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DETRITAL ZIRCON GEOCHRONOLOGY OF UPPER EDIACARAN TO LOWER CAMBRIAN DEPOSITS (SUPERSEQUENCE 4), WESTERN AMADEUS BASIN: TESTING REVISED STRATIGRAPHIC CORRELATIONS

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Detrital zircon geochronology of upper Ediacaran to lower Cambrian deposits (Supersequence 4), western Amadeus Basin: testing revised stratigraphic correlations

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Abstract

Syntectonic siliciclastic sedimentary rocks, comprising Supersequence 4 of the Centralian Superbasin, accumulated within the Amadeus Basin during the Petermann Orogeny (570–530 Ma). This event uplifted the Mesoproterozoic basement of the Musgrave region, supplying sediment from this source to foreland depocentres. Recent Geological Survey of Western Australia (GSWA) revisions to the stratigraphy of the Western Australian Amadeus Basin propose that various siliciclastic units, previously thought by most authors to pre- and post-date the Petermann Orogeny, be reassigned to Supersequence 4. These include the Carnegie Formation, Ellis Sandstone, Sir Frederick Conglomerate, Maurice Formation, Angas Hills Formation (revised name) and the Mu Formation (new name). Here we test the revised stratigraphy using a detrital zircon provenance study of eight samples from these units. The detrital zircons are mostly of late Mesoproterozoic age (dominant component at c. 1.18 Ga) with major age components matching known zircon crystallizing events in the Musgrave region. Minor late Paleoproterozoic age components match events in the Arunta region to the north. Given the refractory nature of zircon, many of these detrital components are likely multicyclic and may include detrital and inherited zircons derived from the Musgrave region. However, the multicyclic components are probably dominated by recycled zircons from older Amadeus Basin units known to have been eroded along with Musgrave material during the Petermann Orogeny. Paleocurrent data for selected fluvial units indicate transport from the south-southwest, on average; this is consistent with derivation from the Petermann Orogen. The pooled age spectrum for detrital zircon from this study is very similar to published data from the Arumbera Sandstone and Winnall beds in the Northern Territory; a statistical analysis (the Kolmogorov–Smirnov test) indicates that the pooled Western Australian data are indistinguishable from pooled data from the Winnall beds and Arumbera Sandstone at >95% confidence. These results strongly support our revised stratigraphy of the Western Australian Amadeus Basin Supersequence 4 because the Arumbera Sandstone is biostratigraphically well dated to the time interval of the Petermann Orogeny and well established as a Supersequence 4 unit. Moreover, the syn-Petermann detrital zircon signature is significantly different to pre- and post-Petermann units in the Northern Territory. Our new data, and that of the Arumbera Sandstone and Winnall beds, contrast with published data from the Mount Currie Conglomerate and Mutitjulu Arkose in the Northern Territory. These latter units belong to Supersequence 4 according to previous authors, but contain no zircons younger than c. 1 Ga. We suggest that their stratigraphic and structural relationships warrant reassessment.

KEYWORDS: Cambrian, geochronology, Proterozoic, provenance, stratigraphy, zircon

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Introduction

The upper Ediacaran – lower Cambrian Petermann Orogeny (570–530 Ma) was a major intraplate tectonic event in central Australia (Scrimgeour and Close, 1999; Aitken et al., 2009; Raimondo et al., 2010; Walsh et al., 2012). This orogeny resulted in considerable shortening and uplift of Mesoproterozoic basement rocks of the Musgrave region and basin inversion of previously overlying parts of the Neoproterozoic Centralian Superbasin, including the southern margin of the Amadeus Basin. The resulting highlands supplied sediment into adjacent foreland depocentres. Such syntectonic deposits are placed into Supersequence 4 of the Centralian Superbasin (Walter et al., 1995). In the north-central and northeastern Amadeus Basin in the Northern Territory (NT) the deltaic succession of the Arumbera Sandstone has long been considered to be a distal foreland deposit connected to the Petermann Orogeny (Wells et al., 1970; Lindsay, 1987b; Lindsay and Korsch, 1991). This interpretation is strongly supported by biostratigraphic constraints which indicate a late Ediacaran to early Cambrian age (Walter et al., 1989; Shergold et al., 1991), paleocurrent data indicating transport from the south and southwest (Lindsay, 1987b), and detrital zircons consistent with a predominantly Musgrave region provenance (Buick et al., 2005; Maidment et al., 2007). Along the southern margin of the basin the thick but localized boulder conglomerate of the Mount Currie Conglomerate (e.g. at Kata Tjuta) and finer Mutitjulu Arkose (restricted to Uluru) near Yulara are usually inferred to be proximal syn-Petermann deposits (Forman, 1966; Wells et al., 1970; Lindsay and Korsch, 1991; Sweet et al., 2012) although the age of these units is only constrained by inferred stratigraphic relationships. Detrital zircon data also support a Musgrave region source for these units (Camacho et al., 2002).

Forman (1965) originally proposed that the Sir Frederick Conglomerate and potentially correlative Ellis Sandstone, and the overlying Maurice Formation of the far western Amadeus Basin, were also deposited during or just after the Petermann Orogeny. However, this relationship was not generally supported by later authors (e.g. Wells et al., 1970; Grey, 1990; Lindsay and Korsch, 1991) who correlated these units, and the equivalent Winnall beds of the southern and western NT Amadeus Basin, with the lower Ediacaran Pertatataka Formation (Supersequence 3) of the northern and eastern Amadeus Basin; thus, the units would pre-date the Petermann Orogeny. The underlying Carnegie Formation was considered significantly older and partly correlative to Cryogenian glacial units. Under this scenario there was a major conundrum: the absence of any preserved Supersequence 4 between the few outcrops of putative proximal deposits of the southern margin, and the thick distal deltaic facies in the north and east (Lindsay and Korsch, 1991, figure 10). Particularly curious was the apparent lack of syn-Petermann deposits in Western Australia (WA) despite the abundant evidence in that area for Petermann tectonism along the southern margin of the Amadeus Basin and adjacent Musgrave region. A solution was proposed by Haines et al. (2010a,b, 2012), Edgoose (2013) and Haines and Allen (2014) through revised stratigraphic correlations between the far western, southern and northeastern parts of the basin. Under the revised scheme, a number of thick siliciclastic units considered by the majority of previous authors to pre-date the Petermann Orogeny (Carnegie Formation, Ellis Sandstone, Sir Frederick Conglomerate and Maurice Formation in WA, and the correlative Winnall beds in the NT) were reassigned to Supersequence 4, thereby comprising this missing stratigraphy. Another two units (Angas Hills Formation, name revised herein) and Mu Formation (new name), previously inferred to be of late Paleozoic age, are here revised downwards to be part of Supersequence 4, based in part on the provenance data discussed herein.

The recent stratigraphic revisions were originally based on sedimentary facies, regional lithostratigraphic comparisons, clast assemblages, paleocurrent data and stromatolite biostratigraphy, and are here further tested using detrital zircon provenance. From previous detrital zircon studies (Zhao et al., 1992; Camacho et al., 2002, 2015; Buick et al., 2005; Maidment et al., 2007; Hollis et al., 2013; Kositcin et al., 2014, 2015), pre-Petermann Amadeus Basin units typically are dominated by late Paleoproterozoic over Mesoproterozoic age components. By contrast, confirmed or putative syn-Petermann deposits show a strong dominance of late Mesoproterozoic age components, specifically ages coeval with the 1.22 – 1.15 Ga Pitjantjatjara Supersuite granites that are widespread in the Musgrave Province (Howard et al., 2015; Camacho et al., 2002; Buick et al., 2005; Maidment et al., 2007). By the late Cambrian, a new allochthonous sediment source dominated by late Neoproterozoic to earliest Paleozoic zircons entered the basin from the east (Maidment et al., 2007; Haines and Wingate, 2007). Therefore, detrital zircon provenance data may provide an effective test to distinguish Supersequence 4 strata from older and younger units. This study represents an investigation of eight detrital zircon samples spanning the six inferred Supersequence 4 units in the WA Amadeus Basin.

Regional geology

Central Australia comprises large inliers of crystalline basement surrounded by folded Neoproterozoic to Paleozoic sedimentary successions of the Amadeus, Officer, Georgina, Ngalia and Murraba Basins (Fig. 1). Crystalline basement includes the mainly Paleoproterozoic Arunta region which is mostly in the southern NT, and the mainly Mesoproterozoic Musgrave region straddling the WA, NT and South Australian borders (Fig. 1). The basin boundaries are now largely tectonic, and the now separated basins are inferred to have been originally connected in the Neoproterozoic as the Centralian Superbasin (Walter et al., 1995). The superbasin model has been criticized because detrital zircon data suggest that adjacent basement continued to supply detritus to the basins during the Neoproterozoic, and thus could not have been totally covered by a thick blanket of sediment (Camacho et al., 2002, 2015). However, stratigraphic similarities and biostratigraphic links between basins are strong and suggest there were connections, even if they were more tenuous than originally proposed.

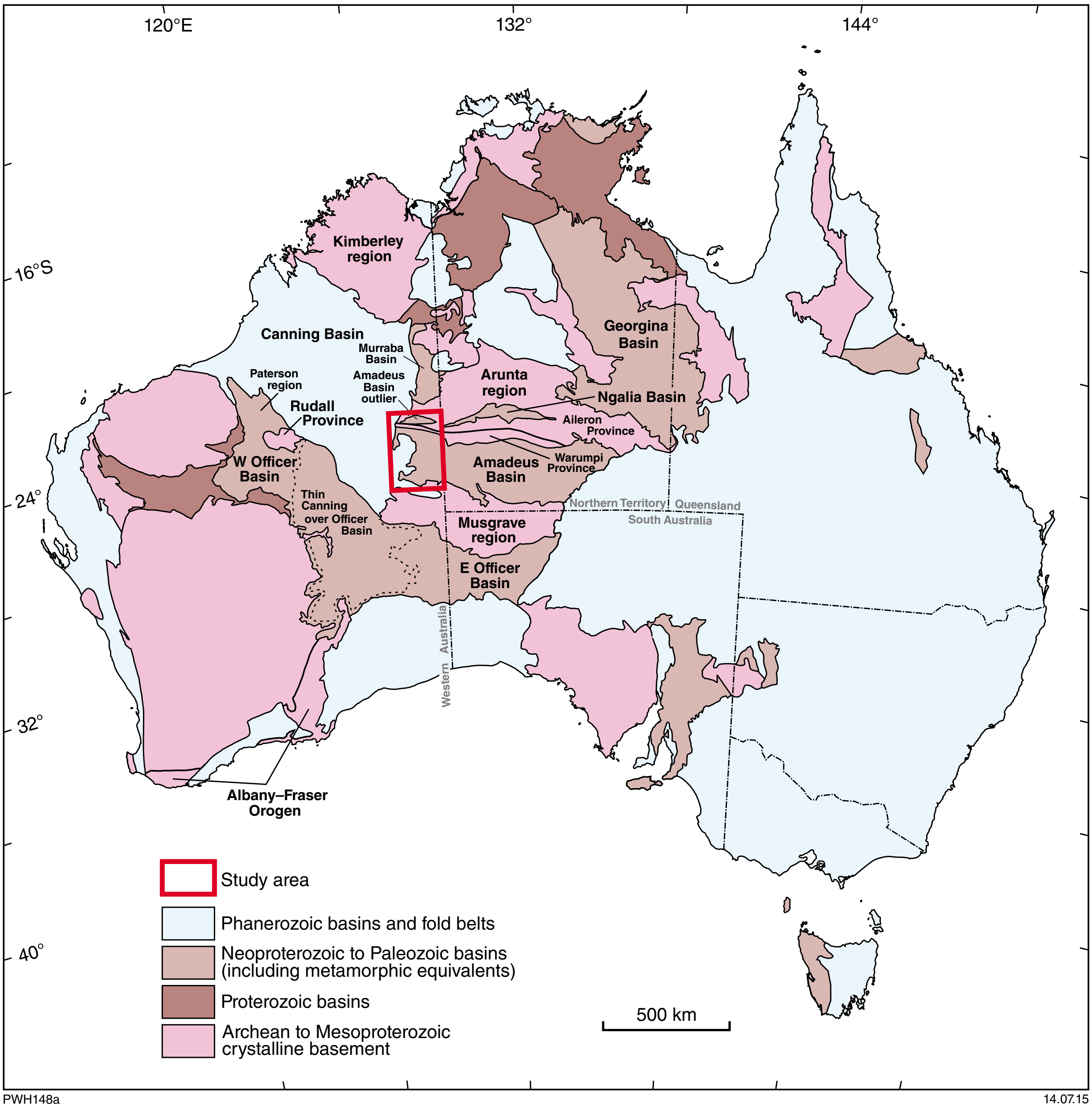


Figure 1. **Tectonic map of Australia showing the study area, basins and basement provinces discussed in the text (modified from Geoscience Australia GIS data)**

Crystalline basement

Musgrave region

This review of the Musgrave region focuses on events likely to have contributed to detrital zircon populations derived from the area. The present exposure of the Musgrave region is about 750 km long and up to 250 km wide. It forms a west-northwest trending belt of igneous, metamorphic, and sedimentary rocks between the Amadeus and Officer Basins (Figs 1 and 2). The bulk of the Musgrave region is assigned to the Musgrave Province, encapsulating rocks formed during, or deformed and metamorphosed by, the 1.22 – 1.15 Ga Musgrave Orogeny. Rocks formed after the cessation of the Musgrave Orogeny, but before deposition of the Kulail Sandstone (the start of Amadeus Basin sedimentation) are excluded from the Musgrave Province, but included in the Musgrave region. Because Petermann Orogeny tectonism affected both, the more inclusive term Musgrave region is more commonly used in the following discussion. The terms 'west' and 'east' Musgrave Province or region are used to refer to areas west and east of the WA–NT/South Australia border, respectively.

The oldest rocks identified are 1.60 – 1.55 Ga orthogneisses in the east Musgrave Province, which are coeval with crust generation, and localized outcrops of granulite facies metagranites of the c. 1575 Ma Warlawurru Supersuite in the west Musgrave Province (Howard et al., 2015). Zircon U–Pb, Hf, and oxygen isotope studies indicate an earlier, juvenile crust-forming event at c. 1.9 Ga, although no preserved crust of this age is known in the region (Kirkland et al., 2013b). The next recorded event, intrusion and possible extrusion of felsic calc-alkaline magma of the c. 1.4 Ga Papulankutja Supersuite (Kirkland et al., 2013b; Howard et al., 2015), is only recognized in a very limited area of the west Musgrave Province. This 1.4 Ga event appears near-coeval with a phase of sediment deposition, now metamorphosed to paragneisses. More voluminous calc-alkaline plutonic rocks (Wankanki Supersuite), and associated clastic and volcaniclastic rocks, characterize the 1345–1293 Ma Mount West Orogeny (Howard et al., 2015). This orogeny is considered to represent the final amalgamation of the combined North and West Australian Craton with the South Australian Craton (Howard et al., 2015). Evidence of this event is best preserved in the southern part of the west Musgrave Province; it is not known in the east.

Granites of the Pitjantjatjara Supersuite, emplaced between 1.22 and 1.15 Ga during the Musgrave Orogeny, dominate the Musgrave Province in outcrop (Smithies et al., 2011). This orogeny is interpreted as an intracontinental and dominantly extensional event characterized by ultra-high temperature conditions between 1.22 and 1.12 Ga. The granites show geochemical, Nd, and Hf isotope homogeneity, indicating a homogenized crustal and mantle source over a wide area (Smithies et al., 2011). In addition to magmatic zircons, this high-temperature event also produced abundant metamorphic zircon rims in both orthogneisses and paragneisses (Smithies et al., 2015).

The 1.09 – 1.04 Ga Giles Event produced voluminous mafic and felsic, mantle-derived intrusive and extrusive magmatic rocks of the Warakurna Supersuite (Smithies et al., 2015). Extrusive rocks are underlain by and interbedded with thick sedimentary successions of the Bentley Basin, including the basal Kunmarnara Group and younger components of the Bentley Supergroup in the west Musgrave region (Howard et al., 2015). The equivalent Tjauwata Group is exposed along the northwestern margin of the Musgrave region and in inliers in the southwestern Amadeus Basin (Edgoose et al., 2004). These combined units were deposited and emplaced within a structural feature referred to as the Ngaanyatjarra Rift (Evins et al., 2010; Aitkin et al., 2012). The Giles Event includes the local expression of the more widespread c. 1075 Ma Warakurna Large Igneous Province, which covered more than 1.5 million km^2 in central and western Australia (Wingate et al., 2004; Smithies et al., 2015). The event also preserves two globally significant magmatic systems in the west Musgrave region (Smithies et al., 2015). The first is the Mantamaru intrusion, one of Earth's largest mafic intrusions. The second, in the Bentley Basin, is a nested series of supervolcanoes representing Earth's longest-lived eruptive centre of low $^{18}O/^{16}O$ rhyolite locked to a specific crustal architecture.

Whereas the Giles Event was the youngest episode of voluminous magmatism, several later minor intrusive events are recorded prior to the Petermann Orogeny. An aplite dyke dated at c. 997 Ma cuts Pitjantjatjara Supersuite granites at one locality in the west Musgrave region (Kirkland et al., 2012; Howard et al., 2015). The more widespread mafic Kullal Dyke Suite has produced a poorly constrained Sm–Nd mineral isochron date of c. 1 Ga (Glikson et al., 1996; Howard et al., 2015), but because of imprecision it is unclear if the event is distinct from the late stages of the Giles Event (Howard et al., 2015). Northwesterly trending dykes of Gairdner Dolerite and equivalent Amata Dolerite extend across northern South Australia into the Musgrave region and are dated at c. 825 Ma (Glikson et al., 1996; Wingate et al., 1998). These dykes have been linked to a hypothetical mantle plume situated beneath the Adelaide Rift Complex in central South Australia (Zhao et al., 1994). The youngest mafic dykes known in the Musgrave region have produced a three-point Sm–Nd isochron of c. 747 Ma, while local pegmatites have been dated at c. 625 Ma (Kirkland et al., 2011b; Howard et al., 2015).

