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RECORD 2016/4

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by
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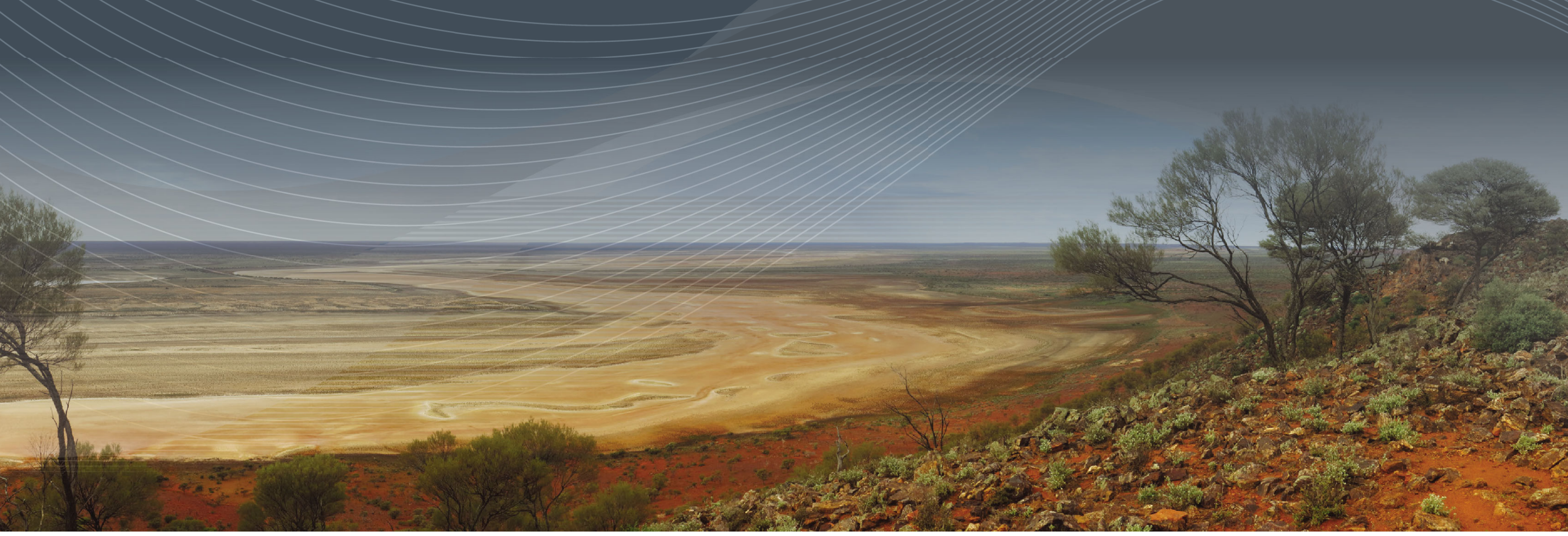

Geological Survey of
Western Australia

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by
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Cover image: Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph taken by I Zibra for the Geological Survey of Western Australia

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Geology and U–Pb geochronology of the Warlawurru Supersuite and MacDougall Formation in the Mitika and Wanarn areas, west Musgrave Province

by

R Quentin de Gromard, MTD Wingate, CL Kirkland*, HM Howard and RH Smithies

Abstract

Recent field mapping and U–Pb zircon geochronology in the Mitika and Wanarn areas revealed a new basement component in the west Musgrave Province. Three samples of strongly foliated to gneissic metasyenogranite yielded U–Pb crystallization ages of c. 1607, 1593, and 1583 Ma. These rocks, assigned to the c. 1600 Ma Warlawurru Supersuite, are the oldest known crystalline rocks in the west Musgrave Province. This result is consistent with Hf isotope data, which suggest that a crust-forming event took place at 1600–1550 Ma. Metagranites of the Warlawurru Supersuite are only found within a northeast-directed thrust sheet in the Wanarn area. They are tectonically interleaved with psammitic gneisses of the MacDougall Formation, the basal unit of the Kunmarnara Group deposited within the Ngaanyatjarra Rift. Elsewhere in the Wanarn area, northwest- to west-directed thrust sheets tectonically interleave metagranites of the 1220–1150 Ma Pitjantjatjara Supersuite with the MacDougall Formation.

Detrital zircon age spectra from metasedimentary rocks of the Mitika and Wanarn areas demonstrate that the large low-magnetic and low-gravity area that disrupts the otherwise high geophysical response of the Musgrave Province is dominated by the MacDougall Formation. The youngest 15 analyses in one sample yielded a mean age of 1153 ± 9 Ma, which is a maximum age for deposition of the formation. Detrital zircon ages in nine samples combined define major age components at c. 1611, 1566, and 1505 Ma, minor groups at c. 1428 and 1405 Ma, and a dominant component at c. 1179 Ma. The absence of zircons older than c. 1620 Ma precludes most of the surrounding regions as sedimentary sources to the MacDougall Formation. Good matches between detrital zircon age components and the ages of likely source regions, together with the absence of 1345–1293 Ma zircons from the west Musgrave Province, suggest that the source of MacDougall Formation detritus was the central and eastern Musgrave Province and/or basement rocks of the Madura or Coompana Provinces beneath the Eucla Basin.

KEYWORDS: crystallization, geochronology, tectonics, zircon

Introduction

Systematic 1:100 000-scale geological mapping of the west Musgrave Province by the Geological Survey of Western Australia (GSWA) started in 2004 and progressed westward from the Northern Territory and South Australian borders (Fig. 1). This program led to a better understanding of the Musgrave Province through geological mapping and the supporting geophysical, geochronological, geochemical, and structural datasets. The west Musgrave Province is divided into three major zones with distinct tectono-magmatic and metamorphic histories: the Walpa Pulka, Tjuni Purlka, and Mamutjarra Zones (Smithies et al., 2009; Howard et al., 2011; Howard et al., 2015). Ongoing mapping and geochronology within the Tjuni Purlka Zone has defined the Mitika and Wanarn areas, each of which has distinct tectono-metamorphic histories.

The Mitika area lies at the junction of the Bentley, Golden Point, and Diorite map sheets (Howard et al., 2013; Quentin De Gromard et al., 2015, 2016) and is interpreted from geophysical images to extend into Table Point (Fig. 2). It is bounded to the south by the Mamutjarra Zone through a series of northeasterly or northwesterly trending faults and to the north by the west-northwesterly trending Mitika Fault. The Wanarn area lies between the Mitika Fault and the Woodroffe Thrust and extends over the Diorite and Dickenson sheets (Fig. 2). The Mitika and Wanarn areas were previously mapped by GSWA and compiled as part of the northeastern corner of the Bentley 1:250 000 map sheet by Daniels et al. (1971).

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The authors interpreted all basement rocks of the Mitika and Wanarn areas as part of an undivided mid-Proterozoic complex of monzogranite gneisses and migmatites locally unconformably overlain by mid-Proterozoic quartzite and quartz–muscovite schist. This overlying metasedimentary unit is highly deformed, leading Daniels et al. (1971) to interpret it as significantly older than the relatively undeformed volcanic succession of the 1085–1040 Ma Bentley Supergroup. However, a metasedimentary succession east of the Mitika and Wanarn areas has since been reattributed to the MacDougall Formation, which constitutes the basal sedimentary unit of the Bentley Supergroup (Evins et al., 2010; Howard et al., 2011). This, in turn, threw doubt on the assumption that the metasedimentary rocks of the Mitika and Wanarn areas were part of an older sedimentary succession as suggested by Daniels et al. (1971) or if they also belonged to the MacDougall Formation. A second incentive for this work arose from a preliminary U–Pb date that suggested that a previously unrecognized basement component of the west Musgrave Province was exposed in the Wanarn area.

In this Record, we present field observations and U–Pb zircon geochronology that characterize the different basement components of the Mitika and Wanarn areas and the younger sedimentary succession, and integrate them into our understanding of the west Musgrave Province. The oldest known basement component in the west Musgrave Province has been identified and is now referred to as the Warlawurru Supersuite. This work also presents all available detrital geochronology data for the MacDougall Formation and explores the sedimentary provenance of this unit.

Regional geology

The Musgrave Province forms an east-trending, positive gravity and magnetic anomaly, approximately 800 km long and 350 km wide. It lies at the junction between the main cratonic elements of Australia: the North, West, and South Australian Cratons (Fig. 1). It is a key region for understanding the amalgamation of Australia, and its position made it the locus of several younger intracontinental reworking events (Howard et al., 2015; Smithies et al., 2015).

The Musgrave Province records over a billion years of tectono-magmatic activity. Hf and O isotope data for magmatic and detrital zircons from the west Musgrave Province suggest two major crust-forming events: at 1950–1900 Ma and 1600–1550 Ma (Kirkland et al., 2012a; Kirkland et al., 2015). No rocks of the 1950–1900 Ma event have been identified. The oldest known rocks are 1600–1540 Ma supracrustal gneisses with limited but unequivocal evidence of orthogneisses of this age, exposed in the east Musgrave Province (Gray and Compston, 1978; Gray, 1978; Maboko, 1988; Camacho and Fanning, 1995; Scrimgeour et al., 1999; Young et al., 2002; Edgoose et al., 2004; Evins et al., 2012). Wade et al. (2006) identified the arc-like geochemical signature of the gneisses of the east Musgrave Province and proposed that a 1600–1580 Ma south-dipping subduction zone between the Arunta block and the Gawler Craton produced a chain of island arcs (proto-Musgrave Province) during periods of slab rollback. In this model, the proto-Musgrave Province was accreted to the Gawler Craton and the Arunta block during ocean closure in the early Mesoproterozoic. Despite the extensive geochronology dataset of the west Musgrave Province, gneisses of 1600–1540 Ma were not identified until recently. Their prevalence in the east Musgrave Province and the extent of subeclogite facies rocks suggests deeper exposed basement levels in the east than in the west Musgrave Province (Evins et al., 2012).

Two supersuites (reflecting specific magma-producing tectonic events), identified so far only in the west Musgrave Province, are the poorly exposed c. 1400 Ma Papulankutja Supersuite (Howard et al., 2011; GSWA 194764, Kirkland et al., 2011b) and the voluminous and widespread 1345–1293 Ma Wankanki Supersuite (Smithies et al., 2010; Howard et al., 2011). Granites of the Papulankutja Supersuite exhibit a foliation that is crosscut by a c. 1318 Ma unfoliated Wankanki Supersuite dyke (GSWA 194765, Kirkland et al., 2012c). They were intruded into paragneisses, the protoliths of which were deposited at about the same time as granite intrusion (Howard et al., 2011). The Wankanki Supersuite consists of metaluminous, calc-alkaline, I-type magmas, interpreted to have formed in a continental arc setting during the Mount West Orogeny (White et al., 1999; Howard et al., 2007; Smithies et al., 2010; Howard et al., 2011), which took place during the final amalgamation of Australia (Giles et al., 2004; Betts and Giles; 2006; Howard et al., 2015). Evins et al. (2012) documented the development of the 1340–1270 Ma Ramarama Basin, which contains metasedimentary and metavolcanic rocks of the Wirku Metamorphics and interpreted it as a syn- to post-Mount West Orogeny basin.

Voluminous, anhydrous, A-type granitic magmas of the 1220–1150 Ma Pitjantjatjara Supersuite are pesent throughout the Musgrave Province (Edgoose et al., 2004; Smithies et al., 2010, 2011, 2014; Howard et al., 2011). These magmas are interpreted to be partly sourced from mantle-derived components, and were produced under continuous ultra-high temperature (UHT) conditions that lasted at least until c. 1120 Ma (Smithies et al., 2011; Kirkland et al., 2015). This major magmatic event, the Musgrave Orogeny, is interpreted to have resulted from the delamination of the mantle lithosphere, localizing asthenospheric upwelling in the nexus between the North, West, and South Australian Cratons and producing near-continuous magmatism and UHT conditions for 100 Ma (Gorczyk et al., 2015).

Only 30 Ma after the end of the Musgrave Orogeny, the Musgrave Province underwent the 1085–1040 Ma Giles Event. The lowermost supracrustal units deposited during the Giles Event consist of siliciclastic metasedimentary rocks of the MacDougall Formation, overlain by the widespread Mummawarrawarra Basalt (Evins et al., 2010). Together, these units form the Kunmarnara Group, interpreted as the basal succession of the failed intracontinental Ngaanyatjarra Rift (Evins et al., 2010; Aitken et al., 2013). All igneous rocks that formed during the Giles Event are grouped into the Warakurna Supersuite and include the giant layered mafic–ultramafic Giles intrusions, mixed and mingled gabbros and leucogranites,

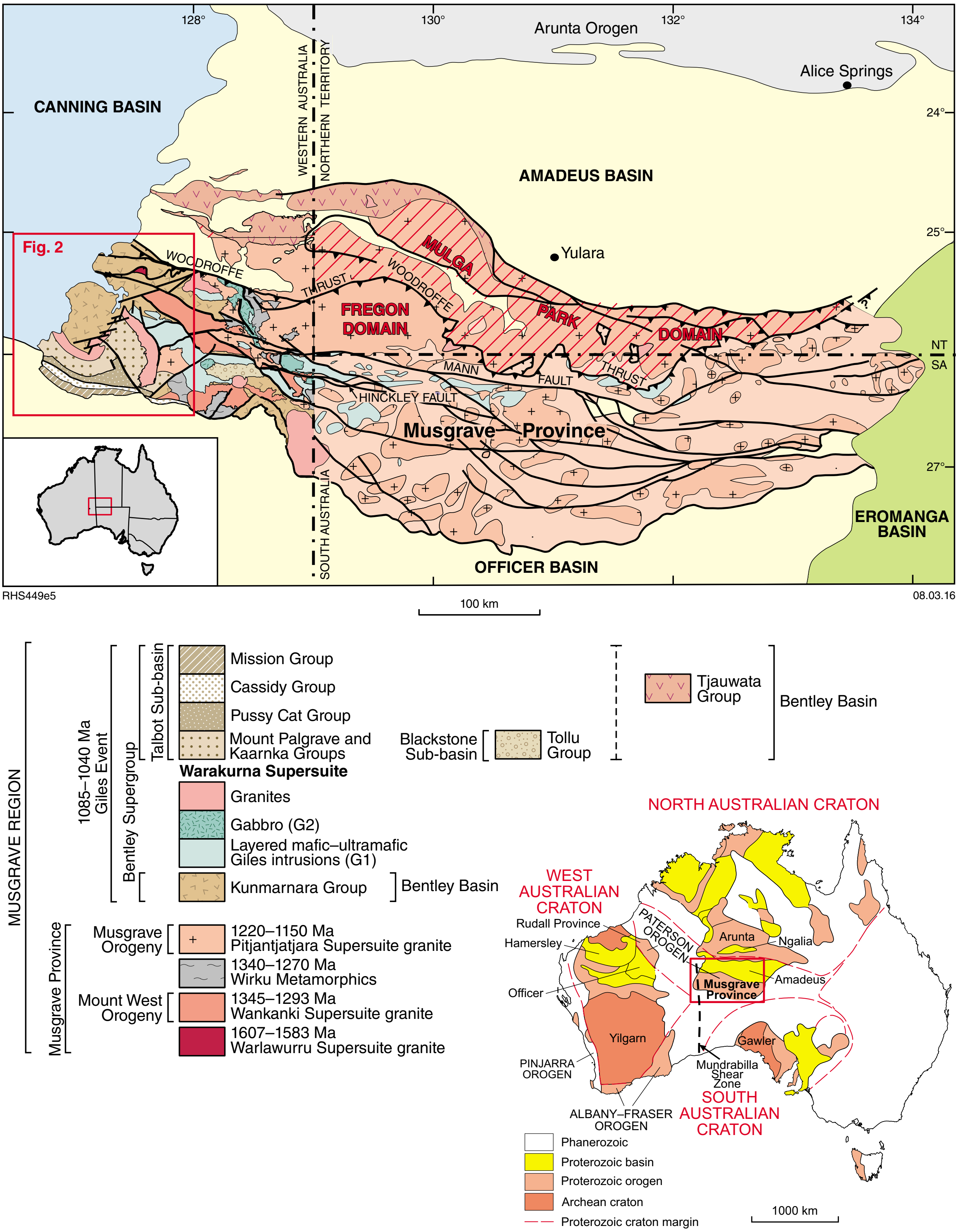


Figure 1. Tectonic map of Australia showing the location of the Musgrave Province and regional geological map of the Musgrave Province (modified from Howard et al., 2015 and references therein). The Musgrave Province refers to all rocks formed during or affected by the Musgrave Orogeny. The Woodroffe Thrust separates the subeclogite facies Fregon Domain from the amphibolite facies Mulga Park Domain (red hatched line).

