbar) during the c. 550 Ma Petermann Orogeny (Scrimgeour and Close, 1999).

Giles Event, Ngaanyatjarra Rift, and Warakurna Supersuite

The Giles Event encompasses intrusion and extrusion of voluminous mafic to felsic magmas in the Musgrave Province from at least 1080 to c. 1030 Ma. This event is responsible for the formation of a long-lived, failed intracontinental rift called the Ngaanyatjarra Rift (Evins et al., 2010), which is almost entirely contained within the west Musgrave Province. Intrusive rocks emplaced during the Giles Event are part of the Warakurna Supersuite. The Warakurna Supersuite crops out across at least 1.5 million km^2 of central and western Australia, forming the Warakurna large igneous province (Wingate et al., 2004; Morris and Pirajno, 2005). In the Musgrave Province, this supersuite includes giant layered-mafic intrusions (Giles intrusions), mafic dykes, and granites. Extrusive rocks formed during the Giles Event are part of the Bentley Supergroup. Smithies et al. (2009a,b) divided the Tollu Group of the Bentley Supergroup into a basal rift succession of pebbly sandstone (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 at least six phases of intrusion during the Giles Event, including emplacement of giant layered-mafic-ultramafic intrusions and a 1075 Ma, crustal-scale, mafic magmatic shear zone.

The giant layered-mafic-ultramafic Giles intrusions were emplaced within the boundary between the Tjuni Purlka Tectonic and Mamutjarra Zone (Fig. 3) between 1120 Ma and 1080 Ma (Smithies et al., 2009a; Evins et al., 2010). The largest of these was dissected into the Bell Rock, Blackstone, Finlay, and Jameson Ranges, although it once occupied a volume of nearly 50 000 km^3. Large bodies of massive, unlayered gabbro emplaced at 1075 Ma form a near-continuous feature focused along synmagmatic shear zones that mark the northeastern boundary of the Tjuni Purlka Tectonic Zone along the Murray Range (Fig. 3). They are locally characterized by zones of co-mingling with felsic magmas. Mafic and felsic magmatism continued to be channelled along the boundaries of the Tjuni Purlka Tectonic Zone until eruption of felsic lavas of the Tollu Group from 1080 to 1030 Ma (Fig. 4). In the Tjuni Purlka Tectonic and Mamutjarra Zones, felsic intrusions of the Warakurna Supersuite range from dykes and sheets to plutons up to 12 km in diameter and were emplaced between 1075 and 1060 Ma (Evins et al., 2010). These locally rapakivi-textured granites typically have ferromagnesian mineral assemblages of clinopyroxene and hornblende ± biotite. The later stage of magmatism was accompanied by mafic dykes associated with orthomagmatic copper mineralization (Howard et al., 2009c).

The age of the Warakurna large igneous province is close to the timing of the assembly of the Rodinia supercontinent (1100–1000 Ma; Evins et al., 2010). The large igneous province has been interpreted as related to a mantle plume which impacted the lithosphere beneath the Musgrave Province at c. 1075 Ma (Wingate et al., 2004; Morris and Pirajno, 2005), although a geodynamic setting more complex than a single mantle plume may be indicated by the long time span and complexity of magmatism during the Giles Event (Smithies et al., 2009a; Evins et al., 2010).

Previous studies supported by geochronological data have regarded the Musgrave Orogeny and the Giles Event as distinctly separate tectono–thermal entities. However, Evins et al. (2010) have shown that the Giles Event spanned at least 50 Ma, starting prior to 1078 Ma and ending at c. 1025 Ma, whereas Smithies et al. (2010) have shown that thermal events related to the Musgrave Orogeny span c. 100 Ma down to a minimum age of c. 1120 Ma (Fig. 4). Accordingly, it might be legitimate to regard the Giles Event as a late component of the Musgrave Orogeny, together forming a combined high-temperature metamorphic and magmatic event spanning c. 200 Ma between 1220 and 1020 Ma.

Younger events

Following the Giles Event, magmatism was limited to mafic dykes and rare pegmatites emplaced at c. 1000 Ma (Howard et al., 2009a,b), mafic dykes at c. 825 Ma (Gairdner and Amata dykes; Glikson et al., 1996; Wingate et al., 2000), and c. 620 Ma tourmaline-bearing pegmatites

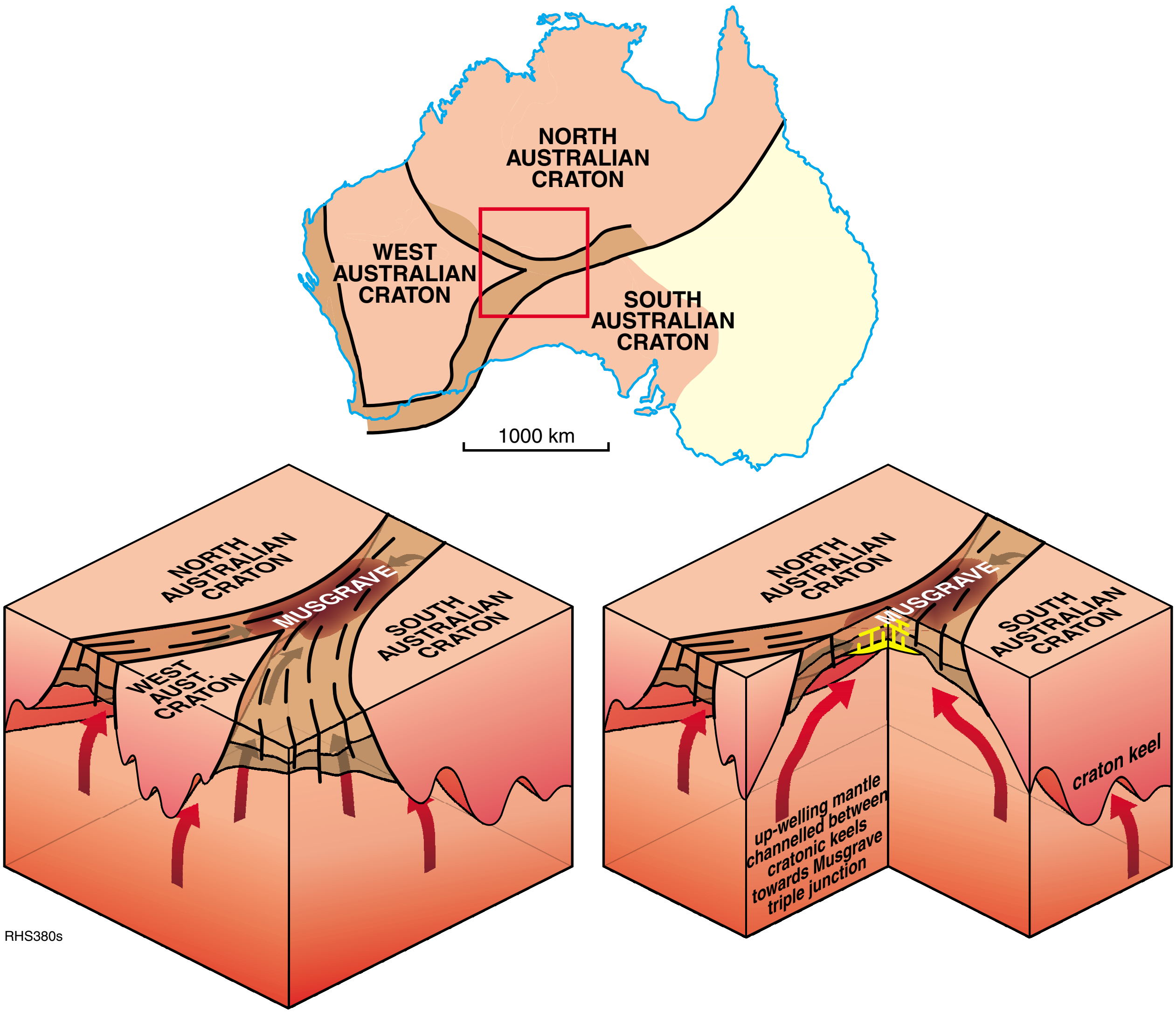

Figure 5. Block diagrams showing the possible role of crustal blocks in directing upwelling mantle during the Musgrave Orogeny (Smithies et al., 2010).

(Kirkland et al., 2011b). Collectively, however, these intrusions are volumetrically minor.

The Musgrave Province was deformed during the c. 550 Ma Petermann Orogeny (Edgoose et al., 2004), which coincides with the global Pan-African episode of plate reorganization that marks the assembly of Gondwana. The Petermann Orogeny appears to have been essentially intracratonic, with very little production of new crust (Edgoose et al., 2004). Granulites and high-grade gneisses of the Musgrave Province were thrust northwards over, or into, rocks of the Neoproterozoic basins (Camacho, 1997; Flöttmann and Hand, 1999; Edgoose et al., 2004) in a process that involved intracontinental channel flow (Raimondo et al., 2009). Significant vertical displacements juxtaposed lower crustal near-eclogite facies rocks against amphibolite facies rocks along the west- to west-northwest-trending Mann Fault in the south and the Woodroffe Thrust in the north (Camacho et al., 1997).

Basement of the Musgrave Province

Previous studies

Major and Conor (1993) grouped all rocks formed prior to, and metamorphosed during, the Musgrave Orogeny into the Olia Gneiss in the Mulga Park domain and Birksgate Complex in the Fregon Domain. The Olia Gneiss has not been correlated with the Birksgate Complex. Several studies have attempted to separate these rocks into components of distinct ages (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; Wade et al., 2005, 2006; Howard et al., 2009a,b). Gray (1971, 1978) and Gray and Compston (1978) reported a Rb–Sr isochron date of c. 1550 Ma for banded composite gneiss at Mount Aloysius (Fig. 3). They interpreted the protoliths of these gneisses to be supracrustal rocks dominated by volcanic material deposited at c. 1550 Ma. However, remapping and resampling of parts of Mount Aloysius has failed to yield any orthogneisses older than c. 1330 Ma. Instead, paragneisses with a dominant c. 1550 Ma detrital zircon age component are present (discussed below). Maboko et al. (1991), Camacho and Fanning (1995), Camacho (1997), and Edgoose et al., (2004) identified 1600–1540 Ma zircons from felsic gneisses in the central and eastern parts of the Musgrave Province (Fig. 2) that were thought to be locally derived from volcanic, volcaniclastic, and clastic protoliths (Major and Conor, 1993; Edgoose et al., 2004). Some of the gneisses have unmistakable granitic protoliths although they present bimodal and more complex zircon age components. In these cases, the older components were interpreted as crystallization ages for granitic protoliths as old as 1591 Ma (Camacho and Fanning, 1995; Edgoose et al., 2004).

Subsequently, Wade et al. (2006, 2008) sampled felsic and mafic gneisses of the Mann Ranges that were considered to be age-equivalent extensions of the 1600–1540 Ma gneisses to the east (Fig. 2). They suggested the samples represented a 1600–1540 Ma juvenile magmatic arc based on their subduction-like geochemical signature and juvenile Nd-isotope composition. This proposed arc plays a central role in Proterozoic tectonic models for the amalgamation of Australia (Wade et al., 2006, 2008; Cawood and Korsch, 2008; Payne et al., 2009). Wade et al. (2005) also showed that the far eastern Musgrave Province includes a succession of supracrustal gneisses that had sedimentary precursors deposited after 1400 Ma and contain reworked components from 1490–1400 Ma sources.

Wirku Metamorphics

The oldest rocks that crop out in the west Musgrave Province are supracrustal packages of the Wirku Metamorphics, deposited between 1340 and 1270 Ma, essentially at the same time as emplacement of the 1326–1293 Ma Wankanki Supersuite that intrudes them (Evins et al., 2009; Howard et al., 2009a,b; Smithies et al., 2009a). Therefore, the Wirku Metamorphics represent supracrustal rocks that are coeval with the Mount West Orogeny. Together with the Wankanki Supersuite, the Wirku Metamorphics form the Ramarama Basin, which subsequently served as infracrustal basement during the Musgrave Orogeny.

Rocks of the Ramarama Basin underwent granulite-facies metamorphism during the Musgrave Orogeny and are now strongly deformed composite gneisses with granoblastic textures. The Wirku Metamorphics and Wankanki Supersuite are best preserved as kilometre-scale, low-strain rafts referred to here, from northwest to southeast, as the Mount West, Mount Holt, and Mount Aloysius rafts (Figs. 3, 6, and 7, respectively). These rafts occur within Pitjantjatjara Supersuite granites of the Tjuni Purlka Tectonic Zone, and comprise about 7% of the area of the zone (Evins et al., 2009; Howard et al., 2009a,b). Culturally sensitive areas are centred on these rafts, and access is very limited. The Wirku Metamorphics also cover 50 km^2 in the Latitude Hills area at the southeast end of the Tjuni Purlka Tectonic Zone (Figs 3 and 8).

The Wirku Metamorphics are poorly exposed (<10% exposure) in the Walpa Pulka Zone owing to preferential weathering. Because deeper crustal levels are exposed in the Walpa Pulka Zone, one might expect to find fewer remnants of this supracrustal package. Their mapped distribution (covering about one-quarter of the Walpa Pulka Zone) is based mostly on geophysical interpretation (Howard et al., 2009a). Basement in the Mamutjarra Zone is dominated by orthopyroxene quartzofeldspathic gneisses with a single provenance similar in age and chemistry to the Wankanki Supersuite (discussed in detail below). The basement is sporadically exposed over a broad expanse south of the Cavenagh Range and locally intruded by Wankanki Supersuite granites (Howard et al., 2009b; Smithies et al., 2009a; Fig. 3). These quartzofeldspathic gneisses cover about 9% of the surface geology and, together with granites of the Wankanki Supersuite, comprise roughly half of the Mamutjarra Zone (Smithies et al., 2009a). Rare garnet ± hercynite ± cordierite quartzofeldspathic interlayers of likely sedimentary origin were sampled for detrital zircon geochronology; however none displays multiple provenances (see below). Another high-grade supracrustal package, similar to rocks at Latitude Hills, covers nearly 200 km^2 around Mount Blythe and Cohn Hill in the far west of the study area (Figs. 3 and 9). This package is dominated by garnet–orthopyroxene–sillimanite ± hercynite ± cordierite quartzofeldspathic pelitic and psammitic gneiss. At Mount Blythe, these gneisses are disconformably overlain by slightly tilted (dipping 30° west) non-metamorphosed sandstones and conglomerates of the MacDougall Formation at the base of the Ngaanyatjarra Rift. At Cohn Hill, the gneisses are intruded by, or are in fault contact with, younger rocks from the Ngaanyatjarra Rift (Evins et al., 2010).

Lithological divisions

On a regional scale, paragneisses of the Wirku Metamorphics typically yield lower gravimetric and aeromagnetic values than surrounding intrusions of the Pitjantjatjara and Warakurna Supersuites. On aeromagnetic images, the paragneisses exhibit a banded or folded appearance, with highs corresponding to magnetite-bearing arkosic metasandstones and hercynite-rich pelitic rocks and lows corresponding to anatectic leucogranites. Paragneisses of the Wirku Metamorphics can be broadly divided into the following main lithological units, ranging from pelitic to psammitic: garnet–hercynite–sillimanite–cordierite pelitic rocks, garnet–sillimanite–orthopyroxene pelitic rocks, garnet–bearing leucogranites (leucosomes), and arkosic metasandstones. The Wirku Metamorphics also contain orthopyroxene–plagioclase ± clinopyroxene ± quartz gneisses and granitic gneisses of probable igneous (volcanic) origin. Gneisses comprising more than half of these volcanic protoliths have been included within the Wankanki Supersuite and are discussed in the corresponding section below. As is the case with most gneisses, layering is defined by changes in composition.

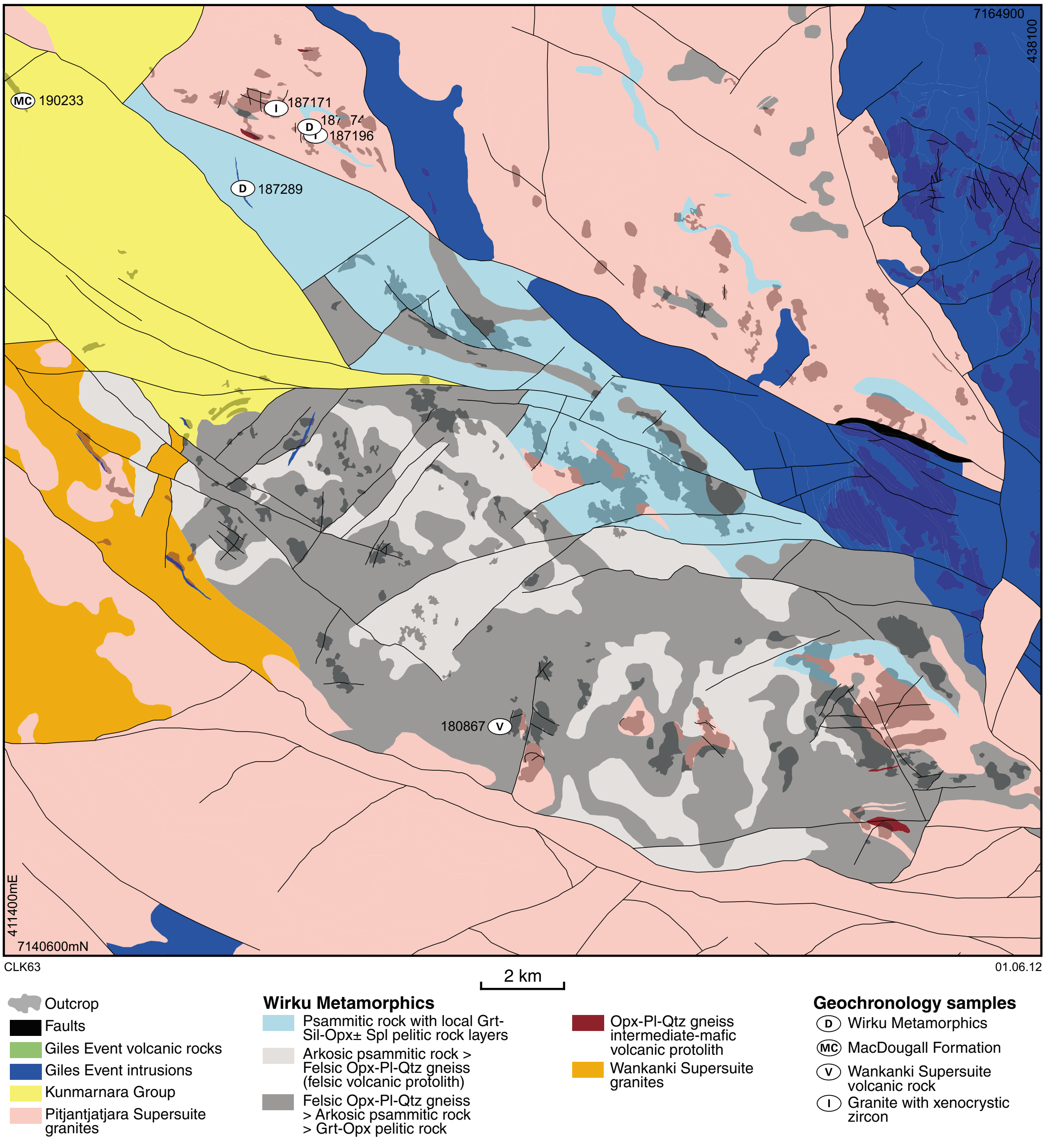

Figure 6. Geological map of the Mount Holt area.