The c. 625 Ma pegmatites are similar in age to a local metamorphic event indicated by an Ar–Ar muscovite date of c. 623 Ma, interpreted to reflect crystallization rather than cooling given the inferred peak metamorphic temperatures (Kirkland et al., 2013a). Detrital zircon cores, overgrown by metamorphic zircon rims dated at c. 631 and 638 Ma, are consistent with zirconium mobility during a metamorphic event at this time (Howard et al., 2015). These dates are approximately contemporaneous with the Miles Orogeny and associated granitic intrusions of the Rudall Province (Howard et al., 2015), which outcrop about 600 km northwest of exposed rocks of the western Musgrave region. Dating of these intrusions is summarized in Rowins et al. (1997) and Dunphy and McNaughton (1998).

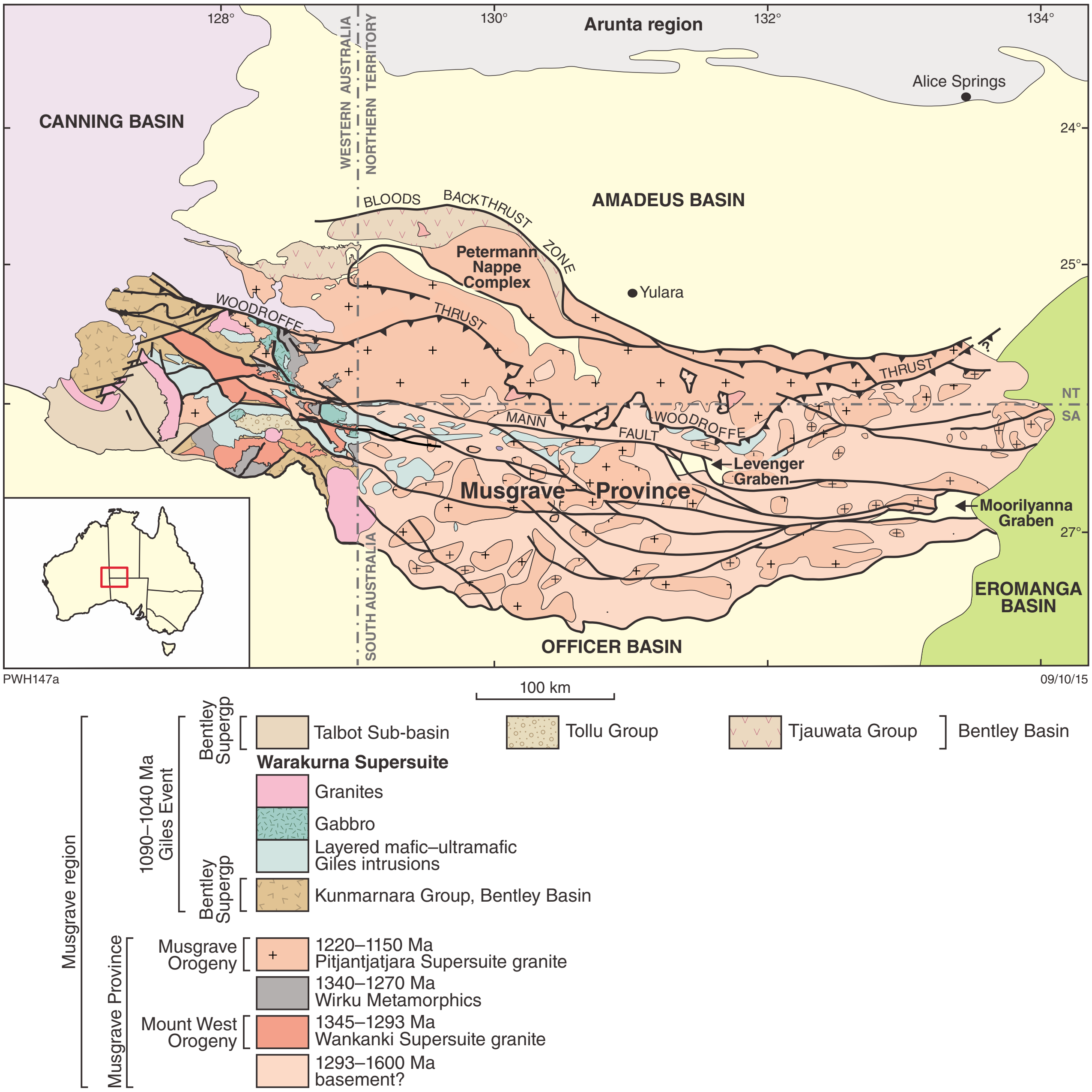


Figure 2. Geological map of the Musgrave region (modified from Howard et al., 2015)

In addition to zircon crystallized during magmatic or high-grade metamorphic events within the Musgrave region, detritus derived from the erosion of that region would include multicyclic detrital zircons from sedimentary and metasedimentary rocks, and inherited zircons in igneous rocks. At least some of these zircons could have been derived from outside the Musgrave region, and thus reflect crystallization events unrelated to that region. Metasedimentary rocks metamorphosed during the Musgrave Orogeny contain detrital zircons with ages mostly ranging between 1.7 and 1.2 Ga, with the greatest concentration between 1.65 and 1.45 Ga (Howard et al., 2011; Evins et al., 2012). Inherited zircons within igneous rocks have a similar age range. However, rocks from one small area (Latitude Hills) display additional detrital zircon components with ages of 1.8 – 1.7 Ga and 2.9 – 2.4 Ga (Howard et al., 2011; Evins et al., 2012).

There are less extensive detrital zircon data for sedimentary units deposited in the Ngaanyatjarra Rift. Detrital zircons from the basal succession (Kunmarnara Group) are dominated by c. 1.2 Ga zircons likely reworked from the Musgrave Province, with a smaller 1.63 – 1.50 Ga component (Kirkland et al., 2010, 2011a, 2014). A sample from the top of the Tjauwata Group (Dixon Range beds) is dominated by zircons with ages between c. 1.22 and c. 1.1 Ga; there is also an older 1.8 – 1.5 Ga component and a minor c. 1.04 Ga contribution (Wingate et al., 2015c).

Arunta region

The Arunta region is divided into two Proterozoic provinces: the more extensive Aileron Province and the smaller Warumpi Province (Scrimgeour, 2003, 2004, 2013a,b) (Fig. 1). The latter is restricted to the southwest of the region, adjacent to the northern margin of the Amadeus Basin. The oldest exposed components of the Aileron Province are metasedimentary rocks deposited between 1.86 and 1.84 Ga (Scrimgeour, 2013a). Major magmatic and metamorphic events restricted to the Aileron Province include the Stafford Event (1.81 – 1.79 Ga), Yambah Event (1.78 – 1.77 Ga), and Strangways Event (1.74 – 1.69 Ga), although magmatism extended between these events in some areas. The Stafford and Yambah Events were accompanied by sedimentary deposition.

The Warumpi Province has metasedimentary successions dated at 1.66 – 1.60 Ga, and magmatic suites with ages of 1.68 – 1.66, 1.64 – 1.63, and 1.61 – 1.60 Ga (Scrimgeour, 2013b). Scrimgeour et al. (2005) considered the Warumpi Province an exotic terrane that accreted to the North Australian Craton during the 1.64 – 1.63 Ga Liebig Orogeny. However, Hollis et al. (2013) demonstrated Hf isotope similarity of the western Warumpi Province and the Aileron Province. These authors inferred that the Warumpi Province rifted away from the southern margin of the North Australian Craton at, or prior to, 1.69 Ga; subsequently it experienced voluminous juvenile magmatism, and then accreted back onto the Aileron Province in the Liebig Orogeny.

The 1.59 – 1.56 Ga Chewings Orogeny was a high-grade metamorphic and locally magmatic event that affected parts of both the Warumpi and Aileron Provinces following accretion (Scrimgeour, 2013a). The Southwark Suite granites (1.57 – 1.53 Ga) are partly coeval with the Chewings Orogeny and restricted to the Aileron Province. The Teapot Event at 1.15 – 1.13 Ga, largely restricted to the Warumpi Province, was the last high-grade metamorphic and felsic magmatic event in the area during the Proterozoic, and may be related to the Musgrave Orogeny of the Musgrave Province (Scrimgeour, 2013b).

Amadeus Basin

The Amadeus Basin (Wells et al., 1970; Korsch and Kennard, 1991; Edgoose, 2012, 2013) covers approximately 170 000 km^2, lying between exposures of older crystalline basement of the Arunta and Musgrave regions to the north and south, respectively (Fig. 2). Most of the basin lies within the NT but about one-fifth of the exposed basin extends into WA (Fig. 3). The current boundaries of the basin do not reflect original depositional limits, but are either tectonic in origin, or are placed where the basin is onlapped by younger depositional systems, such as the Canning Basin to the west. The basin fill is of early Neoproterozoic to late Paleozoic age, up to 12 km thick in the north (Edgoose, 2013). These deposits are mainly of shallow-marine origin, apart from significant deltaic to fluvial siliciclastic wedges shed from adjacent topographic highs during orogenic events. Widespread halite within the lower Neoproterozoic succession is responsible for salt tectonic deformation within the basin (Lindsay, 1987a).

The Neoproterozoic succession of the Amadeus Basin, and of other components of the Centralian Superbasin, were subdivided into four supersequences by Walter et al. (1995) to facilitate regional correlation (Fig. 4). The base of Supersequence 1 is marked by a regional unconformity beneath a basal quartz arenite (Heavitree Quartzite in the north, combined Kulail Sandstone and Dean Quartzite in the south) overlain by a thick succession of carbonates, evaporites, mudstones, sandstones, and minor basalt. The bases of Supersequences 2 and 3 are marked by regional disconformities or unconformities related to the onset of the Sturt ('Sturtian') and Elatina ('Marinoan') glaciations (Hill et al., 2011). In both cases, glacigene intervals are overlain by shallow-marine siliciclastic and carbonate successions.

Supersequence 4 — the subject of this study — comprises deltaic to non-marine siliciclastic rocks straddling the Neoproterozoic–Cambrian boundary. The base of Supersequence 4, unconformable or conformable depending on position in the Amadeus Basin, corresponds to the onset of the Petermann Orogeny and is the base of its associated syntectonic sediment package. Recent stratigraphic revisions increase the volume of inferred Supersequence 4 rocks in the south and west parts of the basin (Haines et al., 2012). Under this new scheme, the end of deposition of Supersequence 4, in the lower Cambrian, marks the end of significant sedimentation in the far western Amadeus Basin; sedimentation continued in shallow-marine environments in the east.

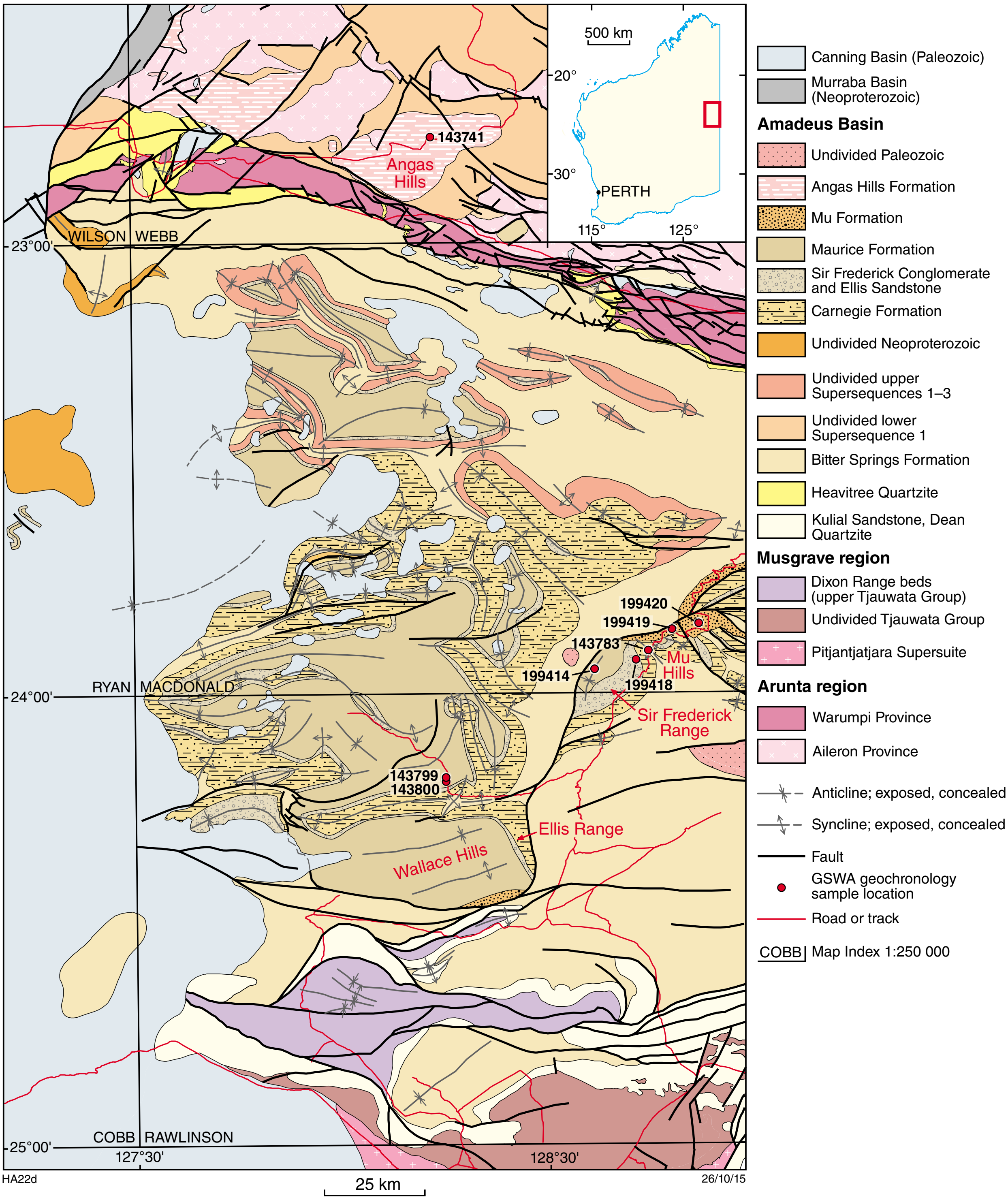


Figure 3. Interpreted bedrock geological map of the western Amadeus Basin and adjoining basement terrains showing detrital zircon sample locations; Cenozoic cover is not shown on the map

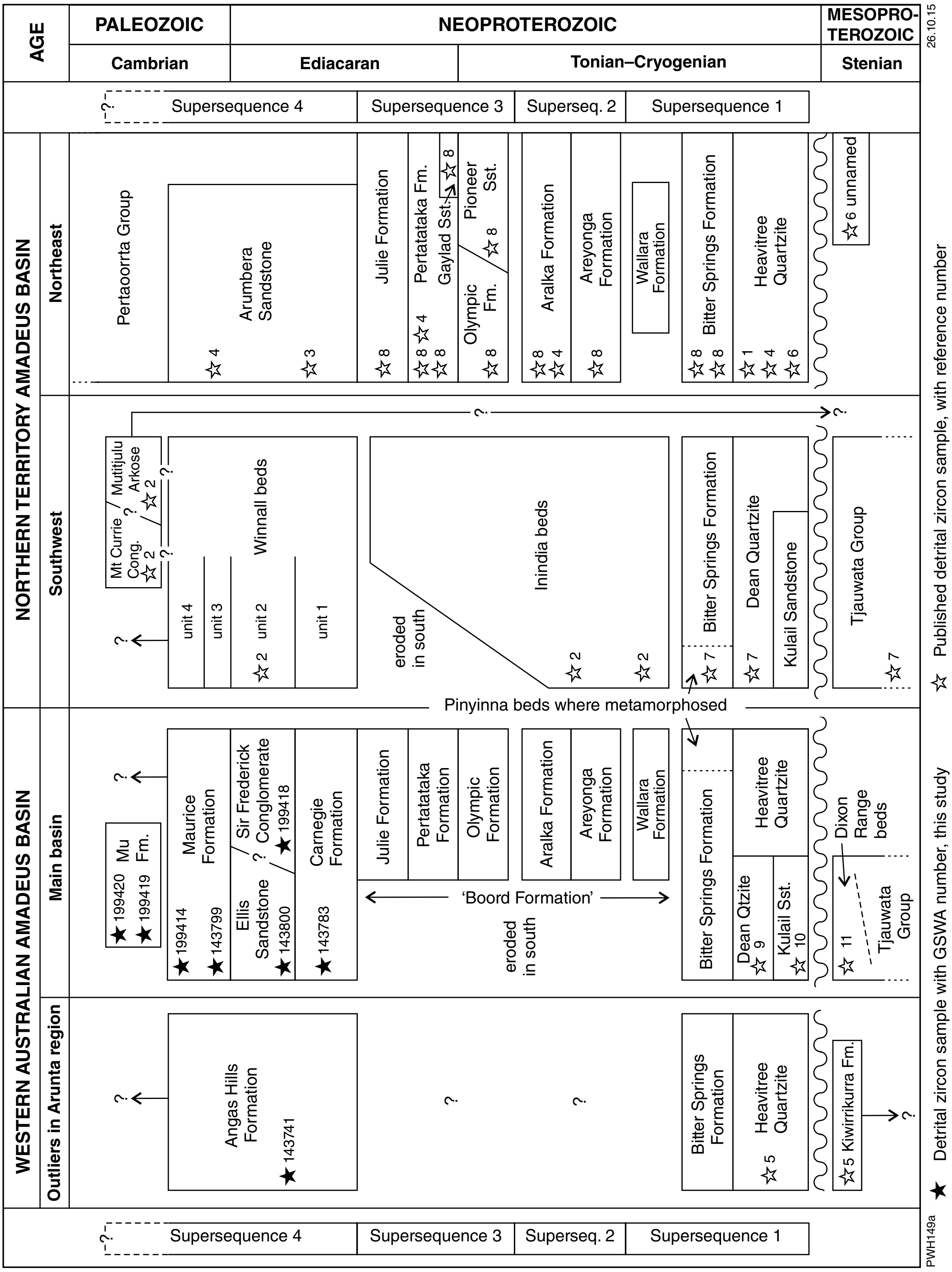


Figure 4. Neoproterozoic to early Cambrian stratigraphy of the Amadeus Basin (modified after Haines et al., 2012) showing the stratigraphic positions of new GSWA detrital zircon samples used in this study (filled stars) and the positions of previously published detrital zircon samples (open stars). Published results are from: 1. Zhao et al. (1992); 2. Camacho et al. (2002); 3. Buick et al. (2005); 4. Maidment et al. (2007); 5. Hollis et al. (2013); 6. Kositcin et al. (2014); 7. Camacho et al. (2015); 8. Kositcin et al. (2015); 9. Wingate et al. (2015a); 10. Wingate et al. (2015b); 11. Wingate et al. (2015c). Supersequence nomenclature is after Walter et al. (1995). Late Mesoproterozoic units unconformably overlain by the Heavitree Quartzite and equivalents comprise an early rift succession traditionally excluded from the Amadeus Basin. The Mount Currie Conglomerate and Mutitjulu Arkose are placed unconformably above the Winnall beds as per traditional inferred relationships, although they may be older as discussed herein.