Alcurra Dolerite intrusions of the Warakurna Large Igneous Province, and the long-lived bimodal volcanism of the Talbot Supervolcano (Evins et al., 2010; Howard et al., 2011; Smithies et al., 2013; Smithies et al., 2014).

Apart from minor mafic dyke intrusion at c. 1000, 825, and 750 Ma (Glikson et al., 1996; Wingate et al., 1998; Howard et al., 2011, 2015), the Musgrave Province was tectonically quiescent from the end of the Giles Event at c. 1040 Ma until intracontinental reactivation during the 580–540 Ma Petermann Orogeny. Deformation during the Petermann Orogeny produced east-trending faults and shear zones that dissect the entire Musgrave Province and can be traced for over 800 km (Lambeck and Burgess, 1992; Camacho et al., 1997; Scrimgeour and Close, 1999; Aitken et al., 2009a,b). The core of the Petermann Orogen between the Mann Fault and the Woodroffe Thrust experienced extensive mylonitic deformation, garnet granulite to subeclogite facies metamorphism, and is thought to have been exhumed via a channel-flow process akin to that suggested for the Himalayan Orogen (Camacho and McDougall, 2000; Raimondo et al., 2009, 2010). North of the Woodroffe Thrust, the Petermann Nappe Complex tectonically interleaves crystalline rocks of the Musgrave Region with sedimentary rocks of the Amadeus Basin (Edgoose et al., 2004; Flöttmann et al., 2004).

Description of rock units

Basement rocks

1607–1583 Ma Warlawurru Supersuite

Basement rocks in the Wanarn area consist of multiply deformed high-grade metagranites of the Warlawurru and Pitjantjatjara Supersuites (Fig. 2). The best exposures of the Warlawurru Supersuite are located about 7 km west-southwest of Wanarn and consist of strongly foliated to gneissic, garnet-bearing, biotite(–hornblende) metasyenogranites (Fig. 3). The Warlawurru Supersuite is commonly migmatitic and contains locally abundant pegmatite veins (Fig. 4a,b). A typical visually estimated modal mineralogy of the Warlawurru metasyenogranite includes about 45–50% quartz, 20–25% K–feldspar, 10–15% plagioclase, 5–7% biotite, 2–3% hornblende, 1% garnet, and accessory sericite, titanite, zircons, and opaque minerals (Fig. 4c–f). Quartz grains commonly display prismatic subgrain boundaries indicative of medium- to high-temperature intracrystalline deformation and recovery. Recrystallization is dominated by subgrain rotation and high-temperature grain boundary migration recrystallization. Feldspars are commonly lightly clouded by cryptocrystalline phyllosilicates. Hornblende is present either as remnants or as subhedral grains containing garnet inclusions (Fig. 4e). Garnet porphyroblasts are commonly anhedral poikilitic or euhedral inclusion-free grains up to 0.5 mm across (Fig. 4f). Opaque minerals are mantled by titanite or garnet coronae and are interpreted to be Fe–Ti oxides, possibly ilmenite (Fig. 4f).

1219–1148 Ma Pitjantjatjara Supersuite

The best exposures of the Pitjantjatjara Supersuite in the Wanarn area are 1.8 km north-northwest of Wanarn (Fig. 3). Pitjantjatjara granites commonly consist of well-foliated to gneissic, garnet-bearing, biotite–hornblende metamonzogranites. They are multiply deformed and locally contain syn- to post-deformation leucogranite veins (Fig. 5a,b). The less-strained granites may contain subhedral alkali feldspar phenocrysts up to six centimetres across. A typical visually estimated modal mineralogy includes about 25–30% quartz, 20–25% K–feldspar, 15–20% plagioclase, 10–15% hornblende, 5–7% biotite and accessory titanite, garnet, sericite, epidote, and zircon. Aligned subhedral amphibole and platy biotite define the mafic bands of the gneissic foliation (Fig. 5c). Granites in high-strain zones contain deformed quartz grains that typically display chessboard subgrain patterns (Fig. 5d) characteristic of high-temperature intracrystalline deformation and recovery. Recrystallization is dominated by high-temperature subgrain rotation and grain boundary migration. Away from shear zones, undulose quartz and prismatic subgrain boundaries dominate (basal subgrain boundaries are rare) and recrystallization is dominated by subgrain rotation and bulging processes (Fig. 5e). Feldspars are commonly lightly clouded by microcrystalline phyllosilicate minerals and perthitic and myrmekitic textures are common. Garnet porphyroblasts are commonly present as light pink anhedral to subhedral, inclusion-poor grains up to 0.5 mm across. Opaque minerals commonly display titanite coronae and are interpreted as Fe–Ti oxide minerals, possibly ilmenite (Fig. 5f).

Kunmarnara Group

1085–1075 Ma MacDougall Formation

The prominent topography in the Mitika area is represented by north-trending ridges, about 6 km long that trace the limbs of regional-scale, west-verging, tight to isoclinal, overturned folds (Figs 6 and 7a). The ridges are dominated by interbedded medium- to coarse-grained quartzite, muscovite–garnet(–magnetite) schist and local quartz-pebble conglomerate (Fig. 7b,c). Bed thickness typically ranges from 10 to 50 cm. The conglomeratic layers commonly contain a well-defined stretching lineation shown by elongate vein quartz pebbles up to 10 cm in length. The more schistose layers commonly consist of about 70% quartz, 25% muscovite, 4% Fe–Ti oxide minerals, and weathered garnet and accessory epidote, clinozoisite, and zircon (Fig. 7d). This unit is interpreted as a fluvial sandstone and pebble conglomerate, metamorphosed under amphibolite-facies conditions.

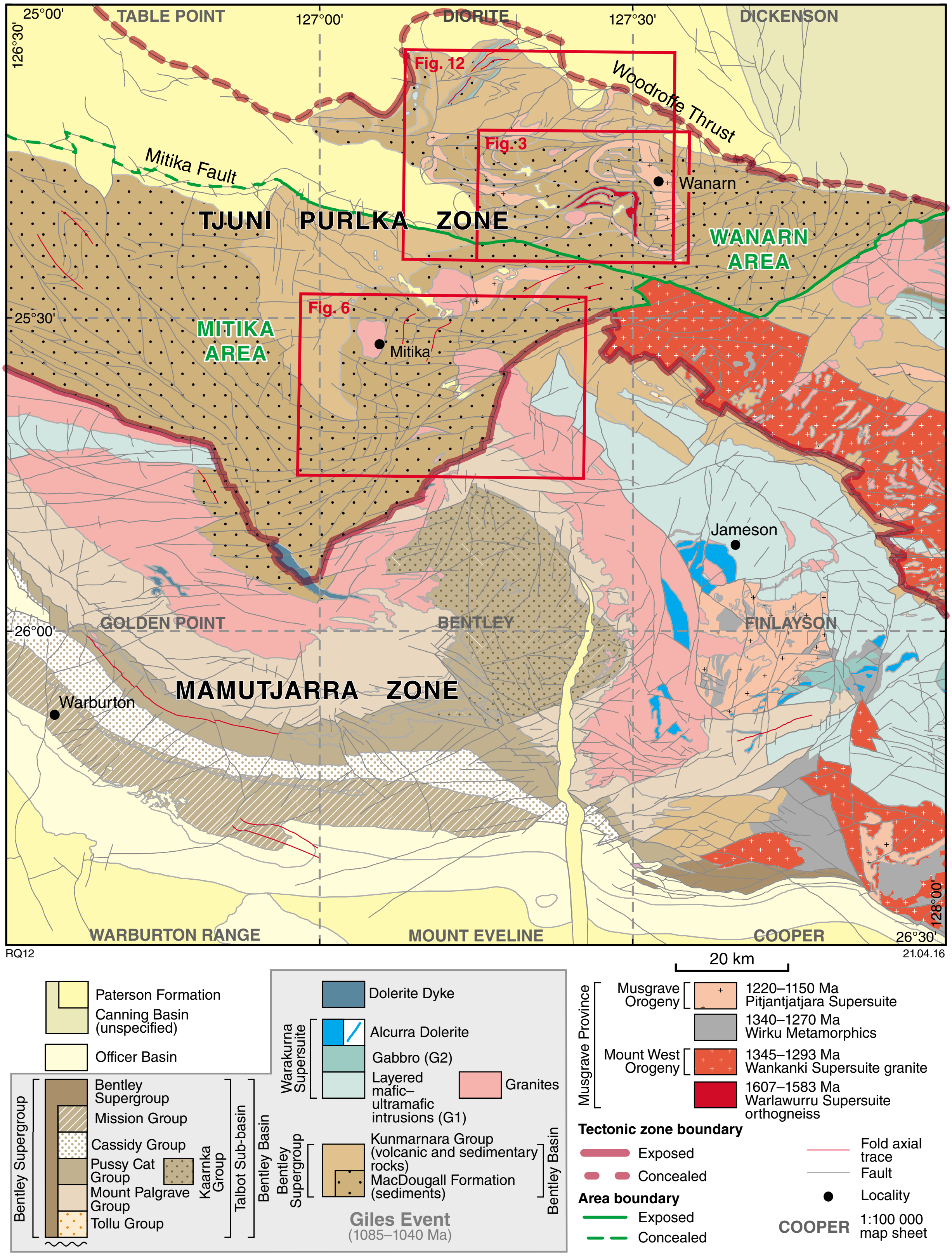


Figure 2. Interpreted bedrock geology map of the western portion of the west Musgrave Province

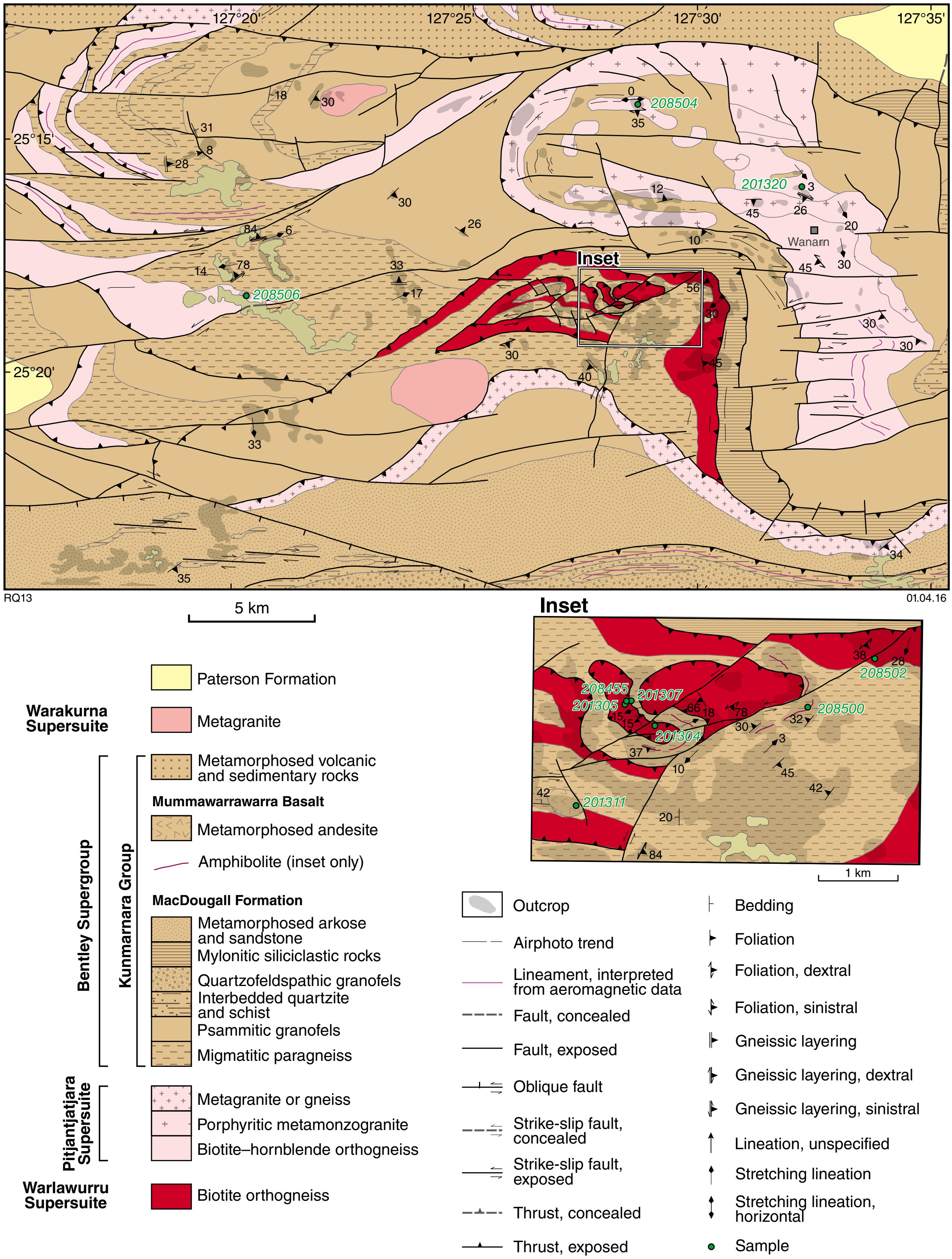


Figure 3. Interpreted bedrock geology map of the Wanarn area, showing the locations of the samples used for U–Pb geochronology

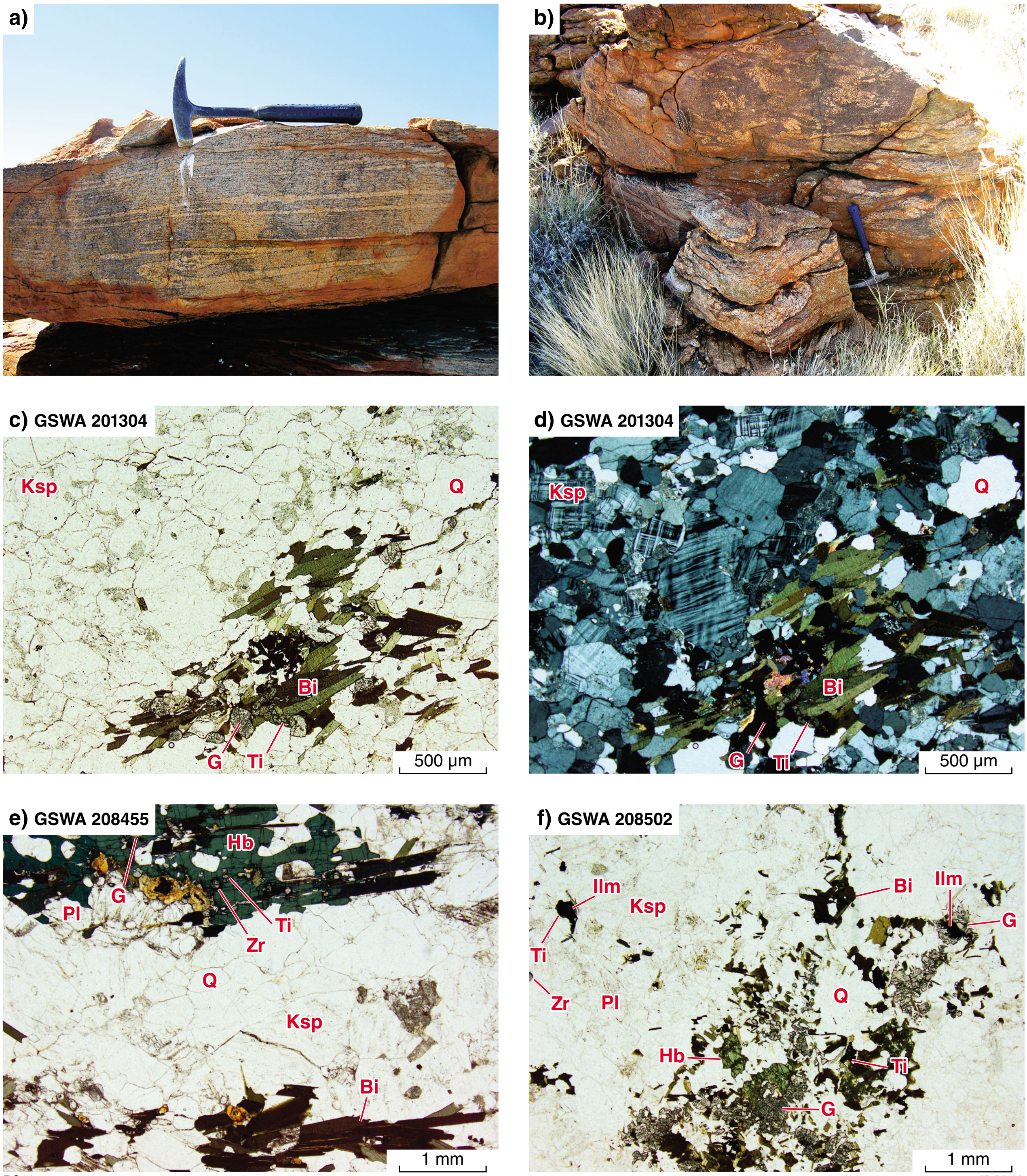


Figure 4. Outcrop and thin section photographs of metagranite and orthogneiss of the Warlawurru Supersuite: a) migmatitic orthogneiss; b) abundant pegmatite veins in orthogneiss; c) characteristic mineralogy of the Warlawurru Supersuite in plane-polarized light (GSWA 201304); d) in cross-polarized light (GSWA 201304); e) garnet, titanite, and zircon inclusions in hornblende from orthogneiss; plane-polarized light (GSWA 208455); f) titanite and garnet coronae around ilmenite, and anhedral poikilitic and subhedral, inclusion-poor garnet from metagranite; plane-polarized light (GSWA 208502). Abbreviations: Q = quartz; Ksp = K-feldspar; Pl = plagioclase; Bi = biotite; Hb = hornblende; G = garnet; Ti = titanite; Ilm = ilmenite; Zr = zircon.