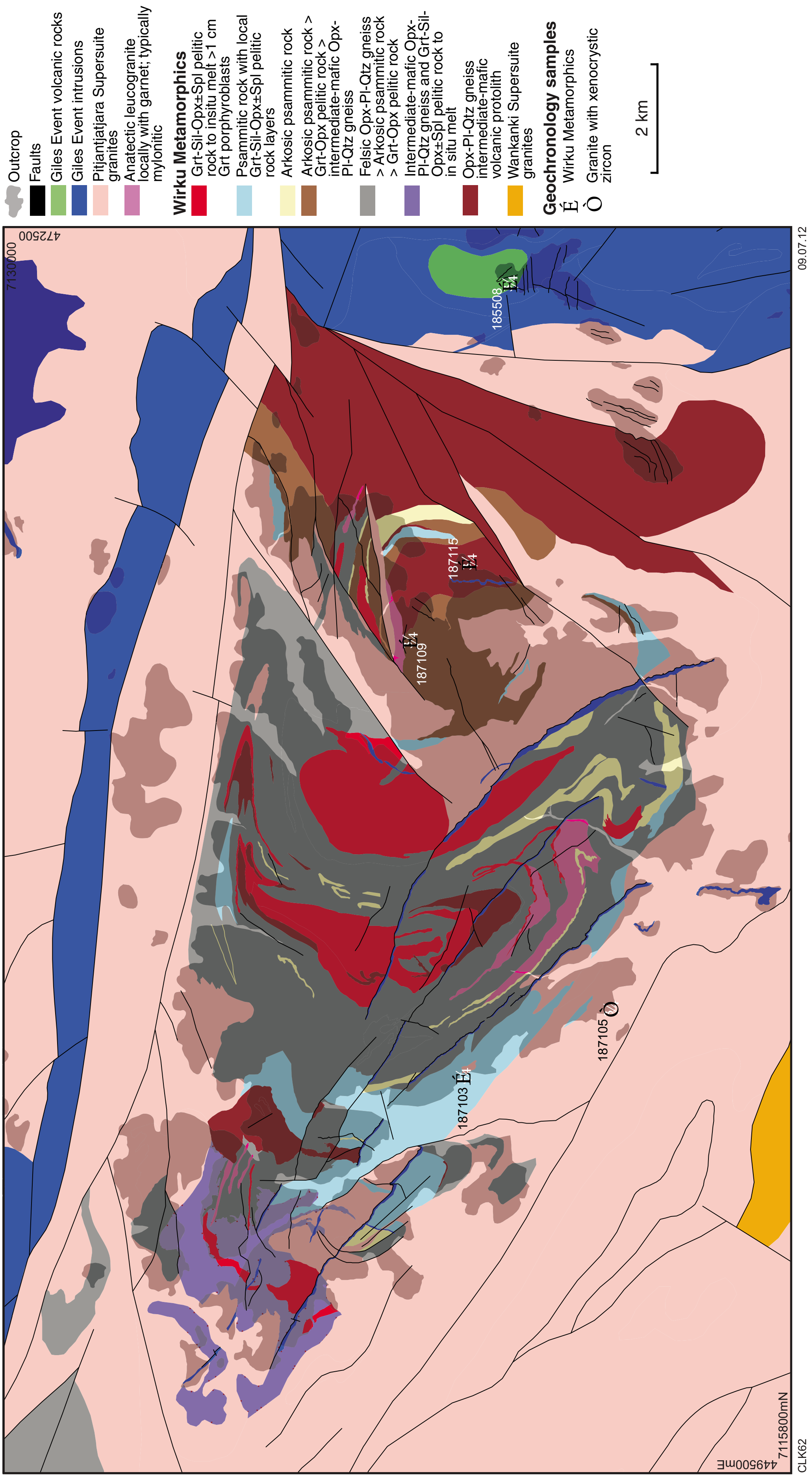

Figure 7. Geological map of the Mount Aloysius area.

Where compositional layering reaches the metre scale, and more than one composition becomes proportionately significant, the gneiss is mapped as a composite unit. Such is the case with felsic gneisses of the Wankanki Supersuite interpreted to have a volcanic protolith. These gneisses are intimately interlayered with metasedimentary gneisses of the Wirku Metamorphics to the extent that they never form a pure volcanic unit. Some overall changes in gneissic composition are gradational at map scale (>100 m). In these situations, composite transitional units were created to mark the gradational zone between the two main gneissic components.

Garnet–hercynite–sillimanite–cordierite pelitic rocks

Garnet–hercynite–sillimanite–cordierite pelitic gneisses occur as two textural varieties: a porphyroblastic variety with garnet porphyroblasts up to 5 cm wrapped by millimetre-scale syntectonic hercynite–garnet–cordierite–sillimanite symplectites (Fig. 10a–c) and a banded variety with lenses up to 3 cm thick and 20 cm long of garnet–hercynite–sillimanite–cordierite symplectite in a host of sillimanite–cordierite quartzofeldspathic gneiss (Figs. 10d, e). Both varieties occur as distinct centimetre- to metre-scale layers within metre-wide layers of quartzite in the Latitude Hills area (Fig. 8) and as 10–100-m-wide, north-trending layers in the Cohn Hill – Mount Blythe area (Fig. 9). In this latter area, these layers correspond to aeromagnetic highs. The banded type is most prevalent as centimetre- to metre-scale layers elsewhere.

Foliation in the gneisses is defined by 5-mm to 1-cm-wide alternating discontinuous mafic and felsic bands. The mafic bands are composed of up to 30% each of garnet (almandine), sillimanite, and/or cordierite, 10% hercynite, 5% opaque minerals, and locally biotite. Felsic bands are granitic in composition and contain significant proportions of perthite and antiperthite. Plagioclase composition is labradorite but it is slightly more sodic in the porphyroblastic variety of this gneiss. Garnet appears in two phases. The earliest phase is relatively enriched in heavy rare earth elements, contains fibrolitic sillimanite and hercynite inclusions, and forms the cores of garnet porphyroblasts. The second phase occurs as inclusion-free rims on early garnet cores and more commonly as <1 mm inclusion-free rims armouring hercynite–cordierite symplectites from the quartzofeldspathic matrix. Hercynite also occurs in two phases. The early phase is intergrown with magnetite, ilmenite, and rutile, and occurs as inclusions within garnet porphyroblasts and as millimetre-size blebs with a second phase of hercynite–cordierite symplectites surrounding them (Fig. 10c,e). Ghanitic varieties of spinel are present only in the porphyroblastic variety of this gneiss. In most cases, the hercynite–cordierite ± garnet symplectites form lenses or replace individual blades of sillimanite, although in the porphyroblastic variety at Cohn Hill, they form lenses that wrap around the earlier phase of garnet (Fig. 10c). Fine-grained orthopyroxene is found along some garnet rims and cracks. Locally, brownish-red biotite overgrows orthopyroxene and opaque minerals in the matrix. Collectively, these assemblages and compositions are indicative of UHT metamorphism (Kelly et al., 2006; King, 2008; Kelsey et al., 2009).

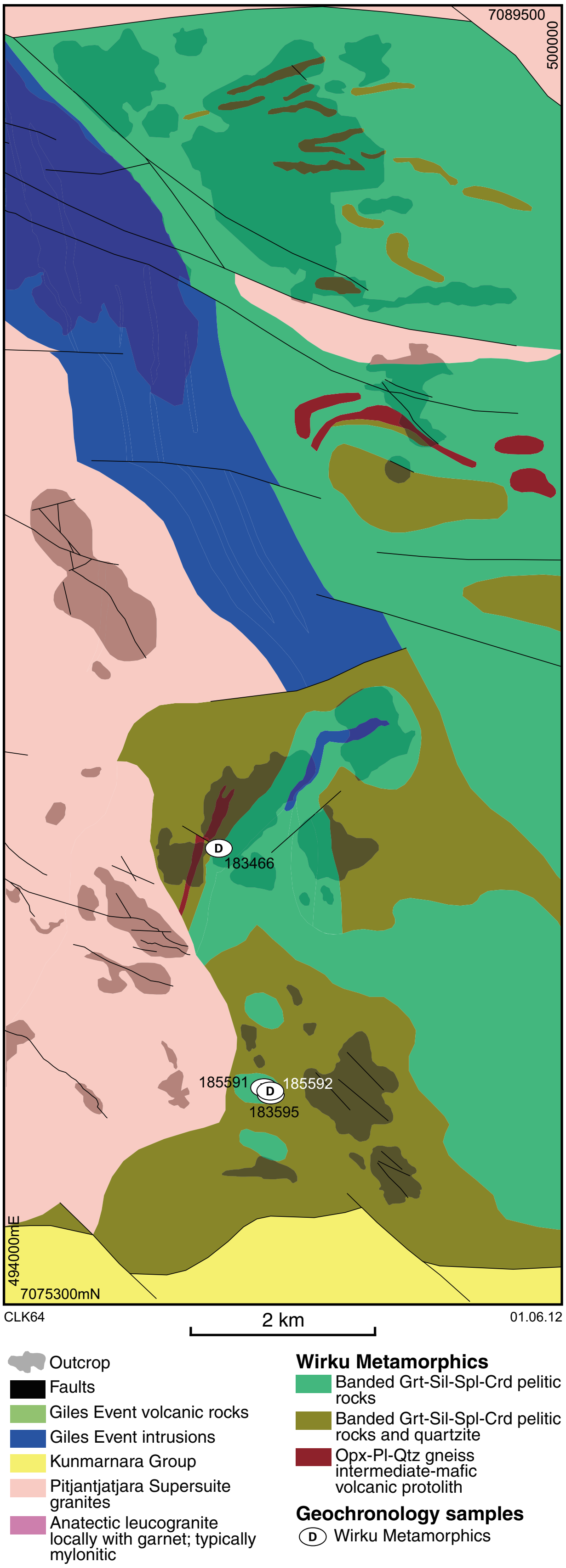

Figure 8. Geological map of the Latitude Hills area.

Samples of both porphyritic and banded varieties of garnet–hercynite–sillimanite–cordierite pelitic rocks were collected from the Latitude Hills and Cohn Hill areas (Fig. 3) for detrital zircon geochronology.

Garnet–orthopyroxene ± sillimanite pelitic rocks

Garnet–orthopyroxene ± sillimanite pelitic rocks are also found in porphyroblastic or lens-shaped varieties, with the porphyroblastic variety dominant. Garnet-bearing granites are always associated with these rocks and in most cases can be shown to be in situ leucosomes derived from their pelitic hosts. This combination of well-layered garnetiferous gneisses has been interpreted to represent pelitic rocks that have undergone partial melting. Although they are found in all domains, they make up most of the pelitic units in the Walpa Pulka Zone and Tjuni Purlka Tectonic Zone. Sillimanite is not present in these two tectonic zones, although garnet is abundant. At Cohn Hill, these pelitic rocks are similar to and adjacent to the hercynite-bearing gneisses, although they occur in low-strain domains, indicating that the presence of hercynite may be intimately linked to high strain.

Garnet porphyroblasts, up to 1 cm in diameter, contain biotite, quartz, plagioclase, and rare inclusions of hercynite and rutile. The porphyroblasts are mainly almandine in composition with Fe increasing towards the rims, and comprise >30% of the rock. A finer grained, more Fe-rich phase of garnet is associated with orthopyroxene in the matrix (Fig. 10f). Prismatic sillimanite can comprise up to 40% of the rock. Orthopyroxene may comprise up to 10% of the rock, is uniform in composition within each tectonic zone, and is in equilibrium with the finer grained phase of garnet. Retrograde biotite overgrows the garnet–orthopyroxene assemblage (Fig. 10f) and typically makes up <2% of the rock. K-feldspars are usually antiperthitic, and plagioclase is present in equal amounts of perthite and labradorite. Six samples of garnet–orthopyroxene ± sillimanite pelitic rocks were collected for detrital zircon geochronology with at least one representative from each tectonic domain.

Arkosic metasandstone

Leucocratic quartzofeldspathic gneisses are found throughout the Musgrave Province. The protoliths of some of these gneisses have been classified as arkosic sandstones and assigned to the Wirku Metamorphics because of their grain size and shape, laminations, along-strike extent, and the presence of coarser-grained quartz. Arkosic metasandstone occurs as metre- to kilometre-thick layers in the Mount Holt and Mount Aloysius rafts, where it corresponds to aeromagnetic highs, the patterns of which define macroscopic folds on the Mount Aloysius raft. Arkosic metasandstone also occurs as minor layers in the Latitude Hills succession. Minor centimetre-scale garnet-bearing layers are interleaved with the gneisses. The arkosic metasandstones are laminated on centimetre scales with a medium to strong foliation defined by all phases in the rock (Fig. 10i,j). They are composed of <3-mm, dismembered, undulatory quartz grains in a finer grained, granoblastic to dynamically recrystallized feldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Angular quartz fragments occur in less-recrystallized examples (Fig. 10k). Orthopyroxene is a minor component of the rock (up to 3%) and is altered to biotite. One sample (GSWA 174588) from the Walpa Pulka Zone contains 10% orthopyroxene with microgarnet coronae formed during the high-pressure Petermann Orogeny (Edgoose et al., 2004). Six samples of arkosic metasandstone were collected for detrital zircon geochronology.

Composite gneiss and transitional units

Most gneissic units described above are composite in that they contain rare layers of other Wirku Metamorphics or Wankanki Supersuite gneiss on the 1- to 10-m scale. However, in many cases, distinctly different gneissic units are interlayered in similar abundance at a scale that prohibits separation of the composite gneiss into its constituent units at map scale. Elsewhere, composite gneisses form gradational zones more than 100 m wide between two gneissic units. These composite gneisses make up significant portions of the Mount Aloysius and Mount Holt rafts, and broad expanses of the Mamutjarra Zone and Latitude Hills area.

A composite gneiss of pyroxene-bearing arkosic metasandstone and garnet–orthopyroxene pelitic to psammitic rock makes up the eastern third of Mount Aloysius (Fig. 6). The protolith of this composite gneiss is interpreted to be a turbidite with some volcanic input in the intermediate to distal portions of a submarine fan. Another composite gneiss of migmatitic garnetiferous pelitic rocks and intermediate to mafic granulites is folded around the nose of the Aloysius antiform (Fig. 6). The protolith of this composite gneiss is interpreted to be intermediate to distal turbidites injected by intermediate to basaltic subvolcanic sills. Yet another composite gneiss represents a gradational zone between the garnetiferous diatexite core of the Aloysius antiform (Fig. 6) and a supracrustal composite gneiss of the Wankanki Supersuite.

Two composite gneiss units make up the southern two-thirds of the Mount Holt raft (Fig. 7). Elsewhere they form interfaces between psammitic metasedimentary rocks and felsic metavolcanic rocks, most notably on Mount Aloysius. They are composed of pyroxene-bearing arkosic metasandstone interleaved with macroscopically identical felsic metavolcanic granulite of the Wankanki Supersuite. The two units differ in the proportion of which component dominates.

Two composite gneisses are found in the Latitude Hills area as gradational zones between more substantial gneissic units (Fig. 8). One forms an enclave of gneiss with a volcanic protolith between garnet–hercynite–sillimanite–cordierite pelitic rocks and composite pelitic–volcanic gneisses south of Latitude Hill. The other composite gneiss in the same area represents a transition from a more volcanic core to more pelitic gneisses surrounding it.

Finally, a composite gneiss unit underlies a large proportion of the southwestern BLACKSTONE map sheet where it is surrounded by coeval intrusions of the Wankanki Supersuite (Fig. 3). This gneiss is interleaved with garnet–hercynite–sillimanite–cordierite pelitic rocks and contains layers, up to 500 m thick, of its dominant

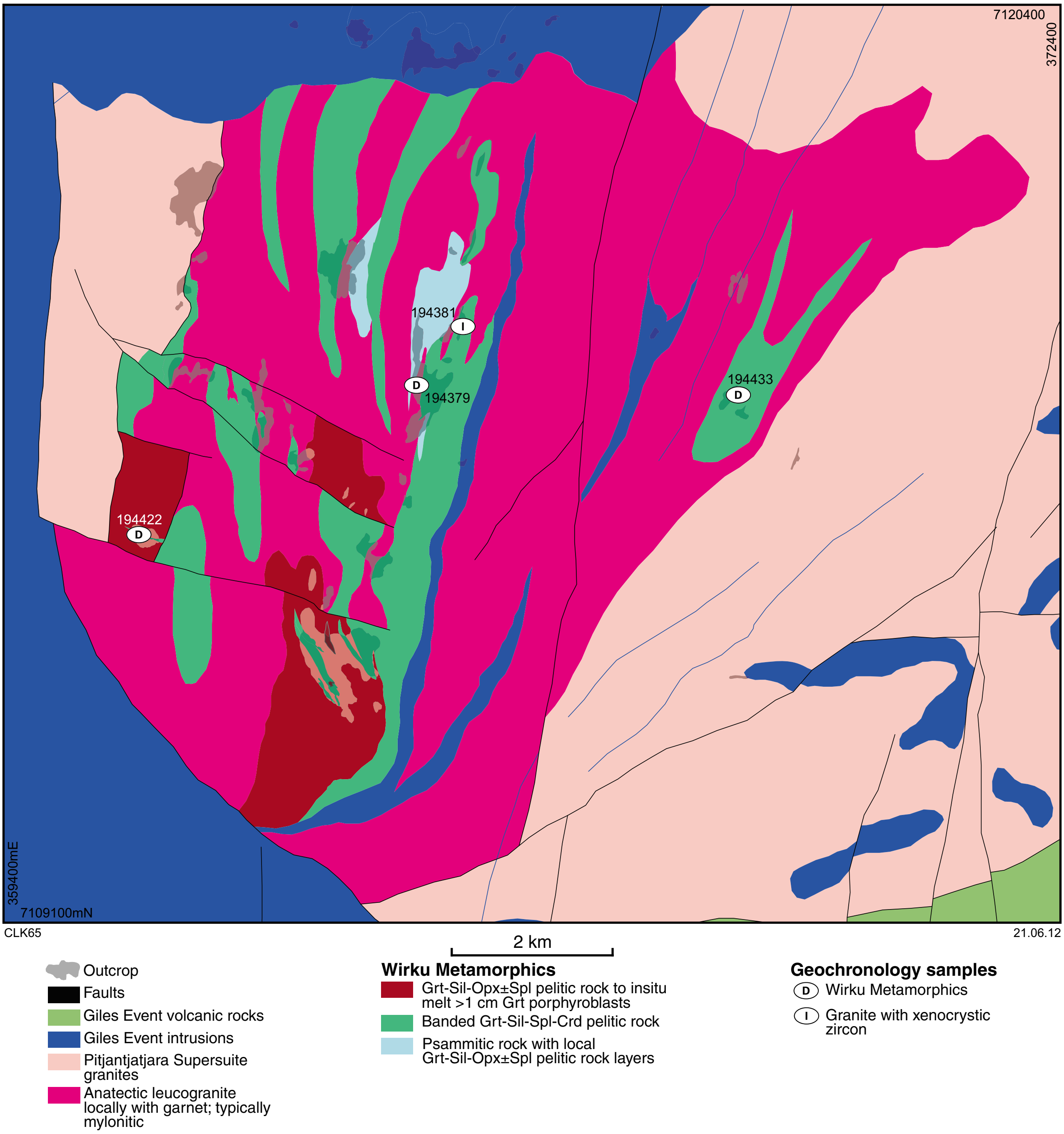

Figure 9. Geological map of the Cohn Hill area.

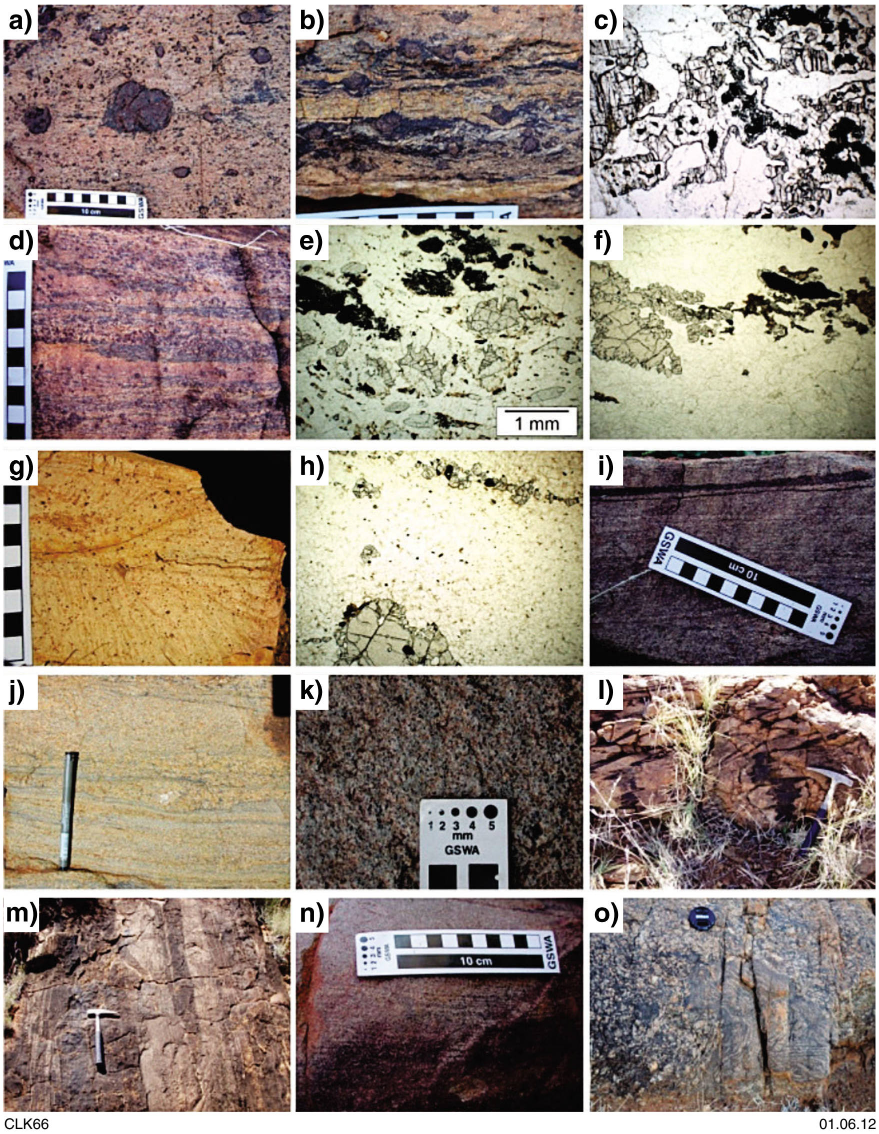

Figure 10. Field photographs of rocks of the Wirku Metamorphics and magmatic supersuites of the west Musgrave Province. a) Large garnet with black hercynite rims in garnet–hercynite–sillimanite –cordierite quartzofeldspathic gneiss near the base of Cohn Hill; b) pelite from Red Rock (Cohn Hill area) with garnet porphyroblasts wrapped by syntectonic black hercynite–garnet–cordierite symplectites surrounded by white blades of sillimanite; c) thin section (all in Figure 10 are in plane-polarized light) from pelite with large garnet porphyroblast and black-green hercynite porphyroblasts wrapped by successive coronae of finer-grained green spinel, cordierite, and garnet; d) garnet–hercynite (dark grey) – sillimanite (white blades) – cordierite bands in sillimanite–cordierite quartzofeldspathic gneiss from Minnie Hill (Cohn Hill area); e) thin section of a typical garnet–hercynite–sillimanite (sillimanite > symplectite; mostly replaced by hercynite–cordierite symplectites) – cordierite quartzofeldspathic gneiss from Red Rock; f) two stages of garnet in thin section from the dated garnet–orthopyroxene quartzofeldspathic gneiss sample GSWA 194381 from Minnie Hill. Orthopyroxene (brown and green) is in equilibrium with the later stage of garnet and overgrown by retrograde brown biotite; g) mylonitic, garnetiferous, anatectic leucogranite west of Red Rock; h) thin section of garnetiferous anatectic leucogranite from Minnie Hill; i) laminated arkosic psammite, located 6 km northeast of Mount Fanny in the Walpa Pulka Zone. There is a pelitic layer at the top and angular quartz grains near the bottom. GSWA 174748 is a more pelitic sample from this locality; j) centimetre-scale screens of psammitic rock in Pitjantjatjara Supersuite granite (g) from the Walpa Pulka Zone; k) quartz (dark grey) rich psammitic rock from Mount Holt; l) folded granitic gneiss (felsic volcanic) from Mount Aloysius, with intermediate to mafic orthopyroxene–plagioclase ± quartz gneiss (mafic volcanic) interlayers; m) orthopyroxene–plagioclase ± quartz gneiss with transposed felsic leucosome; n) typical appearance of homogenous felsic volcanic member of the Wankanki Supersuite from Mount Holt. Compare with photograph i) of arkosic psammitic rock; o) folded raft of Wankanki Supersuite volcanic rock from between Mount Aloysius and Mount Holt with cuspate margins enveloped by nearly coeval porphyritic Wankanki Supersuite granite.

psammitic component. It contains equal proportions of psammitic metasedimentary rock and intermediate volcanic rock with minor garnet–hercynite–sillimanite–cordierite pelitic layers. It also contains variably transposed, centimetre-scale, garnetiferous anatectic leucosomes.