The Mount Currie Conglomerate and assumed laterally equivalent Mutitjulu Arkose have been associated with the Petermann Orogeny and hence included in Supersequence 4 by most authors. The critical evidence for their age was derived from an inferred (not exposed) unconformity between Mount Currie Conglomerate and Winnall beds at one locality on the Ayers Rock 1:250 000 map sheet (Young et al., 2002), although elsewhere the Mount Currie Conglomerate is in fault contact with other units (Sweet et al., 2012). If the inferred unconformable relationship with Winnall beds is correct, this would constrain the age of the Mount Currie Conglomerate to late in the Petermann Orogeny, or even younger, based on the assignment of the Winnall beds to Supersequence 4 by Haines et al. (2012). One difficulty with this scenario is the metamorphic grade of the Mount Currie Conglomerate and Mutitjulu Arkose (Edgoose et al., 2004); greenschist facies would imply moderately deep burial, also presumed to have occurred during the Petermann Orogeny. No such metamorphism has been reported for the adjacent Winnall beds.

The northeastern Amadeus Basin contains a thick Paleozoic section including fossiliferous marine Cambrian and Ordovician strata, and non-marine Silurian–Devonian rocks. The Cambrian succession becomes progressively less marine and exclusively siliciclastic to the west, but correlations between the northeastern and western parts of the basin remain problematic in the absence of biostratigraphic control in the west. The Silurian–Devonian siliciclastic succession was deposited synchronously with the Alice Springs Orogeny (Haines et al., 2001), a prolonged intraplate tectonic event similar to the Petermann Orogeny. The Alice Springs Orogeny involved uplift of the Arunta region and basin inversion of any pre-existing Amadeus Basin strata. Eroded sediment travelled southward into foreland depocentres near the new northern margin of the Amadeus Basin, but very little is preserved in our study area in the far west of the basin.

Petermann Orogeny

The Petermann Orogeny was a major intraplate tectonic event involving high-temperature and high-pressure metamorphism (granulite and sub-eclogite facies), ductile flow and basin inversion (Scrimgeour and Close, 1999; Camacho and McDougall, 2000; Aitken et al., 2009; Gregory et al., 2009; Raimondo et al., 2010; Walsh et al., 2012; Close, 2013; Howard et al., 2015). The high-pressure core of the Petermann Orogen is exposed between the south-dipping mylonitic Woodroffe Thrust and the Mann Fault (Fig. 2). The prevailing tectonic model for the Petermann Orogeny involves rapid burial and exhumation in a transpressional, crustal-scale flower structure (Camacho and McDougall, 2000). Flöttmann et al. (2004) calculated at least 100 km of shortening, the bulk of which was accommodated by pronounced crustal thickening.

Most deformation along the southern margin of the Amadeus Basin, and the basin as a whole in our study area, can be assigned to the Petermann Orogeny. The interaction between Musgrave basement and Amadeus Basin units is perhaps best illustrated by the Petermann Nappe Complex along the northern margin of the Musgrave region, just east of our study area in the NT. This nappe complex formed in response to progressive north-vergent crustal shortening that inserted an internally duplexed basement wedge into the lower Amadeus Basin succession along a basal decollement horizon (Edgoose et al., 2004). An upper detachment zone (Bloods Backthrust Zone, Fig. 2) allowed the southward movement of Amadeus Basin rocks over the inserted basement wedge. Within these structural domains, lower Amadeus Basin rocks were locally buried to more than 20 km and metamorphosed, along with basement, to upper greenschist and lower to middle amphibolite facies (Edgoose et al., 2004; Flöttmann et al., 2004). North of the Bloods Backthrust Zone, Amadeus Basin sedimentary rocks are mostly unmetamorphosed and more gently deformed. This deformation affects both pre-Petermann and inferred syn-Petermann units, indicating continued shortening during deposition. Trends of fold axes in the basin are generally parallel to the structural trends within the orogen core; some notable exceptions in the far west of the Amadeus Basin suggest that some folds were initiated as salt-cored growth structures prior to the Petermann Orogeny. Continued salt movement during the Petermann Orogeny is suggested by significant thickness changes in syn-Petermann units within and adjacent to some structures, as discussed below.

Radiometric dating of the Petermann Orogeny provides comparable age ranges of 580–530 Ma in the Northern Territory (Close, 2013) and 570–530 Ma in Western Australia (Howard et al., 2015). The Petermann Orogeny is at least partly coeval with the c. 550 Ma Paterson Orogeny of the Paterson region (Fig. 1; Bagas, 2004; Czarnota et al., 2009) and the c. 560 Ma King Leopold Orogeny of the southwest Kimberley region (Fig. 1; Tyler et al., 2012). These orogenic domains may be linked beneath the cover of younger sedimentary basins.

The Petermann Nappe Complex is unconformably overlain by Ordovician shallow-marine sedimentary rocks (Flöttmann et al., 2004). Thin, undeformed Middle Ordovician shallow-marine sedimentary rocks are also found overlying deformed Neoproterozoic Amadeus Basin rocks in our study area (Haines et al., 2012). Recently, we identified shallowly dipping fossiliferous Ordovician rocks adjacent to the Woodroofe Thrust in the west Musgrave region; they represent a paralic embayment of the Canning Basin. These observations suggest that topography associated with the Petermann Orogeny had been largely removed by the Middle Ordovician (c. 470 Ma).

Previous detrital zircon studies

Previously acquired detrital zircon age data from the Amadeus Basin are reported in Zhao et al. (1992), Camacho et al. (2002, 2015), Buick et al. (2005), Maidment et al. (2007), Hollis et al. (2013), Kositcin et al. (2014, 2015), and Wingate et al. (2015a,b). The stratigraphic position of all these samples is shown in Figure 4. Compilation of the existing data enabled us to recognize consistent changes in dominant provenance(s) through time (Fig. 5). Although these changes between individual samples were not always obvious, pooling the data by depositional age was particularly powerful for showing these relationships. Age components restricted to a few zircon grains in one or several samples were suppressed, while those represented in all or most samples, even though minor, were emphasized. The discussion below highlights that the detrital zircon signature of Supersequence 4 is distinct from older and younger successions, a property that can thus be used to test the revised stratigraphy for Supersequence 4 in WA.

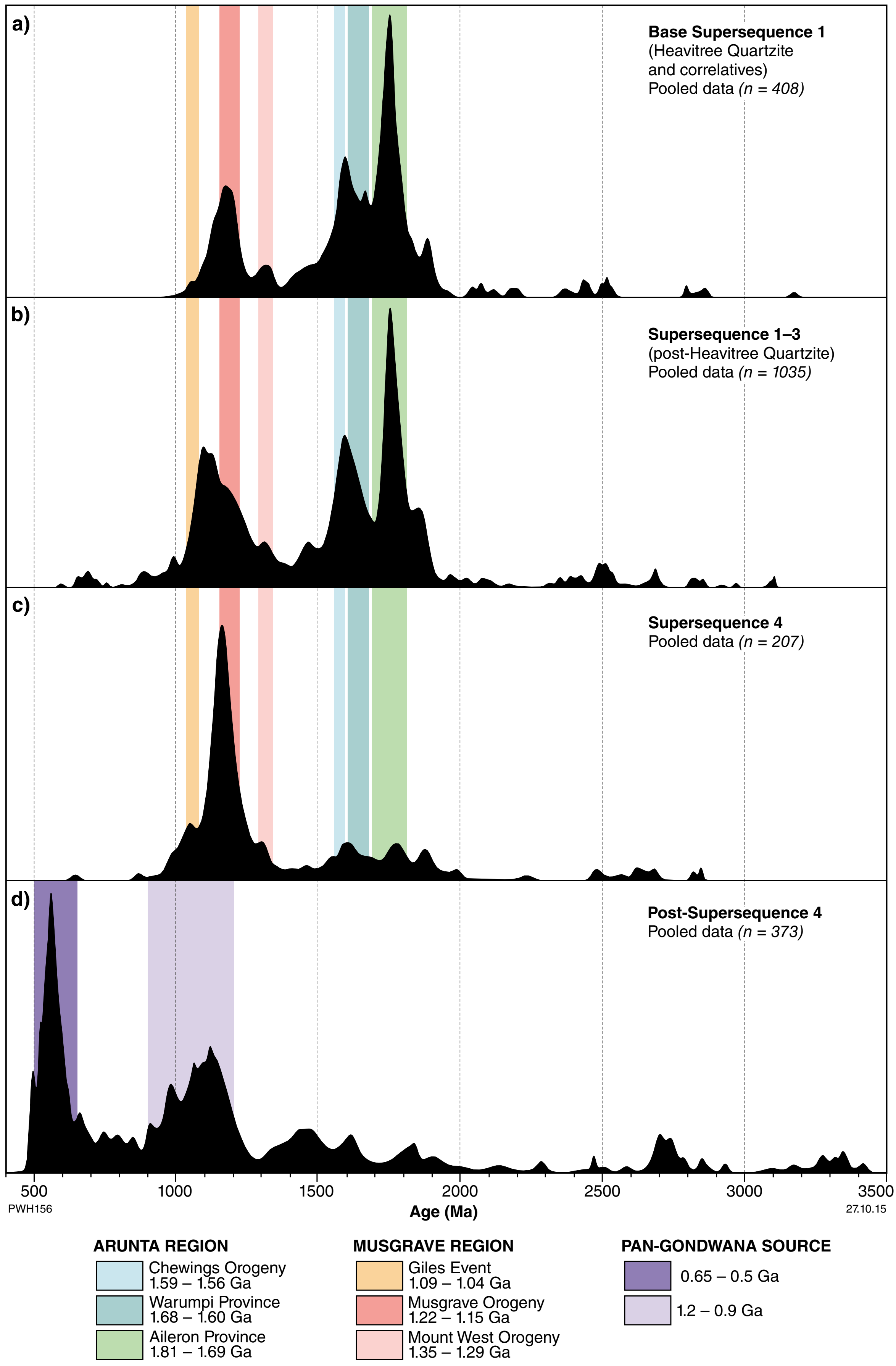
Supersequences 1–3

Detrital zircons from Supersequences 1–3 (Fig. 5a,b) are dominated by late Paleoproterozoic and late Mesoproterozoic age components, with late Paleoproterozoic components being more abundant in most samples. The older age peaks, most notably c. 1.75 and 1.60 Ga, match events in the Arunta region to the north. All previous authors concluded that this region is the likely provenance of these age components and that the late Mesoproterozoic component was derived from the Musgrave region (see Fig. 5 for references). However, we note that the age distribution of these late Mesoproterozoic zircons changes over time. Samples from the basal siliciclastic units of Supersequence 1 (Heavitree and Dean Quartzites and Kulail Sandstone; Fig. 5a) display the main late Mesoproterozoic age peak between 1.20 and 1.15 Ga, coeval with the age of the extensive Pitjantjatjara Supersuite granites and associated metamorphic rocks of the Musgrave Province. This component is most strongly developed close to the Musgrave region (e.g. Dean Quartzite and Kulail Sandstone samples analysed by Wingate et al., 2015a,b), but only weakly developed in more distal samples of Heavitree Quartzite along the northern margin of the basin. In zircon data from many younger rock units from Supersequences 1–3, the peak abundance of Mesoproterozoic zircons is 1.13 – 1.10 Ga (Fig. 5b), an age range which lies between the Musgrave Orogeny and Giles Event. If these zircons were from the Musgrave region, it would be from an area not currently sampled, that additionally did not provide many detrital zircons during the initiation of the Centralian Superbasin nor during the Petermann Orogeny. It is possible that the reconfiguration of the Musgrave region during the Petermann Orogeny led to significant changes in the age distribution of rocks exposed before, during and after the orogeny. As a result, there could be a significant secular change in the proportion of zircons of particular ages available to be supplied to sedimentary depocentres. However, this seems refuted by samples from the base of Supersequence 1 (Fig. 5a), particularly the Kulail Sandstone and Dean Quartzite (Wingate et al., 2015a,b) proximal to the Musgrave region in WA. The late Mesoproterozoic detrital zircons from these samples display age spectra very similar to those seen in Supersequence 4, suggesting that the ages of exposed rocks in the Musgrave region were similar at the initiation of the Centralian Superbasin, and during the Petermann Orogeny. Between these events, the Musgrave region may have been partly or entirely covered by younger rocks, with the 1.13 – 1.10 Ga zircons arriving from a more distal source. This source of zircons may have been to the west, as similar detrital zircon ages are abundant in Neoproterozoic sedimentary rocks in the far western Centralian Superbasin in the Paterson Orogen (Bagas et al., 2001; Bagas and Nelson, 2007).

Supersequence 4

Previous detrital zircon data from Supersequence 4, or purported Supersequence 4, include samples from the Arumbera Sandstone (Buick et al., 2005; Maidment et al., 2007), Winnall beds, Mount Currie Conglomerate, and Mutitjulu Arkose (Camacho et al., 2002). The age of the Arumbera Sandstone, straddling the Ediacaran–Cambrian boundary and coeval with the Petermann Orogeny, is biostratigraphically well established (Walter et al., 1989; Shergold et al., 1991). A recent reassessment of stratigraphic relationships shows that the Arumbera Sandstone and Winnall beds are correlatives (Haines et al., 2012).

Figure 5. (opposite) Compilation of previously published detrital zircon data from the Amadeus Basin presented as pooled probability density diagrams arranged with the depositional age of samples decreasing down the page: a) Basal Supersequence 1 including Heavitree Quartzite (4 samples: data from Zhao et al., 1992; Maidment et al., 2007; Hollis et al., 2013; Kositcin et al., 2014), Dean Quartzite (two samples: data from Camacho et al., 2015; Wingate et al., 2015a), and Kulail Sandstone (data from Wingate et al., 2015b); b) Supersequences 1–3 post-dating the basal clastic succession plotted in; a) data are from Camacho et al., 2002 (upper and lower Inindia beds), Maidment et al., 2007 (Aralka and Pertatataka Formations) and Kositcin et al., 2015 (Bitter Springs, Areyonga, Aralka, Olympic, Pertatataka and Julie Formations, and Pioneer and Gaylad Sandstones); c) Supersequence 4 including Arumbera Sandstone (two samples: data from Buick et al., 2005; Maidment et al., 2007) and Winnall beds (data from Camacho et al., 2002). Mount Currie Conglomerate and Mutitjulu Arkose are not plotted due to uncertainties about their age (see discussions in text); d) Post-Supersequence 4 including Goyder Formation (two samples: data from Zhao et al., 1992; Maidment et al., 2007), Pacoota Sandstone (two samples: data from Buick et al., 2005; Maidment et al., 2007), Stairway Sandstone and Mereenie Sandstone (data from Maidment et al., 2007).


a)
Base Supersequence 1
(Heavitree Quartzite
and correlatives)
Pooled data (n = 408)
b)
Supersequence 1–3
(post-Heavitree Quartzite)
Pooled data (n = 1035)
c)
Supersequence 4
Pooled data (n = 207)
d)
Post-Supersequence 4
Pooled data (n = 373)
500
1000
1500
2000
2500
3000
3500
Age (Ma)
PWH156
27.10.15
ARUNTA REGION
Chewings Orogeny
1.59 – 1.56 Ga
Warumpi Province
1.68 – 1.60 Ga
Aileron Province
1.81 – 1.69 Ga
MUSGRAVE REGION
Giles Event
1.09 – 1.04 Ga
Musgrave Orogeny
1.22 – 1.15 Ga
Mount West Orogeny
1.35 – 1.29 Ga
PAN-GONDWANA SOURCE
0.65 – 0.5 Ga
1.2 – 0.9 Ga

The Mount Currie Conglomerate and Mutitjulu Arkose are widely assumed to be associated with the Petermann Orogeny (Forman, 1966; Wells et al., 1970; Lindsay and Korsch, 1991; Sweet et al., 2012), and hence assigned to Supersequence 4, but their age is only constrained by inferred (not exposed) stratigraphic relationships. All samples are dominated by late Mesoproterozoic zircon ages with a strong mode at c. 1.2 Ga which all authors conclude is sourced from the Musgrave Province (pooled Arumbera Sandstone and Winnall beds are plotted in Fig. 5c). Samples from the Arumbera Sandstone and Winnall beds display additional minor late Paleoproterozoic peaks, suggestive of a small Arunta region component, and sparse older zircons that are as old as Neoarchean. The Arumbera Sandstone sample of Maidment et al. (2007) and the Winnall beds sample also contain minor early Neoproterozoic zircons. The Mutitjulu Arkose sample is unimodal (c. 1.18 Ga), while the Mount Currie Conglomerate sample displays the same dominant mode along with minor modes at c. 1.06 and 1.3 Ga (Camacho et al., 2002). There are no concordant zircon grains older than c. 1.32 Ga, or younger than c. 1 Ga. The lack of Paleoproterozoic and Neoproterozoic zircon age components, common to most other samples from the Amadeus Basin, may have implications for the age and tectonic significance of these units, as discussed later.