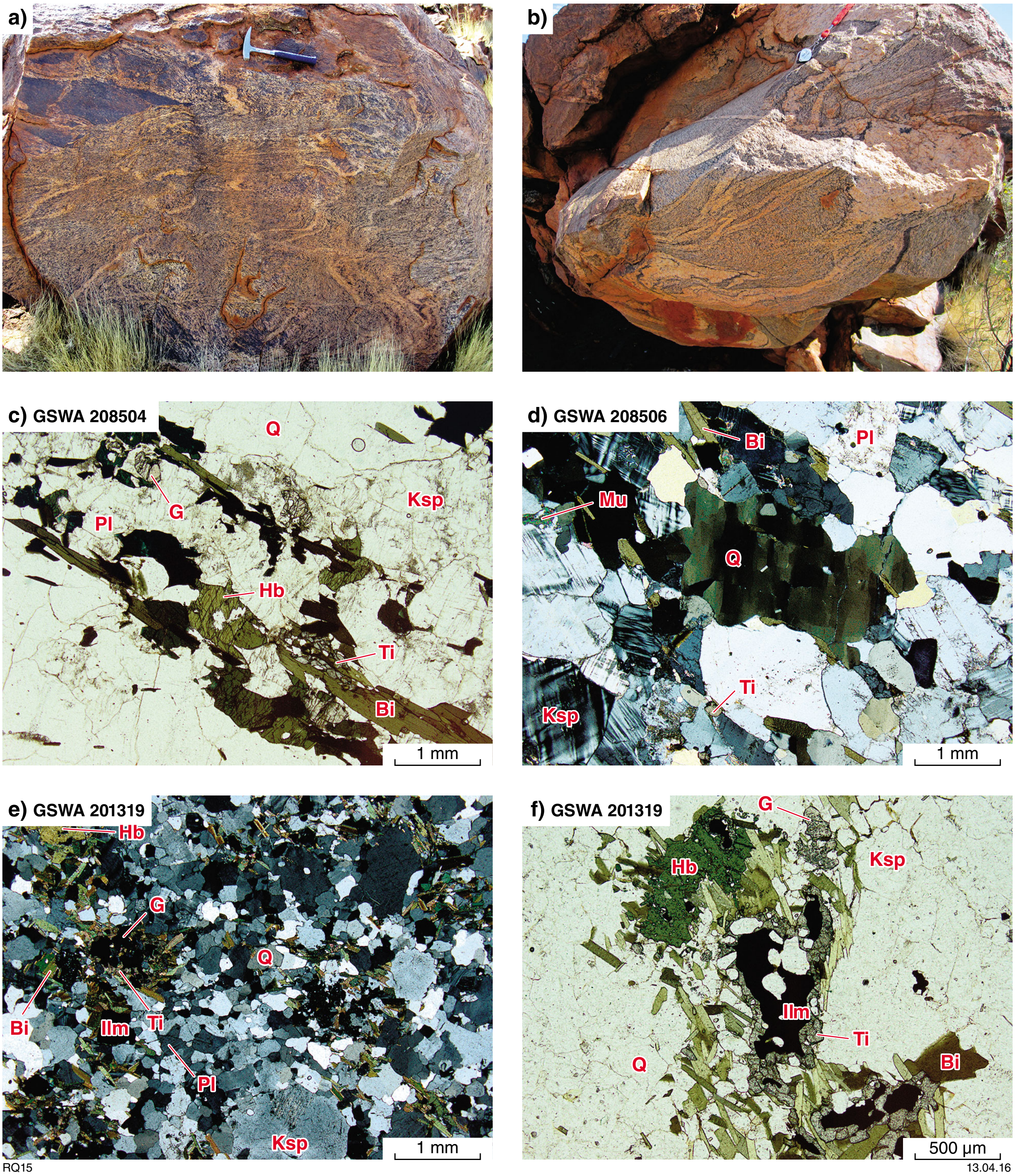


Figure 5. Outcrop and thin section photographs of metagranites of the Pitjantjatjara Supersuite: a) strongly folded and sheared migmatitic orthogneiss; b) syn- to post-folding leucocratic veins (dated at 1186 Ma, GSWA 201320) and melt pocket in folded and sheared migmatitic orthogneiss; c) characteristic mineralogy of a Pitjantjatjara Supersuite granite; plane-polarized light (GSWA 208504); d) plastically deformed quartz grain, showing high-temperature intracrystalline deformation and recovery chessboard subgrain pattern; cross-polarized light (GSWA 208506); e) metagranite, showing grain size reduction during subgrain rotation and bulging recrystallization; cross-polarized light (GSWA 201319); f) titanite coronae around ilmenite grains; plane-polarized light (GSWA 201319). Abbreviations: Q = quartz; Ksp = K-feldspar; Pl = plagioclase; Bi = biotite; Mu = muscovite; Hb = hornblende; G = garnet; Ti = titanite; Ilm = ilmenite.

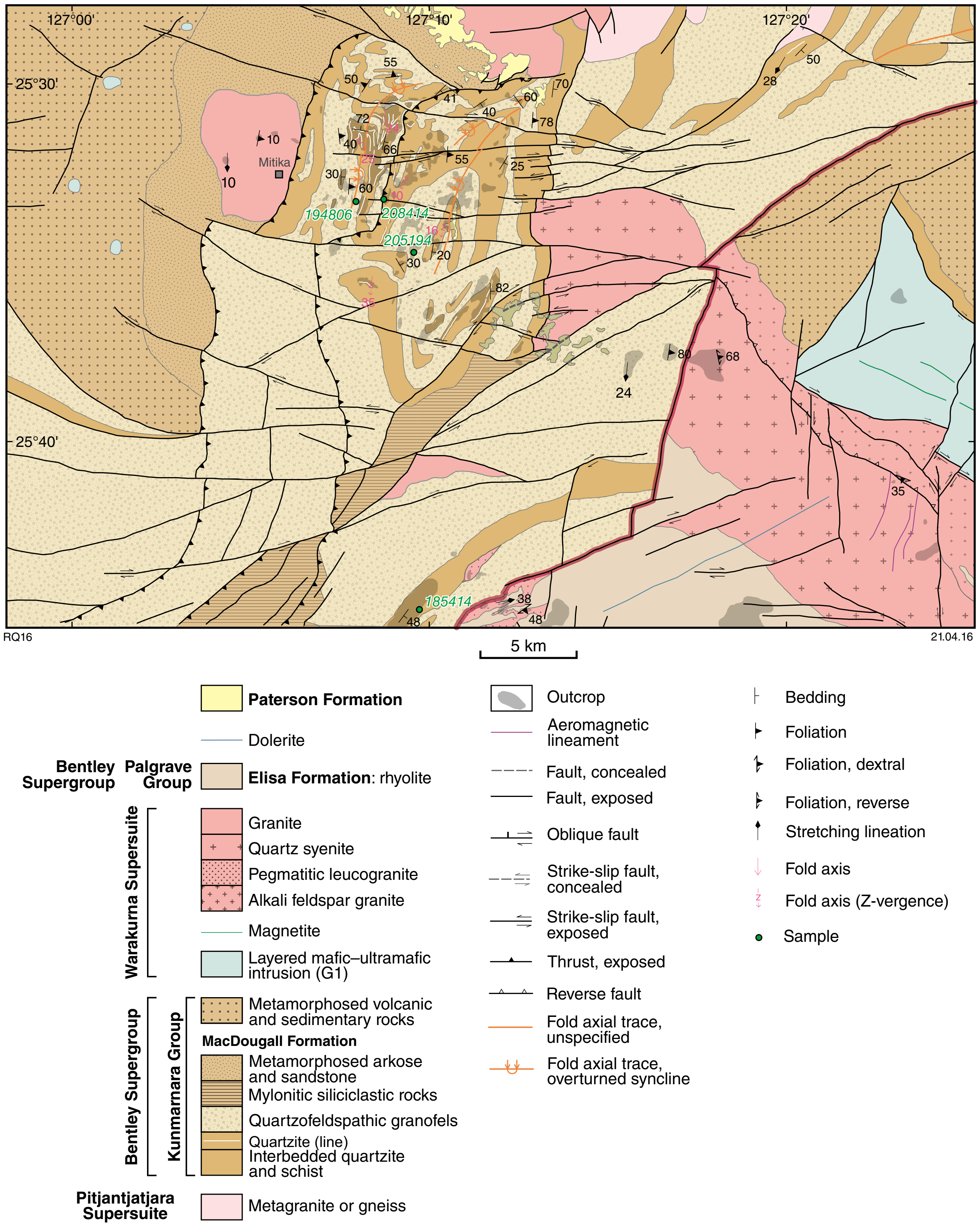
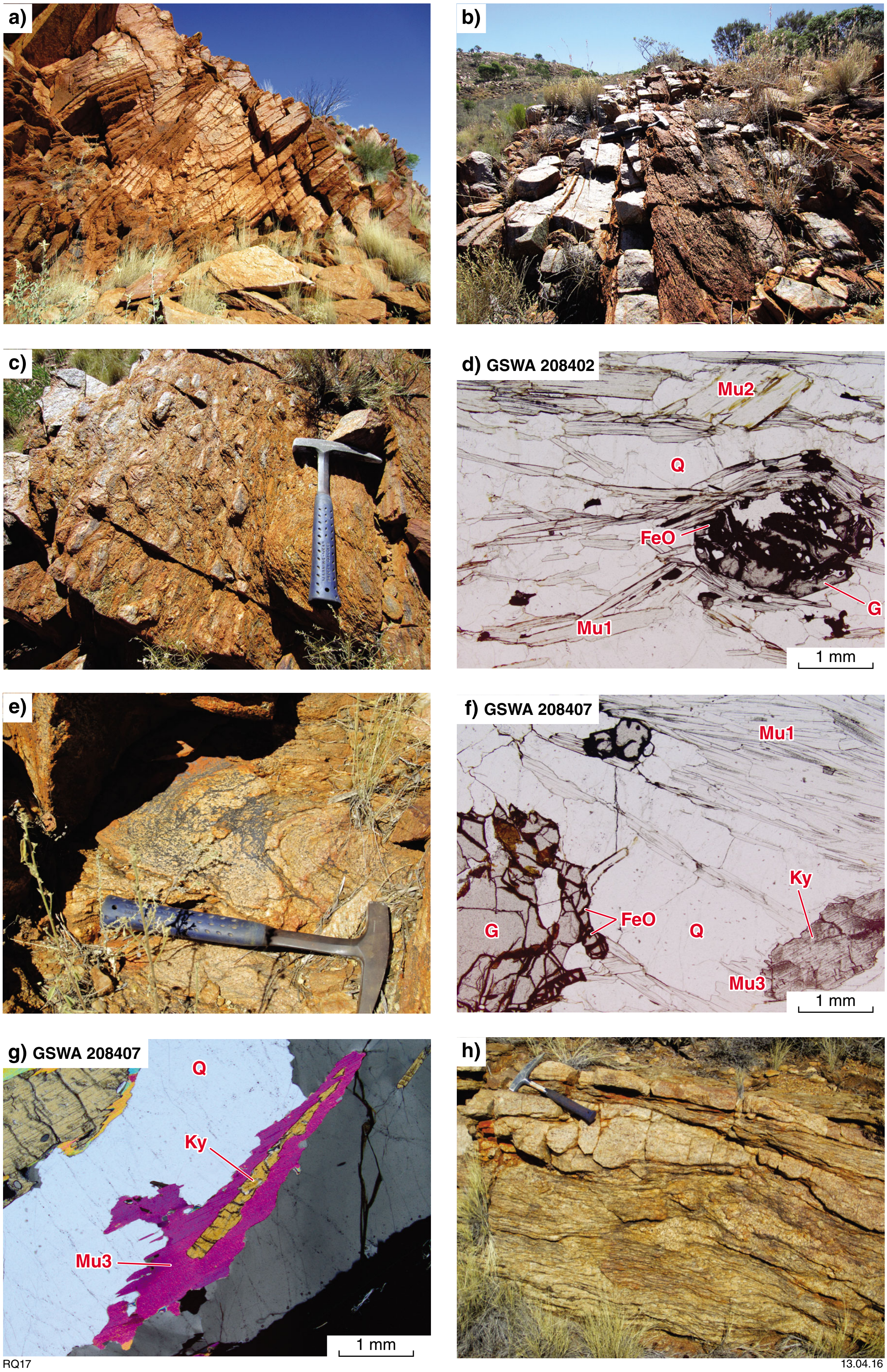


Figure 6. Interpreted bedrock geology map of the Mitika area, showing the location of the samples used for U–Pb geochronology


a)
b)
c)
d) GSWA 208402
Mu2
Q
FeO
G
Mu1
1 mm
e)
f) GSWA 208407
Mu1
Ky
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G
Q
Mu3
1 mm
g) GSWA 208407
Q
Ky
Mu3
1 mm
h)
RQ17
13.04.16

Figure 7. (left) Outcrop and thin section photographs of the MacDougall Formation: a) west-verging tight to isoclinal overturned folds in interbedded quartzite and schist of the Mitika Area, looking south, base of photo is about 5 m across; b) interbedded quartzite and schist, looking north, bed thickness ranges from 10 to 30 cm; c) well-developed stretching lineation defined by elongated and aligned vein quartz pebbles within conglomeratic beds of the MacDougall Formation; d) garnet porphyroblast wrapped by a well-defined muscovite foliation (Mu1), and muscovite porphyroblast (Mu2) post-dating the Mu1 foliation from a muscovite–garnet schist of the MacDougall Formation; plane-polarized light (GSWA 208402); e) tightly folded quartzofeldspathic granofels; f) garnet–kyanite schist, the main foliation is defined by aligned muscovite (Mu1), kyanite is retrogressed in muscovite (Mu3), plane-polarized light (GSWA 208407); g) retrogressed kyanite porphyroblast in muscovite (Mu3); cross-polarized light (GSWA 208407); h) migmatitic paragneiss. Abbreviations: Q = quartz; Mu= muscovite; G = garnet; Ky = kyanite; FeO = iron oxide minerals.