Anatectic leucogranites derived from the Wirku Metamorphics

All the above units are gneissic, recrystallized, and variably migmatized. Large areas of local and in situ anatectic leucogranite generated by metamorphism of the Wirku Metamorphics during the Musgrave Orogeny are assigned to the Pitjantjatjara Supersuite (Figs 3, 6, and 9). Being very leucocratic, these granites correspond to aeromagnetic lows and typically appear white at hand-specimen and outcrop scales. They commonly form ridges where they are mylonitized or silicified. The granites underlie the majority of the Cohn Hill region, where they are garnetiferous, typically silicified, uniformly mylonitic, and form more prominent outcrop compared to pelitic paleosomes (Fig. 9). On Mount Aloysius, anatectic leucogranite forms layers up to 300 m wide that trace an earlier fold generation to the Mount Aloysius antiform (Fig. 7). In the Tjuni Purlka Tectonic Zone and Latitude Hills areas, the leucogranite forms variably transposed centimetre- to metre-scale layers in other units of the Wirku Metamorphics. This granite is quartz-rich (up to 50%) and ranges from syenogranite to monzogranite. Although syenogranite is dominant, most of the paleosome sources are biotite-poor and have more plagioclase than K-feldspar. The composition is expressed as a medium- to fine-grained, moderately foliated to mylonitic arrangement of dynamically recrystallized quartz (always undulatory and typically sutured), plagioclase, and K-feldspar. Less-deformed varieties display interlocking textures between the felsic components. In rare cases the granite may be pegmatitic. The granite is always very leucocratic with only trace amounts of opaque minerals rimmed by biotite, although rare 1-cm-wide laminae may contain up to 5% orthopyroxene, 2% garnet, 2% opaque minerals, and 1% brown biotite. Locally the rock has a spotted appearance caused by up to 1 cm subhedral, inclusion-free, pink syn- to post-tectonic garnets in the Cohn Hill area, or up to 2 cm, grey irregular quartz lenticles typical of the Tjuni Purlka Tectonic Zone (Fig. 10g,h).

Anatectic leucogranite was sampled from the southern flank of Mount Aloysius, the Latitude Hills area, and the Cohn Hill area, to date migmatization and identify the degree of zircon inheritance from adjacent metasedimentary rocks. The inherited zircons are treated as detrital zircons below because these granites are interpreted to be in situ melts.

Geochemistry of the Wirku Metamorphics

The majority of Wirku Metamorphics sampled by GSWA for geochemistry are peraluminous (Fig. 11b). Most metasedimentary rocks in the Latitude Hills area and garnet-rich pelitic rocks around Mount Aloysius and Mount Holt in the Tjuni Purlka Tectonic Zone are highly peraluminous, with an aluminium saturation index (ASI) >2. Only a single example of highly peraluminous paragneiss was found in the Walpa Pulka Zone and Mamutjarra Zone (Fig. 11b). The Wirku Metamorphics are distinguished geochemically from most igneous suites of the western Musgrave Province by their relatively low Eu and K_2O concentrations (Fig. 11a). However, they are similar in composition to the Wankanki Supersuite. In particular, volcanic units interleaved with the Wirku Metamorphics are difficult to distinguish compositionally from, and are the same age as, the Wankanki Supersuite (Fig. 11). Although many dated samples of the Wirku Metamorphics contain detrital zircons (presented below) coeval with the Wankanki Supersuite, some do not, yet they remain chemically very similar to the Wankanki Supersuite. The only chemical distinction that can be made between the Wirku Metamorphics and the Wankanki Supersuite is the high amounts of Zr in some Wirku Metamorphics samples (Fig. 11c). High-Zr samples, however, are not the most peraluminous, suggesting that the Zr enrichment may be due to zircon concentration by sedimentary processes.

Wankanki Supersuite

Only gneisses of the Wankanki Supersuite that are interpreted to have volcanic protoliths are considered in this study. These are typically intimately interlayered with metasedimentary gneisses of the Wirku Metamorphics and are not known to form a pure volcanic unit. Together with arkosic metasandstones of the Wirku Metamorphics, Wankanki Supersuite volcanogenic gneisses form ridges that delineate the Mount Aloysius antiform (Fig. 7) and make up over two-thirds of the Mount Holt raft (Fig. 6). Volcaniclastic units of the Wirku Metamorphics are locally intruded by porphyritic granites of the Wankanki Supersuite in the Tjuni Purlka Tectonic Zone. Where this occurs, rafts of Wankanki Supersuite volcanic rocks are folded, and contacts with their relatively undeformed host granites are diffuse and cuspate (Fig. 10o). This gives the impression that magmas of the Wankanki Supersuite intruded their volcanic carapace at the currently exposed structural level.

This composite gneiss is composed of 1- to 10-m-scale layers of felsic granulite interleaved with metre-scale metasedimentary layers of the Wirku Metamorphics including garnet–orthopyroxene ± sillimanite pelitic rocks (typical of Mount Aloysius) and arkosic metasandstone (typical of Mount Holt). The felsic volcanic granulite component of this gneiss is laminated on centimetre scales with a medium to strong foliation defined by all phases in the rock (Fig. 10n). It is typically syenogranitic, and composed of a fine-grained granoblastic to dynamically recrystallized quartzofeldspathic groundmass with significant antiperthite, perthite, and local myrmekite. Rare, relict 1-mm plagioclase phenocrysts can be seen in thin section. Orthopyroxene is a minor component of the rock (up to 3%), and is altered to biotite. This gneissic component is macro- to microscopically and compositionally identical to some arkosic metasandstones of the Wirku Metamorphics, apart from the absence of quartz clasts and the presence of rare relict 1-mm plagioclase phenocrysts.

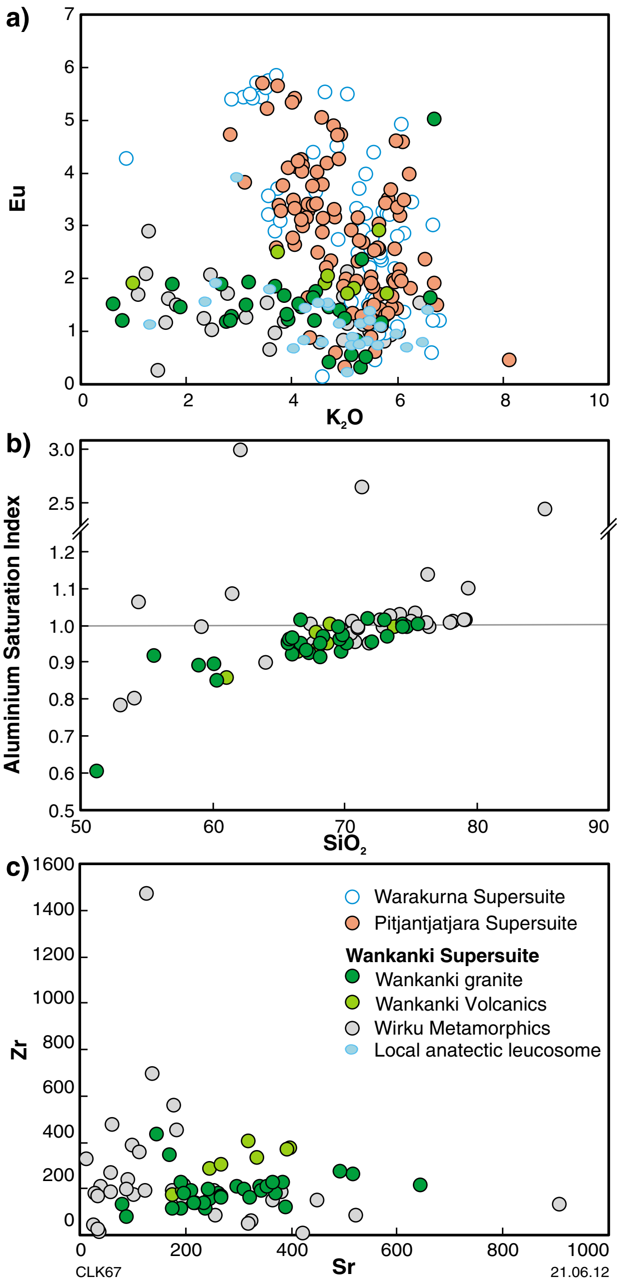

Figure 11. Chemical comparison of the Wirku Metamorphics and magmatic supersuites of the west Musgrave Province. The legend in c) applies to all three diagrams.

Felsic granulite of the Wankanki Supersuite was sampled in three localities to date eruption of its volcanic protolith. One sample was collected 10 km south of Mount Holt where it is interleaved with arkosic metasandstone. Two samples were obtained 8 km apart on the southwest corner of the BLACKSTONE map sheet, where the felsic granulite contains centimetre-scale garnet–hercynite–sillimanite–cordierite pelitic interlayers.

Although less voluminous than the felsic gneisses, mafic gneisses of the Wirku Metamorphics typically form thick, homogeneous layers. Although presently classified with the Wirku Metamorphics, their protoliths appear to be volcanic and they are likely related to the Wankanki Supersuite. This rock is a medium-grained orthopyroxene–plagioclase ± quartz granulite gneiss ranging from intermediate to mafic composition. It is laminated to banded on a millimetre to centimetre scale with banding defined by orthopyroxene content. Orthopyroxene and plagioclase form a granoblastic texture with or without quartz. Orthopyroxene content varies from 20 to 50% and is inversely proportional to quartz content, as quartz makes up to 10% of the rocks with 20% orthopyroxene, and is absent from most rocks with >40% orthopyroxene. Locally, this rock is strongly migmatized. In the nose of the Mount Aloysius antiform (Fig. 6), the rock contains screens of garnetiferous pelitic rocks of the Wirku Metamorphics and is contaminated with garnet throughout.

Geochemistry of the Wankanki Supersuite

The granites and associated volcanic units of the Wankanki Supersuite are metaluminous (ASI = 0.85–1.02), calc-alkaline, I-type rocks (Fig. 11b). They show a large range in SiO_2, from 58.95 to 76.76 wt%, with a compositional gap from 60.33 to 65.79 wt%, which separates rare tonalites and granodiorites from more abundant monzogranites and syenogranites (Fig. 11a). They show a strong compositional similarity to Phanerozoic granites of the Andean continental arc, including strong enrichments in Ba and relative depletions in Nb. Unsurprisingly, rocks of the Wankanki Supersuite consistently fall within the field for volcanic arc granites in tectonic discrimination diagrams (Pearce et al., 1984), and they differ in this respect from most other granites in the west Musgrave Province, which lie within the field of within-plate granites. The single-provenance quartzofeldspathic gneisses described above are geochemically similar to the Wankanki granites (Fig. 11a) and hence are likely to be the volcanic or volcaniclastic equivalents of these granites (Smithies et al., 2009a).

Ion microprobe (SHRIMP) U–Pb zircon geochronology

Twenty-three samples for geochronology were collected from the Wirku Metamorphics and metavolcanic rocks of the Wankanki Supersuite to determine the age of the oldest exposed basement in the west Musgrave Province. Obvious sedimentary units of the Wirku Metamorphics, such as the pelitic rocks described above, were sampled for detrital zircon geochronology to determine their depositional age, provenance, and any affinity their provenance might have with surrounding tectonic domains. Most samples showed textural evidence of high-grade metamorphism. Zircon rims were targeted to date these metamorphic events.

The protoliths of felsic granulites representing the arkosic metasandstones and garnet–orthopyroxene pelitic rocks of the Wirku Metamorphics and metavolcanic rocks of the Wankanki Supersuite were unclear in the field. Their structural setting, composition, and appearance are very similar to gneisses considered to be basement to the west Musgrave Province (Gray, 1971, 1978; Gray and Compston, 1978; Maboko et al., 1991; Camacho, 1997; Edgoose et al., 2004, Wade et al., 2006). These rocks were sampled with the expectation that they would yield crystallization ages older than 1500 Ma. The combination of U–Pb zircon geochronology and whole-rock Sm–Nd isotope and geochemical studies of these possible orthogneisses was intended to test the proposition that a hypothetical juvenile island arc existed in the Musgrave Province between 1500 and 1600 Ma (Wade et al., 2006, 2008).

The sections below summarize the sensitive high-resolution ion microprobe (SHRIMP) U–Pb geochronology of each sample. Analytical details are provided in the cited GSWA Geochronology Record for each sample, and documented in more detail by Wingate et al. (2008) and Wingate and Kirkland (2009, 2010, 2011). Except where noted otherwise, analyses that are >5% discordant, indicate high common Pb, or represent mixtures of core and rim material, are excluded; complete accounts are provided in the cited Geochronology Records. In general, reference to 'concordant' results indicates analyses that are <5% discordant (as defined in Wingate and Kirkland, 2011). Dates based on individual analyses are quoted below with 1σ uncertainties; mean ages based on pooled analyses are quoted with 95% confidence intervals and most are accompanied by values of mean square of weighted deviates (MSWD). Pb* is radiogenic (i.e. common-Pb-corrected) Pb. Table 1 is a summary of results from all Wirku Metamorphics and Wankanki Supersuite samples described below. Probability density diagrams (Figs 12 and 13) illustrate the age spectrum for each sample. Combined spectra for each geographic domain are presented in Figure 14.

Wirku Metamorphics

Walpa Pulka Zone

The Wirku Metamorphics of the Walpa Pulka Zone are dominated by arkosic metasandstones with lesser garnet–orthopyroxene pelitic rocks that typically occur as metre-scale or smaller xenoliths in Pitjantjatjara Supersuite granitic rocks. Well-layered, continuously layered, garnet-rich, peraluminous rocks were sampled for detrital studies. Two samples (GSWA 174748 and 183596) were collected from the western Walpa Pulka Zone near Mount Fanny and two (GSWA 174588 and 174797) from the eastern Walpa Pulka Zone.

GSWA 174748: migmatitic metasandstone, Mount Fanny

This sample is a locally migmatitic garnetiferous pelitic enclave in a Pitjantjatjara Supersuite gabbro dated by Bodorkos et al. (2008d). The sample yielded mostly subhedral, rounded, clear and colourless zircons up to 500 μm long. The crystals are composed of oscillatory zoned cores surrounded by two generations of zircon rims. The intermediate rims are high in uranium (about 600–2500 ppm) and have low Th/U ratios (<0.5), whereas the outermost rims have moderate uranium (about 200–600 ppm) and higher Th/U ratios (>0.45). Some unzoned zircons appear to be composed entirely of the intermediate phase. Forty-two analyses of zircon cores yield dates between 1667 and 1254 Ma. The youngest result is 1254 ± 24 Ma (1σ), although this zircon is cracked and may have undergone loss of radiogenic-Pb. Based on the next oldest group of five core analyses, the maximum depositional age of this sample is estimated to be 1377 ± 33 Ma (mean square of the weighted deviates, MSWD = 2.2). Results for zircon cores define significant age components at c. 1399, 1473, 1533, and 1569 Ma, and minor components at c. 1399 and 1360 Ma (Table 1). Twelve analyses of intermediate rims and structureless zircons yield a weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1214 ± 7 Ma (MSWD = 2.0), interpreted as the age of the first metamorphic event to have affected this rock and also a minimum depositional age for the sedimentary protolith. Ten analyses of the outermost rims yield a mean $^{207}Pb^*/^{206}Pb^*$ date of 1170 ± 8 Ma (MSWD = 0.86), interpreted as the age of a second metamorphic event.

GSWA 183596: laminated paragneiss, Mount Fanny

This sample is a fine-grained, finely laminated, quartz-rich, garnet-bearing paragneiss, dated by Kirkland et al. (2009a). The sample contains colourless zircons about 100 μm long, consisting of oscillatory zoned cores surrounded by two generations of zircon rims. The inner rims exhibit concentric growth zoning, whereas the outer rims are dark in cathodoluminescence (CL) images and are not zoned. Thirty-two analyses of zircon cores yield $^{207}Pb^*/^{206}Pb^*$ dates between 1644 and 1271 Ma, including significant age components at 1576, 1467, and 1355 Ma, and minor components at 1642, 1523, 1400, 1271, and 1242 Ma (Table 1). Results are concentrated within two main age ranges 1425–1500 Ma and 1550–1600 Ma. There is a paucity of c. 1500 Ma zircon within this sample (Fig. 12). The two youngest core analyses yield a weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1272 ± 15 Ma (MSWD = 0.0054), which may represent the maximum depositional age of the sedimentary protolith. A more conservative estimate is given by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1353 ± 19 Ma (MSWD = 0.33) for the next four older analyses. Twenty-seven analyses of outer rims yield a weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1161 ± 7 Ma (MSWD = 2.0), interpreted as the age of a high-grade metamorphic event, and also a minimum age for sediment deposition.