Post-Supersequence 4

Upper Cambrian and younger samples have been analysed by Zhao et al. (1992), Buick et al. (2005) and Maidment et al. (2007). These show the emergence of a new sediment source characterized by abundant late Neoproterozoic – early Paleozoic zircons, secondary late Mesoproterozoic modes and a broad spread of older ages back to c. 3.5 Ga. This age spectra is very similar to that seen in many Paleozoic samples along the Pacific margin of Gondwana and likely entered the basin from the eastern Australian margin (Maidment et al., 2007). The ultimate source is presumably beyond Australia, either hidden beneath the ice of Antarctica (Veevers et al., 2006; Veevers and Saeed, 2008, 2011) or in the East African – Antarctic Orogen (Squire et al., 2006).

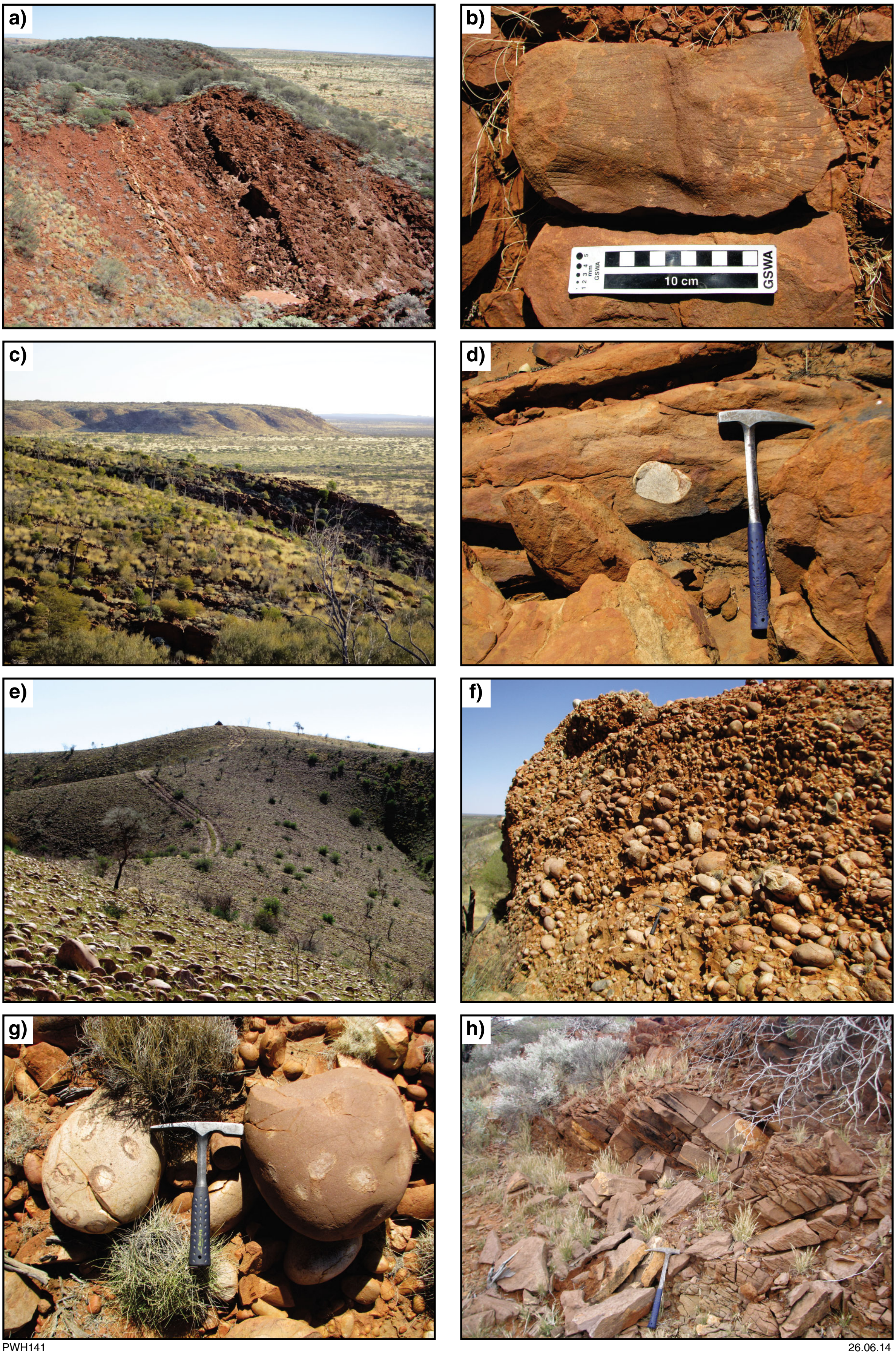
Revised Supersequence 4 stratigraphy, WA

A thick package of siliciclastic strata dominates outcrop of the WA Amadeus Basin north of the Bloods Backthrust Zone; the latter marks the northerly limit of strong Petermann Orogeny deformation. In most areas the siliciclastic units include the Carnegie Formation, Ellis Sandstone, and Maurice Formation, in ascending order (Fig. 4). The Ellis Sandstone is locally replaced by the Sir Frederick Conglomerate. Haines et al. (2012) correlated this package to the Winnall beds across the NT border, and then more distally to the Arumbera Sandstone. The basal Carnegie Formation is separated from older Amadeus Basin units by an unconformity and significant time break in the south, but may be conformable in the north.

Unconformably overlying the Maurice Formation, and locally older units, are siliciclastic sedimentary rocks herein defined as the Mu Formation. This new unit was previously correlated with the upper Paleozoic Ligertwood bed in the NT (Wells, 1968; Wells et al., 1964, 1970). However, the Mu Formation is mainly localized around probable syn-Petermann growth structures; this relationship is suggestive of Supersequence 4. The Angas Hills Formation, restricted to Amadeus Basin outliers in the southern Arunta region and originally also inferred to be upper Paleozoic, is herein assessed as a Supersequence 4 unit because of lithological and paleocurrent similarities to Supersequence 4 further south.

Most of these units have a distinctive red-brown colouration (Figs 6 and 7) due to the abundant presence of iron oxides, as does the Arumbera Sandstone and Winnall beds of the NT. This is not just a surface weathering phenomenon, as can be seen from drillhole intersections in the NT which exhibit the same red-brown colouration in fresh rock, suggesting deposition in an oxidizing environment. The sedimentary rocks are commonly feldspathic and micaceous, but such minerals are typically restricted to the less labile microcline and muscovite. More labile minerals have commonly broken down to produce a common clay matrix. Pebble and cobble clasts are typically quartzite, sandstone and metasandstone, with minor chert and vein quartz; all these lithologies resist chemical breakdown during weathering and erosion. Igneous clasts are rare, and always strongly weathered and kaolinized. These observations suggest that Supersequence 4 was deposited during warm humid conditions with deep weathering, consistent with paleomagnetic data indicating that central Australia was equatorial during deposition of the Arumbera Sandstone (Mitchell et al., 2010). In this context, the putative proximal Supersequence 4 Mount Currie Conglomerate and Mutitjulu Arkose are anomalous.

Figure 6. (opposite) Field photographs of Supersequence 4 units in Western Australia: a) Typical Carnegie Formation, strike ridge of red-brown feldspathic and silty sandstone and siltstone, Mu Hills (MGA 477880E 7443625N); b) *Arumberia* on sole of red-brown medium-grained sandstone, Carnegie Formation, Mu Hills (MGA 468033E 7424527N); c) Strike ridges of Ellis Sandstone in the foreground and middle distance (MGA 468033E 7424527N); d) Medium-grained brown sandstone of Ellis Sandstone, with isolated cobbles of quartzite at the collection site for 143800 (MGA 468033E 7424527N); e) Sir Frederick Conglomerate at Sir Frederick Range (MGA 466352E 7424786N); the friable sandy matrix has disintegrated at surface, leaving loose rounded cobbles and boulders of quartzite and sandstone; f) Clast-supported Sir Frederick Conglomerate with preserved sandstone matrix, Mu Hills (MGA 466556E 7424802N); bedding dips at about 45° to the right; g) Loose 'cratered' cobbles and boulders of sandstone and quartzite in outcrop of Sir Frederick Conglomerate (MGA 466750E 7424666N); the craters are indicative of clast-to-clast contact points and pressure solution during loading and compaction; h) Immature purple-brown micaceous sandstone of the Maurice Formation (MGA 467315E 7424376N).


a)
b)
10 cm
GSWA
c)
d)
e)
f)
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h)
PWH141
26.06.14

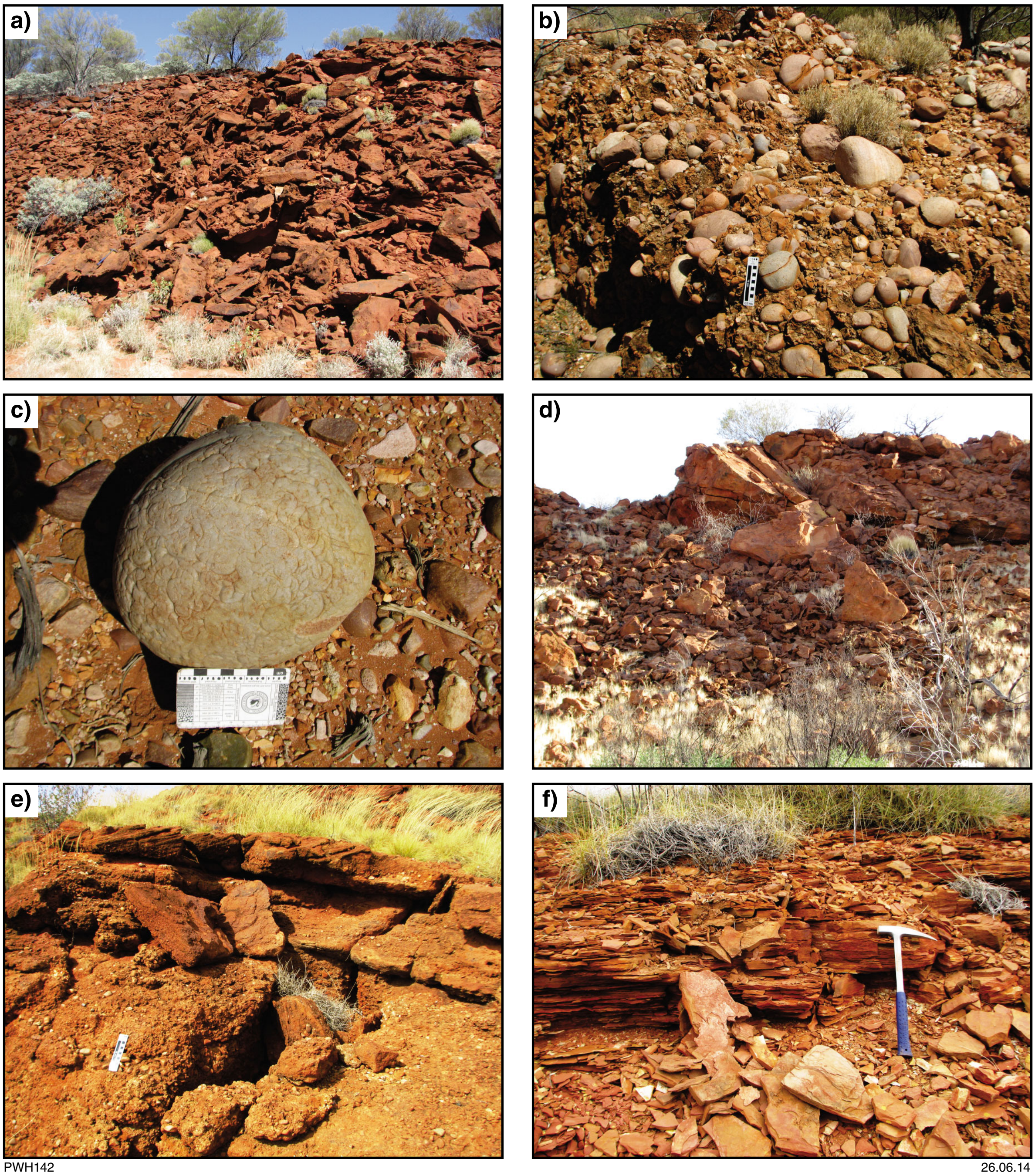


Figure 7. Field photographs of Supersequence 4 units in Western Australia: a) Upper Maurice Formation near collection site of 199414 (MGA 477880E 7443625N), with hammer for scale at bottom left; b) Mu Formation conglomerate, northern Mu Hills (MGA 468033E 7424527N); c) percussion marks on quartzite cobble, indicative of high energy fluvial environment, Mu Formation, northern Mu Hills (MGA 468033E 7424527N); d) Mu Formation sandstone (MGA 459748E 7427386N); e) Angas Hills Formation cross-bedded sandstone and pebbly sandstone (MGA 466352E 7424786N); f) Angas Hills Formation siltstone (MGA 466352E 7424786N)

These units contain abundant fresh labile minerals and igneous clasts, and the matrix has a chemically reduced grey colouration when seen in fresh exposures (such as in caves at Uluru: Sweet et al., 2012), features that might be consistent with deposition during colder conditions.

Carnegie Formation

The Carnegie Formation is a thick siliciclastic unit recognized across the WA Amadeus Basin, and locally into the NT (Wells et al., 1964, 1965, 1970). It was originally correlated with the now subdivided and disused 'Boord Formation' in WA, and the Areyonga Formation and Inindia beds in the NT (Wells et al., 1970). Haines et al. (2012) correlated it with the much younger but lithologically similar lower Arumbera Sandstone, and lower Winnall beds (unit 1). The correlation to Arumbera Sandstone implies a late Ediacaran age (base at c. 570 Ma; Fig. 4) and deposition during the early Petermann Orogeny.

The primary reason for the revised age of the Carnegie Formation is the recognition that it overlies the Julie Formation (top carbonate unit of the former 'Boord Formation') at the Boord Ridges (Haines et al., 2012; Haines and Allen, 2014). This is the same relationship that the Arumbera Sandstone has with the Julie Formation in the eastern Amadeus Basin. The Julie Formation can be confidently correlated from the east to our western study area because it contains a distinctive age-diagnostic stromatolite assemblage in both areas (Allen et al., 2012; Grey et al., 2012). The Carnegie Formation unconformably overlies the Bitter Springs Formation in the south of our study area (Haines et al., 2012), suggesting progressive uplift and erosion of older Amadeus Basin units towards the Petermann Orogen during initiation of orogenic activity.

The Carnegie Formation is dominated by immature red-brown, fine- to medium-grained lithic and feldspathic sandstone and interbedded micaceous siltstone (Fig. 6a). The cement is often calcareous. Cross-beds, ripples, erosive sole marks including flutes, and desiccation cracks are present. Some sandstone beds have channel-like morphologies, and minor conglomerate interbeds are present locally. A deltaic depositional environment is indicated. Although no paleocurrent measurements were made from this unit during this study, Wells et al. (1970) deduced transport from the southwest and west. The formation is less than 2000 m thick in most areas, but reaches or exceeds an estimated 3400 m in thickness in a depocentre west of the Sir Frederick Range (Haines et al. 2012). It thins significantly to the north, and only about 70 m is exposed near the Boord Ridges, although as the base is not exposed here, the complete thickness may be somewhat greater (Haines and Allen, 2014).

Possible organic remains, including *Arumberia* (Fig. 6b) originally described from the lower Arumbera Sandstone (Glaessner and Walter, 1975), were identified in a number of outcrops of the Carnegie Formation (Haines et al., 2010a). It is unclear if any have biostratigraphic significance.

Ellis Sandstone

The Ellis Sandstone is recognized across the WA Amadeus Basin, and locally into the NT (Wells et al., 1964, 1965, 1970). The contact with the underlying Carnegie Formation is poorly exposed, but is at least locally inferred to be disconformable. Within WA, the unit is inferred to locally interfinger with the Sir Frederick Conglomerate (Wells et al., 1964), although the field relationships are not entirely clear (Haines et al., 2012).

The Ellis Sandstone is a ridge-forming unit of pale brown, pebbly, medium-grained sandstone (Fig. 6c,d). Although feldspathic, it is notably 'cleaner' and better cemented than underlying or overlying units. Trough and tabular cross-bedding and current lineations are common and mud pellets are abundant in some beds. Pebble clasts are typically sedimentary, including sandstone, quartzite and chert. The depositional environment is inferred to be fluvial in WA, but likely transitions to deltaic to the east. Paleocurrent directions determined from trough and tabular cross-beds at several locations are unimodal with the average direction from the south and southwest (Fig. 8). The formation is typically about 500 m in thickness, but thins to the north.