Between the quartzite ridges, in the core of the folds, outcrops are dominated by well-banded, fine- to coarse-grained muscovite–garnet(–magnetite) quartzofeldspathic granofels (Fig. 7e). The rock typically has a granoblastic texture and consists of about 60% quartz, 25% feldspar, 10% muscovite, 4% opaque oxide minerals, and accessory zircon, epidote, biotite, and apatite. The matrix consists of quartz and medium-grained, near-equigranular aggregates of microcline and plagioclase. Feldspars are weakly altered to sericite and contain inclusions of microcrystalline quartz. This unit is interpreted as an arkose that was also metamorphosed under amphibolite facies conditions.

East of the prominent fold limb ridges, the same metasedimentary rocks contain garnet and kyanite porphyroblasts. The quartzite-dominated unit consists of typically weathered, interlayered, magnetite-rich, medium- to coarse-grained micaceous quartzite and biotite–garnet–kyanite schist, suggesting upper amphibolite facies conditions. Bed thickness ranges from 10 to 30 cm. In thin section the schistose layers commonly consist of about 65% quartz, 25% muscovite, 5% kyanite, 3% garnet, 2% opaque oxide minerals, and accessory epidote and zircon. Garnet is commonly replaced along cracks by iron oxide minerals (Fig. 7f). The quartzofeldspathic layers are dominated by medium- to coarse-grained granoblastic quartz and feldspar, locally interlayered with fine- to medium-grained muscovite–biotite–garnet–staurolite–kyanite(–magnetite) schist. The quartzofeldspathic-rich facies commonly contains 40% quartz, 29% plagioclase, 29% K-feldspar, and 1% biotite, and accessory epidote. Feldspar is commonly altered to sericite and other clay minerals. The schists are strongly weathered and commonly consist of 60% quartz, 30% muscovite, 5% kyanite porphyroblasts, 3% relict garnet (commonly altered to iron oxides along cracks), 1% biotite, and accessory opaques, titanite, and zircon. Staurolite porphyroblasts are locally preserved as inclusions within kyanite porphyroblasts. Kyanite porphyroblasts are commonly partially replaced by muscovite (Fig. 7f,g). The two units mentioned above are regarded as interbedded sandstone, arkose, and mudstone metamorphosed under upper-amphibolite facies conditions.

The Wanarn area is dominated by medium- to coarse-grained, garnet-bearing, quartzofeldspathic paragneiss, commonly migmatitic (Figs 3 and 7h), which locally contain pegmatite veins that both crosscut and intrude parallel to the gneissic layering. The common banding of these rocks, defined by alternating quartz-rich (>70%) bands and more quartzofeldspathic biotite–garnet–magnetite layers, probably reflects primary sedimentary layering. The texture within bands is granoblastic, indicating strong recrystallization. In thin section, the gneisses consist of about 60% quartz, 20% K–feldspar, 15% plagioclase, 2% garnet, 2% biotite, accessory opaque minerals, zircon, and titanite. Garnet porphyroblasts are commonly disseminated throughout the rock, but also locally appear as garnet-rich bands, approximately 1 mm thick. The more strained rocks contain myrmekite and show grain size reduction, formation of subgrains and mylonitic fabrics. This unit is almost always interlayered with 10 to 20 cm-thick, foliation-parallel, medium-grained amphibolite layers that appear to be part of the sedimentary sequence. A mafic sill within paragneisses of the MacDougall Formation in the Wanarn area contains a clinopyroxene–orthopyroxene–garnet metamorphic assemblage, suggesting that the paragneisses are the granulite facies equivalent of siliciclastic rocks of the MacDougall Formation in the Mitika area.

1085–1075 Ma Mummawarrawarra Basalt

Approximately 9.5 km west-southwest of Wanarn are scattered outcrops of metabasalt in conformable contact with underlying migmatitic paragneiss (Fig. 3). The metabasalt is plagioclase phyric, contains amygdales up to 1 cm, which are either disseminated throughout the rock (Fig. 8a) or appear as amygdale-rich layers alternating with massive metabasalt (Fig. 8b). In thin sections its mineralogy consists of about 35% plagioclase, 25% hornblende, 15% quartz, 10% clinopyroxene, 7% garnet, 5% ilmenite, 2% biotite, and accessory chlorite and sericite (Fig. 8c–e). The vesicles are either filled with a quartz–plagioclase–garnet–hornblende–clinopyroxene assemblage (Fig. 8f) or quartz only. Garnet in vesicles are light pink, subhedral, inclusion poor and up to 0.5 mm, while those disseminated through the groundmass and mantling ilmenite are commonly inclusion rich and only up to 100 µm (Figs. 8d and f). This metabasalt shows a similar trace-element pattern to the Mummawarrawarra Basalt (Howard et al., 2011, figure 29).

U–Pb zircon geochronology

Analytical methods

All samples were collected from surface outcrops. Detailed sample preparation and analytical procedures are described by Wingate and Kirkland (2014). Between 2 and 4 kg of each sample were crushed and zircons were separated using density and magnetic techniques

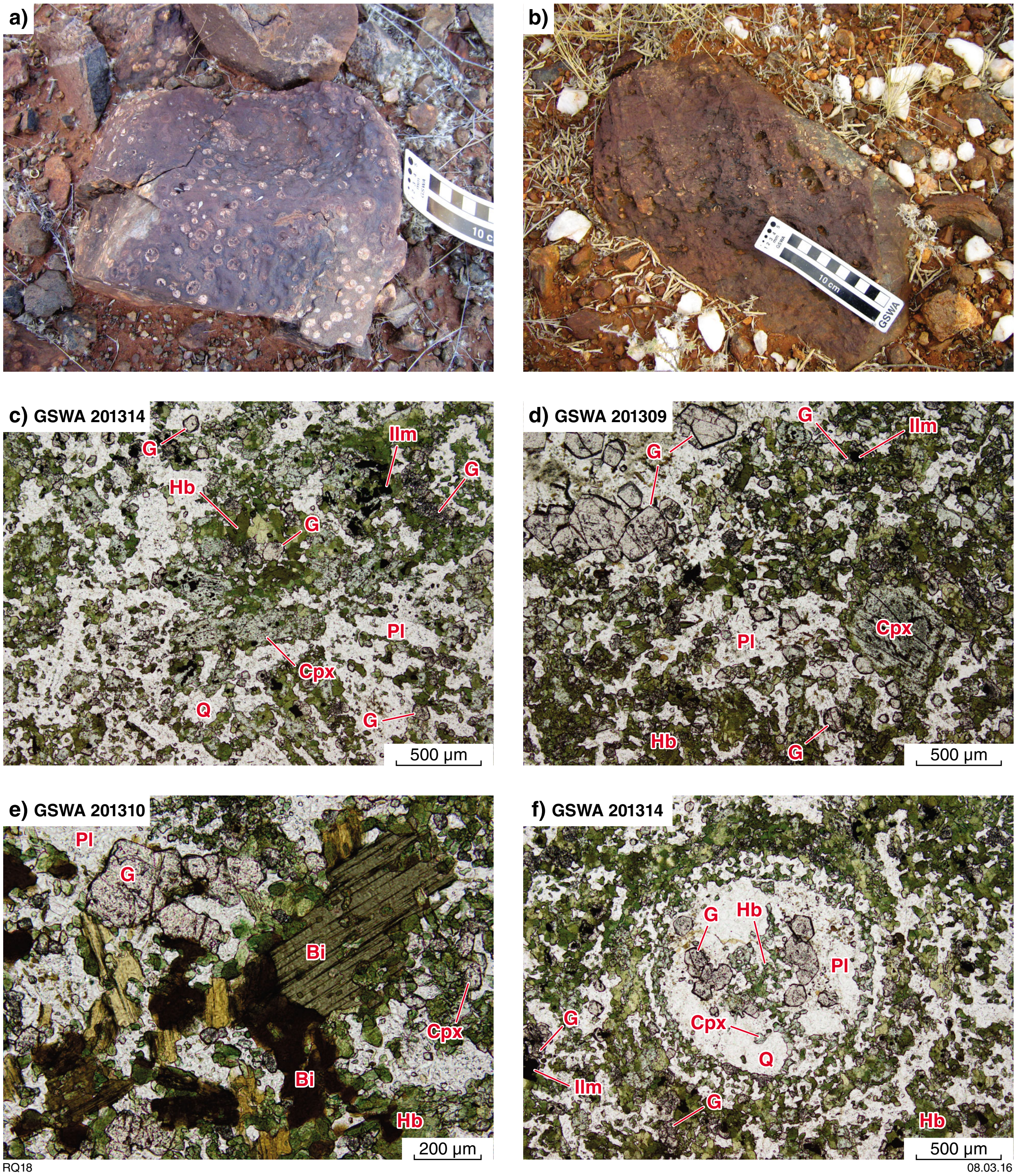

Figure 8. **Outcrop and thin section photographs of the Mummawarrawarra Basalt: a) distributed quartz amygdales in metabasalt; b) amygdale-rich layer in massive metabasalt; c–e) typical mineralogy of metabasalt of the Wanarn area, showing abundant garnet porphyroblasts; note the euhedral inclusion-poor garnet porphyroblasts in the vesicle in d; plane-polarized light (GSWA 201314, GSWA 201309, GSWA 201310); f) quartz–plagioclase–garnet–hornblende–clinopyroxene assemblage filling a vesicle. Note the euhedral inclusion-poor garnet porphyroblasts in the vesicle compared to the smaller inclusion-rich garnets in the groundmass and around ilmenite; plane-polarized light (GSWA 201314). Abbreviations: Pl = plagioclase; Hb = hornblende; Q = quartz; G = garnet; Cpx = clinopyroxene; Bi = biotite; Ilm = ilmenite.**

at the GSWA laboratory. Zircons were hand-picked from each sample and cast, together with zircon reference standards, in an epoxy resin mount. The mount was polished to expose the interiors of the crystals, which were then documented with transmitted and reflected light photomicrographs and cathodoluminescence (CL) images to guide subsequent analyses. Measurements of U, Th, and Pb were conducted using the SHRIMP II ion microprobes in the John de Laeter Centre of Isotope Research at Curtin University. Analyses >5% discordant are generally considered to be unreliable and were not included in the age assessment of each sample. Except where noted otherwise, mean ages for samples or groups of samples, are quoted with 95% confidence intervals. Results for all samples are listed in Tables 1 and 2. The sections below provide a brief summary of the geochronology of each sample. Full details are available in cited references.

Warlawurru Supersuite

GSWA 201304: biotite metasyenogranite, Wanarn area

This sample is a fine-grained, strongly foliated to mylonitic, garnet-bearing, biotite-rich metasyenogranite collected about 7.6 km west-southwest of Wanarn (Fig. 3). This granite contains locally abundant syndeformational, foliation-parallel pegmatite veins (Fig. 4b). The sample consists of about 35–40% quartz, 25–30% K-feldspar, 10–15% plagioclase, 10–15% biotite, 2–3% titanite, 2–3% garnet, and accessory muscovite, iron oxide minerals, and zircon (Fig. 4c,d). The U–Pb geochronology for this sample was reported by Wingate et al. (2015c).

Table 1. Summary of U–Pb zircon geochronology samples and results for the Warlawurru and Pitjantjatjara Supersuites

Sample ID	*Rock type*	*1:100 000 map sheet*	*Easting (m)*	*Northing (m)*	*Magmatic age (Ma)*	*Metamorphic age (Ma)*	*Inheritance (Ma)*
Warlawurru Supersuite							
201304	biotite metasyenogranite	DIORITE	346137	7200012	1583 ± 10	1179 ± 11 (1σ)	1678 ± 30 (1σ)
208455	hornblende–biotite metasyenogranite	DIORITE	345809	7200319	1594 ± 14	1166 ± 5	
208502	biotite–hornblende metasyenogranite	DIORITE	348637	7200884	1607 ± 11	1185 ± 11	
Pitjantjatjara Supersuite							
208504	hornblende–biotite metamonzogranite	DIORITE	346858	7207892	1160 ± 7		
208506	biotite–hornblende metamonzogranite	DIORITE	332784	7200123	1157 ± 9		
201305	granite pegmatite	DIORITE	345791	7200277	1188 ± 6		1660–1586
201320	leucogranite vein	DICKENSON	352722	7204670	1171 ± 4		1186 ± 4 (1σ)
208500	granite pegmatite	DIORITE	347878	7200267	1194 ± 14	545 ± 39	1952–1428

NOTE: Eastings and northings refer to MGA Zone 52. Ages are quoted with 95% confidence intervals, except where noted otherwise.

Table 2. Summary of U–Pb zircon geochronology samples and results for the MacDougall Formation

Sample ID	*Rock type*	*1:100 000 map sheet*	*Easting (m)*	*Northing (m)*	*Max deposition age (Ma)*	*Age components (Ma)*	*Metamorphic age (Ma)*
205194	psammitic gneiss	BENTLEY	315092	7169700	1190 ± 12	1190	628 ± 4
194806	metasandstone	BENTLEY	312342	7172295	1179 ± 5	1539, 1186	
208414	quartzite	BENTLEY	313654	7172427	1179 ± 13	1424, 1187	631 ± 12
201311	metasandstone	DIORITE	345248	7199002	1180 ± 8	1615, 1592, 1565, 1197	
201307	metasandstone	DIORITE	345864	7200322	1172 ± 10	1643, 1568, 1174	
185414	quartzite	BENTLEY	315618	7151266	1153 ± 9	1518, 1491, 1185	
190233	phyllite	HOLT	411877	7162469	1172 ± 8	1520, 1171	
190292	metasandstone	FINLAYSON	388680	7139970	1176 ± 7	1577, 1179	
194420	feldspathic sandstone	COOPER	372425	7091845	1173 ± 6	1578, 1173	

NOTE: Eastings and northings refer to MGA Zone 52. Ages are quoted with 95% confidence intervals.

Zircons from this sample are subhedral to euhedral, colourless to light brown, and predominantly elongate. Concentric zoning is ubiquitous and some grains have thin high uranium overgrowths. Twenty-five analyses were obtained from 22 zircons (Fig. 9a). Fifteen analyses yielded a concordia age of 1583 ± 10 Ma (MSWD = 1.0), interpreted as the age of magmatic crystallization of the syenogranite protolith. One analysis of a zircon rim yielded a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1179 ± 11 Ma (1σ), interpreted as the age of high-grade metamorphism, and one analysis of an inherited zircon core returned a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1678 ± 30 Ma (1σ).

GSWA 208455: hornblende–biotite metasyenogranite, Wanarn area

This sample is a medium-grained, strongly foliated to mylonitic, garnet-bearing, mafic metasyenogranite, collected about 7.8 km west-southwest of Wanarn (Fig. 3). This granite contains pegmatite veins that post-date a main foliation but are pre- to synfolding with respect to a younger deformation event. The sample contains about 45–50% quartz, 25–30% K-feldspar, 5–10% plagioclase, 5–7% hornblende, 3–5% biotite, 1–2% titanite, and accessory garnet, sericite, zircon, epidote, and iron oxide minerals. Aligned subhedral hornblende up to 2 mm long and platy biotite about 1 mm long define the foliation. Hornblende contains inclusions of garnet, titanite, and zircon (Fig. 4e). The U–Pb geochronology was reported by Wingate et al. (2015e). Zircons are colourless to dark brown and mainly subhedral and slightly rounded. Most crystals consist of concentrically zoned, angular or resorbed cores, overgrown by high-U zircon rims. Forty-four analyses were obtained from 42 zircons (Fig. 9b). Seventeen analyses of zircon cores yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1594 ± 14 Ma (MSWD = 1.8), interpreted as the age of magmatic crystallization of the granite protolith. Thirteen analyses of zircon rims yield a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1166 ± 5 Ma (MSWD = 1.1), interpreted as the age of high-grade metamorphism.

GSWA 208502: biotite–hornblende metasyenogranite, Wanarn area

This sample is a strongly foliated to mylonitic, fine- to medium-grained, garnet-bearing, metamonzogranite to metasyenogranite, collected about 5.1 km west-southwest of Wanarn (Fig. 3). This granite contains abundant pegmatite veins, although the geochronology sample was homogeneous and free of veins. The sample contains about 45–50% quartz, 20–25% K-feldspar, 10–15% plagioclase, 5–7% biotite, 2–3% opaque oxide minerals, 1% garnet, and accessory hornblende, sericite, titanite, and zircon. The U–Pb geochronology was reported by Wingate et al. (2015g). Zircons from this sample are colourless to dark brown, anhedral to subhedral, and variably rounded. In CL images, the crystals consist of variably resorbed or corroded cores that exhibit concentric zoning, overgrown by internally featureless, high-uranium zircon rims. Thirty-four analyses were obtained from 30 zircons (Fig. 9c). Twelve analyses yielded a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1607 ± 11 Ma (MSWD = 1.2), interpreted as the age of magmatic crystallization of the granite protolith. Nine analyses of zircon rims yielded a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1185 ± 11 Ma (MSWD = 0.29), interpreted as the age of high-grade metamorphism.