GSWA 174588: migmatitic metasandstone, Mirtutu Camp

This sample is an orthopyroxene-bearing psammitic enclave in a Pitjantjatjara Supersuite granite dated by Bodorkos et al. (2008e). The rock contains subspherical to

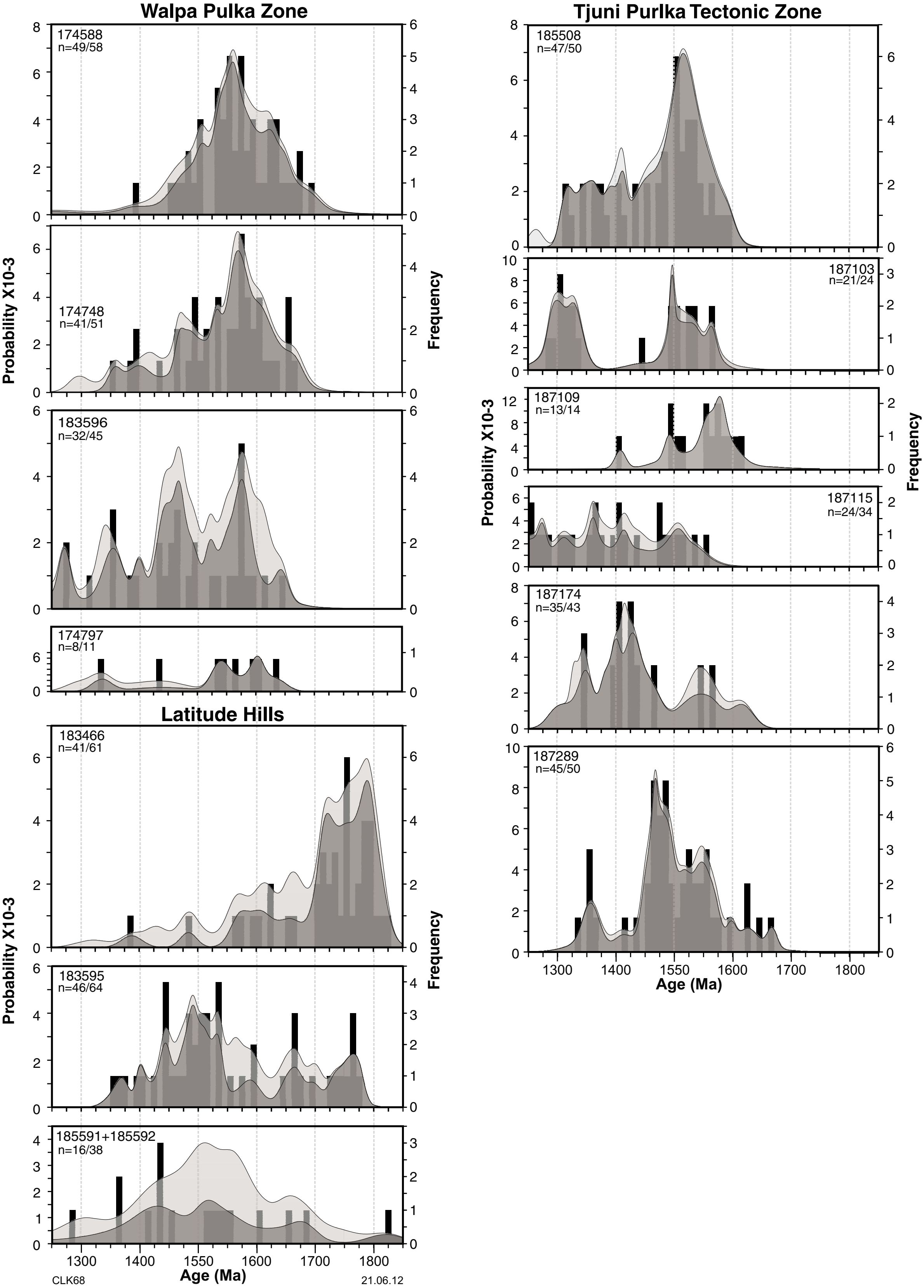

Figure 12. Probability density diagrams of detrital zircon ages from GSWA samples of the Wirku Metamorphics divided by geographical location (tectonic zone); zircons interpreted to have originated by metamorphic or migmatitic growth are not included. Histograms are divided into 10 Ma bins, and heights are normalized by frequency for direct cross-comparison between datasets. Only data <5% discordant are included in histograms; these data are also represented by the dark grey shaded areas. Light grey shaded areas include all (concordant + discordant) data. n = concordant analyses/total analyses.

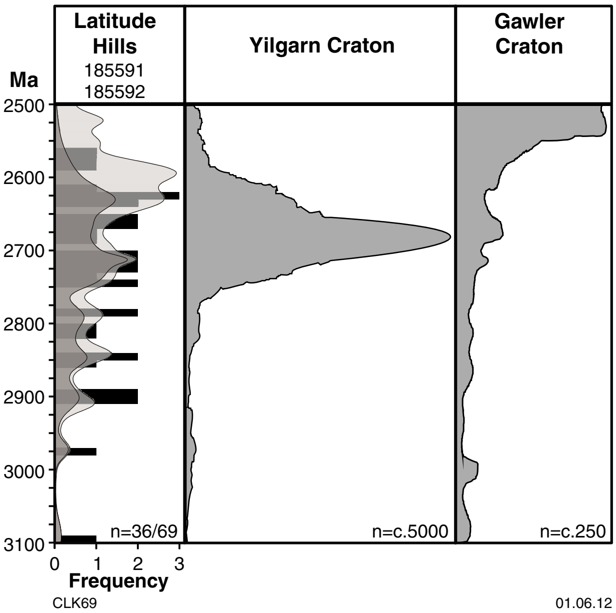

Figure 13. Probability density diagrams of Archean detrital zircon dates from GSWA samples of the Wirku Metamorphics from the Latitude Hills area. The histogram is divided into 10 Ma bins, and only data >5% concordant are plotted. Other notes as in Figure 12. Zircon age spectra (not to scale) from the Yilgarn (Nelson, 2008) and Gawler (Belousova et al., 2009). Cratons are shown for comparison.

subhedral, clear to pale brown zircons, up to 300 µm long. The crystals consist of oscillatory zoned cores embayed by thick, structureless rims that are low in uranium (<100 ppm) and have high Th/U ratios (>0.68). Forty-nine analyses of zircon cores yield $^{207}Pb^*/^{206}Pb^*$ dates between 1694 and 1394 Ma, including a main component at 1560 Ma (45% of data) and minor components at 1623 and 1509 Ma (Table 1, Fig. 12). A single Archean zircon, at 2742 ± 20 Ma (1σ), is also present. The date of 1394 ± 26 Ma (1σ) for the youngest analysis is interpreted as a maximum depositional age for the sedimentary protolith. Fifteen analyses of zircon rims yield a concordia intercept age of 1193 ± 10 Ma (MSWD = 1.4), interpreted as the age of metamorphism during the Musgrave Orogeny and also a minimum depositional age for this sample.

GSWA 174797: paragneiss, Heathers Hill

This sample is a melt-free garnet–orthopyroxene pelitic paleosome within a banded paragneiss, dated by Kirkland et al. (2008a). The sample yielded clear, anhedral, rounded zircons, up to 300 µm long. The crystals consist of relatively small oscillatory zoned cores and thick, homogenous rims. Only a small number of zircon cores were analysed owing to their small size. Nine zircon cores yield $^{207}Pb^*/^{206}Pb^*$ dates of 1630–1340 Ma, including minor age components at c. 1600 and 1540 Ma (Table 1, Fig. 12). The maximum depositional age of this sample is defined by the $^{207}Pb^*/^{206}Pb^*$ date of 1340 ± 8 Ma (1σ) for the youngest zircon core. A minimum depositional age of 1173 ± 8 Ma (MSWD = 1.7) is provided by 28 analyses of both newly grown zircon rims and cores interpreted to have lost Pb during high-grade metamorphism and melting.

Summary

A probability density diagram of detrital zircon ages from all four samples (Fig. 14) shows a major age component at c. 1570 Ma with shoulders at c. 1650 and 1530 Ma. More than half the results are older than 1550 Ma. Younger age components at c. 1470, 1400, and 1360 Ma are defined by ten, seven, and four analyses, respectively. The two oldest zircons are dated at 2741 and 1694 Ma. Conservative maximum depositional ages range from 1394 to 1340 Ma, although samples GSWA 183596 and 174748 contain single cores dated at 1272 and 1245 Ma, respectively. Minimum depositional ages, constrained mainly by zircon rims, reflect metamorphism and magmatism during the Musgrave Orogeny (1170–1160 Ma in the western Walpa Pulka Zone; 1190–1170 Ma in the eastern Walpa Pulka Zone). The ages of crosscutting granites, dated at 1173 ± 10 Ma in the western Walpa Pulka Zone (GSWA 174736; Bodorkos et al., 2008a) and 1181 ± 6 Ma in the eastern Walpa Pulka Zone (GSWA 180300; Bodorkos et al., 2006) are consistent with the ages of metamorphism indicated by zircon rims in the paragneisses.

Tjuni Purlka Tectonic Zone

The Tjuni Purlka Tectonic Zone contains the best exposures of the Wirku Metamorphics. The Mount Aloysius raft comprises equal proportions of arkosic metasandstones, volcanic sandstones, and orthopyroxene psammitic rocks folded around a migmatitic, pelitic core (Howard et al., 2009a,b). The Mount Holt raft is dominated by volcanic sandstones, arkosic metasandstones, and orthopyroxene-bearing psammitic rocks, with only minor pelitic rocks (Evins et al., 2009). Migmatitic pelitic rocks occur sporadically around Prostanthera Hill and to the south. At Mount West, pelitic rocks form two 100-m wide layers in a succession dominated by felsic gneiss (White et al., 1999). Four samples (GSWA 185508, 187103, 187109, and 187115) were collected from the flanks of Mount Aloysius and three (GSWA 187174, 187289, and 187195) from the Prostanthera Hill area. Mount West was sampled previously by White et al. (1999).

GSWA 185508: felsic paragneiss, Mount Aloysius

This rock is a fine- to medium-grained, discontinuously laminated, arkosic metasandstone, analysed by Kirkland et al. (2009b). The sample yielded euhedral, elongate, colourless to pale brown zircons up to 300 µm long. The crystals consist of oscillatory zoned cores and multiple, homogenous rims. Forty-one analyses of zircon cores yield $^{207}Pb^*/^{206}Pb^*$ dates of 1580–1351 Ma, most of which (81%) are older than 1450 Ma. The main age component

Table 1. Summary of U–Pb zircon results from GSWA samples of the Wirku Metamorphics and Wankanki Supersuite volcanic rocks (shaded). Dates in italics are from single analyses and have uncertainties displayed at the 1σ level. All other dates are weighted means or concordia ages and have uncertainties at the 95% level. Significant detrital age components are indicated in bold font.

Sample	*Crystallization or maximum age of deposition*	*Metamorphism or migmatization*	*Detrital age components*
Walpa Pulka Zone			
174748	1377 ± 33	*1214 ± 7, 1170 ± 8*	1400, **1470**, 1530, **1570**, 1660
183596	1272 ± 15 or 1353 ± 19	1158 ± 6	1300, 1350, 1410, **1470**, 1520, **1580**, 1620
174797	*1340 ± 8*	*1161 ± 7*	1540, 1600
174588	*1161 ± 26*	1173 ± 8	1510, **1560**, 1620, 2740
Tjuni Purlka Tectonic Zone			
185508	*1351 ± 8*	1216 ± 13, 1067 ± 17	1370, 1390, 1410, 1460, **1520**, 1570
187103	1293 ± 10	1191 ± 4	1500, 1560
187109	*1411 ± 8*	1205 ± 5	1500, 1550, **1580**
187174	*1301 ± 13*	1208 ± 6	1350, **1410**, **1430**, 1550,1620
187289	*1240 ± 21*	1180 ± 9	1360, **1470**, 1550, 1630
187195	*1296 ± 26*	*1196 ± 4, 1179 ± 4*	1380, **1410**, 1560
180867	1324 ± 7	1191 ± 12	
187115	1360 ± 10	1194 ± 3	1360, 1410, **1510**
Latitude Hills			
183466	*1385 ± 24*	1221 ± 7	**1720**, 1750, **1790**
183595	1363 ± 14	*1034 ± 17*	1460, **1500**, 1510, 1530, 1560, 1600, 1670, **1770**
185591	1430 ± 30	1210 ± 78	1480, 2565-2789, 2580 2660
185592	1571 ± 51	*1163 ± 13*	**2630**, **2710**, 2850, 2900
Mamutjarra Zone			
184150	1310 ± 7	1172 ± 14	
190245	1334 ± 6		
Cohn Hill – Mount Blythe			
194381	1319 ± 20 or *1599 ± 95*		1560
194422	>1266	1266–1072	
194379	1306 ± 11 or *1400 ± 9*	1127 ± 9	1400
194433	*1595 ± 29*	1156 ± 8	1595, 1618
189540		1177 ± 8	

NOTES: Dates in italics are from single analyses and have uncertainties displayed at the 1σ level. All other dates are weighted means or concordia ages and have uncertainties at the 95% confidence level. Samples re-interpreted as Wankanki Supersuite volcanic rocks are within grey fill. Significant detrital age components are indicated in bold font.

is at c. 1520 Ma with shoulders at c. 1570 and c. 1460 Ma, and minor components at c. 1425–1350 Ma (Table 1, Fig. 12). A weakly oscillatory zoned overgrowth yields a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1351 ± 8 Ma (1σ), interpreted as a maximum age of deposition. Two analyses of zircon rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1216 ± 13 Ma (MSWD = 1.8), interpreted as the age of the first stage of metamorphism associated with the Musgrave Orogeny, and a minimum depositional age for the sample. Six analyses of outer rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1067 ± 17 Ma (MSWD = 2.1), interpreted to reflect a second stage of metamorphism associated with the Giles Event.

GSWA 187103: granoblastic garnetiferous granite, Mount Aloysius

This sample, analysed by Kirkland et al. (2009c), is a weakly foliated, garnetiferous granite, thought to be a leucosome derived by melting of a pelitic metasedimentary rock. The sample yielded mainly rounded, brown to black zircons, many of which contain oscillatory zoned cores. Twenty-three analyses of zircon cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1568–1255 Ma, mainly in two groups, at 1568–1442 Ma and 1344–1255 Ma (Fig. 12). The seven youngest analyses of zircon cores yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1293 ± 10 Ma (MSWD = 1.1),

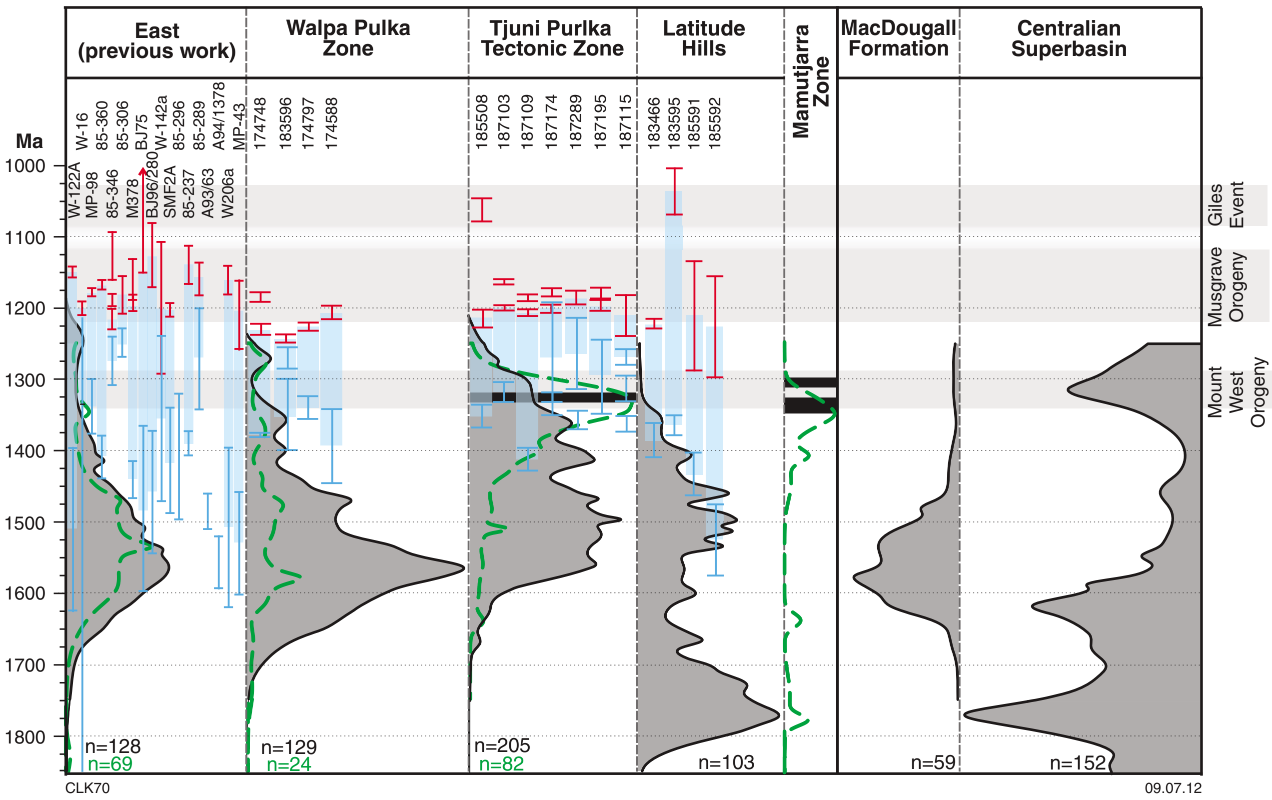

Figure 14. Probability density diagrams of early Mesoproterozoic zircon ages from GSWA and previous workers' samples divided by geographical location and host supergroup. Summary probability density diagrams for concordant, early Mesoproterozoic, detrital (grey fill), and inherited (green dashed line) zircon dates have been grouped for each tectonic zone in the Musgrave Province (see main text). Summary probability density diagrams for early Mesoproterozoic detrital zircon dates from younger successions within and adjacent to the Musgrave Province are shown on the right. The blue error bars show the age of the youngest detrital zircon or group of zircons in each sample, and the red error bars show the weighted average age of the metamorphic zircons dated from each sample. Transparent blue boxes show the age range of deposition for the precursor sediment as defined by the youngest detrital zircon and the subsequent metamorphic overprint. Black bars show the age of Wankanki Supersuite volcanic rocks. The age of the known orogenic events are superimposed as grey bars.

interpreted as a maximum depositional age for the sedimentary precursor of the metasedimentary protolith to the granite. Thirty-three analyses yield a weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1191 ± 4 Ma (MSWD = 1.8), interpreted as the likely age of the granitic leucosome intruded during the Musgrave Orogeny and a minimum depositional age for the sedimentary protolith.

GSWA 187109: quartzofeldspathic paragneiss, Mount Aloysius

This sample is a laminated, leucocratic quartzofeldspathic paragneiss, for which geochronology was reported by Kirkland et al. (2009d). The sample contains mostly homogeneous, high-uranium (up to about 2800 ppm), low-Th/U (about 0.3) zircons that are dark in CL images. Some crystals contain oscillatory zoned, low-uranium (about 120–580 ppm), high-Th/U (about 0.5–1.5) cores that are bright in CL images. Twelve analyses of detrital zircon cores yield significant age components at 1577, 1564, and 1492 Ma (Fig. 12). The oldest core is 1592 ± 51 Ma (1σ) and the youngest, at 1411 ± 8 Ma (1σ), provides a maximum age of deposition. Two analyses yield slightly discordant dates of 1258 ± 21 Ma (–7% discordant) and 1289 ± 7 Ma (6% discordant), which are similar to dates for the youngest slightly discordant cores from the previous samples and possibly represent a maximum age of deposition. High-uranium (dark-CL) zircons and rims yield dates between 1240 and 1136 Ma. The oldest 12 analyses define an age component at 1205 ± 4 Ma (MSWD = 1.3), which provides a minimum depositional age for this sample. This date was interpreted by Kirkland et al. (2009d) as the age of high-grade metamorphism, and the younger results were interpreted to reflect loss of radiogenic-Pb. It is also possible that the spread of these dates is indicative of prolonged UHT metamorphism during the Musgrave Orogeny.

GSWA 187115: diatexitic migmatite, Mount Aloysius

This sample, analysed by Kirkland et al. (2009e), is an orthopyroxene-bearing melanosome within a migmatitic quartzofeldspathic gneiss. Zircons in this rock are up to 300 µm long, subhedral and rounded to spherical, and clear to brown, with oscillatory zoned, detrital cores surrounded by thick, homogenous, low-uranium (bright-CL) rims. Analyses of 29 cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1555–1212 Ma, and include significant age components at 1507, 1413, 1360, 1310, 1272, and 1230 Ma. Although these zircons appear to have undergone variable amounts of radiogenic-Pb loss during Musgrave Orogeny metamorphism, the main age gap, between 1507 and 1413 Ma, is seen also in results for GSWA 187109 (Table 1, Fig. 12), suggesting that at least the older dates represent detrital ages. The oldest concordant zircon is 1555 ± 20 Ma (1σ). The five youngest analyses of zircon cores yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1215 ± 11 Ma (MSWD = 1.3), which either represents a maximum depositional age, or reflects loss of radiogenic-Pb. Similarly, the age component at 1310 Ma may also reflect Pb loss, or could represent detritus from distant Wankanki Supersuite volcanism. A conservative estimate of the maximum depositional age can be based on five analyses that yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1360 ± 10 Ma (MSWD = 0.67). The oldest dates for metamorphic rims are about 1200 Ma, which, together with the age of 1194 ± 3 Ma for a crosscutting pegmatite (GSWA 187113; Kirkland et al., 2009f) at this locality, provide a minimum age for deposition of the sedimentary protolith.

GSWA 187195: leucogranitic gneiss, Mount Scott

This sample of arkosic paragneiss was dated by Kirkland et al. (2010a). The zircons are equant to elongate, clear to dark brown, and most consist of oscillatory zoned, low-uranium cores surrounded by high-uranium rims. Twenty-seven analyses of zircon cores yield dates of 1561–1298 Ma, and include significant age components at 1409 and 1375 Ma and minor components at 1555 and 1460 Ma (Table 1, Fig. 12). The youngest core analysis, at 1298 ± 26 Ma (1σ), represents a maximum age for deposition of the sedimentary protolith. Two analyses of zircon rims yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates (1σ) of 1196 ± 4 and 1179 ± 4 Ma. These dates are interpreted to reflect Musgrave Orogeny metamorphism and provide a minimum age for deposition.