Wells et al. (1970) correlated the Ellis Sandstone with part of the Winnall beds (unit 2) in the southern NT Amadeus Basin, which we support. Their long-standing regional correlation of the Ellis Sandstone with the Pertatataka Formation was rejected in favour of correlating it to the middle or upper Arumbera Sandstone (Haines et al., 2012). No biostratigraphic evidence for the age of the Ellis Sandstone has been found in WA, but based on the correlation given above, its age could range from latest Ediacaran to early Cambrian. Ranford et al. (1965) mention 'numerous indeterminate fossil tracks and trails' in Winnall beds unit 2 in the south-central part of the NT Amadeus Basin, additionally referring to a form comparable with the lower Cambrian *Syringomorpha* at one locality. Such occurrences, if confirmed, could allow a refined age for the unit. However, possible trace fossils in the Winnall beds illustrated by Wells et al. (1966, figure 1 of Plate 1) appear to be inorganic shrinkage cracks.

Sir Frederick Conglomerate

The Sir Frederick Conglomerate is restricted to the southern half of the WA Amadeus Basin where Wells et al. (1964, 1970) considered that it interfingers with the Ellis Sandstone. However, the relationship to the Ellis Sandstone is not very clear due to poor outcrop (Haines et al., 2012), and intervals mapped as Sir Frederick Conglomerate locally occupy positions both below and above the Ellis Sandstone. In the massive conglomerate outcrops at Sir Frederick Range, that are about 2000 m in thickness, no Ellis Sandstone is present. There, the Sir Frederick Conglomerate unconformably overlies Carnegie Formation and is apparently overlain by Maurice Formation. The massive conglomerate exposed at Sir Frederick Range passes laterally northwards into two thinner conglomerate units separated by thickly bedded recessive red-brown sandstone in the Mu Hills.

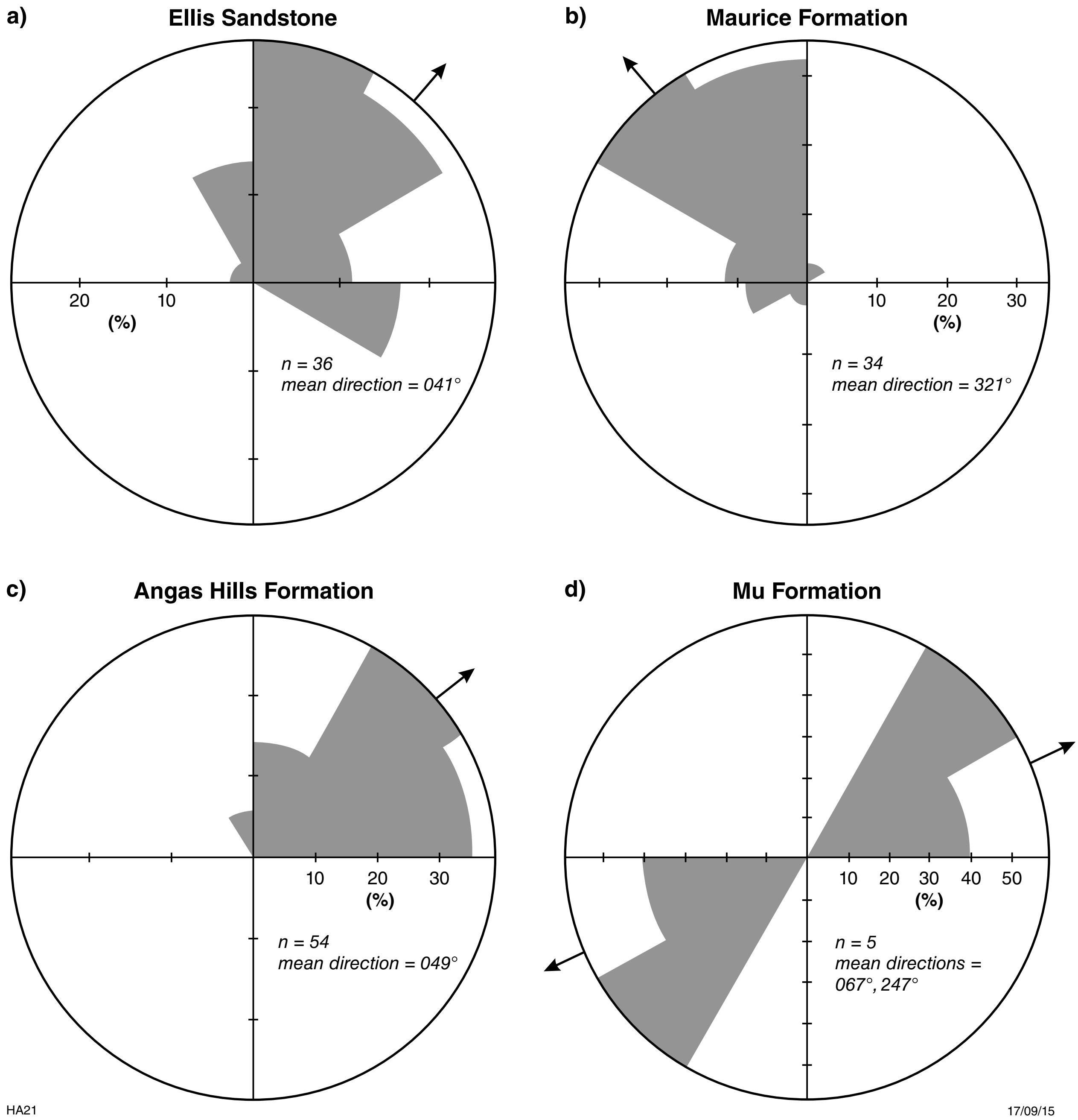


Figure 8. **Paleocurrent rose diagrams for cross-bed data from the a) Ellis Sandstone, b) Maurice Formation and c) Angas Hills Formation, and current lineation data from the d) Mu Formation. The plotting interval is 30°, n = number of measurements, and the arrows indicate mean direction.**

This local sandstone unit is lithologically distinct from the Ellis Sandstone.

The Sir Frederick Conglomerate is typified by clast-supported cobble to boulder conglomerate, with well-rounded clasts dominated by quartzite, sandstone and metasandstone, and minor pebbles of chert and vein quartz (Fig. 6e–g). The matrix consists of friable kaolinitic sandstone, but this commonly disintegrates during weathering to leave hills of loose round cobbles and boulders. The dominant clasts were likely derived from the Dean Quartzite, Kulail Sandstone and Dixon Range beds. Rarely, where the matrix is preserved, the conglomerate is seen to also contain sparse cobbles of very weathered granite and metamorphic rocks, but these have apparently preferentially weathered away in the more common loose cobble outcrops.

Although no accurate paleocurrent measurements could be made in the conglomerate, clast imbrication in cemented outcrops suggests a southerly provenance, and also the observation of Wells et al. (1970) that the largest boulders (exceeding 1 m diameter) were observed at the most southerly outcrop. A high-energy fluvial setting is indicated by the lithofacies.

The local thickening of the Sir Frederick Conglomerate in the Sir Frederick Range is likely related to salt diapirism triggered, or enhanced by, the Petermann Orogeny. Outcrops of carbonate breccia northwest of the Sir Frederick Range are likely remnants of the actual diapir, while the synclinal Sir Frederick Range may be the centre of a salt withdrawal mini-basin that provided locally enhanced accommodation space for sediment accumulation as salt was removed from below.

Maurice Formation

The Maurice Formation is recognized across the WA Amadeus Basin, and locally into the NT (Wells et al., 1964, 1965, 1970). It overlies either Ellis Sandstone or Sir Frederick Conglomerate (Fig. 4), although the nature of the contact is unclear due to poor exposure. The unit is correlated with the Winnall beds (units 3 and 4) of the southern NT Amadeus Basin, and with the upper Arumbera Sandstone or higher in the northeast (Haines et al., 2012).

The Maurice Formation comprises a lower very recessive unit that is rarely exposed. This unit probably correlates with the similarly recessive Winnall beds unit 3, and appears to comprise mainly red-brown micaceous siltstone and very friable fine-grained sandstone. The upper unit is dominated by red-brown immature micaceous sandstone and lesser amounts of siltstone, and local conglomeratic sandstone (Figs 6h and 7a). Lithofacies suggest a mainly fluvial origin, with paleocurrent measurements indicating unimodal currents from the southeast (Fig. 8). The formation thickens to the south with an estimated 3600 m exposed in the southern Wallace Hills (Haines et al., 2012).

Mu Formation

Most outcrops here assigned to the newly named Mu Formation (defined in Appendix 2) were originally mapped as Ligertwood beds by Wells et al. (1964, 1965). At the type area of the Ligertwood beds on Mount Rennie in the NT, this unit is unaffected by the last phase of folding (Alice Spring Orogeny) and thus was inferred to be younger than the folded Devonian Pertnjara Group that is exposed nearby (Wells et al., 1965; Edgoose, 2013). Edgoose (2013) suggested the Ligertwood beds were Carboniferous to Permian. However, the Mu Formation has clearly been affected by at least one phase of folding, and locally dips steeply, indicating that it is older than the Ligertwood beds.

The Mu Formation is a succession of conglomerate, minor sandstone and pebbly sandstone that crops out mainly in and north of the northern Mu Hills (Figs 3 and 7b–d). The conglomerate contains well-rounded cobbles and boulders of quartzite and sandstone resembling those of the Sir Frederick Conglomerate, but it is clear that the Mu Formation is younger, and rests with pronounced angular unconformity over units ranging from the Bitter Springs Formation to the Maurice Formation. Isolated outcrops of cobble and boulder conglomerate south of the Wallace Hills (Fig. 3) were previously mapped as Sir Frederick Conglomerate (Wells et al., 1964), but are now considered more likely to overlie the Maurice Formation and are also tentatively assigned to Mu Formation.

Many of the cobbles and boulders in the Mu Formation may have been recycled from the Sir Frederick Conglomerate. The sandstone and pebbly sandstone is red-brown and immature, resembling sandstone units in the Maurice Formation and Sir Frederick Conglomerate. The depositional environment was likely high-energy fluvial, and although no paleocurrent direction was determined from cross-beds, limited measurements of current lineations trend southwest–northeast (Fig. 8). The Mu Formation is at least 600 m thick, although the top is not exposed.

The pronounced unconformity beneath the Mu Formation probably resulted from diapiric salt movement, as previously discusse-d for the Sir Frederick Conglomerate. Older sedimentary rocks were turned up steeply and eroded near the diapir margin. As such, the Mu Formation may be largely composed of recycled sediment. Continued diapiric activity led to the eventual tilting and folding of the Mu Formation itself. The timing of these movements is uncertain, but it is likely that the movement responsible for Mu Formation tilting was during a late phase of the Petermann Orogeny, probably during the Cambrian. Small outcrops of essentially flat-lying, marine Middle Ordovician rocks are found only a few kilometres southwest of outcrops of diapiric breccia and dipping Mu Formation. These suggest that significant diapiric activity had concluded by the Middle Ordovician and that the Alice Springs Orogeny had little effect in the area.

Angas Hills Formation

The Angas Hills Formation (previously the Angas Hills beds of Blake and Towner, 1974) is restricted to outliers of the Amadeus Basin (Fig. 3) within the Arunta region in the WEBB 1:250 000 geological map sheet area (Blake, 1977). The definition and stratigraphic information for the revised formation are in Appendix 2. The Angas Hills Formation unconformably overlies Proterozoic crystalline basement, Heavitree Quartzite and Bitter Springs Formation in the Pollock Hills area (Blake and Towner, 1974), but in most areas the base is not exposed. Blake (1977) suggested a late Paleozoic age and a correlation with the syntectonic (Alice Springs Orogeny) Pertnjara Group of the northern NT Amadeus Basin. Haines et al. (2010a,b, 2012) suggested an Ediacaran to Cambrian age and a revised correlation with the collective Carnegie to Maurice Formations (Fig. 4) based on lithological similarities, the clast assemblage and paleocurrent measurements.

The best exposures are in the Angas Hills and surrounding area where the unit comprises pebble and cobble conglomerate, red-brown cross-bedded sandstone and minor siltstone (Fig. 7e,f). Pebble and cobble clasts include quartzite, sandstone, vein quartz, chert and locally grey carbonates. The sedimentary facies indicate a fluvial depositional environment. Paleocurrent measurements from cross-beds indicate currents mainly from the southwest (Fig. 8). Outcrops in the Angas Hills area are typically flat lying to gently dipping, but are locally upturned near faults. Blake and Towner (1974) estimated an exposed thickness of 300 m on the western side of the Angas Hills. This is a minimum for original depositional thickness as neither base nor top are exposed in this area.

Methods

All samples were collected from surface outcrops and typically weighed 5–15 kg. Samples were crushed and zircons separated using density and magnetic techniques at the GSWA mineral separation laboratory. U–Pb detrital zircon geochronology was performed using the sensitive high-resolution ion microprobe (SHRIMP) at the John de Laeter Centre for Isotope Research at Curtin University in Perth via the secondary ionization technique. Details of the geochronological methods are provided in Wingate and Kirkland (2014), and in Appendix 1. Data tables are provided in the individual Geochronology Records for each sample (Wingate et al., 2013a,b,c,d; Wingate et al., 2014a,b,c,d), and can be downloaded from the GSWA website (www.dmp.wa.gov.au/geochron).

To ensure consistent interpretation and to avoid introducing any bias when comparing results from different samples, all data <1000 Ma have been reprocessed for common or initial Pb using the 207-correction method (e.g. Gibson and Ireland, 1996). The 207-method assumes that the radiogenic composition is concordant, and the 207-corrected $^{238}U/^{206}Pb$ date is determined by extrapolating the measured composition to concordia along a trajectory defined by Stacey and Kramers' (1975) common-Pb composition for the $^{238}U/^{206}Pb^*$ date of the sample (Pb* refers to radiogenic Pb produced by the in-situ decay of uranium). For data >1000 Ma, dates are calculated from $^{207}Pb^*/^{206}Pb^*$ ratios with correction for common Pb made via the measured $^{204}Pb/^{206}Pb$ ratio, and data >5% discordant are excluded. Analytical results (excluding data >1000 Ma that are >5% discordant) are illustrated in probability density diagrams. Ages based on single analyses are reported with 1σ uncertainties, and weighted mean ages are quoted with 95% confidence intervals.

Geochronology samples and results

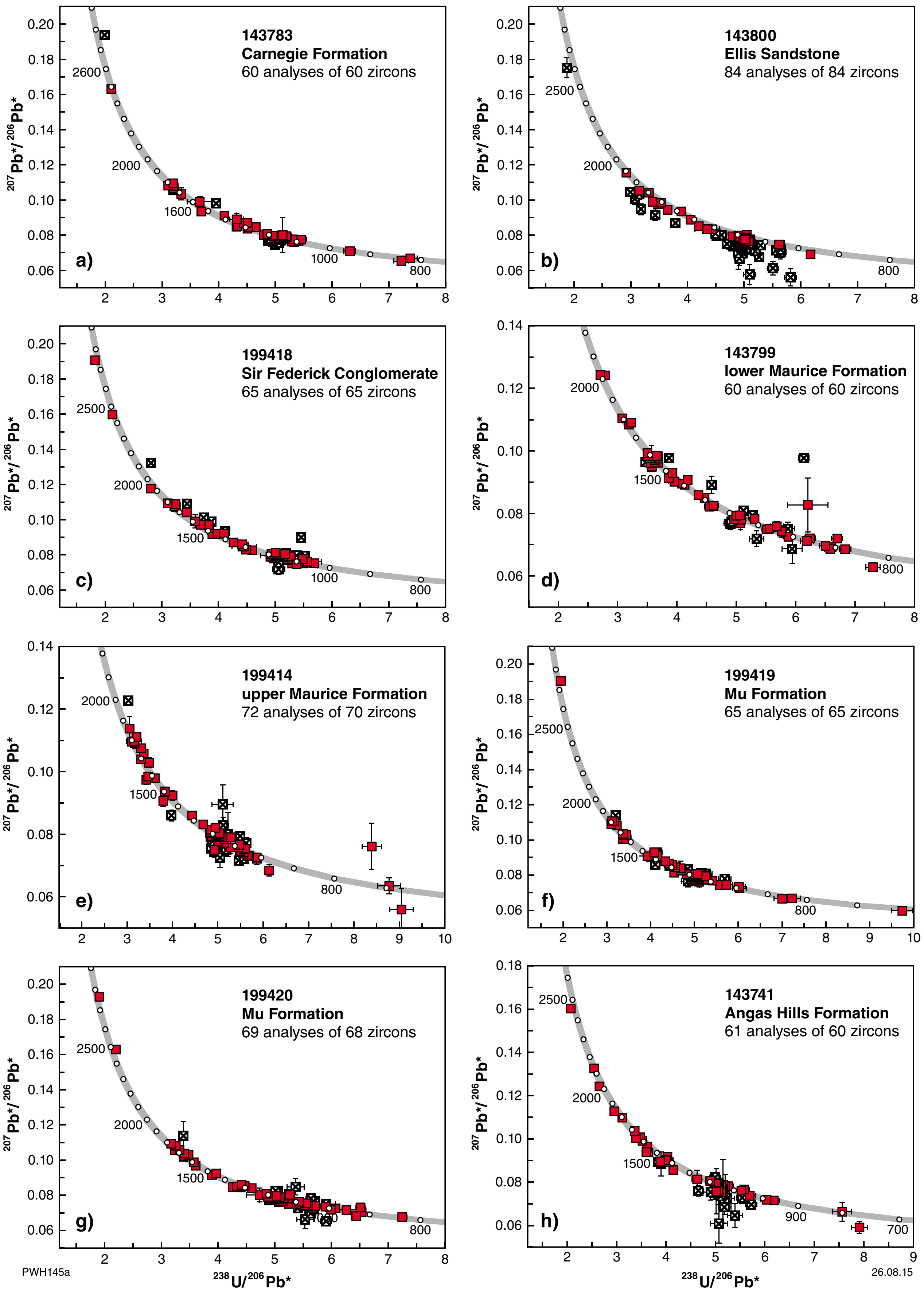
Detrital zircons from eight sandstone samples were analysed from Supersequence 4 of the WA Amadeus Basin as it is defined in this Record. Sampled units include Carnegie Formation (1), Ellis Sandstone (1), Sir Frederick Conglomerate (1), Maurice Formation (2), Mu Formation (2), and Angas Hills Formation (1). Sample details are summarized in Table 1, collection sites plotted in Figure 3, and stratigraphic positions indicated in Figure 4. U–Pb analytical results are presented in Figure 9, and as probability density plots and histograms (Fig. 10). In the sections below, 'concordant' refers to analyses with discordance <5%. Zircon grains analysed in this study often had pitted surfaces and, in CL images, many exhibit concentric zoning truncated at grain edges; these features are consistent with abrasion during sedimentary transport.