Pitjantjatjara Supersuite

GSWA 208504: hornblende–biotite metamonzogranite, Wanarn area

This sample is a strongly foliated to gneissic, medium-grained, garnet-bearing, weakly feldspar-phyric, hornblende–biotite metamonzogranite, collected about 8.2 km northwest of Wanarn (Fig. 3). This granite contains foliation parallel amphibolite dykes and is cut by two sets of quartz veins. The estimated mineralogy consists of 25–30% quartz, 20–25% K-feldspar, 15–20% plagioclase, 10–15% hornblende, 5–7% biotite, and accessory titanite, garnet, sericite, epidote, and zircon (Fig. 5c). The U–Pb geochronology was reported by Wingate et al. (2015a). Zircons from this sample are mainly colourless and subhedral to euhedral. Concentric zoning is ubiquitous. Eighteen analyses were obtained from 18 zircons (Fig. 9d). A regression from initial $^{207}Pb/^{206}Pb$ through all data yielded an intercept date of 1160 ± 7 Ma (MSWD = 0.78), interpreted as the magmatic crystallization age of the granite protolith.

GSWA 208506: biotite–hornblende metamonzogranite, Wanarn area

This sample is a strongly foliated to gneissic, fine- to medium-grained, garnet-bearing, biotite–hornblende metamonzogranite, collected about 20.7 km west of Wanarn (Fig. 3). The sample consists of about 35–40% quartz, 25–30% K-feldspar, 10–15% plagioclase, 10–15% biotite, 5% hornblende, 3% titanite, and accessory garnet, zircon, and iron–titanium oxide minerals. Quartz commonly displays chessboard subgrains and grain boundary migration recrystallization (Fig. 5d). The U–Pb geochronology for this sample was reported by Wingate et al. (2015b). Zircons are colourless to yellow and predominantly euhedral. Concentric zoning is ubiquitous and sector zoning is common. Twenty-eight analyses were obtained from 28 zircons (Fig. 9e). A regression from initial $^{207}Pb/^{206}Pb$ through 26 analyses yielded an intercept date of 1157 ± 9 Ma (MSWD = 1.1), interpreted as the magmatic crystallization age of the granite protolith.

GSWA 201305: granite pegmatite, Wanarn area

This sample was collected about 7.9 km west-southwest of Wanarn (Fig. 3). The pegmatite intrudes a foliated metasyenogranite of the Warlawurru Supersuite. The latter was sampled and dated (GSWA 208455, described above) and yielded magmatic and metamorphic ages of c. 1594

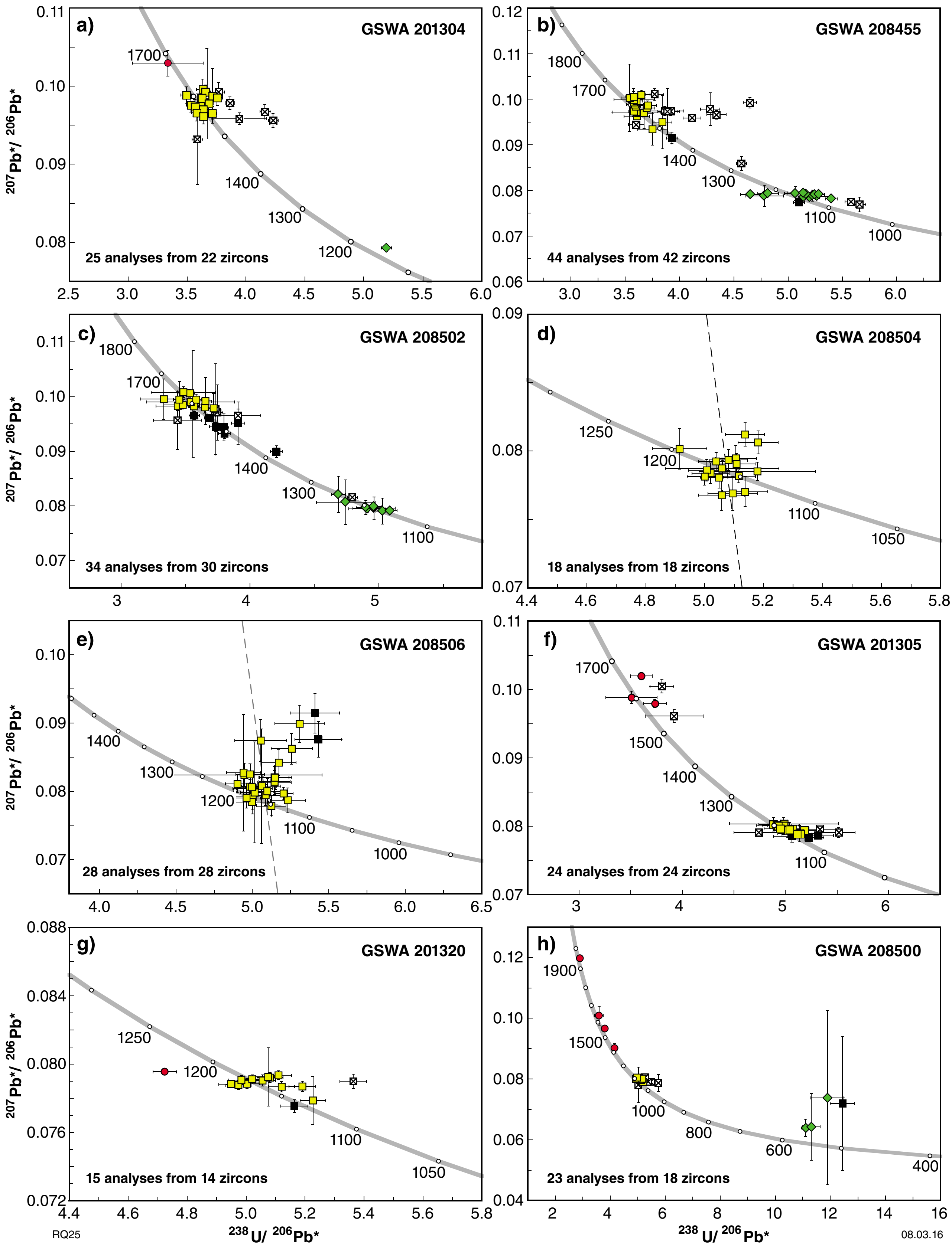

Figure 9. **U–Pb analytical data for zircons from samples of the Warlawurru and Pitjantjatjara Supersuites. Yellow squares indicate magmatic zircons, green diamonds indicate metamorphic zircon rims, red circles indicate xenocrystic zircons, black squares indicate analyses affected by Pb loss, and crossed squares indicate excluded analyses (discordance >5%). The dashed lines on d) and e) indicate regression from initial Pb through data, not corrected for common Pb, for magmatic zircons.**

and 1166 Ma, respectively. The pegmatite sample consists of about 70% K-feldspar, 15% plagioclase, 10% quartz, and minor muscovite, biotite and Fe–Ti oxide minerals. The U–Pb geochronology was reported by Wingate et al. (2015d). Zircons are subhedral to euhedral, equant to elongate, and some contain apparently older zoned cores. Twenty-four analyses were obtained from 24 zircons (Fig. 9f). Thirteen analyses yielded a concordia age of 1188 ± 6 Ma (MSWD = 2.0), interpreted as the magmatic crystallization age of the pegmatite. Three analyses of zircon cores yielded $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1660–1586 Ma, interpreted as the ages of inherited components.

GSWA 201320: leucogranite vein, Wanarn area

This quartz-rich leucosyenogranite vein was collected about 1.9 km north of Wanarn (Fig. 3), where it intrudes folded, fine-grained, biotite-rich gneiss. The dated vein belongs to a set of veins that are folded, but also locally form undeformed melt pockets that disrupt the gneissic layering (Fig. 5b). These veins are thus interpreted as syn- to post-folding. The syenogranite vein contains about 50% quartz, 45% microcline, 4% plagioclase, and accessory saussurite, opaque oxide minerals, and zircon. The U–Pb geochronology was reported by Kirkland et al. (2014g). Zircons from this sample are brown or opaque, subhedral to euhedral, and equant to elongate. The crystals exhibit weak concentric zoning or are internally homogeneous. Fifteen analyses were obtained from fourteen zircons (Fig. 9g). Twelve analyses yielded a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1171 ± 4 Ma (MSWD = 0.64), interpreted to be the magmatic crystallization age of the vein. One analysis of a zircon core yielded a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1186 ± 4 Ma (1σ), interpreted as the age of an inherited component or of an earlier leucosome component in this rock.

GSWA 208500: granite pegmatite, Wanarn area

This sample is a coarse-grained, inequigranular granite pegmatite, collected about 6 km west-southwest of Wanarn (Fig. 3). It belongs to a set of vertical pegmatite veins that crosscut the gneissic banding of their paragneiss host. The sample consists of 55–60% K–feldspar, 25–30% quartz, 10% perthite, and accessory sericite, zircon, iron oxide minerals, and white mica. The U–Pb geochronology was reported by Wingate et al. (2015f). Zircons from this sample are mainly colourless, anhedral to subhedral, and variably rounded. In CL images most crystals consist of concentrically zoned cores overgrown by low-uranium zircon rims. Twenty-three analyses were obtained from 18 zircons (Fig. 9h). Seven analyses of zircon cores yielded a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1194 ± 14 Ma (MSWD = 0.35), interpreted as the age of magmatic crystallization of the pegmatite. Four analyses of two zircon rims indicated low to very low uranium contents (7–62 ppm) and relatively high common-Pb contents (up to 9.3% common-^{206}Pb), and dates are therefore calculated from 207-corrected ratios. Three analyses of two zircon rims yielded a weighted mean 207-corrected $^{238}U/^{206}Pb^{*}$ date of 545 ± 39 Ma (MSWD = 2.0), interpreted as the age of high-grade metamorphism. The rejected analysis is significantly younger than other analyses of the same zircon rim and is interpreted to reflect the loss of radiogenic Pb.

MacDougall Formation

Six samples for detrital zircon geochronology were collected from metasedimentary rocks along a 60 km northeast-trending transect across the Mitika and Wanarn areas (Figs 2, 3, and 6). We also included results for three samples from the MacDougall Formation, collected about 70 km east of the Mitika and Wanarn areas (Evins et al., 2010, figs 3 and 8).

GSWA 205194: psammitic gneiss, Mitika area

This psammitic gneiss sample was collected about 7.6 km southeast of the Mitika Homestead (Fig. 6). The gneiss consists of about 40% quartz, 29% plagioclase, 29% K-feldspar, 1% biotite, and accessory epidote, sericite, opaque oxide minerals, and zircon. The U–Pb geochronology was reported by Kirkland et al. (2014c). Zircons from this sample are colourless to black, anhedral to euhedral, heavily fractured, and variably rounded. The crystals exhibit a variety of textures, including homogeneous cores, cores with faded concentric zoning, and thin zircon overgrowths, which in places penetrate along apparent alteration fronts. Thirteen analyses were obtained from thirteen zircons (Figs 10a and 11a). Seven analyses of zircon cores yielded a weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1190 ± 12 Ma (MSWD = 0.49). This date is interpreted as a maximum depositional age for the sedimentary precursor, and is likely to be the crystallization age of a magmatic rock in the source of the detritus. Four analyses of zircon rims yielded a concordia age of 628 ± 4 Ma (MSWD = 0.5), interpreted as the age of metamorphism.

GSWA 194806: metasandstone, Mitika area

This sample is an arkosic metasandstone collected about 3.9 km east-southeast of the Mitika Homestead (Fig. 6). The rock contains about 60% quartz, 25% feldspar, 10% muscovite, 4% opaque oxide minerals, and accessory zircon, epidote, biotite, and apatite. The U–Pb geochronology for this sample was reported by Kirkland et al. (2014b). Zircons from this sample are colourless to dark brown or opaque, subhedral to euhedral, and variably rounded. Sixty analyses were obtained from 56 zircons (Figs 10b and 11b). Fifty-three analyses yielded $^{207}Pb^{*}/^{206}Pb^{*}$ dates of 1607–1137 Ma. A conservative estimate of the maximum depositional age is provided by the weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1179 ± 5 Ma (MSWD = 0.99) for the 30 youngest analyses. Significant age components are at c. 1539 and 1186 Ma.

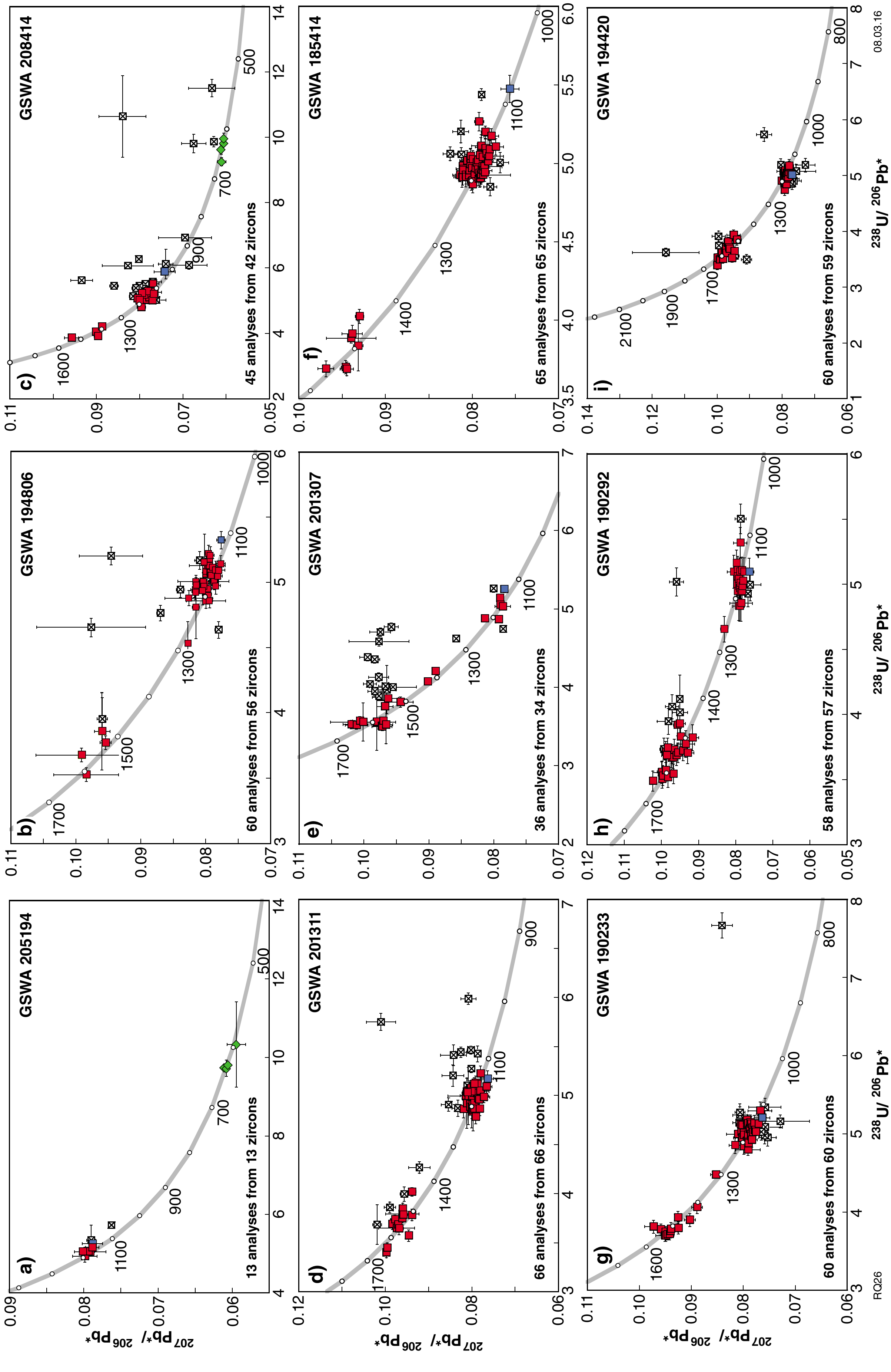

Figure 10. U–Pb analytical data for zircons from samples of the MacDougall Formation. Blue squares indicate the youngest detrital zircon, red squares denote older detrital zircons, green diamonds indicate metamorphic zircon rims, and crossed squares indicate excluded analyses (discordance >5%).