GSWA 187174: metasandstone, Prostanthera Hill

This metasandstone sample was analysed by Kirkland et al. (2011a). The zircons are anhedral to subhedral and rounded to subspherical, with oscillatory zoned cores and high-uranium, low-Th/U rims. Thirty-five analyses of cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1619–1301 Ma, and include significant age components at 1552, 1429, 1414, 1377, 1341, and 1305 Ma, defined by 13, 17, 16, 11, 10, and nine analyses, respectively. The youngest analysis of a zircon core, at 1301 ± 13 Ma (1σ), represents a maximum age for deposition of the protolith. Eight analyses of high-uranium rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1208 ± 6 Ma, interpreted as the age of Musgrave Orogeny metamorphism and a minimum age for deposition.

GSWA 187289: metasandstone, Prostanthera Hill

This metasandstone sample was analysed by Kirkland et al. (2011b). The zircons are colourless, equant, and strongly rounded, and consist of oscillatory zoned cores overgrown by high-uranium rims. Forty-four analyses of zircon cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1648–1240 Ma, with significant age components at 1634, 1597, 1545, 1489, 1467, 1409 and 1363 Ma, defined by 9, 10, 19, 20, 20, 9, and 10 analyses, respectively. The youngest analysis of a zircon core, at 1240 ± 21 Ma (1σ), represents a maximum age of deposition for the sandstone. Ten analyses of high-uranium rims yield a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1180 ± 9 Ma, interpreted as the age of high-grade metamorphism and a minimum age for deposition.

Summary

The probability density diagram (Fig. 14) for all seven samples shows a broad peak centred on c. 1500 Ma. The oldest concordant detrital zircon core is c. 1650 Ma. Only about 20% of zircon ages are older than 1550 Ma, whereas about 40% are younger than 1450 Ma, including a large peak at c. 1410 Ma. Twenty percent of all Tjuni Purlka Tectonic Zone detrital zircon ages range between 1360–1300 Ma, with a peak at about 1360 Ma. In the Prostanthera Hill – Mount Scott area, there are twice as many core ages between 1500 and 1400 Ma (responsible for a peak at c. 1470 Ma) and half as many between 1600 and 1500 Ma than in the Mount Aloysius raft. GSWA 185508, collected east of Mount Aloysius, differs from all the other samples in that it contains an abundance of detrital zircons older than 1500 Ma. Six of the samples contain at least one zircon core younger than c. 1270 Ma, providing a maximum depositional age at about this time. Minimum depositional ages, constrained by zircon rims, reflect Musgrave Orogeny metamorphism and magmatism from c. 1210 to c. 1170 Ma. Pitjantjatjara Supersuite granites in the same age range as the metamorphic rims crosscut at least one of the sampled rock units.

Latitude Hills

The Latitude Hills area (Figs 3 and 8) is composed of alternating centimetre- to metre-scale layers of pelitic and psammitic metasedimentary rocks, quartzite, and rare arkosic metasandstone. Anatectic leucosomes occur throughout this succession. Four samples were recovered from hercynite-bearing pelitic metasedimentary rocks that are rare elsewhere in the Musgrave Province.

GSWA 183595: diatexitic migmatite, Latitude Hill

This diatexitic migmatite was analysed by Kirkland et al. (2009g). Most zircons are subspherical and consist of concentrically zoned cores mantled by overgrowths that round the crystal's terminations. The discordance limit for this sample was set at 10%, because a large number of analyses were >5% discordant. Sixty-seven analyses of 54 zircon cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1777–1352 Ma with significant age components at 1769, 1733, 1700, 1666, 1598, 1561, 1535, 1513, 1498, 1460, 1407, and 1363 Ma. The weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1363 ± 14 Ma (MSWD = 0.86) for the youngest three cores represents a maximum age of deposition of the sedimentary precursor. A single analysis of a zircon rim yields a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1034 ± 17 Ma (1σ), interpreted as the age of high-grade metamorphism and a minimum depositional age for the sedimentary precursor.

GSWA 183466: banded gneiss, Latitude Hill

The geochronology of this banded gneiss was reported by Kirkland et al. (2008b). The zircons are elongate, mainly translucent, and consist of concentrically zoned cores overgrown by high-uranium rims. Forty-one analyses yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates between 1825 and 1385 Ma with significant age components at 1790, 1720, and 1580 Ma, defined by 17, 14, and six analyses, respectively. The youngest analysis of a zircon core yields a date of 1385 ± 24 Ma (1σ), interpreted to represent a maximum depositional age for the sedimentary precursor. Nine analyses of zircon rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1221 ± 7 Ma (MSWD = 3.9), interpreted as the age of Musgrave Orogeny metamorphism and a minimum age for deposition.

GSWA 185591: garnet-rich leucogranite, Latitude Hill

This garnet-rich leucogranite is interlayered with paragneiss, and was analysed by Kirkland et al. (2009h). The rock is interpreted as a product of melting of metasedimentary rocks followed by crystallization at relatively high pressure. Zircons are colourless to pale brown, rounded, with oscillatory zoned cores and low-uranium rims. Thirty-seven analyses of zircon cores and discrete crystals yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 2789–1157 Ma with significant age components at 2653, 2581, 1559, 1507, and 1437 Ma, defined by contributions from 11, 10, 7, 7, and five analyses, respectively. Assuming that these crystals represent detrital zircons from the adjacent paragneiss, a maximum depositional age is provided by a coherent group of six analyses with a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1430 ± 30 Ma (MSWD = 0.09). A minimum depositional age is constrained by analyses from two low-uranium zircons with faded oscillatory zoning that yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1210 ± 78 Ma (MSWD = 0.54), interpreted to represent complete resetting of the U–Pb system during Musgrave Orogeny metamorphism.

GSWA 185592: banded quartz-rich psammitic gneiss, Latitude Hill

This banded quartz-rich psammitic rock was analysed by Kirkland et al. (2009i). Zircons are colourless, up to 300 μm long, with oscillatory zoned cores overgrown by rims. Twenty-nine analyses of zircon cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 3096–1524 Ma, with significant age components at 2838, 2713, 2622, and 1527 Ma, and several minor components between 3096 and 1524 Ma. The three youngest analyses of zircon cores yield a concordia age of 1571 ± 51 Ma, which represents a maximum age for deposition of the sedimentary protolith. A single analysis of a zircon rim with a low Th/U ratio (0.22) yields a slightly discordant $^{238}U/^{206}Pb^{*}$ date of 1163 ± 13 Ma (1σ), which may represent the age of Musgrave Orogeny metamorphism and a minimum age for deposition of the protolith.

Summary

Archean detrital zircons were only found in two samples from the Latitude Hills area. Most Archean dates are between 2750 and 2600 Ma (Fig. 13), with secondary age components at c. 2900 and 2850 Ma. The oldest detrital zircon is 3096 ± 14 Ma (1σ). Combining all Proterozoic detrital dates for the four samples yields a broadly bimodal distribution (Fig. 12), with a third of Proterozoic detrital ages between 1400 and 1560 Ma and about half between 1700 and 1820 Ma. The younger age range is typical of the Tjuni Purlka Tectonic Zone, whereas the older age range is unique to the Latitude Hills area and includes detrital zircon age peaks at c. 1770 and 1730 Ma. Detrital zircons younger than 1350 Ma are absent. The youngest detrital zircons in two of the samples constrain the maximum depositional age to c. 1360 Ma. Minimum depositional ages defined by metamorphic zircon rims range from 1220 to 1030 Ma. Within this range are a 1207 ± 11 Ma granitic gneiss (GSWA 174737, Bodorkos et al., 2008b) intruding the sedimentary package and an adjacent charnockite dated at 1198 ± 5 (GSWA 185590, Kirkland et al., 2009j).

Mamutjarra Zone

Banded felsic and intermediate gneisses make up the Wirku Metamorphics in the Mamutjarra Zone. These rocks are mainly fine- to medium-grained orthopyroxene–plagioclase ± clinopyroxene ± quartz gneisses and granitic gneisses, which locally contain centimetre-scale layers of garnet ± hercynite ± cordierite gneiss. Two samples with suspected sedimentary protoliths taken from this region produced unimodal zircon age components, perhaps suggesting that their protoliths may have been volcanic rather than sedimentary rocks. Hence, their geochronology is discussed below, together with that of Wankanki Supersuite igneous rocks.

Cohn Hill – Mount Blythe area

The rocks of the Cohn Hill – Mount Blythe area are texturally and compositionally similar to those of the Latitude Hills area. However, the gneisses in the Cohn Hill – Mount Blythe area are more deformed (typically mylonitic) and contain significantly more leucosome and a lower proportion of quartzite. Both paleosome-dominant (GSWA 194422 and 194433) and neosome-dominant (GSWA 194379 and 194381) rocks were sampled from the Cohn Hill area. Paleosome was also sampled from the Mount Blythe area (GSWA 189540).

GSWA 194422: quartzite, Cohn Hill

This sillimanite-bearing quartzite, analysed by Kirkland et al. (2010b), contains two zircon types: rounded, colourless grains up to 200 µm, with low-uranium cores and high-uranium rims, and light brown, sector-zoned, ‘soccer ball’ zircons (e.g. Corfu et al., 2003). However, all zircon rims, ‘soccer ball’ crystals, and detrital cores yield ^{207}Pb*/^{206}Pb* dates between 1266 and 1072 Ma. These dates are interpreted to reflect a long period of high-temperature metamorphism during the Musgrave Orogeny (Smithies et al., 2010), during which new zircon was formed and detrital zircon cores underwent radiogenic-Pb loss.

GSWA 194433: pelitic gneiss, Minnie Hill

This sample of banded garnet–sillimanite–hercynite–cordierite gneiss was analysed by Kirkland et al. (2011c). The zircons are brown, rounded, and consist of oscillatory zoned cores overgrown by homogeneous, high-uranium rims. Two analyses of zircon cores yield ^{207}Pb*/^{206}Pb* dates (1σ) of 1618 ± 8 and 1595 ± 29 Ma. Five additional cores yield ^{207}Pb*/^{206}Pb* dates between 1318 and 1203 Ma, interpreted to reflect partial to near-complete dissolution–reprecipitation (and Pb loss) during a 1156 ± 8 Ma (MSWD = 1.9) metamorphic event recorded by 20 analyses of 18 zircon rims.

GSWA 189540: pelitic gneiss, Mount Blyth

This sample, a mylonitic garnetiferous pelitic gneiss, was analysed by Kirkland et al. (2010c). The sample contains two zircon types: round, colourless to light brown, sector-zoned, high-U ‘soccer ball’ crystals and a minor group consisting of faded, oscillatory zoned cores overgrown by high-uranium rims. Forty-five analyses of ‘soccer ball’ zircons and rims yield a concordia intercept (defined by a regression from initial Pb through data uncorrected for common Pb) of 1177 ± 8 Ma (MSWD = 1.3), whereas the cores yield a concordia age of 1170 ± 11 Ma (MSWD = 1.8). Similar dates from both zircon types imply essentially complete re-equilibration of the U–Pb isotopic system within cores (that show faded oscillatory zoning) at the same time that the ‘soccer ball’ zircons and rims were forming.

GSWA 194381: granitic gneiss, Minnie Hill

The geochronology of this granitic gneiss was reported by Kirkland et al. (2011d). Zircons are subhedral with rounded terminations, and consist of cores that exhibit faded idiomorphic zoning, overgrown by homogeneous, low-uranium zircon rims. Three analyses yield a weighted mean ^{207}Pb*/^{206}Pb*date of 1319 ± 20 Ma, interpreted as the age of magmatic crystallization of the dacite protolith. Alternatively, this date could reflect loss of radiogenic-Pb during metamorphism, in which case the date constitutes a minimum age for protolith crystallization. Dates of 1306–1077 Ma for 51 analyses are interpreted to represent both new metamorphic zircon growth and various degrees of partial re-equilibration of pre-existing zircons during high-grade metamorphism. A ^{207}Pb*/^{206}Pb* date of 1599 ± 95 Ma (1σ) for a single analysis of a zircon core is interpreted as the age of a protolith component of the gneiss.

GSWA 194379: biotite granite, Minnie Hill

This mylonitic biotite granite was analysed by Kirkland et al. (2011e). Zircons are mainly large, equant, and highly enriched in uranium, although several are smaller, elongate, lower in uranium, and exhibit euhedral growth zoning. Many crystals are overgrown by low-uranium rims. Nine analyses of zoned zircon cores yield a weighted mean ^{207}Pb*/^{206}Pb* date of 1306 ± 11 Ma (MSWD = 2.2), interpreted as the magmatic crystallization age. A single analysis of an oscillatory zoned core from the low-uranium zircon group yields a date of 1400 ± 9 Ma (1σ), interpreted as the age of an inherited component. Two analyses of zircon rims yield a weighted mean ^{207}Pb*/^{206}Pb* date of 1127 ± 9 Ma, interpreted to represent the latest metamorphic phase of the Musgrave Orogeny (Table 1). An alternative interpretation, that the zircon cores represent inherited components and the rims reflect magmatic growth, is considered less likely, because the absence of zoning in the zircon rims is more consistent with a metamorphic origin.

Summary

UHT metamorphism during the 1220–1120 Ma Musgrave Orogeny affected the Cohn Hill – Mount Blythe area to the extent that the U–Pb isotopic systems in nearly all detrital or inherited zircons in that area have been partially or completely reset. The only crystals to retain unmodified detrital ages (15 from over 200 total analyses) come from zircon cores in which the oscillatory zoning is not faded. Most (about 80%) of these ages are between 1320 and 1300 Ma, and likely were derived from Wankanki Supersuite volcanism. This volcanic detritus provides a maximum depositional age in the Cohn Hill – Mount Blythe area. A 1155 ± 15 Ma norite dyke (GSWA 194376; Kirkland et al., 2010d) cuts all rock units and fabrics in the Cohn Hill area and provides a minimum depositional age constraint. The mafic magmatism represented by this dyke may have provided the thermal impetus for growth of zircon rims in GSWA 194433 (Kirkland et al., 2011c).

Central and Eastern Musgrave Province

Among the approximately 100 samples dated by GSWA so far, no orthogneisses older than 1360 Ma have been found in the west Musgrave Province. This invites re-evaluation of the evidence for 1600–1500 Ma orthogneisses in the remainder of the Musgrave Province. Most 1600–1500 Ma orthogneisses are located in the central Musgrave Province more than 100 km east of the Western Australian border.

A re-evaluation of published data (Camacho, 1997; Maboko, 1988; Young et al., 2002; Edgoose et al., 2004) in light of the Wirku Metamorphic detrital zircon age structure permits an alternative interpretation of much of the data from presumed orthogneisses: they could in fact be from paragneisses. Reclassification of orthogneiss samples from previous studies is feasible because textural descriptions and aluminous assemblages are consistent with sedimentary precursors. Furthermore, these apparent orthogneiss lithologies are similar to those of the Wirku Metamorphics. Zircon U–Pb age spectra are also similar to those for the Wirku Metamorphics.

Of the 18 gneissic samples reclassified from previous studies, nine have petrographic descriptions and U–Pb zircon age spectra consistent with a metasedimentary affinity. Another eight yield U–Pb zircon age spectra that: (i) strongly resemble those of the Wirku Metamorphics; or (ii) include a significant number of ages younger than 1500 Ma (which define a tighter age peak than do the ages older than 1500 Ma); or (iii) have multiple age components older than 1500 Ma. Roughly half of the total 249 U–Pb analyses of zircon cores are <5% discordant.

A probability density diagram (Fig. 14) of detrital zircon ages <5% discordant from all 18 samples shows a large peak at c. 1570 Ma with a substantial shoulder at c. 1540 Ma and a smaller peak at 1470 Ma. Nearly 80% of all dates fall between 1650 and 1450 Ma, and half are older than 1550 Ma. The youngest significant age component at 1410 Ma is defined by six analyses. Only 5% of dates are younger than 1350 Ma. The oldest $^{207}Pb^{*}/^{206}Pb^{*}$ date is 1960 ± 38 Ma (1σ). Most maximum depositional ages with 1σ uncertainties <30 Ma range from 1440 to 1250 Ma, with several samples showing a maximum depositional age at c. 1410, 1360, or 1270 Ma. Minimum depositional ages, constrained mostly by the ages of metamorphic zircon rims, range from c. 1220 Ma to 1125 Ma and reflect Musgrave Orogeny metamorphism and magmatism.

Samples re-interpreted as Wankanki Supersuite volcanic rocks

Petrographic descriptions and U–Pb zircon age spectra allow alternative interpretations of the protoliths for some previously dated rocks.

GSWA 180867: quartz metamonzonite, Pirntirri Mulari

This sample of foliated, fine- to medium-grained, granoblastic quartz monzonite was dated by Kirkland et al. (2010e). The zircons are subhedral to euhedral and have oscillatory zoned cores with homogenous rims. The cores have lower Th/U ratios (0.06–2.34) than the rims (1.07–3.88). Twenty-eight analyses of 27 zircon cores yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1324 ± 7 Ma (MSWD = 1.5), interpreted as the age of magmatic crystallization. Nineteen rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1191 ± 12 Ma (MSWD = 1.03), interpreted as the age of Musgrave Orogeny metamorphism (Fig. 15 and Table 1). In this work we infer that the protolith of this sample is a volcanic rock.

GSWA 184150: metasandstone, Kampurarr Pirti

Zircons from this metasandstone sample were dated by Kirkland et al. (2011f). The crystals consist of oscillatory zoned zircon cores overgrown by oscillatory zoned zircon rims. Th/U ratios are higher in the cores (0.6–2.0) than in the rims (<0.60). Thirty-five analyses of cores yield a concordia age of 1310 ± 7 Ma (MSWD = 1.3), interpreted as a maximum age for deposition of the sandstone protolith, and six analyses of rims yield a concordia age of 1172 ± 14 Ma (MSWD = 0.66), interpreted as the age of high-grade metamorphism (Fig. 15 and Table 1). An alternative protolith to this sample was also considered to be a mylonitized granite, in which case the date of 1310 ± 7 Ma reflects the igneous crystallization age. In this work we infer that the protolith of this sample is a volcanic rock.

GSWA 190245: migmatitic quartzofeldspathic gneiss, Kampurarr Pirti

The geochronology of this sample was reported by Kirkland et al. (2011g). The zircons are uniformly elongate, euhedral, colourless to pale brown, and exhibit oscillatory zoning. Thirty-four analyses form a single group and yield a concordia age of 1334 ± 6 Ma (MSWD = 1.4; Fig. 15 and Table 1), interpreted as a maximum age of deposition. An alternative protolith for this sample was also considered to be an intrusive granite, in which case the date of 1334 ± 6 Ma reflects the igneous crystallization age. In this work we infer that the protolith of this sample is a volcanic rock.

Inherited zircons

Evaluating inheritance through U–Pb dating of inherited zircons is another means of investigating the basement to the Musgrave Province. In this case, the inherited zircons reveal the ages of basement units surrounding or underlying the intrusive host rocks of the zircons. We have compiled all data for inherited zircons from the Musgrave Province sourced from GSWA (124 zircons from 17 samples), Northern Territory Geological Survey (NTGS) (52 zircons from seven samples), Camacho (1997) (61 zircons from seven samples), and Maboko (1988) (44 zircons from five samples). Only dates significantly older (beyond 2σ uncertainty) than the crystallization ages of their host rock were considered.

Most granites in the Musgrave Province do not contain inherited zircons. Those that do contain inherited zircons typically intrude into, and contain rafts of, Wirku Metamorphics. The similarities between the ages of inherited zircons in these granites and the ages of detrital zircons in the Wirku Metamorphics (described in detail below), and the proximity of xenocryst-rich samples to Wirku Metamorphics paragneisses, imply that most inherited zircons were derived from the Wirku Metamorphics.