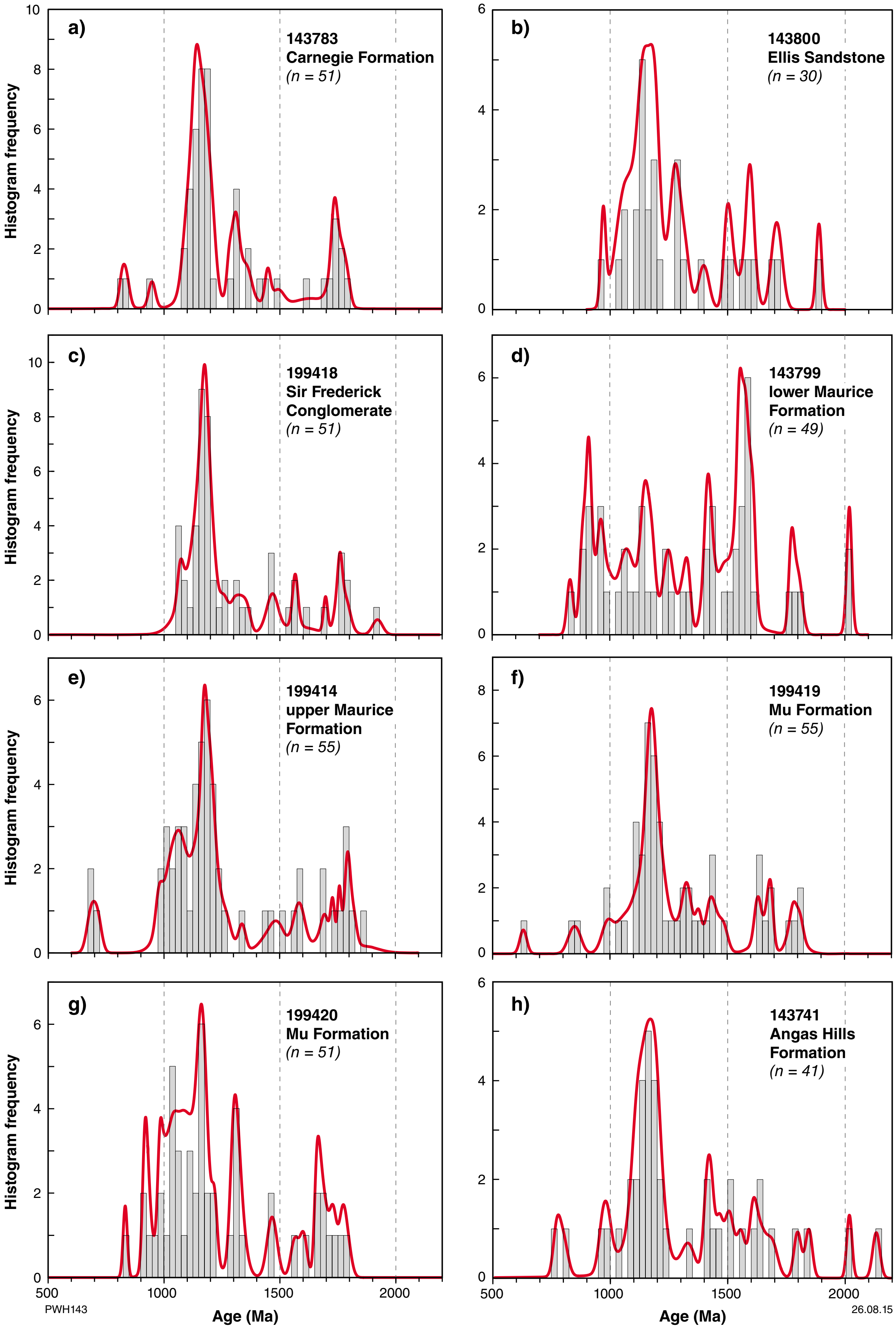
GSWA 143783: Carnegie Formation

Sample 143783 was collected from a low strike ridge of middle Carnegie Formation within the Mu Hills adjacent to the Sandy Blight Junction Track (MGA 473709E 7354988N). The sample comprises reddish fine- to medium-grained sandstone, consisting of 60–70% single-crystal quartz grains, 20–25% lithic grains and 5% pore spaces. Accessory minerals include tourmaline and zircon, and interstitial clay is present.

Zircon crystals isolated from this sample are colourless to dark brown, and range from very well-rounded and anhedral to subhedral. The zircons are up to 250 μm long, and equant to elongate, with aspect ratios up to 5:1.

Figure 9. (opposite) U–Pb analytical data for detrital zircons from the WA Amadeus Basin: a) Carnegie Formation, sandstone (143783); b) Ellis Sandstone (143800); c) Sir Frederick Conglomerate, sandstone (199418); d) lower Maurice Formation, sandstone (143799); e) upper Maurice Formation, sandstone (199414); f) Mu Formation, sandy breccia (199419); g) Mu Formation, sandstone (199420); h) Angas Hills Formation, sandstone (143741). Crossed squares indicate data with discordance >5% (not used on subsequent probability and histogram plots); error bars are ± 1σ.


a)
143783
Carnegie Formation
60 analyses of 60 zircons
b)
143800
Ellis Sandstone
84 analyses of 84 zircons
c)
199418
Sir Federick Conglomerate
65 analyses of 65 zircons
d)
143799
lower Maurice Formation
60 analyses of 60 zircons
e)
199414
upper Maurice Formation
72 analyses of 70 zircons
f)
199419
Mu Formation
65 analyses of 65 zircons
g)
199420
Mu Formation
69 analyses of 68 zircons
h)
143741
Angas Hills Formation
61 analyses of 60 zircons
207Pb*/206Pb*
238U/206Pb*
PWH145a
26.08.15



a)
143783
Carnegie Formation
(n = 51)
b)
143800
Ellis Sandstone
(n = 30)
c)
199418
Sir Frederick
Conglomerate
(n = 51)
d)
143799
lower Maurice
Formation
(n = 49)
e)
199414
upper Maurice
Formation
(n = 55)
f)
199419
Mu Formation
(n = 55)
g)
199420
Mu Formation
(n = 51)
h)
143741
Angas Hills
Formation
(n = 41)
Histogram frequency
Age (Ma)
500
1000
1500
2000
PWH143
26.08.15

Table 1. GSWA geochronology sample details

Sample number	*Stratigraphic unit*	*Location, MGA coordinates (Zone 52)*	*Lithology*	*Number of analyses*	*Age of youngest zircon(s)*
143741	Angas Hills Formation	420909E 7481561N	Pink, medium- to coarse-grained quartz–lithic sandstone	61 from 60 zircons	781 ± 24 Ma (MSWD = 1.2)
199420	Mu Formation	488146E 7362421N	Red, silty medium-grained sandstone	69 from 68 zircons	833 ± 9 Ma (1σ)
199419	Mu Formation	481692E 7360928N	Red, silty sandstone breccia	65 from 65 zircons	631 ± 15 Ma (1σ)
199414	Maurice Formation	460869E 7350368N	Pink, medium-grained, quartz–lithic sandstone	72 from 70 zircons	698 ± 20 Ma (MSWD = 1.0)
143799	Maurice Formation	424807E 7323497N	Red-brown, medium- to coarse-grained quartz–lithic sandstone	60 from 60 zircons	831 ± 13 Ma (1σ)
199418	Sir Frederick Conglomerate	470636E 7353379N	Red, fine-grained, quartz–lithic sandstone	65 from 65 zircons	1059 ± 57 Ma (1σ)
143800	Ellis Sandstone	424306E 7322366N	Pale grey, fine- to coarse-grained quartz–lithic sandstone	84 from 84 zircons	967 ± 11 Ma (1σ)
143783	Carnegie Formation	473709E 7354988N	Reddish fine- to medium-grained sandstone	60 from 60 zircons	819 ± 13 Ma (1σ)

SHRIMP U–Pb geochronology on detrital zircon from this sample is reported with data tables in Wingate et al. (2013b). Sixty analyses were obtained from 60 zircons (Fig. 9a). The majority of concordant dates range from c. 1.78 to c. 0.82 Ga, with a single older zircon at c. 2.49 Ga. The youngest result yields a 207-corrected $^{238}U/^{206}Pb^*$ date of 819 ± 13 Ma (1σ), giving a maximum possible depositional age considerably older than the Ediacaran age inferred from stratigraphic position. The dominant age component lies between c. 1.22 and 1.08 Ga, with minor age components between 1.36 and 1.28 Ga, and 1.78 and 1.68 Ga (Fig. 10a).

GSWA 143800: Ellis Sandstone

Sample 143800 was collected from a low outcrop of Ellis Sandstone 13 km northwest of the Ellis Range (MGA 424306E 7322366N). The sample consists of fine- to coarse-grained, lithic–quartz sandstone, containing 75–80% single-crystal quartz grains, 20–25% lithic grains, and 2–3% pore space.

Zircons isolated from this sample are colourless to dark brown, anhedral to euhedral, and well rounded. The crystals are up to 200 µm long, and equant to elongate, with aspect ratios up to 3:1.

Figure 10. (opposite) Probability density diagrams and histograms of detrital zircon ages between 500 and 2200 Ma from the: a) Carnegie Formation (143783); b) Ellis Sandstone (143800); c) Sir Frederick Conglomerate (199418); d) lower Maurice Formation (143799); e) upper Maurice Formation (199414); f) Mu Formation sandy breccia (199419); g) Mu Formation sandstone (199420); h) Angas Hills Formation (143741). Data >5% discordant for dates >1000 Ma were excluded; n = the number of analyses displayed in each diagram.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2013d). Eighty-four analyses were obtained from 84 zircons (Fig. 9b). The youngest result yields a 207-corrected $^{238}U/^{206}Pb^*$ date of 967 ± 11 Ma (1σ), providing a maximum depositional age that is considerably older than the Ediacaran to early Cambrian age inferred from stratigraphic position. Concordant dates range from c. 1.9 to c. 0.97 Ga. The dominant component has ages between c. 1.22 and c. 1.04 Ga, with minor components at c. 1.3, 1.5, 1.6 and 1.7 Ga (Fig. 10b).

GSWA 199418: Sir Frederick Conglomerate

Sample 199418 was collected from a low rubbly outcrop of sandstone on the western side of the Mu Hills (MGA 470636E 7353379N). The outcrop sampled is a reddish, medium-grained, cross-bedded sandstone lens between conglomerate beds of the Sir Frederick Conglomerate. The sample is a fine-grained, quartz–lithic sandstone, consisting of 60–65% quartz grains, 25–30% microcrystalline matrix, and 7–10% chert, siltstone, and feldspar clasts. It has a ferruginous matrix.

Zircons isolated from this sample are colourless to dark brown, anhedral to subhedral, and generally very well rounded. The crystals are up to 300 µm long, and equant to elongate, with aspect ratios up to 4:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2014b). Sixty-five analyses were obtained from 65 zircons (Fig. 9c). The analyses are concordant to strongly discordant. The youngest result yields a $^{207}Pb^*/^{206}Pb^*$ date of 1059 ± 57 Ma (1σ), a maximum depositional age that is considerably older than the Ediacaran to early Cambrian age inferred from stratigraphic position.

Concordant dates range from c. 2.7 to c. 1.06 Ga, although there are only two zircons older than c. 1.92 Ga. The dominant age component is between c. 1.32 and 1.05 Ga, with minor components at c. 1.47, 1.57 and 1.76 Ga (Fig. 10c).

GSWA 143799: lower Maurice Formation

Sample 143799 was collected from the northeast end of a low strike ridge of lower Maurice Formation 13 km northwest of the Ellis Range (MGA 424807E 7323497N). The sample is a reddish brown medium- to coarse-grained lithic quartz sandstone that contains abundant matrix-supported, bedding-parallel intraclasts of mudstone or siltstone. The sandstone matrix consists of 40–45% mostly single-crystal quartz grains, 40% hematized interstitial clay, 12–13% quartz-rich and sericite-rich lithic grains, and 3% detrital muscovite ± biotite.

Zircons isolated from this sample are colourless to dark brown, and range from very well rounded and anhedral to euhedral. The crystals are up to 200 μm long, and equant to elongate, with aspect ratios up to 5:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2013c). Sixty analyses were obtained from 60 zircons (Fig. 9d). The majority of analyses are concordant to slightly discordant. The youngest result yields a $^{207}Pb^{*}/^{206}Pb^{*}$ date of 831 ± 13 Ma (1σ), providing a maximum depositional age for the sample that is considerably older than the Ediacaran to early Cambrian age inferred from its stratigraphic position. Concordant dates range from c. 2.03 to c. 0.83 Ga (Fig. 9d). The dominant component is between c. 1.62 and 1.48 Ga (Fig. 10d). There is a broad spread of younger Mesoproterozoic to early Neoproterozoic ages, with notable modes at c. 1.45, 1.26, 1.16, 1.07, 0.96, and 0.91 Ga. Minor Paleoproterozoic components are at c. 2.03 and 1.77 Ga.

GSWA 199414: upper Maurice Formation

Sample 199414 was collected from the base of a hill of upper Maurice Formation about 2.5 km to the north of Sir Frederick Range (MGA 460869E 7350368N). The sample is a pink medium-grained, quartz–lithic sandstone, consisting of 55–60% quartz grains, 35–40% cryptocrystalline matrix, and 5% chert and quartz–sericite clasts.

Zircon grains isolated from this sample are colourless to dark brown, anhedral to subhedral, and generally very well rounded. The crystals are up to 400 μm long, and equant to elongate, with aspect ratios up to 4:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2014a). Seventy-two analyses were obtained from 70 zircons (Fig. 9e). The analyses are concordant to strongly discordant. Three analyses of the youngest zircon yield a weighted mean 207-corrected $^{238}U/^{206}Pb^{*}$ date of 698 ± 20 Ma (MSWD = 1.0), providing a maximum depositional age that is considerably older than the Ediacaran to early Cambrian depositional age inferred from its stratigraphic position. Concordant dates range from c. 1.87 to c. 0.7 Ga (Fig. 10e). The dominant age component ranges from c. 1.26 to c. 1.12 Ga, with a secondary age component between c. 1.1 and 0.99 Ga. There is a scatter of older Mesoproterozoic to late Paleoproterozoic ages, with a minor group between c. 1.86 and 1.69 Ga.

GSWA 199419: Mu Formation

Sample 199419 was collected from low rubbly outcrop of the Mu Formation near the northern edge of the Mu Hills (MGA 481692E 7360928N). The sample is a red-brown silty sandstone breccia, consisting of 40–45% quartz grains, 50–60% ferruginous, cryptocrystalline matrix, and 7–10% chert and feldspar clasts. Quartz grains are angular to subrounded and up to 0.1 mm in diameter. Feldspar and chert fragments are up to 1 or 2 mm long.

Zircons isolated from this sample are colourless to dark brown, anhedral to subhedral, and generally strongly rounded. The crystals are up to 300 μm long, and equant to elongate, with aspect ratios up to 5:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2014c). Sixty-five analyses were obtained from 65 zircons (Fig. 9f). The analyses are concordant to moderately discordant. The youngest zircon yields a 207-corrected $^{238}U/^{206}Pb^{*}$ date of 631 ± 15 Ma (1σ), providing a maximum depositional age that is considerably older than the Cambrian (or younger) age inferred from its stratigraphic position. The majority of concordant dates range from c. 1.81 to c. 0.63 Ga, with a single older zircon at c. 2.75 Ga. There is a broad spread of Mesoproterozoic ages, with a dominant component between c. 1.22 and 1.1 Ga (Fig. 10f). There are minor Paleoproterozoic components between c. 1.81 and 1.63 Ga, and there are five Neoproterozoic zircons.

GSWA 199420: Mu Formation

Sample 199420 was collected from an outcrop of Mu Formation exposed by grading of the Sandy Blight Junction Track near the northeastern end of the Mu Hills (MGA 488146E 7362421N). The outcrop comprises red silty medium-grained sandstone. The sample consists of 35–40% quartz, 25–30% chert and feldspar clasts, 25% ferruginous cryptocrystalline matrix, 5–8% iron–titanium oxide minerals, and accessory muscovite, chlorite and epidote. Quartz grains are angular to subrounded and up to 0.4 mm in diameter. Altered feldspar and chert fragments are up to 2 mm long.

Zircons isolated from this sample are colourless to dark brown, anhedral to subhedral, and generally very well rounded. The crystals are up to 300 μm long, and equant to elongate, with aspect ratios up to 4:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al. (2014d). Sixty-nine analyses were obtained from 68 zircons (Fig. 9g). The analyses are concordant to strongly discordant. The youngest zircon yields a 207-corrected $^{238}U/^{206}Pb^*$ date of 833 ± 9 Ma (1σ), providing a maximum depositional age for the sample that is considerably older than the Cambrian (or younger) age inferred from its stratigraphic position. The majority of concordant dates range between c. 1.79 and 0.83 Ga, with two older zircons at c. 2.49 and c. 2.77 Ga. The majority of zircon dates are within the range 1.22 – 0.92 Ga, with modes at c. 1.16 and 1.05 Ga (Fig. 10g). Notable older components are c. 1.31 Ga, and between c. 1.79 and 1.65 Ga.