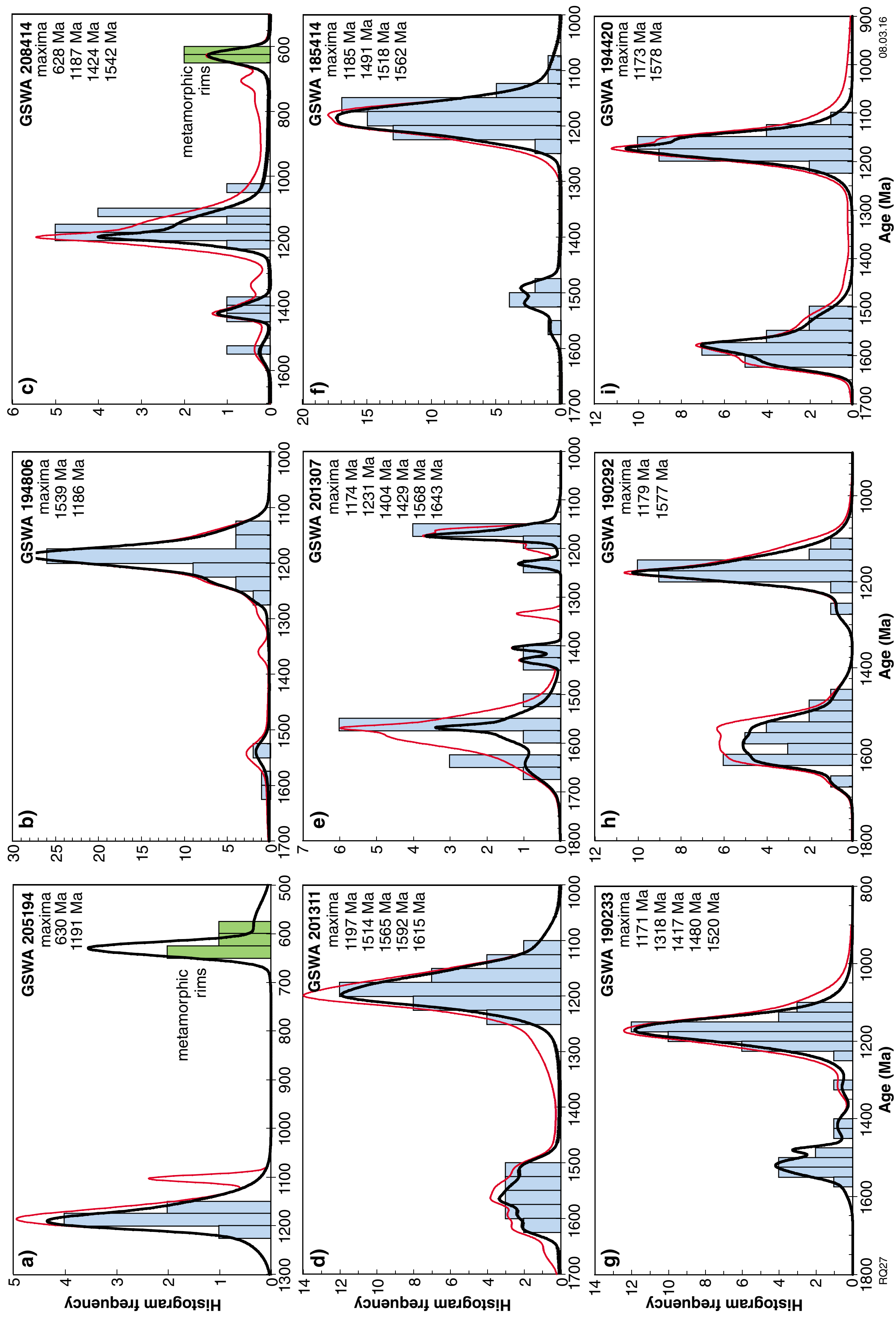

Figure 11. Probability density diagrams and histograms of detrital zircon ages from samples of the MacDougall Formation. Thick curve, maxima values, and frequency histograms (bin width 25 Ma) include only data <5% discordant. Thin curve includes all data.

GSWA 208414: quartzite, Mitika area

This quartzite was collected about 5.2 km east-southeast of the Mitika Homestead (Fig. 6). The rock consists of about 98% quartz, 1% muscovite, and accessory opaque oxide minerals and zircon. The U–Pb geochronology was reported by Kirkland et al. (2014d). Zircons are colourless to light brown, anhedral to euhedral, variably rounded, and many grains contain high-uranium overgrowths. Forty-five analyses were obtained from 42 zircons (Figs 10c and 11c). Twenty-one analyses yielded $^{207}Pb/^{206}Pb^*$ dates of 1542–1048 Ma. A conservative maximum depositional age is provided by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1179 ± 13 Ma (MSWD = 1.8) for the 17 youngest analyses. Significant age components are at c. 1424 and 1187 Ma. Four analyses of zircon rims or discrete crystals yielded a concordia age of 631 ± 12 Ma (MSWD = 3.0), interpreted as the age of metamorphism.

GSWA 201311: metasandstone, Wanarn area

This sample of metasandstone was collected about 8.9 km southwest of Wanarn (Fig. 3). The visually estimated mineralogy is about 60% quartz, 38% feldspar, 1% muscovite, and accessory biotite, opaque oxide minerals, and zircon. The U–Pb geochronology of this sample was reported by Kirkland et al. (2014a). Zircons are colourless to dark brown, subhedral to euhedral, and variably rounded. Sixty-six analyses were obtained from 66 zircons (Figs 10d and 11d). Fifty-one analyses yielded dates of 1620–1106 Ma, with significant age components at c. 1615, 1592, 1565, and 1197 Ma. A conservative maximum age of deposition is provided by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1180 ± 8 Ma (MSWD = 1.5) for the 27 youngest analyses.

GSWA 201307: metasandstone, Wanarn area

This sample is a metasandstone that was collected about 7.7 km west-southwest of Wanarn (Fig. 3). The rock consists of about 60% quartz, 35% feldspar, 2% biotite, 1% muscovite, 1% garnet, and accessory opaque oxide minerals, chlorite, and zircon. The U–Pb geochronology was described by Kirkland et al. (2014f). Zircons are colourless to dark brown, subhedral to euhedral, and variably rounded, and many grains are metamict and inclusion rich. Thirty-six analyses were obtained from 34 zircons (Figs 10e and 11e). Twenty analyses yielded dates of 1660–1157 Ma, including significant age components at c. 1643, 1568, and 1174 Ma. A conservative maximum age of deposition is provided by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1172 ± 10 Ma (MSWD = 1.2) for the five youngest analyses.

GSWA 185414: quartzite, Bentley Hill

This quartzite sample was collected about 23 km southeast of the Mitika Homestead (Fig. 6). The sample consists of about 75% quartz, 20% muscovite, 3% opaque oxide minerals, 1% feldspar, and accessory zircon, epidote, biotite, and apatite. The U–Pb geochronology was described by Kirkland et al. (2014e). Zircons are colourless to dark brown, subhedral to euhedral, and variably rounded. The crystals exhibit ubiquitous concentric zoning and some display features suggestive of dissolution and regrowth. Sixty-five analyses were obtained from 65 zircons (Figs 10f and 11f). Fifty-nine analyses yielded dates of 1565–1086 Ma and include significant age components at c. 1518, 1491, and 1185 Ma. A single analysis yielded a date of 1068 ± 28 Ma (1σ), which represents the maximum depositional age for the sedimentary precursor. A more conservative estimate of the maximum depositional age is provided by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1153 ± 9 Ma (MSWD = 0.66) for the 15 youngest analyses.

GSWA 190233: phyllite, Prostanthera Hill

This sample of phyllitic metasedimentary rock was collected about 5.9 km west of Prostanthera Hill. The sample consists of about 80% quartz, 15% muscovite, 4% feldspar, and accessory garnet, zircon, and opaque oxide minerals. The U–Pb geochronology is provided by Kirkland et al. (2014e). Zircons are colourless to dark brown, subhedral to euhedral, and variably rounded. Sixty analyses were obtained from 60 zircons (Figs 10g and 11g). Fifty analyses yielded dates of 1573–1115 Ma and include significant age components at c. 1520 and 1171 Ma. A conservative estimate of the maximum depositional age is provided by the weighted mean $^{207}Pb^*/^{206}Pb^*$ date of 1172 ± 8 Ma (MSWD = 1.2) for the 36 youngest analyses.

GSWA 190292: metasandstone, Mount Finlayson

This sample of medium- to coarse-grained metasandstone with quartz pebble horizons was collected about 5.1 km northwest of Mount Finlayson. The sample consists of about 45–50% quartz, 20% muscovite, 15–20% microcline, 10–15% plagioclase, 2% garnet, and 1% opaque oxide minerals. The U–Pb geochronology was reported by Kirkland et al. (2014e). Zircons are colourless to yellow, mainly euhedral, and elongate. The crystals are zoned and some are overgrown by low-uranium rims. Fifty-eight analyses were obtained from 57 zircons (Fig. 10h and 11h). Forty-eight analyses yielded dates of 1666–1104 Ma and include significant age components at c. 1577 and 1179 Ma. A conservative estimate of the maximum depositional age is provided by the concordia age of 1176 ± 7 Ma (MSWD = 1.7) for the 24 youngest analyses.

GSWA 194420: feldspathic sandstone, Mount Blyth

This sample of poorly sorted arkosic sandstone was collected about 3.9 km southeast of Mount Blyth. The sample consists of about 60–70% quartz, 20–30% K–feldspar, and accessory garnet, zircon, and white mica. The U–Pb geochronology is described by Kirkland et al. (2014e). Zircons are colourless to yellow, mainly euhedral, and variably rounded. The crystals are zoned and some are overgrown by low-uranium rims. Sixty analyses were obtained from 59 zircons (Figs 10i and 11i). Forty-seven analyses yielded dates of 1626–1121 Ma and include significant age components at c. 1578 and 1173 Ma. A conservative estimate of the maximum depositional age is provided by the weighted mean $^{207}Pb^{*}/^{206}Pb^{*}$ date of 1173 ± 6 Ma (MSWD = 1.4) for the 27 youngest analyses.

Discussion

The Warlawurru Supersuite: oldest known basement in the west Musgrave Province

Three metasyenogranite samples yielded crystallization ages of c. 1607, 1594, and 1583 Ma (Table 1). These rocks are assigned to the Warlawurru Supersuite, and are the oldest rocks identified in the west Musgrave Province. The Warlawurru Supersuite has been identified only in a northeast-directed thrust sheet and not in other structural blocks in the Wanarn area, which contain Pitjantjatjara Supersuite granites (Fig. 3). The 1607–1583 Ma age range of the Warlawurru Supersuite is consistent with zircon Hf isotope data that suggest a crust-forming event took place at 1600–1550 Ma (Kirkland et al., 2012a, 2015).

A pegmatite vein that intrudes the Warlawurru Supersuite is dated at c. 1188 Ma (GSWA 201305, Wingate et al., 2015d). Its zircons contain 1660–1586 Ma cores, which are interpreted as xenocrysts, inherited in part from the c. 1594 Ma granite host (GSWA 208455, Wingate et al., 2015e). U–Pb zircon dates in the 1665–1540 Ma range have been obtained from the central and eastern parts of the Musgrave Province and many have been interpreted as the crystallization ages of granite protoliths to orthogneisses (Maboko, 1988; Camacho and Fanning, 1995; Scrimgeour et al., 1999; Young et al., 2002; Edgoose et al., 2004). However, Evins et al. (2012) suggested that many of these samples are volcanic or sedimentary in origin and thus likely to represent components of the Wirku Metamorphics that were deposited at c. 1300 Ma. Because outcrops of 1665–1540 Ma orthogneisses are scarce and exclusively located between the Mann Fault and the Woodroffe Thrust, Evins et al. (2012) proposed that these rocks were possibly limited to tectonic slices, emplaced during the c. 550 Ma Petermann Orogeny, and that rocks of this age were not necessarily exposed elsewhere in the Musgrave Province. The crystallization ages presented herein for metasyenogranites of the Wanarn area confirm the presence of isolated slivers of c. 1600 Ma crust in the west Musgrave Province.

The extensive geochronology data obtained by GSWA during the detailed mapping of the west Musgrave Province reveal that exposed Warlawurru Supersuite is extremely uncommon and it has so far only been identified in the Wanarn area. The Wanarn area consists of a wedge-like structure bounded to the south by the steeply south-dipping Mitika Fault and to the north by the shallowly south-dipping Woodroffe Thrust (Fig. 2). The Warlawurru Supersuite lies on an arcuate magnetic anomaly convex towards the northeast (Fig. 12) and exhibits consistent shallow southwest-plunging stretching lineations, overturned to recumbent northeast-verging folds, and northeast-striking vertical sinistral tear faults (Fig. 13). Rocks of the Warlawurru Supersuite are always mylonitic at the contact with structurally underlying paragneisses of the Kunmarnara Group. These observations are consistent with emplacement of the Warlawurru Supersuite as a tectonic sliver within the Kunmarnara Group during northeast-directed thrusting.

Musgrave Orogeny and Pitjantjatjara Supersuite

High-grade metamorphism and partial melting at 1190–1160 Ma is recorded by metamorphic growth of zircon rims in Warlawurru Supersuite samples (Fig. 9a–c; GSWA 201304, Wingate et al., 2015c; GSWA 208455, Wingate et al., 2015e; GSWA 208502, Wingate et al., 2015g), and by the crystallization of a pegmatite and a leucogranite vein (Fig. 9f,g, GSWA 201305, Wingate et al., 2015d; GSWA 201320, Kirkland et al., 2014g). This age range corresponds to the main metamorphic event of the 1220–1150 Ma Musgrave Orogeny (Smithies et al., 2014, fig. 3). The leucogranite vein (GSWA 201320, Kirkland et al., 2014g) is located 2 km north of Wanarn in a thrust sheet that is separate to the one containing the Warlawurru Supersuite (Fig. 3). The vein contains a zircon core dated at 1186 ± 4 Ma interpreted as the age of an inherited component or an earlier leucosome component in the granite host. The granite host has not been dated directly but the lack of older inheritance may imply that the granite host belongs to the Pitjantjatjara Supersuite rather than to the Warlawurru Supersuite. The two granites (GSWA 208504, Wingate et al., 2015a; GSWA 208506, Wingate et al., 2015b) sampled outside the northeast-directed thrust sheet containing the Warlawurru Supersuite yielded magmatic crystallization ages of c. 1160 Ma (Fig. 9d,e). This corresponds to the youngest main magmatic peak of the Musgrave Orogeny (Smithies et al., 2014, fig. 3). The basement to the Kunmarnara Group in the Wanarn area therefore comprises at least two age components: a 1607–1583 Ma Warlawurru Supersuite component and a 1190–1160 Ma Pitjantjatjara Supersuite component.

The relative extent of Pitjantjatjara versus Warlawurru granites is difficult to assess as the two supersuites contain components that may be texturally, mineralogically, and compositionally similar. Both supersuites contain intrusive phases that may be feldspar-phyric, biotite- and/or hornblende bearing, highly deformed, and range between monzogranite and syenogranite in composition. All of the above make the two supersuites difficult to differentiate in the field without the help of geochronology data.