Nearly all early Mesoproterozoic inheritance in the western Musgrave Province is confined to the Pitjantjatjara Supersuite. Although about one-third of Wankanki Supersuite samples contain inherited material, almost two-thirds of this inheritance falls within the c. 1280–1350 Ma (including 2σ uncertainties) time interval of Wankanki

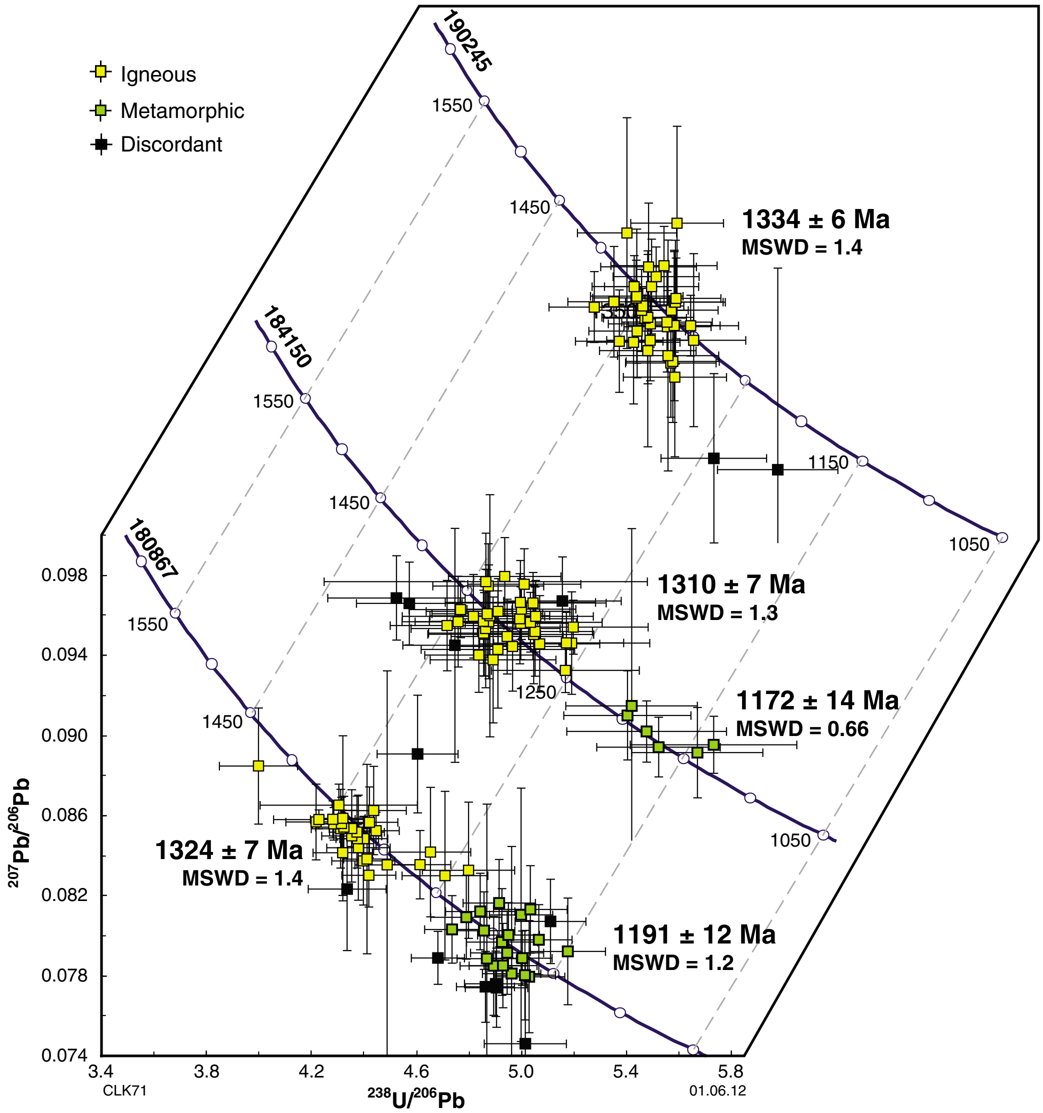

Figure 15. U–Pb analytical data for GSWA samples of Wankanki Supersuite volcanic rocks in the west Musgrave Province. See text for details.

magmatism as a whole and only one analysis is older than c. 1400 Ma. Inherited zircons are present in only one (GSWA 187177; Kirkland et al., 2010f) of the 15 dated samples of the Warakurna Supersuite in the west Musgrave Province. For the purposes of this study, inherited zircon components were divided by region (Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, and Mamutjarra Zone; no inherited zircons have been found in the Latitude Hills and Cohn Hill – Mount Blythe areas). Summary probability curves (dashed green lines) in Figure 14 illustrate the ages of inherited zircons from each geographic zone.

Walpa Pulka Zone

Twenty-two of the 30 analyses of inherited zircons in Walpa Pulka Zone samples are from a rare, early Pitjantjatjara Supersuite gabbro (GSWA 174747; Bodorkos et al., 2008c) that intrudes the Wirku Metamorphics (GSWA 174748; Bodorkos et al., 2008d) described above. Eighteen of 22 U–Pb zircon dates from the gabbro sample fall within a similar age range (1614–1276 Ma) as the ages of detrital zircons in the host rock of the gabbro (1667–1295 Ma; GSWA 174748). The gabbro's inherited-zircon age spectrum contains a main peak defined by four tightly grouped analyses at 1480 Ma, which is similar to the significant 1470 Ma detrital age component in the metamorphic host. Other age components in the gabbro, defined by three or more loosely grouped analyses, occur at c. 1590, 1510, 1340, and 1280 Ma (Fig. 14). These do not directly correspond to detrital age components in the host rock. A Pitjantjatjara Supersuite leucogranite dyke (GSWA 193850; Kirkland et al., 2008c) has three concordant analyses around c. 1580 Ma (Fig. 14). Nearly half of all analyses of inherited zircons in the Walpa Pulka Zone are discordant, which may be a result of the high-pressure metamorphism that affected the area during the Petermann Orogeny.

Tjuni Purlka Tectonic Zone

Of the 87 analyses (79 of these <5% discordant) of inherited zircons from the Tjuni Purlka Tectonic Zone, 29 are from a late Pitjantjatjara Supersuite granite (GSWA 187171; Kirkland et al., 2012a). Inherited-zircon ages from GSWA 187171 range from 1640 to 1310 Ma, with a main peak at c. 1350 Ma defined by seven analyses. Only five analyses are older than c. 1510 Ma. The sample was collected near Prostenthera Hill, and it shares similar c. 1400 and c. 1430 Ma zircon peaks (defined by five and three analyses, respectively) with nearby Wirku Metamorphics detrital spectra. Another 19 analyses are from the youngest Wankanki Supersuite sample dated (1314 ± 8 Ma, GSWA 183726; Kirkland et al., 2012b). The single inherited zircon dated in this sample [1378 ± 23 Ma (1σ)] is older than 1360 Ma (Fig. 14).

The remaining 39 analyses of inherited zircons from the Tjuni Purlka Tectonic Zone define a main age component at c. 1310 Ma (18 analyses from four samples) and a secondary component at 1360 Ma (11 analyses from five samples). Included in this dataset are six analyses from White et al. (1999): samples M057, M096, and M175. A late Pitjantjatjara Supersuite granite (GSWA 183509; Kirkland et al., 2007) contains a concordant Archean inherited zircon of 3141 ± 8 Ma (1σ), which is the oldest known zircon in the Musgrave Province. The dominance (over half of all analyses) of 1360–1300 Ma inheritance in the Tjuni Purlka Tectonic Zone reflects the abundance of underlying Wankanki Supersuite magmatic rocks that are absent in the Walpa Pulka Zone. Most of the inherited zircons in this age range are presumably from Wankanki Supersuite granites, although the peak at c. 1360 Ma is older than the oldest dated Wankanki Supersuite granite at 1345 ± 7 Ma (GSWA 194393; Kirkland et al., 2010g). In the Tjuni Purlka Tectonic Zone, only Pitjantjatjara Supersuite granites contain inherited zircons older than 1410 Ma.

Mamutjarra Zone

The pattern of inheritance in the Mamutjarra Zone does not differ substantially from that in the Tjuni Purlka Tectonic Zone, in that more than half of the ages of inherited zircons are between c. 1380 and 1330 Ma (Fig. 14). They form a broad age peak at 1350 Ma and are restricted to two samples of Wankanki Supersuite granite (GSWA 187151, GSWA 185606; Kirkland et al., 2009k and GSWA 185606; Kirkland et al., 2009k). The youngest (slightly discordant) inherited zircon (1326 ± 12 Ma) is the sole xenocryst in early Pitjantjatjara Supersuite granites. This is the only representative of the Pitjantjatjara Supersuite in the Mamutjarra Zone that contains inherited zircons. Zircon inheritance older than 1400 Ma is restricted to a 1026 ± 6 Ma dacite (GSWA 187171; Kirkland et al., 2012a) from the Smoke Hill Volcanics. The dacite is contaminated with zircon and metamorphic garnet from the Wirku Metamorphics. Five zircon cores yield $^{207}Pb^{*}/^{206}Pb^{*}$ dates of c. 1780, 1740, 1630, 1450, and 1340 Ma. The two oldest cores from this sample are older than any Proterozoic inherited zircons in the Walpa Pulka and Tjuni Purlka Tectonic Zones, although similar ages are recognized in the detrital zircon age spectra for metasedimentary samples from the Latitude Hills.

Central and eastern Musgrave Province

In light of the absence of 1600–1500 Ma orthogneisses in the west Musgrave Province, previous workers' zircon age data for 1600–1500 Ma porphyritic granites or granitic gneisses of indisputable igneous parentage in the central and eastern Musgrave Province have been re-examined. Six granites were reclassified as having crystallization ages younger than their published ages of 1600–1500 Ma: three from Scrimgeour et al. (1999), and one each from Camacho (1997), Young et al. (2002), and Maboko (1988). The general criteria applied for reclassification is similar to that described above for the Wirku Metamorphics, except that compositional and textural criteria were not applied because it has already been established that the rocks have igneous protoliths. In most of the reclassified samples, zircon cores span a significantly larger age range than do zircon rims, suggesting that the cores are inherited. The ages of inherited zircons from the reclassified samples were added to the existing dataset reported by previous workers from the central and east Musgrave Province.

All 19 samples were collected north of the Mann Fault and Tjuni Purlka Tectonic Zone. Their protoliths belong to the Pitjantjatjara and Warakurna Supersuites. Of the 156 analyses of inherited zircon cores, only 69 are <5% discordant. A probability density diagram (Fig. 14) of inherited U–Pb zircon dates from all 19 samples shows a broad peak (about 80% of analyses) between c. 1650 and 1450 Ma. Within this range, the largest age component is at c. 1570 Ma with substantial shoulders at c. 1540 and 1470 Ma. Individual $^{207}Pb^{*}/^{206}Pb^{*}$ ages range from 1301 to 1830 Ma. Only about 5% of dates are younger than 1350 Ma. The oldest date is 1830 ± 19 Ma (1σ).

Detrital zircons in younger units

The Wirku Metamorphics are the currently exposed basement to the west Musgrave Province and their source was the early Mesoproterozoic basement exposed at c. 1300 Ma. Detrital zircons in sedimentary rocks younger than the 1220–1120 Ma Musgrave Orogeny may reveal which basement units were exposed during and after the 1120–1030 Ma Giles Event. The basal units of the Ngaanyatjarra Rift were deposited between c. 1120 and c. 1080 Ma (Evins et al., 2010). The Centralian Superbasin was a depocentre since the mid-Neoproterozoic and includes the present Amadeus and Officer Basins to the north and south of the Musgrave Province, respectively. All three sedimentary basins contain a record of detritus from the Musgrave Province.

Ngaanyatjarra Rift (MacDougall Formation)

The MacDougall Formation is the basal unit of the Ngaanyatjarra Rift succession (Evins et al., 2010). Detrital zircon age spectra (Fig. 16) were obtained from three samples of muscovite quartzite from the MacDougall Formation located more than 80 km apart in the western Musgrave Province (Fig. 2). Most detrital zircons from these samples yield ages (<5% discordant) that correspond to the 1220–1155 Ma Pitjantjatjara Supersuite [about 70% in GSWA 190233 (Kirkland et al., 2012c), about 60% in GSWA 194420 (Kirkland et al., 2010h), and about 50% in GSWA 190292 (Kirkland et al., 2011h)], forming an age component at c. 1175 Ma. The remaining detrital dates span similar age ranges to those of Wirku Metamorphics detrital zircons and are shown on the right side of Figure 14.

GSWA 190233 is the only sample located within the Tjuni Purlka Tectonic Zone. Its pre-Musgrave Orogeny (older than 1220 Ma) detrital zircon age spectrum is similar to Wirku Metamorphics detrital zircon spectra from the Tjuni Purlka Tectonic Zone, as it is dominated by a c. 1520 Ma age component (defined by eight analyses). The spectrum also includes a subsidiary peak at c. 1480 Ma (defined by two analyses) (Fig. 16). The oldest detrital age in the sample is 1573 ± 34 Ma (1σ). The youngest pre-1220 Ma detrital age in the sample is 1322 ± 12 Ma (1σ), and may represent Wankanki Supersuite provenance.

Pre-Musgrave Orogeny detrital zircon ages in GSWA 194420 fall within a restricted age range of 1626–1513 Ma, and include two age components, at 1578 and 1178 Ma (Fig. 16).

The detrital spectrum of GSWA 190292 is remarkably similar to that of GSWA 194420, even though they were collected on opposite sides of the Ngaanyatjarra Rift (Fig. 3). Pre-Musgrave Orogeny detrital zircon ages in this sample range between 1666 and 1460 Ma, and contain major age components at 1577 and 1179 Ma. The older component can be further deconvolved into components at c. 1610, 1590, 1565, and 1520 Ma (composed of five, five, five, and six analyses, respectively) (Fig. 16). The youngest pre-1220 Ma detrital age in the sample is 1271 ± 23 Ma (1σ).

The detrital zircon age spectrum of GSWA 190233 differs markedly from those of GSWA 190292 and 194420 in that detrital zircon ages are generally 50 Ma older in the latter two samples. Their detrital zircon age spectra more strongly resemble that of the Wirku Metamorphics from the distant Walpa Pulka Zone. The latter two samples are located in the Mamutjarra Zone, whereas the former is from within the Tjuni Purlka Tectonic Zone. This supports the conclusion of 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.

Centralian Superbasin

Published detrital ages from sediments in the Neoproterozoic Amadeus Basin that overlie the Musgrave Province are compiled in Figure 17. Camacho (written comm., 2008) dated sediments from the Dean Quartzite, Pinyanna ‘beds’, Tjuninanta ‘beds’, Winnall ‘beds’, Mutitjulu Arkose, the Mount Currie Conglomerate, and the lower and upper Inindia ‘beds’ in the central Amadeus Basin roughly 100–200 km northeast of the junction of the Western Australia – Northern Territory – South Australia State borders. Detrital zircons have been dated (GSWA 184339; Kirkland et al., 2009l) from the Heavitree Quartzite in the Mount Webb area, roughly 300 km north of the junction. Zhao et al. (1992), Buick et al. (2005), and Maidment et al. (2007) dated more distal sediments of the Heavitree Quartzite, Arumbera Sandstone, Cyclops Member, and Goyder Formation in the northeastern Amadeus Basin, roughly 100–200 km further to the northeast. Sedimentary rocks with depositional ages younger than 500 Ma were excluded from this compilation due to possible influx of ‘Pacific Gondwana’ zircons (Maidment et al., 2007).

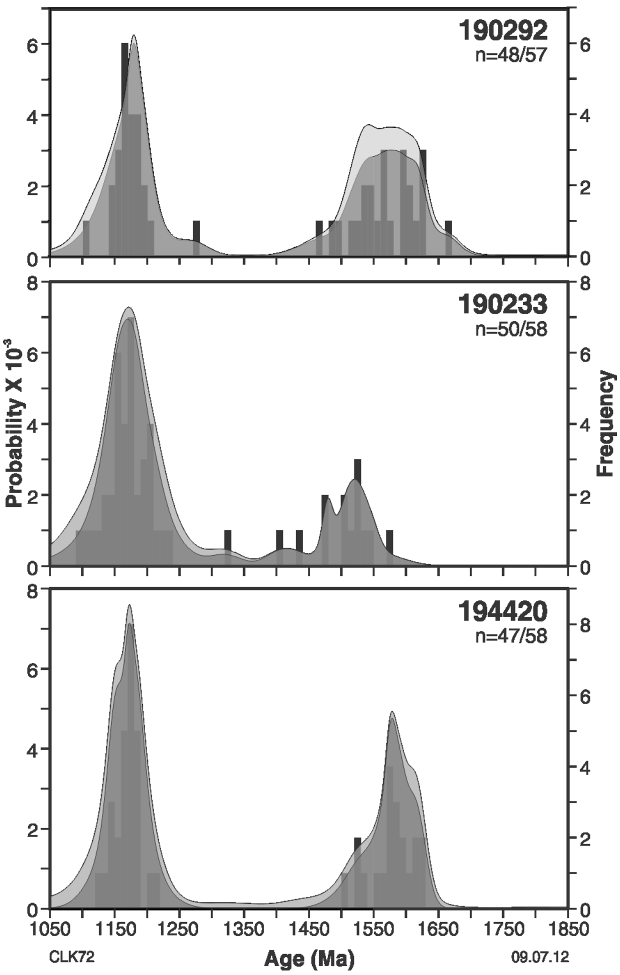

Figure 16. Probability density diagrams of detrital zircon ages from GSWA samples of the MacDougall Formation; zircons interpreted to have originated by metamorphic or migmatitic growth are not included. Notes as in Figure 12.

As with the MacDougall Formation, sedimentary rocks in the Amadeus Basin contain an overwhelming component of 1220–1120 Ma Pitjantjatjara Supersuite detritus. This is consistent with Pitjantjatjara Supersuite granites making up over half of the currently exposed rocks in the Musgrave Province. A significant detrital zircon age component at c. 1310 Ma confirms the presence of Wankanki Supersuite sources for many of the Amadeus Basin sediments. Significant Warakurna Supersuite detrital components were also found in the Amadeus Basin sedimentary samples.

Only about one-quarter of the remaining 187 concordant analyses with ages older than the Wankanki Supersuite are between 1650 and 1450 Ma, with small age peaks at 1550 and 1460 Ma defined by five analyses each. More than half of the results are between 1950 and 1650 Ma, with peaks defined by 10 or more analyses at c. 1880, 1840, 1770, 1670, 1620, and 1590 Ma. Only the 1770 Ma age component is similar to those found in detrital zircon spectra from the Latitude Hills area (Fig. 14). A small number of early Paleoproterozoic detrital zircon ages between 2500 and 2000 Ma have no age equivalents in the Musgrave Province. A few Archean detrital zircons with ages up to 3960 ± 8 Ma (1σ) are also present (Fig. 17); they form age peaks at 2860, 2660, and 2630 Ma defined by two to three analyses each, although there are too few to compare with Archean detrital zircon ages from the Wirku Metamorphics in the Latitude Hills area. Instead, most of the Paleoproterozoic and Archean detrital ages from the Amadeus Basin are similar to the ages of major magmatic events in the more proximal Arunta Block to the north and the Gawler Craton to the southeast (Fig. 14).

Most noteworthy is the absence (only about 8%) of 1600–1500 Ma material that typifies detritus in both the Wirku Metamorphics and MacDougall Formation and inherited zircons in the Musgrave Province (Fig. 14). This implies that the Wirku Metamorphics and the 1600–1500 Ma components of its provenance region were poorly exposed or exposed on the other side of the watershed during deposition into the Amadeus Basin from the Neoproterozoic to the Early Cambrian.

Discussion

Metamorphism

Kelly et al. (2006) interpreted c. 1300, 1200, and 1140 Ma monazite age components from Wirku Metamorphics pelitic rocks at Cohn Hill as the result of three separate stages of metamorphism. We interpret the oldest c. 1300 Ma age as detrital rather than metamorphic, based on the assumption that the Cohn Hill supracrustal succession is part of the Wirku Metamorphics deposited between c. 1340 and 1270 Ma. Furthermore, this c. 1300 Ma age is similar to the maximum age of disturbed zircon cores (1318, 1316, and 1306 Ma) in three of the Cohn Hills samples and corresponds to the age of Wankanki Supersuite volcanism.

UHT metamorphism during the 1220–1120 Ma Musgrave Orogeny is well represented throughout the Musgrave Province (Smithies et al., 2010). This metamorphism is manifested in the Wirku Metamorphics and Wankanki Supersuite throughout the west Musgrave Province as thick zircon rims (Figs. 14 and 15). Zircons in pelitic rocks from the Latitude Hills and Cohn Hill – Mount Blythe areas were particularly affected. Most zircon cores from the Latitude Hills area are discordant, and less than 10% of detrital zircons from the Cohn Hill – Mount Blythe area

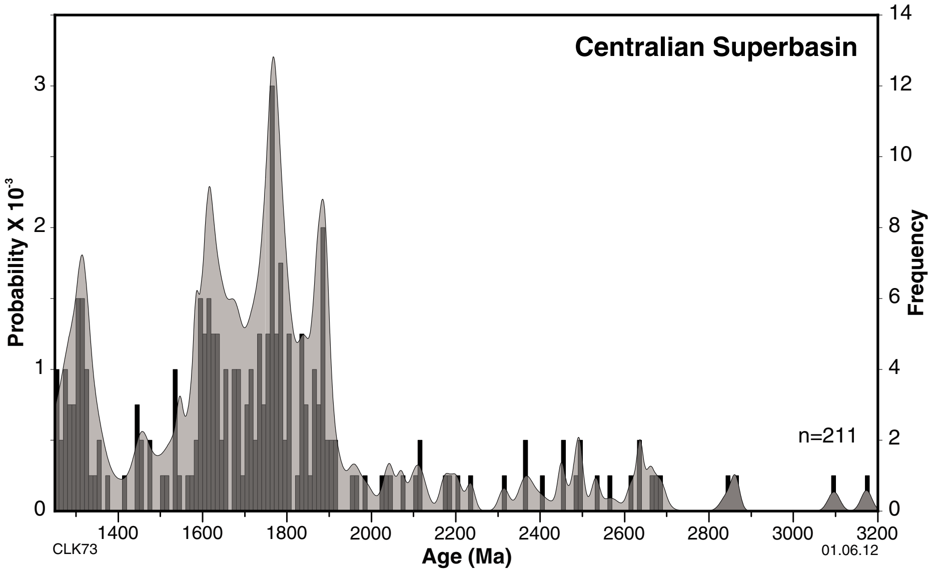

Figure 17. Probability density diagrams of detrital zircon ages from selected formations in the Centralian Superbasin. Notes as in Figure 12.

are preserved. Instead, the U–Pb isotopic system in the zircon cores was either partially to nearly completely reset or the cores were embayed by newly grown zircon rims by dissolution and reprecipitation. New homogenous zircons also grew in many of the samples. Most homogeneous zircon rim and discrete crystal ages are between 1227 and 1156 Ma, coincident with the main stage of Pitjantjatjara Supersuite magmatism and metamorphism during the Musgrave Orogeny (Smithies et al., 2010). Metamorphism during the younger Musgrave Orogeny and 1080–1030 Ma Giles Event is indicated by 1127 ± 9 and 1067 ± 17 Ma (GSWA 194379 and GSWA 185508, respectively) zircon rims and cores from GSWA 194381 and 194422 that underwent radiogenic-Pb loss to produce dates as young as 1062 Ma (Fig. 14).