GSWA 143741: Angas Hills Formation

Sample 143741 was collected adjacent to a southeast-trending vehicle track where it skirts the southern end of a low sandstone ridge at the northeast end of the Angas Hills (MGA 420909E 7481561N). The location is about 47.9 km east of Kiwirrkurra and 20.4 km north-northeast of Mount Webb. The sample comprises pink, medium- to coarse-grained quartz–lithic sandstone, consisting of 55–60% quartz grains, 20% clay ± limonite (as grains, interstitial material, and rims on pore spaces), 10–15% polycrystalline quartz grains ± clay ± limonite, 10–15% porosity, and accessory muscovite, zircon, and possible tourmaline.

Zircons isolated from this sample are pale to dark brown, anhedral to subhedral, and generally well rounded. The crystals are up to 250 µm long, and equant to elongate, with aspect ratios up to 4:1.

SHRIMP U–Pb geochronology on the detrital zircons is reported with data tables in Wingate et al., (2013a). Sixty-one analyses were obtained from 60 zircons (Fig. 9h). The majority of analyses are concordant to slightly discordant. Two analyses of the youngest zircon yield a weighted mean 207-corrected $^{238}U/^{206}Pb^*$ date (2σ) of 781 ± 24 Ma (MSWD = 1.2), providing a maximum depositional age for the sample. Concordant dates range between c. 2.46 and c. 0.78 Ga. The dominant age component lies between 1.23 and 1.09 Ga, with a smaller concentration of latest Paleoproterozoic to early Mesoproterozoic ages (1.7 – 1.4 Ga), and four early Neoproterozoic zircons (Fig. 10h).

Discussion

Concordant detrital zircon ages in our full dataset range from the late Archean (c. 2.77 Ga) to the late Neoproterozoic (c. 631 Ma), although the majority fall between the late Paleoproterozoic (c. 1.8 Ga) and the early Neoproterozoic (c. 800 Ma). A clear relationship can be observed when these ages are compared with known zircon-crystallizing events and detrital and inherited zircon components in the Musgrave region. This is seen particularly well in the pooled data plot in the top frame of Figure 11; the ensuing discussion is based largely on that plot.

The pooled data show a dominant zircon age peak at c. 1.18 Ga, which is coeval with the widespread 1.22 – 1.15 Ga Pitjantjatjara Supersuite granites. This component is dominant in all individual samples with the exception of 143799 (lower Maurice Formation), where it is present, but subdued by other larger age peaks, as discussed below. In some samples the main age peak has a younger 'shoulder' or separate peak at c. 1.07 Ga, coeval with the 1.09 – 1.04 Ga Giles Event.

All samples contributed to a minor mode in the pooled data at c. 1.32 Ga. This age component is coeval with the 1.35 – 1.29 Ga Mount West Orogeny and associated Wankanki Supersuite granites; the latter restricted to the west Musgrave Province.

The interval between 1.8 and 1.4 Ga shows a continuum of detrital zircon ages on the pooled data plot, with minor clusters around 1.80 – 1.75, c 1.69, 1.60 – 1.55, and 1.50 – 1.42 Ga. The majority of these clusters do not correspond with known events in the Musgrave Province, although the 1.60 – 1.55 Ga cluster is coeval with orthogneiss in the east Musgrave Province and the local c. 1.58 Ga Warlawurra Supersuite in the west. A peak at this age is particularly strong in only one sample, 143799 (lower Maurice Formation), where it forms the dominant mode. The c. 1.4 Ga Papulankutja Supersuite is currently known from only a small area of the west Musgrave Province. However, it is a possible source of a distinct component of zircons close to this age, most notably in 143741 (Angas Hills Formation) and 143799 (lower Maurice Formation). A multicyclic origin, ultimately derived from beyond the Musgrave region, is the likely source of most zircons in the c. 1.8 to 1.4 Ga range, and those in the sparse older components. There are two possible intermediate sources: 1) detrital and inherited zircons from the Musgrave region; and 2) detrital zircons recycled from Supersequences 1–3 rocks of the Amadeus Basin. The latter is an expected component of Supersequence 4 because of the major unconformity and extent of erosion below Supersequence 4 in the southern part of the field area, and the assemblages of pebble and cobble clasts in Supersequence 4 that match rocks in older Amadeus Basin units. The probable original source of 1.81 – 1.56 Ga zircons within these units is the Arunta region. The Arunta region could also have sourced the sparse older components as detrital populations analysed from metasedimentary rocks of the Arunta region contain older Paleoproterozoic to Neoarchean components (Beyer et al., 2013; Kositcin et al., 2014). Since pre-1.8 Ga detrital and inherited zircons are generally absent from the Musgrave region, with the local exception of a Neoarchean component in some samples from the Latitude Hills of the west Musgrave region, it is more likely that such components reached Supersequence 4 units via reworking of Amadeus Basin rocks.

Detrital zircons younger than the Giles Event are sparse in the majority of samples, although they are present in all except 199418 (Sir Frederick Conglomerate). The pooled plot shows minor age peaks at c. 980, 915, and 825 Ma (Fig. 11). The c. 980 Ma age could reflect the 'c. 1000 Ma event' (Howard et al., 2015), recorded in an aplite dyke and poorly age-constrained mafic dykes. If so, this event may be more widespread than previously thought.

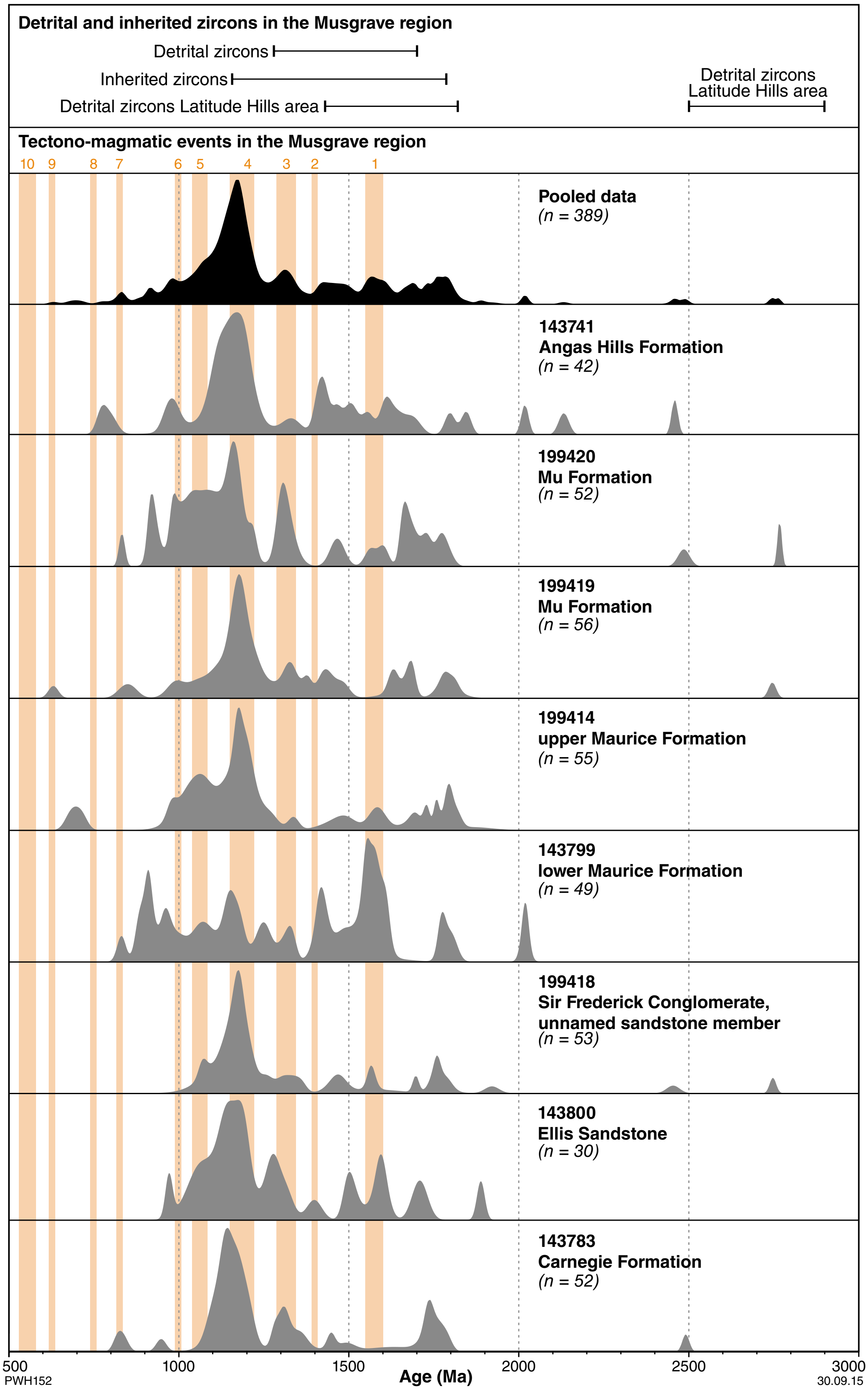

Detrital and inherited zircons in the Musgrave region
Detrital zircons
Inherited zircons
Detrital zircons Latitude Hills area
Detrital zircons Latitude Hills area
Tectono-magmatic events in the Musgrave region
10 9 8 7 6 5 4 3 2 1
Pooled data
(n = 389)
143741
Angas Hills Formation
(n = 42)
199420
Mu Formation
(n = 52)
199419
Mu Formation
(n = 56)
199414
upper Maurice Formation
(n = 55)
143799
lower Maurice Formation
(n = 49)
199418
Sir Frederick Conglomerate, unnamed sandstone member
(n = 53)
143800
Ellis Sandstone
(n = 30)
143783
Carnegie Formation
(n = 52)
500
1000
1500
2000
2500
3000
Age (Ma)
PWH152
30.09.15

Figure 11. (opposite) Probability density diagrams of detrital zircon U–Pb ages for each sample, with pooled data depicted in top frame. Samples are arranged by upward-decreasing depositional age, except for Angas Hills Formation for which the stratigraphic position relative to other formations is unknown. Coloured vertical bars indicate the ages of known magmatic, metamorphic and tectonic events and the ages of detrital and inherited zircons in the Musgrave region (see text for references; n = number of analyses plotted): 1) 1.60 – 1.55 Ga orthogneiss in the east Musgrave region and c. 1.575 Ga Warlawurra Supersuite in the west Musgrave region; 2) c. 1.4 Ga Papulankutja Supersuite; 3) 1.35 – 1.29 Ga Mount West Orogeny and Wankanki Supersuite; 4) 1.22 – 1.15 Ga Musgrave Orogeny and Pitjantjatjara Supersuite; 5) c. 1.09 – 1.04 Ga Giles Event and Warakurna Supersuite; 6) '1000 Ma event'; 7) c. 825 Ma Gairdner–Amata Dolerite dykes; 8) c. 747 Ma mafic dykes; 9) 623–638 Ma metamorphism and pegmatites (coeval with Miles Orogeny in Rudall Province); 10) 570–530 Ma Petermann Orogeny

The c. 915 Ma component is contributed mainly from two samples (143799, 199420) and lacks a known primary source in the Musgrave region or elsewhere in central Australia. Zircons with ages within error of c. 825 Ma are present in four samples. These may be related to the Gairdner and Amata Dolerites (827 ± 6 Ma; Wingate et al., 1998), some of which are zircon bearing. Although the dolerite dykes occupy only a small volume of the Musgrave region, they may have fed a more extensive system of flood basalt that has been eroded or concealed. This was argued by Barovich and Foden (2000) to explain the Nd-isotope signature of Neoproterozoic sedimentary rocks of the Amadeus Basin and Adelaide Rift Complex.

No zircon grains with ages corresponding to the Petermann Orogeny were present in any samples. This is consistent with the lack of magmatism (apart from minor pegmatite) associated with this orogeny. Metamorphic zircon overgrowths of Petermann age have been reported locally (Scrimgeour et al., 1999), although these may not have been exhumed until later.

There are no apparent strong trends relating to relative depositional age, as is sometimes noted with the progressive unroofing of an orogen. The Mu and Angas Hills Formations, previously thought to be of late Paleozoic age, show no trace of the post-Supersequence 4 zircon age spectrum (c.f. Figs 5 and 11). The age spectra of these units are indistinguishable from those obtained from the succession bracketed by the Carnegie and Maurice Formations. Even considering recycling of zircons from older Supersequence 4 formations, it is likely that the Mu and Angas Hills Formations also would have incorporated some material from the pervasive post-Supersequence 4 detrital zircon components if they were deposited during or after the Alice Springs Orogeny. The Angas Hills Formation is here interpreted as a lateral equivalent of the much thicker and vertically differentiated Supersequence 4 succession further south. The Mu Formation was likely deposited late in the Petermann Orogeny, or just after it; its distribution is restricted to local sub-basins and probably related to salt withdrawal.

The provenance of a subgroup of detrital zircons from this study has been further investigated using Hf isotopes. The details, reported in Haines et al. (2015), are consistent with the proposed Musgrave region and Arunta region provenance for the main Mesoproterozoic and Paleoproterozoic age components, respectively.

In summary, the modes of detrital zircon age spectra of our samples can be matched to all significant pre-Petermann magmatic and metamorphic events of the Musgrave region. The minor populations of older zircons are consistent with a recycled component from pre-Supersequence 4 Amadeus Basin rocks, which are typically dominated by Arunta-derived material. It is also possible that some were directly transported from the Arunta region at the time of deposition. While it is conceivable that some of the Mesoproterozoic age components could be derived from the Albany–Fraser Orogen to the southwest of the Musgrave region, this is unlikely as the Petermann Orogen would have provided a topographic barrier to such transport.

Comparison with existing detrital zircon data

A comparison of our pooled data with previous age data on detrital zircons from the Arumbera Sandstone and Winnall beds (cf. Figs 11 and 5c), shows a strong visual match between the datasets. All significant age components match and minor components show similar age ranges (Fig. 12a,b); major age components characteristic of older successions are minimal and modes representing younger successions are absent. This visual comparison suggests that Supersequence 4 typically contains zircon components that both post-date the Giles Event and pre-date most Musgrave region events (Fig. 12), and were likely partly derived from recycled older Amadeus Basin units. By contrast, pooled data from the Mount Currie Conglomerate and Mutitjulu Arkose (Fig. 12c) only show similarity in the late Mesoproterozoic age components, as other components are absent.

To provide a more objective measure of the similarity for these datasets, we employed the Kolmogorov–Smirnov (K–S) statistical test (Press et al., 1992). The K–S test is a non-parametric method for comparing cumulative probability distributions. The test returns a P-value indicating the probability that random chance alone might produce the observed difference in two distributions drawn from the same parent population. A low probability on the test indicates that the differences between the two distributions are significant. We took a P-value of >0.05 to indicate that the differences between populations are not statistically significant and therefore that such samples have a similar source. The K–S test was run on the pooled data depicted in Figure 12 for both the full age spectrum and on a subset of data restricted to the 1.4 – 1.0 Ga interval (Table 2). The purpose of examining the restricted dataset was to provide further clarity on the similarity or dissimilarity for the dominant age components in these samples.