A syn- to post-folding leucogranite vein dated at 1171 ± 4 Ma (GSWA 201320, Kirkland et al., 2014g) intrudes a folded, biotite-rich gneiss. The gneiss is

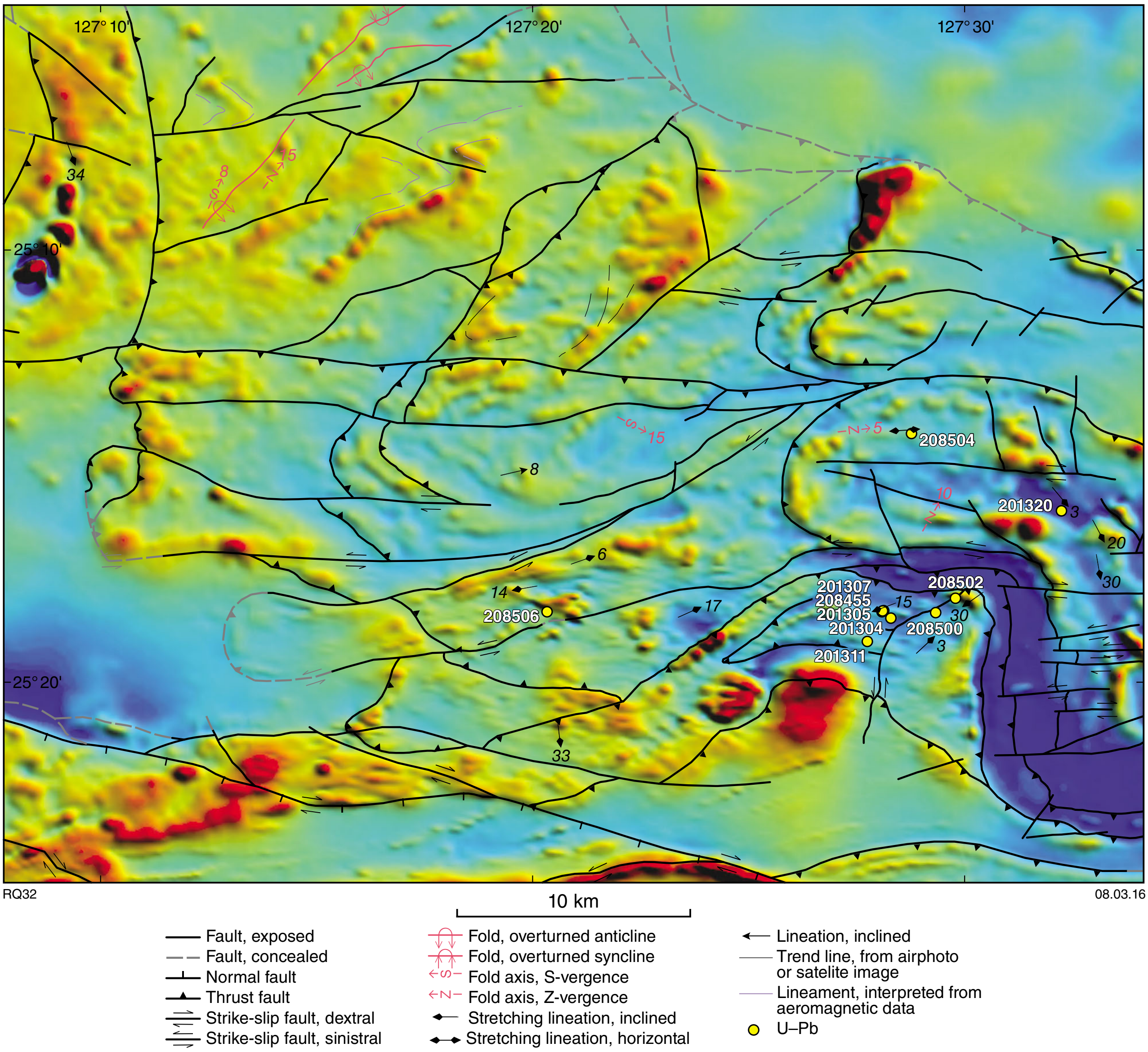

Figure 12. Reduced to pole, total magnetic image of the Wanarn area, showing the locations of U–Pb geochronology samples with respect to structures interpreted from magnetic anomalies

interpreted as a metagranite of the Pitjantjatjara Supersuite and contains shallow southeast-plunging stretching lineations and recumbent northwest-verging folds and shear-sense indicators, consistent with a northwesterly transport direction (Fig. 14). A Pitjantjatjara Supersuite granite, 6.5 km northwest of the leucocratic vein, is dated at 1160 ± 7 Ma (GSWA 208504, Wingate et al., 2015a), and contains east-trending horizontal stretching lineations. From aeromagnetic data we interpret this granite to belong to the same fault-bounded structural block as the leucocratic vein, together forming an arcuate magnetic anomaly convex towards the west (Fig. 12). We interpret this aeromagnetic feature to represent a north-northwest- to west-directed thrust sheet that tectonically interleaves granites of the Pitjantjatjara Supersuite with paragneisses of the Kunmarnara Group. A Pitjantjatjara Supersuite granite, located 20 km further west, dated at 1157 ± 9 Ma (GSWA 208506, Wingate et al., 2015b) also lies within an arcuate magnetic anomaly convex towards the west, that is similarly interpreted as a west-directed thrust sheet.

No inherited zircons appear to be present in the two samples of the c. 1160 Ma granites from the north-northwest to west-directed thrust sheets (GSWA 208504, Wingate et al., 2015a; GSWA 208506, Wingate et al., 2015b). It is therefore possible that there may not be an older granite basement component in the vicinity of these granites. We interpret the series of arcuate, convex towards the west magnetic anomalies in the Wanarn area (Fig. 12) as a series of west-directed thrust sheets that emplaced Pitjantjatjara Supersuite granites onto rocks of the Kunmarnara Group. The occurrence of Warlawurru Supersuite granites is so far restricted to the northeast-directed thrust sheet (Figs 2 and 3).

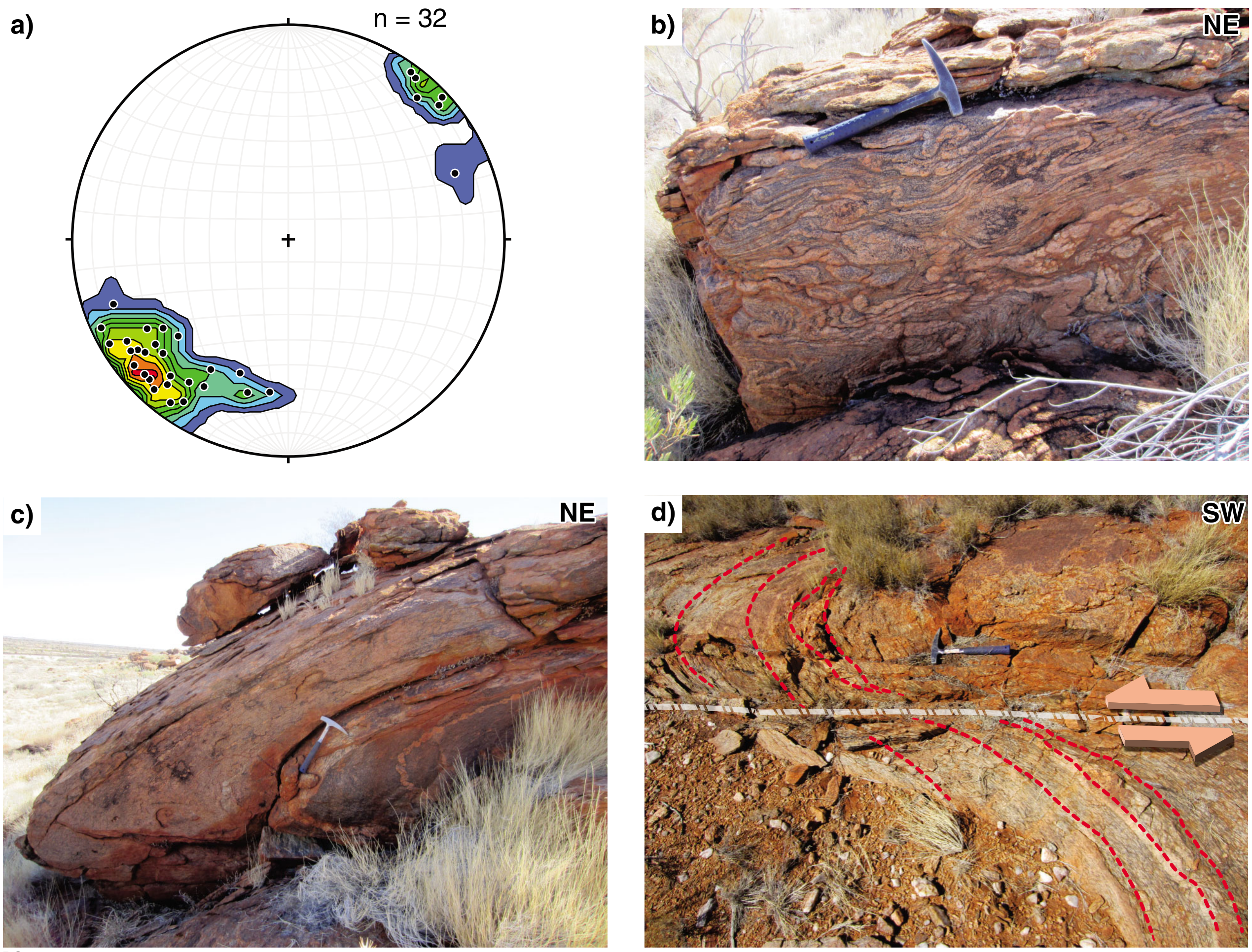

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Figure 13. **a) Lower hemisphere, equal-area stereographic projection of stretching lineations from the northeast-directed thrust sheet of the Wanarn area, containing rocks of the Warlawurru Supersuite; b) and c) field photographs of the Warlawurru Supersuite, showing overturned northeast-verging folds; d) a northeast-striking sinistral tear fault.**

MacDougall Formation

Detrital zircon geochronology

Evins et al. (2010) suggested that the maximum age for the deposition of the MacDougall Formation can be constrained by the regional maximum age of c. 1085 Ma for magmatism associated with the Giles Event, which was nearly coeval with the onset of the Ngaanyatjarra Rift and the deposition of the Kunmarnara Group. A minimum age of 1078–1075 Ma for the deposition of the MacDougall Formation is provided by the age of 1078 ± 4 Ma for the conformably overlying Mummawarrawarra Basalt (Howard et al., 2011; GSWA 183847, Kirkland et al., 2012b) and by the age of 1076 ± 6 Ma for a granitic intrusion into the Mummawarrawarra Basalt (Smithies et al., 2009; Howard et al., 2011; GSWA 194762, Kirkland et al., 2011a).

The youngest zircons in all samples range from c. 1197 to 1171 Ma, with an average of c. 1180 Ma. Other significant age components lie between c. 1610 and 1500 Ma and between c. 1430 and 1400 Ma (Table 2, Figs 15 and 16). Maximum ages of deposition for nine samples of the MacDougall Formation range from c. 1190 to 1153 Ma (Table 2) and, of these ages, eight fall within the analytical precision of 1177 ± 4 Ma (MSWD = 1.5). A robust maximum age for deposition of the unit is therefore 1177 ± 4 Ma.

A Kolmogorov-Smirnov (K-S) test was used to test for similarity between the detrital zircon age spectra from the nine MacDougall Formation samples. The K-S test converts the datasets into cumulative distribution functions and tests the probability of the samples being drawn from the same distribution. In Table 3 the hypothesis that two samples come from the same source is rejected when the probability (p) falls below 0.05, indicating a 95% level of confidence that the samples are derived from different sources. High values close to 1 indicate very similar age spectra and suggest that the samples were derived from the same or similar sources.

The K-S test indicates that the detrital zircon age spectra of all samples of the MacDougall Formation from the Mitika area are statistically similar, showing probability values varying between 0.279 and 0.999 (Table 3).

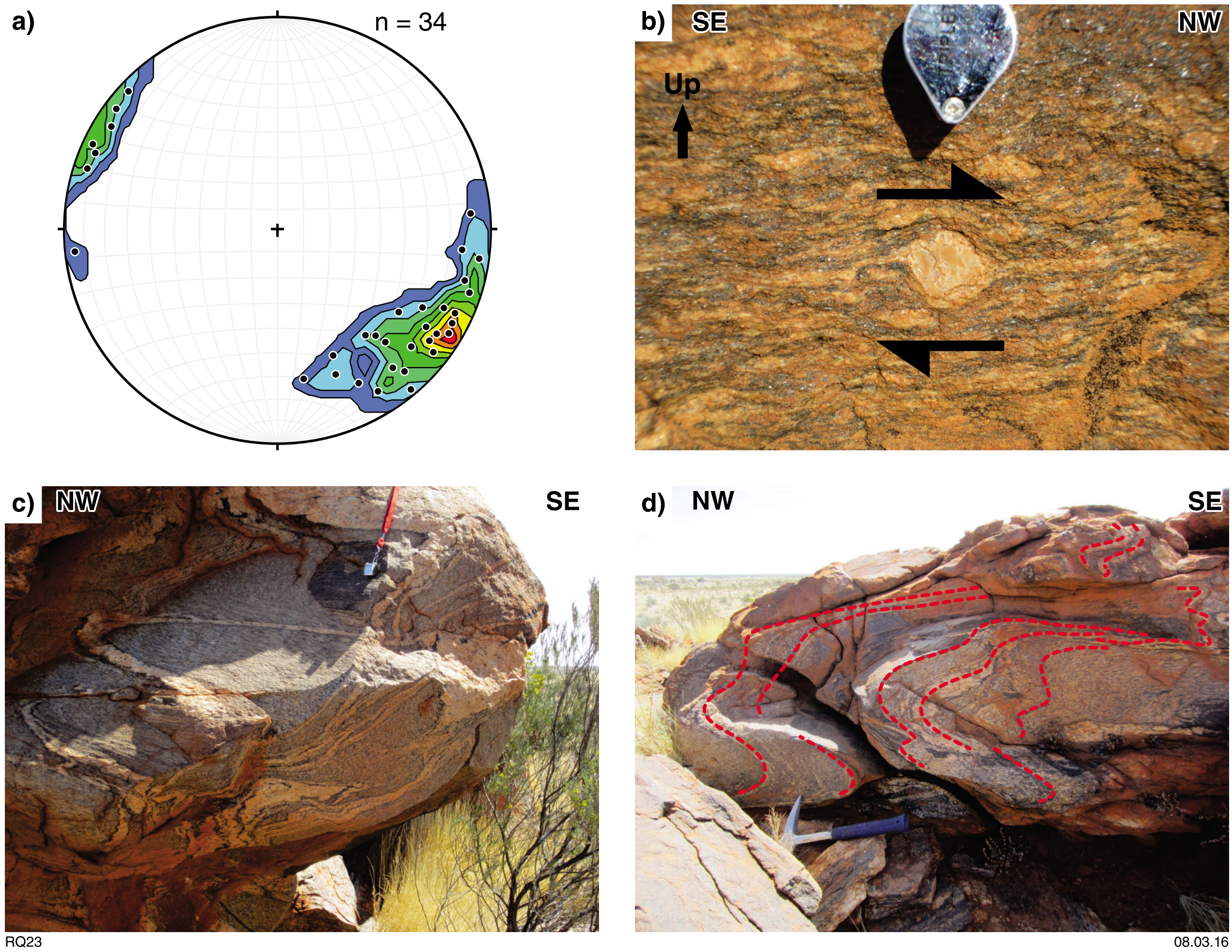

Figure 14. **a) Lower hemisphere, equal-area stereographic projection of stretching lineations from the northwest-directed thrust sheet containing rocks of the Pitjantjatjara Supersuite; b) field photograph of the Pitjantjatjara Supersuite, showing a delta porphyroclast indicating top to the northwest shear-sense; c) well-defined southeast-plunging stretching lineation of the Pitjantjatjara Supersuite; d) northwest-verging recumbent folds of the Pitjantjatjara Supersuite.**

Table 3. Kolmogorov-Smirnov (K-S) test matrix for samples of the MacDougall Formation

		MacDougall Formation								
		Mitika area				*Wanarn area*		*Eastern area*		
	Sample	*185414*	*208414*	*194806*	*205194*	*201307*	*201311*	*190233*	*190292*	*194420*
Mitika area	185414		0.492	0.987	0.999	0.000	0.373	0.415	0.001	0.004
	208414	0.492		0.279	0.990	0.004	0.362	0.732	0.006	0.029
	194806	0.987	0.279		0.999	0.000	0.251	0.290	0.000	0.004
	205194	0.999	0.990	0.999		0.012	0.619	0.722	0.090	0.220
Wanarn area	201307	0.000	0.004	0.000	0.012		0.011	0.005	0.624	0.211
	201311	0.373	0.362	0.251	0.619	0.011		0.796	0.163	0.428
Eastern area	190233	0.415	0.732	0.290	0.722	0.005	0.796		0.021	0.022
	190292	0.001	0.006	0.000	0.090	0.624	0.163	0.021		0.987
	194420	0.004	0.029	0.004	0.220	0.211	0.428	0.022	0.987	

NOTES: Only accepted detrital zircon ages (discordance <5%) were used. Numbers refer to the probability (at 95% confidence) of two samples being sourced from the same zircon age population. Values of <0.05 indicate that samples were derived from distinctly different populations. High values (in yellow boxes) denote that populations are similar.