Comparison of detrital and inherited zircon data

Walpa Pulka Zone

The main 1580 Ma age component, and subsidiary components at 1520 and 1480 Ma, for inherited zircons from the Walpa Pulka Zone typically correspond to the main 1570 Ma, and secondary 1530 and 1470 Ma, age components for detrital zircons in the Wirku Metamorphics in the same zone (Fig. 14). Minor components at 1440 Ma in the inheritance dataset and 1400 Ma in the detrital dataset do not have counterparts. The youngest age component for zircon cores in both datasets is around 1270 Ma, providing further credence to the existence of detritus of this age.

Tjuni Purlka Tectonic Zone

The cumulative age spectrum for inherited zircons from the Tjuni Purlka Tectonic Zone is swamped by 1360–1300 Ma inheritance, which is prevalent in Wankanki Supersuite granites. A significant proportion of the Wirku Metamorphics sedimentary precursors were deposited just prior to this magmatic event; hence, they do not contain as much detritus in this age range. The main inherited-zircon age component for the Tjuni Purlka Tectonic Zone at 1510 Ma, and a smaller peak at 1560 Ma, correspond to two of the main detrital age components of the Wirku Metamorphics from the same zone (Fig. 14). Although detrital and inherited-zircon age components in the Tjuni Purlka Tectonic Zone do not correspond exactly between 1450 and 1400 Ma, both datasets contain numerous analyses within this range, and are confined to the Prostanthera Hill – Mount Scott area in the western Tjuni Purlka Tectonic Zone.

Central and eastern Musgrave Province

The cumulative age spectra for detrital and inherited zircons from previous workers' datasets from the central and eastern Musgrave Province are remarkably similar, with 77% and 80% of their respective concordant ages between 1650 and 1450 Ma, and 45% and 36% of their respective concordant ages older than 1550 Ma. Their main age components at 1570, 1540, and 1470 Ma also coincide. The two spectra also compare favourably with Walpa Pulka Zone spectra in that the main age component in each is centred on 1570 Ma. This indicates that the basement north of the Mann Fault and east of our study area is similar to that in the Walpa Pulka Zone.

Provenance of sedimentary precursors to the Wirku Metamorphics

Spatial trends within tectonic zones

A Kolmogorov–Smirnov (K–S) test was used to statistically compare detrital zircon ages older than 1350 Ma between individual samples (Table 2), both within and between the tectonic zones of the west Musgrave Province. The K–S test is a non-parametric method of statistical comparison that includes the uncertainty in the cumulative density function propagated from the uncertainty in individual age measurements (Press et al., 1986). Only crystals interpreted to record a primary magmatic age (i.e. the detrital zircons) are used. Only samples with n >20 and discordance <5% were used in the test. The K–S method constructs a series of cumulative distribution functions (the sum of the probabilities with increasing age) and tests the probability that samples were drawn from the same distribution. The value (1 – p) represents the probability that two samples have different distributions. We reject the hypothesis that samples come from the same source when the probability (p) is below 0.05, indicating that there is 95% confidence that the samples are from different sources. High values, close to 1, indicate very similar age spectra, and suggest that the samples were derived from the same source or from similar sources.

The test reveals that the zircon ages are statistically similar in all Walpa Pulka samples and confirms the difference in provenance between the central Tjuni Purlka Tectonic Zone and Prostanthera Hill – Mount Scott area. There are anomalous results for samples within the Tjuni Purlka Tectonic Zone. For example, the distribution of zircon ages in GSWA 187115, from the central subdivision, is dissimilar to those in the other samples. Results for GSWA 185508, from the same area, are nearly identical to those for GSWA 187289, in the Prostanthera Hill area. The Latitude Hills region also stands out in the K–S test as being distinctly different. There is no statistical similarity between individual Latitude Hills samples because of the presence of Archean detritus in only some of the samples. GSWA 183466 is spatially separated from the other samples and is lithologically distinct. The maximum depositional age for samples with exceptional provenance in their respective tectonic zones is usually significantly younger than that of other samples from the same zone (Table 1, Fig. 14). This implies that the exceptional samples not only sampled different sediment source areas, but also may represent a younger part of the Wirku Metamorphic stratigraphy than the majority of their counterparts within each tectonic zone.

Table 2. **Kolmogorov–Smirnov (K–S) test matrix for GSWA samples of the Wirku Metamorphics divided by region. Only detrital zircon ages with discordance <5% are used. Each number refers to the probability that the two samples are sourced from the same zircon population and considers the uncertainty in age measurement. The value (1 – p) represents the probability that the two samples have different distributions. A value of (1 – p) less than 0.05 (95% confidence) indicates that the samples are from distinctly different populations (high values indicate that the populations are similar and are in grey boxes). Values close to 1.0 indicate very similar age spectra. Italic font means very low numbers in sample population, insufficient for robust correlation. Sample IDs are coloured according to lithotectonic zone.**

	Walpa Pulka Zone				*Tjuni Purlka Tectonic Zone*							*Latitude Hills*				*MacDougall Formation*		
					Central Tjuni Purlka Tectonic Zone				*Prostanthera Hill - Mount Scott*									
Sample	**174748**	**183596**	***174797***	**174588**	**185508**	***187103***	***187109***	**187115**	187174	187289	187195	**183466**	**183595**	**185591**	**185592**	**190233**	**194420**	190292
174748		0.066	0.993	0.913	0.010	0.031	0.795	0.000	0.000	0.016	0.000	0.000	0.176	0.001	0.000	0.000	0.000	0.000
183596	0.066		0.738	0.002	0.716	0.296	0.188	0.014	0.199	0.755	0.004	0.000	0.074	0.001	0.000	0.000	0.000	0.000
174797	0.993	0.738		0.777	0.664	0.513	0.988	0.032	0.219	0.574	0.018	0.000	0.611	0.082	0.000	0.001	0.014	0.047
174588	0.913	0.002	0.777		0.000	0.009	0.408	0.000	0.000	0.000	0.000	0.000	0.159	0.003	0.000	0.000	0.000	0.000
185508	0.010	0.716	0.664	0.000		0.040	0.242	0.000	0.005	0.974	0.000	0.000	0.002	0.000	0.000	0.000	0.000	0.000
187103	0.031	0.296	0.513	0.009	0.040		0.111	0.282	0.405	0.083	0.068	0.000	0.031	0.004	0.000	0.000	0.001	0.010
187109	0.795	0.188	0.988	0.408	0.242	0.111		0.002	0.007	0.306	0.000	0.000	0.254	0.024	0.000	0.000	0.004	0.016
187115	0.000	0.014	0.032	0.000	0.000	0.282	0.002		0.061	0.000	0.093	0.000	0.000	0.000	0.000	0.000	0.000	0.008
187174	0.000	0.199	0.219	0.000	0.005	0.405	0.007	0.061		0.002	0.405	0.000	0.000	0.000	0.000	0.000	0.000	0.000
187289	0.016	0.755	0.574	0.000	0.974	0.083	0.306	0.000	0.002		0.000	0.000	0.017	0.000	0.000	0.000	0.000	0.000
187195	0.000	0.004	0.018	0.000	0.000	0.068	0.000	0.093	0.405	0.000		0.000	0.000	0.000	0.000	0.000	0.000	0.001
183466	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.007	0.000	0.000	0.000	0.000
183595	0.176	0.074	0.611	0.159	0.002	0.031	0.254	0.000	0.000	0.017	0.000	0.000		0.001	0.000	0.000	0.000	0.000
185591	0.001	0.001	0.082	0.003	0.000	0.004	0.024	0.000	0.000	0.000	0.000	0.007	0.001		0.000	0.000	0.000	0.000
185592	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.000	0.000	0.000
190233	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000		0.024	0.021
194420	0.000	0.000	0.014	0.000	0.000	0.001	0.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.024		0.977
190292	0.000	0.000	0.047	0.000	0.000	0.010	0.016	0.008	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.021	0.977	

Spatial trends between tectonic zones

Most paragneisses (reclassified from previous studies) east of the study area were collected north of the Davenport Shear Zone (Fig. 2), and contain significant age components older than 1550 Ma that are similar to those for samples from the Walpa Pulka Zone. A few samples within the Davenport Shear Zone yield detrital zircon age spectra similar to those for the Tjuni Purlka Tectonic Zone, although the two zones have not been linked by geological mapping.

The probability density diagram of detrital zircon ages from the Tjuni Purlka Tectonic Zone shows a broad peak spanning a similar age range to that of the Walpa Pulka Zone and paragneisses to the east, but shifted 50 Ma to younger ages (Fig. 14). However, GSWA 183596 (Kirkland et al., 2009a), a paragneiss from the Walpa Pulka Zone, exhibits a remarkable affinity to all Tjuni Purlka Tectonic Zone samples (Table 2). This sample is the only one collected southwest of the Fanny Fault and does not exhibit the high-pressure mineral assemblages typical of samples to the east, which were exhumed during the Petermann Orogeny. Furthermore, GSWA 183596 is the only sample from the Walpa Pulka Zone with a concordant zircon core older than 1280 Ma and may represent a different stratigraphic level of the Wirku Metamorphics than exhumed samples further to the east. The Tjuni Purlka Tectonic Zone samples also contain a substantially larger proportion of concordant detrital zircons younger than 1360 Ma (19% vs 7% in the Walpa Pulka Zone). This young detrital zircon component most likely comes from the Wankanki Supersuite felsic volcanic sources with which they are interleaved (e.g. GSWA 180867; Kirkland et al., 2010e). The ages of the oldest detrital zircon cores in the Walpa Pulka and Tjuni Purlka Tectonic Zones are within uncertainty of one another.

All of the early Mesoproterozoic detrital zircon age components from the Latitude Hills area correspond to the main detrital zircon age components from the Tjuni Purlka Tectonic Zone. However, only a minor proportion (about 10%) of early Mesoproterozoic detrital zircon ages in the Latitude Hills area are within the 1650–1560 Ma range that makes up about 40% of the detrital zircon ages in the Walpa Pulka Zone (Fig. 14). This implies that the Latitude Hills sediments originated from sources similar to the Tjuni Purlka Tectonic Zone, but not similar to the Walpa Pulka Zone. The presence of Paleoproterozoic and Archean detrital zircons sets the metasedimentary rocks of the Latitude Hills area apart from all other rocks in the Ramarama Basin. The absence of detrital zircons older than 1350 Ma in the Latitude Hills area implies that the Wankanki Supersuite did not contribute to their provenance.

Maximum depositional ages

The new and reclassified data presented above provide depositional age constraints for precursors to the Wirku Metamorphics in each of the tectonic zones. Conservative youngest maximum depositional ages from the Walpa Pulka Zone, Tjuni Purlka Tectonic Zone, Mamutjarra Zone, Latitude Hills, and central and eastern Musgrave Province (1340 ± 16, 1320 ± 17, 1316 ± 38, 1363 ± 14, and 1341 ± 39 Ma, respectively) are all within 95% analytical uncertainty of one another (Table 1, Fig. 14). The average maximum depositional age in the western Musgrave Province is c. 1335 Ma, and slightly older (c. 1360 Ma) to the east. Similar geochemistry between the Wirku Metamorphics and Wankanki Supersuite (Fig. 11a) in all tectonic zones of the west Musgrave Province implies a component of 1360–1300 Ma detritus throughout. Rare, 1270–1250 Ma detrital zircon cores (Table 1, Fig. 14) are concentrated in samples from the Prostanthera Hill – Mount Scott area, suggesting that a younger portion of the Wirku Metamorphics is exposed in this area. These younger parts also contain a dominant, c. 1410 Ma, detrital zircon age component that is poorly represented elsewhere, indicating that the source of these zircons was unique and not dominated by older parts of the Wirku Metamorphics.

Minimum depositional ages

Protracted metamorphism during the 1220–1120 Ma Musgrave Orogeny caused extensive recrystallization of the Wirku Metamorphics throughout the west Musgrave Province. This event overprinted metamorphic fabrics and assemblages that were produced during the earlier Mount West Orogeny, and which would potentially have provided tighter minimum depositional age constraints for many of the samples. It also appears that the 1345–1293 Ma Mount West Orogeny did not extend into the Walpa Pulka Zone or to the east. For these reasons, most minimum depositional ages defined by the ages of metamorphic zircon rims in individual samples cluster around the c. 1200 Ma peak of the Musgrave Orogeny (Fig. 14). In some cases (particularly in the Cohn Hill area and among samples analysed by Maboko, 1988), the U–Pb isotopic system in zircon was reset during the latest stage of the Musgrave Orogeny, producing ages as young as 1120 Ma.

Direct constraints on depositional age

Magmatic rocks of the Wankanki Supersuite provide the best age constraints on deposition of sedimentary precursors to the Wirku Metamorphics. Inclusions of Wirku Metamorphics occur in Wankanki Supersuite granites within and to the south of the Tjuni Purlka Tectonic Zone. This provides a c. 1300 Ma minimum depositional age constraint on precursors to the Wirku Metamorphics in those areas. The most direct constraints come from dated metavolcanic layers of the Wankanki Supersuite interleaved with the Wirku Metamorphics. GSWA 180867, from the Tjuni Purlka Tectonic Zone, was deposited at 1324 ± 7 Ma (Kirkland et al., 2010e), providing depositional age constraints for the surrounding metasedimentary rocks. In the Mamutjarra Zone, two interleaved rocks which may be metavolcanic layers yield slightly different ages of 1310±7 Ma (GSWA 184150; Kirkland et al., 2011f) and 1334 ± 6 Ma (GSWA 190245; Kirkland et al., 2011g) implying an interval of at least 12 Ma between deposition of the two layers (Fig. 15 and Table 1). Considering the maximum depositional age of c. 1300 Ma in the Mamutjarra Zone, the older volcanic layer must be somewhere near the base of the stratigraphic pile in that area.

Summary

The Wirku Metamorphics within each tectonic zone may represent distinct sedimentary basins, or a single, larger depositional basin (the Ramarama Basin) with an older component deposited between 1340 and 1300 Ma over the majority of the Musgrave Province, and a younger component deposited along the southwestern edge of the Tjuni Purlka Tectonic Zone between 1270 and 1220 Ma. This younger stratigraphic level is unlikely to be exposed in the Walpa Pulka Zone and further eastwards because of the deeper crustal levels exposed there. However, this depositional age is concomitant with uplift and cooling of the eastern Biranup and Fraser Zone of the Albany–Fraser Orogen to the west between c. 1290 and 1260 Ma (Bunting et al., 1976; Spaggiari et al., 2009).

Depositional environment of sedimentary precursors to the Wirku Metamorphics

The composition, associations, textures, and geochronology of most of the rock units described above can be used to decipher the depositional environment of each unit and provide a model for the regional depositional setting of the Ramarama Basin.

The Walpa Pulka Zone is dominated by arkosic metasandstones, the precursors of which may have been deposited in a fluvial environment or in the proximal portions of submarine fans. Wankanki Supersuite magmatism is absent in this zone and Wankanki-age zircons are also absent from detritus in these rocks (see below). This implies that the submarine fan or fluvial system that deposited the precursors to the Wirku Metamorphics of the Walpa Pulka Zone was fed from the northeast on a southwest-dipping paleoslope (present coordinates).

The Wirku Metamorphics of the Tjuni Purlka Tectonic Zone are dominated by psammitic gneisses although they contain a noteworthy proportion of pelitic metasedimentary rocks (particularly southeast along the strike of the zone toward the Latitude Hills area). More importantly, Wirku Metamorphics of the Tjuni Purlka Tectonic Zone may contain a significant volcanic–volcaniclastic component throughout and are associated with volcanic units of the Wankanki Supersuite. Most highly peraluminous samples from the Wirku Metamorphics come from this zone. Together, these observations imply that the precursors to the Wirku Metamorphics were deposited as both proximal and distal (submarine) deposits with the depositional influence of nearby active volcanoes. The presence of pelitic units indicates deeper water or more distal deposition and implies that the Ramarama Basin was once much wider than its present extent. Deformation in the Tjuni Purlka Tectonic Zone was responsible for significant shortening of the basin after deposition.

The only metasedimentary rocks found in the Mamutjarra Zone are rare and of pelitic composition. Most of the exposed rocks in this zone are volcanic rocks of the Wankanki Supersuite. The Mamutjarra Zone likely represents the highest concentration of Wankanki Supersuite volcanic rocks in the Ramarama Basin.

The Latitude Hills and Cohn Hill – Mount Blythe areas are occupied almost exclusively by pelitic metasedimentary rocks. The precursors of these rocks were likely deposited within the deeper portions of the Ramarama Basin. The unique detritus (see below) preserved in the Latitude Hills area indicates provenance from an Archean craton to the south or west (present coordinates). However, the presence of Wankanki Supersuite detritus implies these units of the Wirku Metamorphics were not deposited along a passive margin. Instead, the Ramarama Basin between the Mamutjarra Zone and the southern or western craton may have been narrow, deep, and fault bounded.

Evolution of the Ramarama Basin

Volcanic rocks of the c. 1345–1293 Ma Wankanki Supersuite and sedimentary precursors of the Wirku Metamorphics are the main constituents of the Ramarama Basin. The salient observations above portray the Ramarama Basin as a c. 1340–1270 Ma sedimentary basin with coeval felsic volcanism. A summary of the most important characteristics of this basin is presented below, with an emphasis on aspects relevant to the early tectonic history of the Musgrave Province.

Basement

Although a tectonic model (Wade et al., 2006) has been proposed for the 1600–1500 Ma history of the Musgrave Province, very little is known about the rocks formed during that period. The model portrays the creation of a c. 1600 Ma Musgrave island arc and eventual 1580–1550 Ma collision of that arc with the Gawler Craton along a south-dipping subduction zone, which was responsible for the Hiltaba Event and formation of the Gawler Range Volcanics on the Gawler Craton (Betts and Giles, 2006). The island arc model is reliant on arc-like geochemical signatures and juvenile Nd values (calculated from 1550 Ma crystallization ages) for samples collected from the Musgrave Province within 100 km of the Western Australian border. However, only one of those samples has been dated by U–Pb methods (sample PR95IRS361 of Scrimgeour et al. 1999, equivalent to sample 95/361 of Wade et al., 2006), and its geochemistry and zircon age spectrum resemble that of Warakurna Supersuite charnockitic syenogranite GSWA 187171 (Fig. 18; Kirkland et al., 2012a;). The remaining samples were assumed to be 1600–1500 Ma orthogneisses similar to those dated further east in the central and eastern Musgrave Province (Maboko et al., 1991; Camacho and Fanning, 1995; Camacho, 1997; Scrimgeour et al. 1999; Young et al., 2002; Edgoose et al., 2004).

Of the previously dated 1600–1500 Ma orthogneiss samples in the central and eastern Musgrave Province, few yield unambiguous magmatic crystallization ages. The Outounya Gneiss (sample S5; Camacho and Fanning,

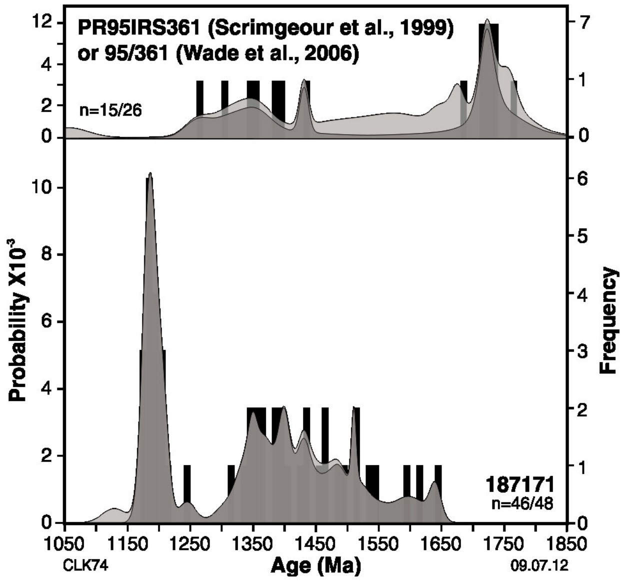

Figure 18. Probability density diagrams of zircon dates from Smoke Hills Volcanic sample GSWA 187171 (lower) and the only sample with U–Pb zircon data (upper) used in the tectonic model of Wade et al. (2006). Notes as in Figure 12.