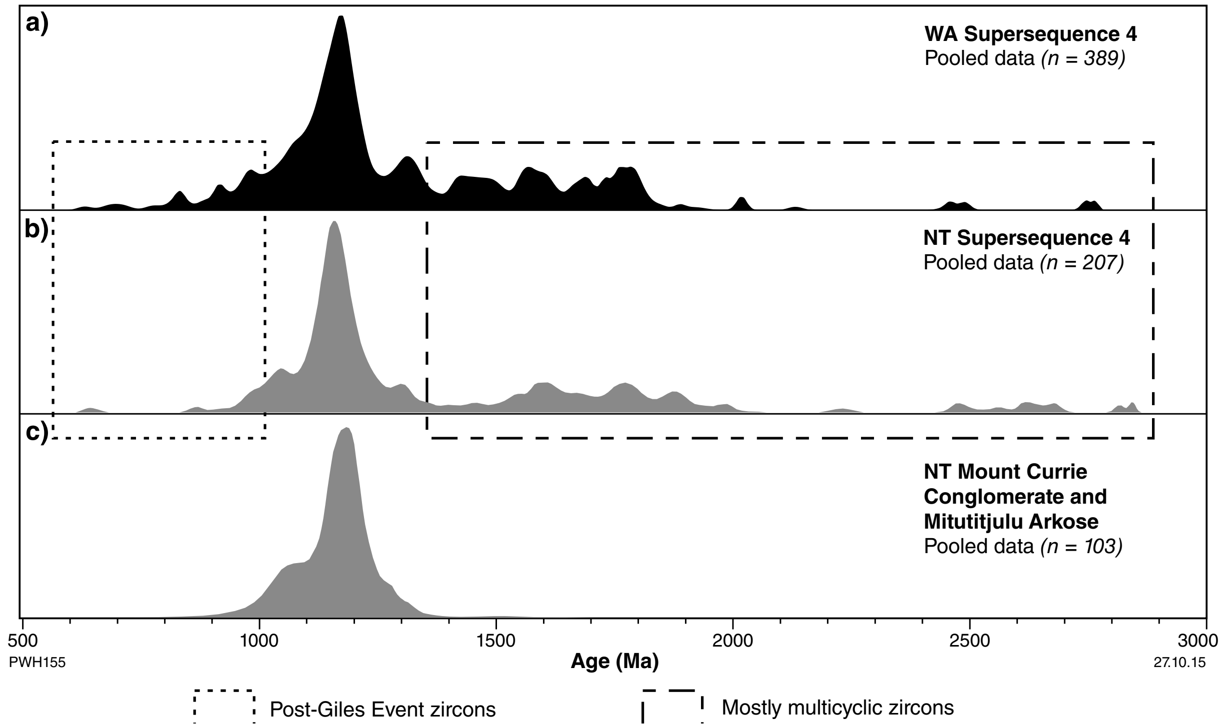


Figure 12. Comparison of probability density diagrams of detrital zircon U–Pb ages from: a) pooled WA Supersequence 4 (from top frame of Fig. 11); b) NT Supersequence 4 (from Fig. 5); c) the Mount Currie Conglomerate and Mutitjulu Arkose (pooled data from Camacho et al., 2002)

Table 2. Statistical comparison, using the Kolmogorov–Smirnov test*, of pooled detrital zircon age data for WA Supersequence 4 with the pooled NT data plotted in Figure 12

a) All zircon ages included	*This study*	*NT Supersequence 4*	*Mount Currie Conglomerate and Mutitjulu Arkose*
WA Supersequence 4 (this study)		*0.089*	*0.339*
NT Supersequence 4	**0.235**		*0.332*
Mount Currie Conglomerate and Mutitjulu Arkose	0	0	

b) Zircon ages restricted to 1.4 – 1.0 Ga	*This study*	*NT Supersequence 4*	*Mount Currie Conglomerate and Mutitjulu Arkose*
WA Supersequence 4 (this study)		*0.063*	*0.093*
NT Supersequence 4	**0.889**		*0.082*
Mount Currie Conglomerate and Mutitjulu Arkose	**0.582**	**0.839**	

* Comparison used the Kolmogorov–Smirnov statistic (Press et al., 1992). Numbers in the matrix refer to the probability that any two samples are sourced from the same zircon population, with consideration of the uncertainty in age measurement. The higher the P-value (shown in lower left of matrix) the more likely it is that the two age distributions being compared were drawn from the same population. P-values >0.05 (in **bold**) imply a correlation at >95% confidence. P-values <0.05 indicate that the samples are from distinctly different populations. The upper half of the matrix shows D-values (in *italics*) calculated from the distance between cumulative probability curves accounting for the uncertainty within the density function. While we do not discuss these numbers here, critical values can be found in Massey (1951).

The 1.4 – 1.0 Ga age range encompasses most magmatic and metamorphic zircon-crystallizing events known to have affected the Musgrave region.

When the K–S test was run on the entire dataset of zircon ages, the WA Amadeus Basin data showed a strong correlation at >95% confidence (P-values >0.05) with the NT Amadeus Basin Supersequence 4 data (Table 2a). However, no significant correlation was found with data from the Mount Currie Conglomerate and Mutitjulu Arkose despite the similarity of the dominant age components. This reflects the sensitivity of the method to differences in the quantity of both major and minor age components. When the test was reapplied to a restricted dataset of zircons within the range of 1.4 – 1.0 Ga, all three datasets were statistically similar at >95% confidence (Table 2b), consistent with derivation of this component from essentially the same parent source with only minor contributions from elsewhere.

The absence in the Mount Currie Conglomerate and Mutitjulu Arkose of post-1 Ga zircons, and of the detrital zircon component inferred to be recycled from pre-Petermann Amadeus Basin rocks (Fig. 12) is consistent with these units pre-dating the Amadeus Basin, and perhaps forming part of the Ngaanyatjarra Rift. If so, this would reconcile the metamorphism to greenschist facies of these units, which indicates significant burial. It also resolves the greater lithological similarity of the two units to Ngaanyatjarra Rift sedimentary rocks (with preserved fresh labile minerals), than to confirmed Supersequence 4 rocks (with evidence for deep weathering in the source area). However, this interpretation is only possible if the concealed contact between the Winnall beds and Mount Currie Conglomerate is a fault rather than an unconformity, as previously inferred. We suggest that this relationship needs reassessment. If the putative unconformity between the Mount Currie conglomerate and the Winnall beds is confirmed, the Mount Currie Conglomerate must be either restricted to a late phase of the Petermann Orogeny, or be even younger.

Conclusions

Detrital zircon U–Pb age spectra from samples collected from units of the recently revised Supersequence 4 of the WA Amadeus Basin are dominated by late Mesoproterozoic age components. These are coeval with known magmatic events in the Musgrave region, most notably the widespread granites of the Pitjantjatjara Supersuite emplaced between c. 1.22 and 1.15 Ga during the Musgrave Orogeny; they also include components of the older Mount West Orogeny (1.35 – 1.29 Ga) and younger Giles Event (1.09 – 1.04 Ga). The zircon age spectra are consistent with derivation from rocks of the Musgrave region exhumed during the 570–530 Ma Petermann Orogeny. The pooled age spectrum from eight WA samples (391 concordant zircons) is statistically identical (based on the K–S test, 95% confidence) to pooled published detrital zircon age data from Supersequence 4 in the NT. This test indicates that the stratigraphic revisions in the poorly known western end of the Amadeus Basin are appropriate, as pre- and post-Supersequence 4 successions have significantly different zircon age spectra based on a number of studies in the NT Amadeus Basin.

Supersequence 4 in both the NT and WA exhibits small populations of late Paleoproterozoic and older zircons that pre-date preserved rocks in the Musgrave region. These are interpreted as a multicyclic component, possibly contributed in part from detrital and inherited zircons of the Musgrave region, but also expected to include a component from older Amadeus Basin rocks uplifted and eroded, along with basement, during the Petermann Orogeny. Specific age components in these older zircons match events and detrital populations in the Arunta region as do the majority of detrital zircons in older Amadeus Basin units.

A poor statistical match was found between confirmed Supersequence 4 and commonly assumed proximal syn-Petermann deposits represented by the Mount Currie Conglomerate and Mutitjulu Arkose. These lack older multicyclic components, or any zircons significantly younger than the Giles Event, suggesting they might be much older than currently assigned. The age and tectonic significance of these poorly constrained formations needs reassessment.

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Appendix 1

U–Pb zircon analytical methods

All samples were collected from surface outcrops and typically weighed 5–15 kg. The samples were crushed and zircons separated using density and magnetic techniques at the mineral separation laboratory of GSWA. A representative fraction of about 300 zircons was selected from each sample and cast, together with zircon reference standards (including BR266 and OGC1), in an epoxy resin mount. The mount was polished to approximately half-grain thickness to expose the interiors of the crystals, which were then documented with transmitted and reflected light photomicrographs and cathodoluminescence (CL) images. Approximately 60 zircons per sample were then dated by the U–Pb method using the Sensitive High Resolution Ion Microprobe (SHRIMP II) at the John de Laeter Centre for Isotope Research at Curtin University in Perth. Although it was intended that the dated zircons be as representative as possible of the true population in the sampled rock, some bias is inevitable because crystals with abundant cracks and inclusions were avoided, and a few crystals could not be dated successfully, owing to excessive uranium and common-Pb contents. In addition, biases inherent in sampling and mineral separation are unavoidable (Sircombe and Stern, 2002; Black et al., 2004).

Full details of analytical methods are described in Wingate and Kirkland (2014). To ensure consistent interpretation and to avoid introducing any bias when comparing results from different samples, all data <1000 Ma have been reprocessed for common or initial Pb using the 207-correction method (e.g. Gibson and Ireland, 1996). The 207-method assumes that the radiogenic composition is concordant, and the 207-corrected $^{238}U/^{206}Pb$ date is determined by extrapolating the measured composition to concordia along a trajectory defined by Stacey and Kramers' (1975) common-Pb composition for the $^{238}U/^{206}Pb^*$ date of the sample (Pb* refers to radiogenic Pb produced by the in situ decay of uranium). For data >1000 Ma, dates are calculated from $^{207}Pb^*/^{206}Pb^*$ ratios, corrections for common Pb are made using measured $^{204}Pb/^{206}Pb$ ratios, and data >5% discordant are excluded. Analytical results (excluding data >1000 Ma that are >5% discordant) are illustrated in probability density diagrams. Ages based on single analyses are reported with 1σ uncertainties, and weighted mean ages are quoted with 95% confidence intervals.

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Appendix 2

New and revised lithostratigraphic definitions submitted to Australian Stratigraphic Units Database

Angas Hills Formation (variation of published name)

Rank: Formation

State: WA

Status of unit: Variation of published name

Proposers: Peter Haines and Heidi Jane Allen (Geological Survey of Western Australia); original definition by Blake and Towner (1974).

Date: 18 March 2015

Reserved in stratigraphic units database: Not applicable

Derivation of name: Angas Hills (latitude 22°52'S, longitude 128°9'E).

Synonymy, unit name history: Previously named Angas Hills beds (Blake and Towner, 1974; Blake, 1977).

Constituent units: None

Parent unit: None

Type locality: A cliff section 36 m high in the eastern Angas Hills, 12 km northeast of Mt Webb (latitude 22°51'00"S, longitude 128°12'30"E). This locality is the reference section nominated by Blake and Towner (1974) elevated herein as no type locality had been nominated. Closest access is via a track from Kiwirrkurra to Lake Mackay.

Description at type locality:

Lithology: Based on Towner and Blake (1974) the basal 12 m at the type locality consists of coarse pebble conglomerate with some thin lenses and layers of clayey sandstone. The conglomerate is overlain by 24 m of partly pebbly cross-bedded sandstone, in the middle of which there are some interbeds of maroon mudstone about 10 cm thick. At this locality the strata dip 10° west.

Thickness: About 36 m exposed at the type locality (Blake and Towner, 1974).

Fossils: None observed.

Diastems or hiatuses: None observed.

Relationships and boundary criteria: Unconformably overlies Arunta region basement, Heavitree Quartzite and probably Bitter Springs Formation (Blake and Towner, 1974). Overlain by Cenozoic units.

Distinguishing or identifying features: May be distinguished from pebbly sandstone, conglomerate and diamictite of the partly glacigene Permian–Carboniferous Paterson Formation by its deep red-brown colouration (freshly broken Paterson formation is typically white) and the lack of evidence for glacial influence.

Age and evidence: Upper Ediacaran to lower Cambrian based on detrital zircon provenance data (Wingate et al., 2013) which suggests deposition synchronously with the Petermann Orogeny (Haines et al., 2012). This is also supported by paleocurrent data (transport from the southwest) and lithological and clast similarities to Supersequence 4 units in the main part of the Amadeus Basin to the south.

Correlation with other units: Correlated with Supersequence 4 of the main Amadeus Basin, although correlation with any specific units has not been possible.

Regional aspects/general geological description: Regionally the unit consists of interbedded pebble and cobble conglomerate, sandstone, pebbly sandstone and siltstone. Pebble and cobble clasts are typically well rounded and are mainly of sedimentary or metasedimentary lithologies including quartzite, sandstone, metasandstone and chert, with minor vein quartz. Carbonate clasts were identified locally. The clayey sandstone matrix is friable and some exposures are limited to loose rounded pebbles and cobbles. Sandstone and siltstone are typically red-brown in colour due to iron oxides. Sandstones may be quartz-rich, but also contain a lithic content and clay matrix. Cross-beds are common in sandstone facies while siltstones are finely laminated.

Extent: Known outcrops are restricted to the southern half of the Webb 1:250 000 scale map sheet in WA, most notably around the Angas Hills. The unit is restricted to outliers of the Amadeus Basin lying within basement of the Arunta region.

Geomorphic expression: Low hills, scarps, rises and plateaus.

Thickness variations: About 300 m is exposed on the west side of the Angas Hills where the formations dips 15° to 20° southeast (Blake and Towner, 1974); this is a minimum thickness for the unit in this area as neither base nor top are exposed.

Structure and metamorphism: Mostly flat lying or gently dipping (locally up to 20°), and unmetamorphosed.

Alteration and mineralisation: None known.

Geophysical expression: Not distinguished on geophysical datasets.

Geochemistry: No data.

Genesis/depositional environment: Fluvial based on sedimentary facies. Paleocurrent data indicate derivation from the southwest. Detrital zircon data indicate derivation of the sandy component largely from the Musgrave region, consistent with deposition during the Petermann Orogeny. The laminated siltstones probably represent local lacustrine facies.

Comments: Previously inferred to be of late Paleozoic age (Blake and Towner, 1974).

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Mu Formation (new name)

Rank: Formation

State: WA and NT

Proposers: Peter Haines and Heidi Jane Allen (Geological Survey of Western Australia)

Date: 18 March 2015

Reserved in stratigraphic units database: Yes

Derivation of name: Mu Hills (latitude 23°53’S, longitude 128°49’E)

Synonymy, unit name history: Most outcrops of Mu Formation were previously mapped as Ligertwood beds by Wells et al. (1964) and Wells (1968). However, these outcrops are now inferred to be distinct from and significantly older than the unit exposed at the Ligertwood beds type locality in the NT (Ligertwood beds at type locality is inferred to be upper Paleozoic, post-dating the Alice Springs Orogeny: Edgoose, 2013). Some outcrops previously mapped as Ligertwood beds in WA are now assigned to Bitter Springs Formation diapiric carbonate breccia and Sir Frederick Conglomerate.

Constituent units: None

Parent unit: None

Type locality: Northern edge of the Mu Hills in the vicinity of the Sandy Blight Junction Track. Outcrop is generally poor and discontinuous, so no single type section can be nominated. The conglomeratic facies is best exposed around latitude 23°52'16"S, longitude 128°52'2"E, where it unconformably overlies poorly exposed and silicified Bitter Springs Formation to the south. This location is also the basal stratotype. The sandstone facies is best exposed in a small cluster of hills around latitude 23°51'1"S, longitude 128°53'11"E. Access to the type area is via the Sandy Blight Junction Track.

Description at type locality:

Lithology: Cobble and boulder conglomerate is the dominant lithofacies. Sandstone with interbeds of conglomeratic sandstone is locally present, and siltstone is a minor component. Conglomerate clasts are well rounded and are mostly sedimentary and metasedimentary including quartzite, silicified sandstone, metasandstone, with minor chert and vein quartz. Many of the conglomerate clasts may be reworked from the locally underlying Sir Frederick Conglomerate. The sandy matrix is often ferruginous and is typically very friable, with many exposures dominated by loose rounded cobbles and boulders at surface. The sandstone is typically red-brown, medium grained and lithic. Beds are typically massive, with current lineations common on bedding surfaces.

Thickness: At least 600 m estimated in the type area; top not exposed.

Fossils: None observed.

Diastems or hiatuses: None observed, but this may be a function of poor outcrop. Local hiatuses are possible, based on tectonic setting.

Relationships and boundary criteria: Unconformably overlies Maurice Formation, Sir Frederick Conglomerate, Carnegie Formation and Bitter Springs Formation. No top contact exposed.

Distinguishing or identifying features: In isolation the conglomeratic facies is difficult to distinguish from the older Sir Frederick Conglomerate (although the Mu Formation conglomerate matrix is often more ferruginous), while the sandstone facies resembles sandstone units in the Maurice Formation and Sir Frederick Conglomerate. It is only possible to confidently distinguish the Mu Formation where the pronounced basal angular unconformity over the older units can be recognized.

Age and evidence: Younger than the Maurice Formation, which is probably lower Cambrian (Haines et al., 2012). Probably deformed prior to the Middle Ordovician because nearly flat-lying Middle Ordovician limestone is exposed nearby (Haines et al., 2012). Detrital zircon geochronology (Wingate et al., 2014a,b) is consistent with sediment derivation from the Petermann Orogen during or after the late Ediacaran to early Cambrian Petermann Orogeny. Probably lower Cambrian but could be somewhat younger.

Correlation with other units: Correlative of lower Pertaoorrta Group in NT.

Regional aspects/general geological description: The conglomeratic facies, as described for the type area is the most regionally widespread expression. The sandstone facies is only well developed around the type area.

Extent: Most confirmed outcrops are distributed along the northern edge of the Mu Hills. Isolated outcrops of conglomerate up to 20 km northeast of the type area may belong to the Mu Formation. Outcrops previously mapped as Ligertwood beds near the western edge of the Mount Rennie 1:250 000 map sheet area in the NT are probably Mu Formation (but the Ligertwood beds type area is excluded). Outcrops of cobble and boulder conglomerate near latitude 24°27'S, longitude 128°23'E south of Wallace Hills are inferred to overlie the Maurice Formation and are tentatively included in the Mu Formation.

Geomorphic expression: Low hills and rubbly rises.

Thickness variations: The thickest exposure of at least 600 m is inferred in the type area. Significant thickness variations are expected due to the tectonic setting, but cannot be quantified due to poor and discontinuous outcrop.

Structure and metamorphism: Outcrops at and near the type locality mostly dip north at around 20°, or steeper close to the basal unconformity. No metamorphism.

Alteration and mineralization: None observed.

Geophysical expression: Not distinguished on geophysical datasets.

Geochemistry: No data.

Genesis/depositional environment: Alluvial fan and fluvial environments based on sedimentary facies. Deposition in the Mu Hills area was controlled by local uplift and subsidence likely related to diapiric movement of Bitter Springs Formation salt, probably during a late phase of the Petermann Orogeny. The Mu Formation appears to fill local mini-basins related to salt withdrawal. The formation was tilted by continuing salt movements during deposition. The sediment was ultimately derived from uplift of the Petermann Orogen, but was at least in part recycled from earlier syn-Petermann deposits.

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RECORD 2015/8

DETRITAL ZIRCON GEOCHRONOLOGY OF UPPER EDIACARAN TO LOWER CAMBRIAN DEPOSITS (SUPERSEQUENCE 4), WESTERN AMADEUS BASIN: TESTING REVISED STRATIGRAPHIC CORRELATIONS

Haines et al.

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