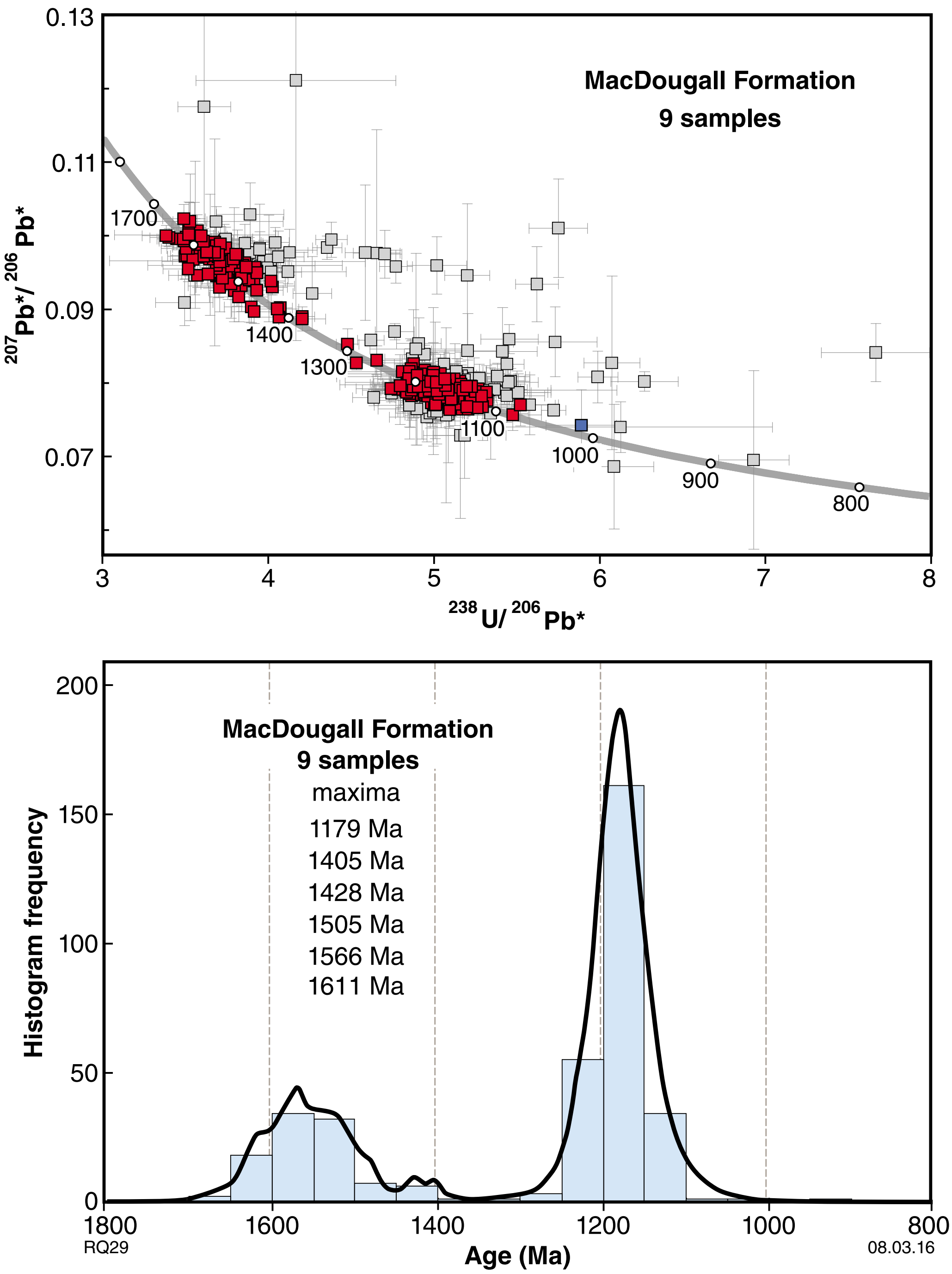

Figure 15. **a) U–Pb analytical data for zircons from nine combined samples of the MacDougall Formation. The blue square denotes the youngest detrital zircon, red squares symbolize older detrital zircons, and open squares mark excluded data (discordance >5%); b) probability density diagram and histogram of accepted zircon ages (n = 356, excluding metamorphic zircon dates) from nine combined samples of the MacDougall Formation.**

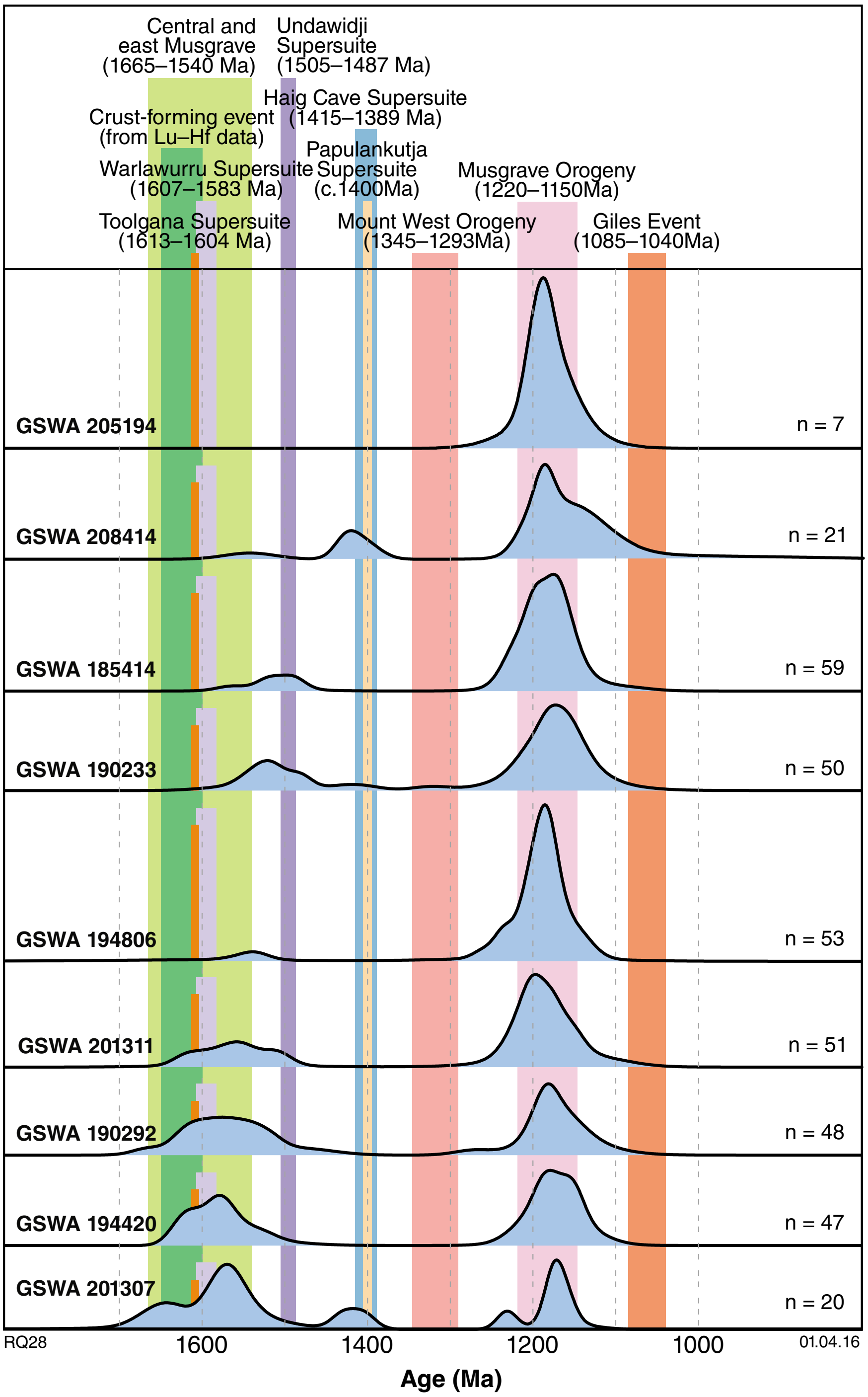

Figure 16. Normalized probability density curves of detrital zircon ages from nine samples of the MacDougall Formation. The age ranges for major magmatic and orogenic events of the Musgrave, Madura, and Coompana Provinces are shown for comparison. The dates for the central and east Musgrave combine data from Jagodzinski and Dutch (2013) and Edgoose et al. (2004) and references therein. The letter 'n' denotes the number of analyses from each sample.

This test corroborates the conclusion based on field observations that the quartzofeldspathic rocks in the Mitika area are part of the MacDougall Formation. This differs from the early interpretation of Daniels et al. (1971) who considered the quartzofeldspathic rocks as a complex of monzogranite gneiss forming the basement of the quartzite ridges of the MacDougall Formation. The MacDougall Formation is now reinterpreted as comprising a quartzofeldspathic metasandstone component interbedded with quartzite and muscovite-schist that form the north-trending ridges of the Mitika area. All samples of the Mitika area are also statistically similar to sample GSWA 201311 (Kirkland et al., 2014a) of the Wanarn area (probability values range between 0.251 and 0.619), which was collected from an outcrop in conformable contact with the amygdaloidal Mummawarrawarra Basalt. This field relationship, together with the detrital age spectrum of sample GSWA 201311 (Kirkland et al., 2014a), provides a strong argument that the well-banded quartzofeldspathic gneisses of the Wanarn area also constitute components of the MacDougall Formation.

Sample GSWA 201307 (Kirkland et al., 2014f) differs statistically from all samples of the Mitika and Wanarn area (all probability values are below 0.05). However, this dataset consists of only 20 analyses and the age spectrum may not be representative of the population in the rock unit. Nevertheless, the age spectrum for this sample (Fig. 11e) is still broadly similar to the characteristic age components of the MacDougall Formation.

Sedimentary provenance of the MacDougall Formation

The combined detrital zircon age data for nine samples of the MacDougall Formation fall into two main groups at 1620–1470 Ma and c. 1179 Ma and two subordinate groups at c. 1428 and 1405 Ma (Fig. 15). Within the older group, there are significant age components at c. 1611, 1566, and 1505 Ma (Fig. 15).

The MacDougall Formation age components match well with the ages of magmatic rocks within the Musgrave Province (Fig. 16). In the South Australian portion of the central Musgrave Province, magmatic protolith ages of 1665–1565 Ma have been reported by Jagodzinski and Dutch (2013) for several orthogneiss samples. The central and east Musgrave Province in the Northern Territory comprises 1600–1540 Ma gneisses (Edgoose et al., 2004 and references therein). This study demonstrates that the west Musgrave Province comprises 1607–1583 Ma orthogneisses, i.e. the Warlawurru Supersuite. Finally, Lu–Hf isotope data indicate a crust-forming event at 1650–1600 Ma (Kirkland et al., 2012a, 2015). All of the above dates that range from c. 1665 to 1540 Ma could at least partly account for the older detrital component of the MacDougall Formation (Fig. 16). The c. 1400 age of the Papulankutja Supersuite is a close match with the c. 1405 Ma detrital peak; and the 1220–1150 Ma ages for the Pitjantjatjara Supersuite encompass the c. 1179 Ma peak. However, there are 1565–1480 Ma detrital zircons in the detrital spectrum of the MacDougall Formation which do not correspond to the ages of known rocks in the Musgrave Province (Fig. 16).

Outside the Musgrave Province, the MacDougall Formation age components at 1620–1470 Ma overlap with 1613–1604 Ma and 1505–1487 Ma ages for the Toolgana and Undawidgi Supersuites in the Forrest Zone of the Coompana Province (Wingate et al., 2015h). Detrital zircons at c. 1610 Ma could also have been derived from granites of the 1647–1604 Ma St Peters Suite of South Australia (Symington et al., 2014). Age components at c. 1428 and 1405 Ma are similar to 1415–1389 Ma ages for the Haig Cave Supersuite of the Madura Province (Wingate et al., 2015i). The c. 1179 Ma age component in the MacDougall Formation correlates well with the 1200–1140 Ma Esperance Supersuite in the eastern Albany–Fraser Orogen (Spaggiari et al., 2014) and the 1192–1130 Ma Moodini Supersuite of the Madura Province and Forrest Zone (Wingate et al., 2015h,i).

The absence of detrital zircon age components older than c. 1620 Ma in the MacDougall Formation precludes the Capricorn Orogen, the Rudall Province, or the Arunta Inlier from being the source of detrital material of this age. Similarly, the c. 1611 Ma component is younger than 1710–1650 Ma granites emplaced in the Albany–Fraser Orogen during the Biranup Orogeny (Spaggiari et al., 2014). The 1345–1293 Ma Wankanki Supersuite granites of the west Musgrave Province and their time-equivalent, the 1330–1280 Ma Recherche Supersuite of the Albany–Fraser Orogen, are not represented in the MacDougall Formation age spectrum.

In summary, the available data suggest that the source of MacDougall Formation detritus probably derives from the central and eastern Musgrave Province or from basement rocks of the Madura or Coompana Provinces beneath the Eucla Basin.

Are all metasedimentary rocks of the Wanarn area part of the MacDougall Formation?

Pegmatite sample GSWA 208500 (Wingate et al., 2015f) is dominated by zircons dated at 1194 ± 14 Ma, which are interpreted as the age of crystallization of the pegmatite (Fig. 9h; Wingate et al., 2015f). In this case, the paragneiss host cannot belong to the MacDougall Formation (Fig. 3), but must be part of a sedimentary unit deposited prior to or during the Musgrave Orogeny.

However, paragneiss samples GSWA 201307 (Kirkland et al., 2014f) and GSWA 201311 (Kirkland et al., 2014a) collected a kilometre to the south of the pegmatite, yield distinct 1180–1170 Ma age components (Fig. 11d,e; Table 1) and are conformably overlain by lavas of the c. 1078 Ma Mummawarrawarra Basalt. Furthermore, the paragneiss intruded by the pegmatite sample does not show evidence of prolonged high-temperature metamorphism commonly observed in rocks affected by the Musgrave Orogeny. We therefore prefer the interpretation that all zircon cores from pegmatite sample GSWA 208500 (Wingate et al., 2015f) are inherited, possibly from the paragneiss host rock. The paragneiss, in turn, is interpreted as part of the MacDougall Formation.

The pegmatite may be related to the Giles Event (1080–1040 Ma) or be younger, possibly c. 545 Ma (the imprecise age determined for three analyses of two low-uranium zircon rims in the pegmatite; GSWA 208500, Wingate et al., 2015f).

A single c. 1950 Ma zircon: evidence for crust of this age?

Pegmatite sample GSWA 208500 (Wingate et al., 2015f) contains a single zircon dated at 1952 ± 11 Ma (Fig. 9h). This is the only material of that age known in the west Musgrave Province. Kirkland et al. (2012a) proposed a crust-forming event at 1950–1900 Ma from Hf and O isotope data from younger zircons of the west Musgrave Province. Although Hf isotope data are not available for the c. 1950 Ma zircon to date, a juvenile Hf isotopic signature for this zircon would support the hypothesis proposed by Kirkland et al. (2012a). Results for a single zircon are insufficient to fully confirm this hypothesis; therefore, additional geochronology and Hf isotope studies of zircons from the paragneiss host of the pegmatite may reveal more material in the 1950–1900 Ma range and, hence, provide stronger support for a crust-forming event at this time.

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GEOLOGY AND U–PB GEOCHRONOLOGY OF THE WARLAWURRU SUPERSUITE AND MACDOUGALL FORMATION IN THE MITIKA AND WANARN AREAS, WEST MUSGRAVE PROVINCE

Quentin de Gromard et al.