1995) shows convincing evidence of a crystallization age older than 1500 Ma. The sample contains zircon cores dated at 1557 ± 24 Ma, interpreted as the magmatic crystallization age of the granitic protolith, and zircon rims dated at 1124 ± 43 Ma. This K-feldspar augen gneiss is cut by granite dated at 1152 Ma (Camacho and Fanning, 1995), consistent with the older date in the Outounya Gneiss representing crystallization of the protolith.

These samples and most areas mapped as 1600–1500 Ma orthogneiss basement are located between the Mann Fault and Woodroffe Thrust (Fig. 2; Edgoose et al., 2004). Considering the extreme vertical and horizontal displacements (tens of km) these rocks underwent in this area during the c. 550 Ma Petermann Orogeny (Clarke and Powell, 1991; Ellis and Maboko, 1992; Scrimgeour and Close, 1999), it cannot be assumed that similar basement is exposed elsewhere in the Musgrave Province. Exposures of orthogneisses older than 1500 Ma in the Musgrave Province are scarce, and are likely limited to tectonic slices exposed during the Petermann Orogeny. Geochemical and isotopic evidence for a 1600–1500 Ma juvenile arc in the Musgrave Province (Wade et al., 2006) comes from samples with inferred igneous protoliths with inferred crystallization ages. The observations above show that little can be deduced with confidence about the nature of the basement to the Ramarama Basin from the current database of direct observations. Below, we explore what may be revealed about the basement through the provenance of the Wirku Metamorphics.

Provenance

This study indicates a spatial pattern of younging provenance for the Wirku Metamorphics (Fig. 14). In the Walpa Pulka Zone, the bulk of the detritus is dated between 1650 and 1530 Ma and centred on c. 1570 Ma. Moving into the Tjuni Purlka Tectonic Zone, to the southwest, the age of most of the detritus is c. 50 Ma younger, with most detritus between 1580 and 1450 Ma and centred on c. 1520 Ma. The western portion of the Tjuni Purlka Tectonic Zone shows a predominance of 1500 to 1400 Ma detritus. Major 1370 and 1320 Ma detrital contributions from the Wankanki Supersuite also begin to appear in the Tjuni Purlka Tectonic Zone. Further southwest in the Mamutjarra Zone, there is only sparse evidence of inheritance or detritus older than 1410 Ma. Instead, Wankanki Supersuite magmatic material dominates the basin infill. This southwesterly younging of detritus is corroborated by a similar southwesterly shift in inherited-zircon ages. However, it is impossible to know if younging of detritus to the southwest reflects the original distribution of 1600–1500 Ma basement. If this is the case, it may indicate a continuation of the southward-younging accretionary process in the North Australian Craton as suggested by Close et al. (2006).

Internal sources

The rarity of exposure of igneous rocks older than 1410 Ma, together with the abundance of 1600–1500 Ma zircons and local Archean zircons in the Musgrave Province, is a conundrum. However, the evidence for basement of this age in the Musgrave Province is compelling. At least one c. 1550 Ma orthogneiss (Outounya Gneiss; Camacho and Fanning, 1995) appears to exist in the Musgrave Province. The narrow range (2040–1840 Ma) of Hf- and Nd-depleted-mantle model ages from the Wankanki, Pitjantjatjara, and Warakurna Supersuites is older than any intrusive age known from the Musgrave Province (Smithies et al., 2010). Because of the lack of magmatic, inherited, and detrital zircons of this age in the Musgrave Province (as shown above) or in its surrounding Proterozoic basins, the model ages may not reflect the true age of the crustal component. Instead, the model ages may reflect the combined provenance of the Wirku Metamorphics, which is a mixture of dominantly c. 1570, 1500, and 1400 Ma detritus with Archean components. Furthermore, all field observations of the Wirku Metamorphics paragneisses point to relatively proximal depositional environments for their precursors.

Potential external sources

An alternative hypothesis for the lack of exposed sources for early Mesoproterozoic zircons and Paleoproterozoic Hf and Nd model ages in the Musgrave Province is that most or all inherited and detrital zircons of this age were sourced from outside the Musgrave Province. Below we postulate potential source regions for the Wirku Metamorphics detritus outside of the Musgrave Province. Alternatively, these sources may be viewed as extensions of the basement to the Musgrave Province.

Wade et al. (2006) considered the 1600–1580 Ma Gawler Range Volcanics and Hiltaba Event (Betts and Giles, 2006) to be the magmatic products of a south-dipping subduction zone under the Gawler Craton related to closure of a similar-age, juvenile Musgrave Province arc to the north. Younger, 1420–1400 Ma magmatism (Nelson, 2005a,b,c; Bunting, 2007) has also been reported from the Coompana Block of the Eucla Basement. The youngest magmatism in the Aileron and Warumpi Provinces to the north of the Musgrave Province is confined to 1600–1550 Ma and the c. 1530 Ma Southwark granite (Close et al., 2006). However, protolith ages for these rocks are between 1690 and 1630 Ma (Close et al., 2006) and outside the age range of protoliths thought to contribute to Musgrave Province rocks (Smithies et al., 2010). The Krackatinny Supersuite in the Tabletop Terrane of the Rudall Province is composed of 1600–1550 Ma igneous rocks (Maidment and Kositcin, 2007). The Rudall Province of the West Australian Craton has also been linked to the Musgrave Province via the Anketell Regional Gravity Ridge (Fraser, 1976).

An Archean contribution to provenance in the Ramarama Basin is implied by two lines of evidence:

1. Archean detrital zircons in the Wirku Metamorphics of the Latitude Hills area (Fig. 13)
2. Hf and Nd model ages of 2010–1840 Ma (Smithies et al., 2010), which require a very old crustal source component in Wankanki and Pitjantjatjara Supersuite magmas to offset a dominant 1600–1300 Ma crustal component.

Archean detrital zircons are only found in the Latitude Hills area; their ages closely match magmatic events in the Yilgarn Craton to the west (Fig. 13). Most zircons in the Yilgarn Craton crystallized between 2750 and 2600 Ma (Nelson, 2008). About two-thirds of the Archean detrital zircons in the Latitude Hills samples fall within this range. The few zircons older than 2750 Ma at Latitude Hills do not correspond to magmatic ages in the nearest (central and southern) parts of the Yilgarn Craton and are, perhaps, better represented in the Gawler Craton to the southeast. The Gawler Craton shows evidence of magmatic activity between 3200 and 3000 Ma (Hand et al., 2007; Fraser et al., 2008; Belousova et al., 2009), which may account for the oldest, c. 3100 Ma detrital zircons in the Latitude Hills samples. However, Archean magmatic zircons in the Mawson Craton are dominated by a component older than 2600 Ma, which is represented by only three concordant detrital zircons in the Latitude Hills samples (Fig. 13).

Zircon ages between 1550 and 1400 Ma are conspicuously absent from all orogens currently surrounding the Musgrave Province, although they are abundant in the Tjuni Purlka Tectonic Zone and ubiquitous throughout the Wirku Metamorphics. This suggests that a large component of the Musgrave Province basement is indeed unique in central Australia.

Mount West Orogeny

Deposition of the Wirku Metamorphics in the Ramarama Basin occurred during the Mount West Orogeny, which is characterized by emplacement of the 1345–1293 Ma, calc-alkaline Wankanki Supersuite. The data presented in this study provide several constraints on the potential Wankanki magmatic arc and its surrounding Ramarama Basin. An oceanic (arc) setting for the Mount West Orogeny maybe incompatible with the lack of distal, pelitic sedimentary components in the Wirku Metamorphics and by Hf- and Nd-depleted-mantle model ages that indicate continental crust older than 1400 Ma beneath the arc. The subduction-like geochemistry and relatively juvenile isotopic compositions of the Wankanki Supersuite (Smithies et al., 2009a) best support a hypothesis in which the supersuite formed within a subduction zone setting similar to that which produced Andean-style continental arc magmatism. The absence of Wankanki Supersuite magmatism north of the Tjuni Purlka Tectonic Zone may indicate that the Tjuni Purlka Tectonic Zone is a subduction-related suture. Younger granites on either side of the Tjuni Purlka Tectonic Zone have indistinguishable Nd-isotope source characteristics, suggesting that the basement was essentially the same on either side of the zone and contains a significant 1600–1500 Ma component and minor Archean component (Smithies et al., 2010). North-dipping subduction beneath juvenile 1600–1540 Ma crust is the most plausible architecture to explain the available data. This scenario is supported by the southwesterly increasing (from the Walpa Pulka Zone to the Mamutjarra Zone) proportion of Wankanki Supersuite magmatism coupled with a southwesterly decrease in the proportion of detrital zircons older than 1330 Ma in the Wirku Metamorphics. Initially, the Tjuni Purlka Tectonic Zone may have been activated as an incipient back-arc rift (e.g. Smithies et al., 2010). Anomalously young c. 1270 and 1250 Ma detrital zircons in the Tjuni Purlka Tectonic Zone suggest that waning magmatism may have been focused along this crustal-scale zone of weakness.

Alternatively, the Wankanki Supersuite and Wirku Metamorphics could have formed a retro-back-arc or even an intracontinental basin during the Mount West Orogeny. This is supported by the isotopic similarity of crustal sources for the Wankanki, Pitjantjatjara, and Warakurna Supersuites (Smithies et al., 2010), by the absence of a distinct suture, and by the predominance of moderately proximal sedimentary precursors for the Wirku Metamorphics. The arc-like geochemical characteristics of the Wankanki Supersuite do not necessarily imply magma genesis in an arc setting. The ‘arc signature’ of the Wankanki Supersuite may have been inherited through incorporation of a crustal component, produced during earlier subduction, into a mantle-derived melt by assimilation-fractional crystallization (AFC)- or melting, assimilation, storage, and homogenization (MASH)-type processes in a non-subduction environment. However, the major and trace element compositions of the Wankanki Supersuite differ markedly from those of rocks of the Pitjantjatjara and Warakurna Supersuites that crystallized from intracontinental A-type magmas within the same area (Smithies et al., 2009a). Furthermore, the lower emplacement temperatures of the Wankanki Supersuite indicate a different thermal impetus for magma generation (Smithies et al., 2010).

A retro-back-arc setting for the Wankanki Supersuite is also difficult to reconcile with the larger-scale tectonic setting of the Musgrave Province. The only similar-age arc nearby was the Albany–Fraser Orogen (Spaggiari et al., 2009). However, if subduction was south-directed in the Albany–Fraser Orogen (e.g. Clark et al., 2000; Bodorkos and Clark, 2004; Cawood and Korsch, 2008) it would necessitate a back-arc to the southeast, whereas the Musgrave Province lies slightly north of, and along-strike from, the Albany–Fraser Orogen. In a north-dipping subduction scenario for the Albany–Fraser Orogen, the Biranup Complex would represent a back-arc correlative with the Tjuni Purlka Tectonic Zone and indeed such a setting is consistent with Hf-isotopic evolution patterns (Kirkland et al., 2011j).

It is unlikely that the Wankanki Supersuite represents a continuation of the same Paleoproterozoic subduction setting responsible for southward-younging accretionary process in the North Australian Craton (Close et al., 2006) or the 1600–1500 Ma juvenile arc proposed by Wade et al. (2006). Evidence for magmatism between 1450 and 1345 Ma would correspond to only about 8% of the detrital and inherited-zircon ages from the Musgrave Province presented in this study. Furthermore, it would require a change in subduction polarity from south- to north-dipping during that time interval.

Regardless of tectonic setting, it is unlikely that the Ramarama Basin was particularly large, because the Wirku Metamorphics are dominated by moderately proximal metasedimentary components and contain only rare, thin, distal pelitic units. Although geochronological evidence for Wankanki Supersuite magmatism northeast of the Tjuni Purlka Tectonic Zone is lacking, all components of the Ramarama Basin may have been present in the central and eastern Musgrave Province, although the Ramarama Basin components may have been uplifted and removed by erosion during the Petermann Orogeny.

Correlatives to the Ramarama Basin

It is tempting to correlate the Mount West Orogeny with Stage I (1345–1290 Ma) of the Albany–Fraser Orogen to the southwest, which is classically regarded as involving south-dipping subduction, convergence, collision and suturing of the West Australian Craton to the Mawson Craton (e.g. Condie and Myers, 1999; White et al., 1999; Clark et al., 2000; Bodorkos and Clark, 2004; Cawood and Korsch, 2008; Spaggiari et al., 2009). Fletcher et al. (1991), Nelson et al. (1995), and Spaggiari et al. (2009) discussed 1330–1300 Ma ages in the Albany–Fraser Orogen (Stage I) that are similar to the ages of magmatism during the Mount West Orogeny. In particular, the combination of the 1330–1280 Ma Recherche Granite and paragneisses with c. 1560 Ma and Archean detrital zircons in the Nornalup Complex is reminiscent of the Wankanki Supersuite and Wirku Metamorphics, respectively.

The presence of the juvenile mafic Fraser Complex (equivalent zircon and two-stage depleted-mantle Nd model ages at c. 1290 Ma; Condie and Myers, 1999), exposure of high-pressure mafic rocks, and crustal-scale folding, make a strong case for subduction and collision in the Albany–Fraser Orogen. The evidence that subduction was south-dipping is based on age trends in the c. 1300 Ma Recherche Supersuite (Bodorkos and Clark, 2004; Spaggiari et al., 2009). It is unlikely that the Mount West Orogeny resulted from a large arc-basin complex. Instead, it may simply represent the dwindling eastern termination of the Albany–Fraser Orogen. In this scenario, the north-dipping subduction setting of the Mount West Orogeny would have been separated from the south-dipping subduction setting of the Albany–Fraser Orogen by a transform fault in a situation akin to modern-day New Zealand. However, subduction in the Albany–Fraser Orogen may have been towards and beneath the craton, based on the orogen's isotopic connection to the Yilgarn Craton, the presence of Archean tectonic fragments within new Proterozoic crust of the orogen, and the Proterozoic reworking of Archean lithologies on the margin (Kirkland et al., 2011j; Spaggiari et al., 2011).

Conclusions

The presence of an early Mesoproterozoic basement to the Ramarama Basin is necessitated by: (i) rare exposures of c. 1550 Ma orthogneiss in the central and eastern Musgrave Province; (ii) the abundance of detrital and inherited zircons of this age throughout the Musgrave Province; and (iii) ubiquitous granites with 2040–1840 Ma Hf and Nd model ages, which are older than any intrusive ages in the Musgrave Province (Smithies et al., 2010). However, the true distribution of this basement is poorly constrained. The hypothesis of Wade et al. (2006, 2008), that this basement was a juvenile magmatic arc formed during south-dipping subduction under the Gawler Craton, is plausible, although this remains to be proven.

Coeval deposition of sedimentary precursors to the Wirku Metamorphics and 1345–1293 Ma calc-alkaline magmatism of the Wankanki Supersuite collectively formed the Ramarama Basin. This basin constitutes the oldest exposed basement within the west Musgrave Province. The Wirku Metamorphics occurs throughout the west Musgrave Province, whereas Wankanki Supersuite magmatism is restricted to the southwest Musgrave Province (Tjuni Purlka Tectonic and Mamutjarra Zones). The lithological characteristics and distribution of the Wirku Metamorphics suggests that its sedimentary precursors were deposited in generally proximal environments adjacent to volcanic (Wankanki) centres and in the proximal portions of submarine fans. Detrital- and inherited-zircon age data and Nd and Hf isotope data imply that deposition and magmatism occurred above older crust that contained 1600–1500 Ma and Archean components (Smithies et al., 2010).

Detrital zircon age spectra from the Wirku Metamorphics and inherited-zircon age spectra from younger magmatic rocks (Fig. 14) reveal distinct age trends for the newly defined Walpa Pulka, Tjuni Purlka Tectonic, and Mamutjarra Zones. The Wirku Metamorphics of the Walpa Pulka Zone in the northeast contain a main 1650–1530 Ma detrital zircon component dominated by

1570 Ma zircons. More varied and slightly more pelitic rocks in the Tjuni Purlka Tectonic Zone in the centre contain a main 1580–1450 Ma detrital zircon component dominated by 1520 Ma zircons and include significant 1370 and 1320 Ma detrital zircon contributions from the Wankanki Supersuite. The western portion of the Tjuni Purlka Tectonic Zone (Prostanthera Hill – Mount Scott area) contains higher stratigraphic levels of the Wirku Metamorphics dominated by 1500–1400 Ma detrital zircons. The absence of 1550–1400 Ma zircon ages in orogens currently surrounding the Musgrave Province, together with the abundance of zircons of this age in the Wirku Metamorphics, make this component of the Musgrave Province basement unique in central Australia.

Samples from the Mamutjarra Zone in the southwest did not yield detrital zircons. Instead, the zone is characterized by younger 1345 to 1293 Ma Wankanki Supersuite magmatism and widespread zircon inheritance older than 1410 Ma. Most zircon inheritance in these rocks is within the timeframe of the Wankanki Supersuite, indicating no contamination of the magmas by significantly older felsic crust. This suggests that magmas of the Wankanki Supersuite travelled through dominantly mafic crust.

Wirku Metamorphics from the Latitude Hills area in the southeast yield unique detrital zircon age spectra with major Proterozoic components at 1820–1700 Ma and 1560–1400 Ma and an Archean component. Archean detrital zircons are potentially correlative with rock ages in the Yilgarn Craton (Fig. 14). Zircons in the Wirku Metamorphics of the Cohn Hill – Mount Blythe area to the far southwest are variably to completely reset by later metamorphism and deformation and yield no protolith detrital zircon ages.

The distribution and character of the Ramarama Basin is better constrained than the early Mesoproterozoic basement to the Musgrave Province. The Ramarama Basin is sufficiently well exposed to permit a reasonable interpretation of the presence of a relatively juvenile, calc-alkaline magmatic arc (Wankanki Supersuite) with subduction-like geochemical signatures and similarities to Andean-type continental arcs. Age similarities between the igneous and detrital components of the Nornalup Zone and the Ramarama Basin suggest that the basin may also be a component within the Albany–Fraser Orogen. Detrital and inherited-zircon age data presented in this study, and Nd and Hf isotope data (Smithies et al., 2010), suggest that the Ramarama Basin formed along a north-dipping subduction zone. In this scenario, Proterozoic Australia was not amalgamated until, or after, the 1345–1293 Ma Mount West Orogeny.

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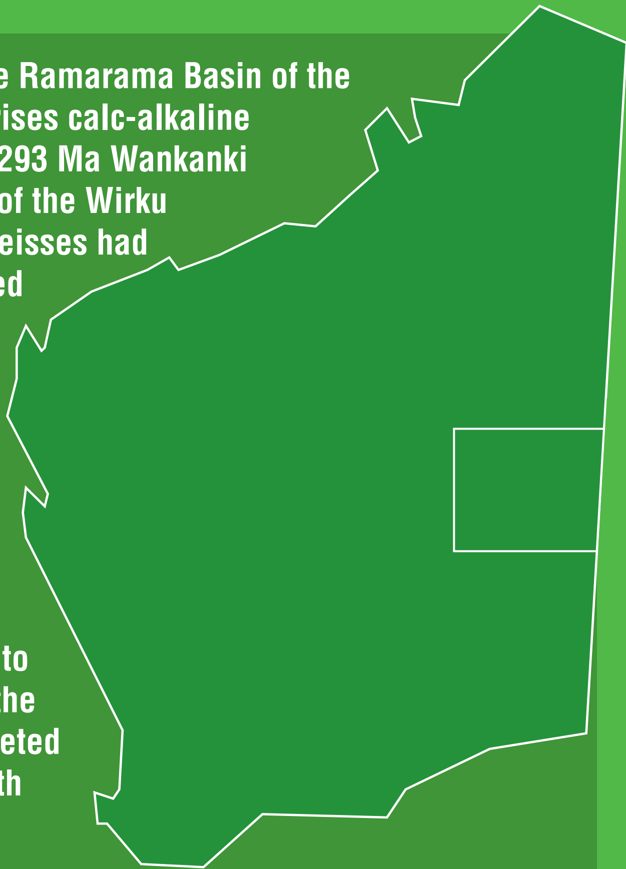
This report outlines the development of the Ramarama Basin of the west Musgrave Province. The basin comprises calc-alkaline volcanic and intrusive rocks of the 1345–1293 Ma Wankanki Supersuite interleaved with paragneisses of the Wirku Metamorphics. The majority of the paragneisses had sedimentary precursors that were deposited between c. 1340 and 1300 Ma. Detrital zircon age spectra from samples of Wirku Metamorphics reveal younging trends within northwest-trending geographic/tectonic zones. Dominant detrital zircon age components range from c. 1570 Ma in the northeast to c. 1520 Ma in the centre to c. 1330 Ma in the southwest. Detrital zircons with Archean ages similar to those in the Yilgarn Craton are present to the southeast. The Ramarama Basin is interpreted as part of a calc-alkaline magmatic arc with compositional similarities to Andean-style continental arcs. Constraints from this study suggest development of the Ramarama Basin above a north-dipping subduction zone between the North and South Australian Cratons in the c. 1340 to 1300 Ma period.



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