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RECORD 2017/4

GEOLOGICAL RECONNAISSANCE OF THE SOUTHERN MURRABA BASIN, WESTERN AUSTRALIA: REVISED STRATIGRAPHIC POSITION WITHIN THE CENTRALIAN SUPERBASIN AND HYDROCARBON POTENTIAL

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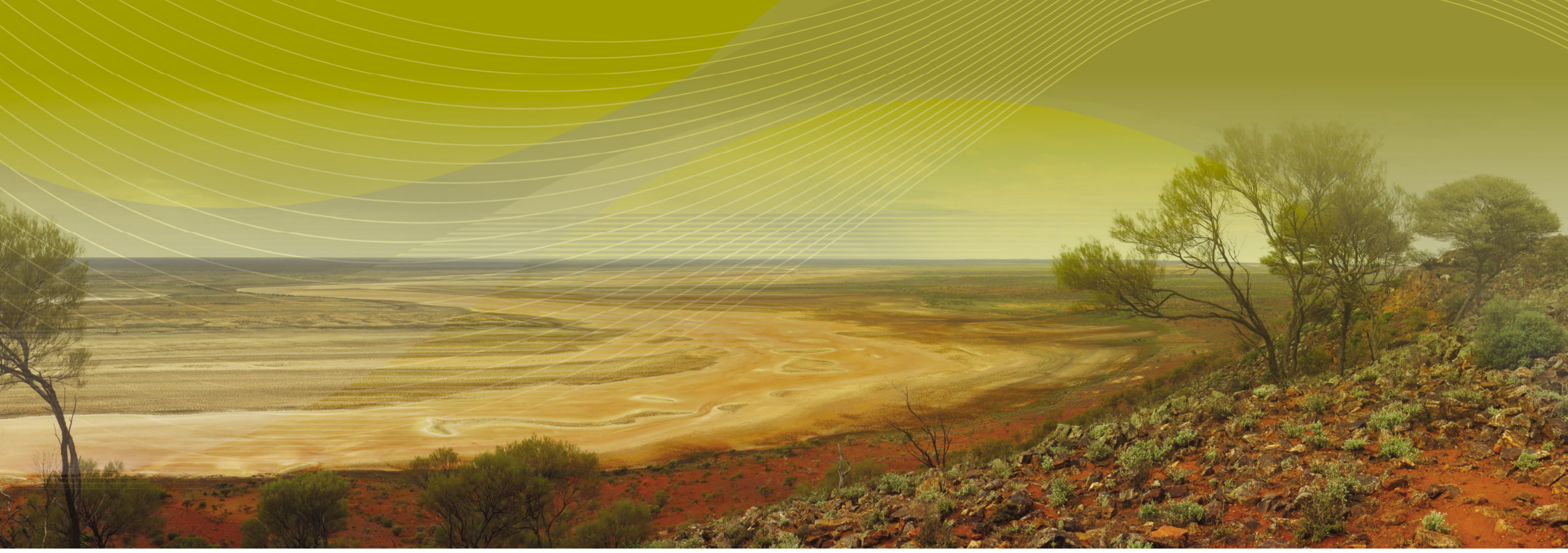
PW Haines and HJ Allen



Geological Survey of Western Australia

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Perth 2017

Geological Survey of Western Australia

MINISTER FOR MINES AND PETROLEUM
Hon Bill Johnston MLA

ACTING DIRECTOR GENERAL, DEPARTMENT OF MINES AND PETROLEUM
Tim Griffin

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Rick Rogerson

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

Contents

Appendix

Figures

Geological reconnaissance of the southern Murraba Basin, Western Australia: revised stratigraphic position within the Centralian Superbasin and hydrocarbon potential

by

PW Haines and HJ Allen

Abstract

The Murraba Basin is a poorly exposed succession of mostly Neoproterozoic sedimentary rocks cropping out east of the Canning Basin and straddling the Western Australia – Northern Territory border. It is inferred to be a component of the former Centralian Superbasin, forming a link between the western Amadeus Basin in the south, and the Wolfe and Louisa Basins of the Kimberley region to the north. The basin succession was previously correlated with only the basal succession (Supersequence 1) of the Amadeus Basin. Our revised interpretation correlates the succession with all four supersequences of the Centralian Superbasin, likely ranging in age from the Tonian (lower Neoproterozoic) to the lower Cambrian, although significant parts of the succession lie under cover and can only be inferred from regolith. The Redcliff Pound Group is revised to include only those units exposed in the Redcliff Pound area, which are probably mainly of Ediacaran age. The similarity of the succession to the Neoproterozoic of the Amadeus Basin allows the possibility that equivalents to some of the Neoproterozoic petroleum systems identified in that basin could also be present in the Murraba Basin. In particular, the possibility of an equivalent to the subsalt, high-helium 'Gillen–Heavitree petroleum system', that has a high success rate in the Amadeus Basin (two technical successes from two wells drilled), should be considered. Salt is present at the appropriate level in many other areas of the Centralian Superbasin. While the presence of equivalent salt in the Murraba Basin cannot be proven from the limited surface data, structural style is locally suggestive of halotectonics. Ediacaran–Cambrian hydrocarbon systems, analogous to the Dingo Gas Field of the Amadeus Basin, if present, are unlikely to have had sufficient burial or be sealed in the Murraba Basin. The Hidden Basin beds, previously considered to overlie the Redcliff Pound Group, are probably older and in fault contact. It is possible that they are part of the much older Birrindudu Basin.

KEYWORDS: biostratigraphy, Cambrian, hydrocarbon exploration, Proterozoic, sedimentary geology, stratigraphy

Introduction

The predominantly Neoproterozoic Centralian Superbasin, an inferred connection of now tectonically separated intracratonic basins, is locally prospective for hydrocarbon resources. To date, exploration has been largely restricted to the eastern Amadeus Basin, and parts of the Officer Basin, where oil and gas shows and gas discoveries have been encouraging. The recent building of a pipeline from the Dingo Gasfield to Alice Springs (Department of Mines and Energy, Energy Directorate, 2016) represents the first commercialization of Neoproterozoic-sourced gas from the Centralian Superbasin. Other gas discoveries, although currently not commercial, have been technical successes, and indicate the presence of multiple Neoproterozoic hydrocarbon systems. Similar Neoproterozoic to lower Cambrian basins in Oman, Russia and China host giant oil and gas fields (Ghori et al., 2009; Craig et al., 2013; Zhu et al., 2015). In the Centralian Superbasin, the scarcity of wells and seismic data, poor outcrop and extensive cover in most areas, and the lack of high-resolution biostratigraphy means that much of the superbasin remains poorly known, and long-distance correlations within and between component basins are often problematic.

A good example is the remote Murraba Basin straddling the Western Australia (WA) – Northern Territory (NT) border, which, due to limited geological data, has not previously been assessed for hydrocarbon potential. This Record, which focuses on a reassessment of stratigraphy, interbasin correlations and tectonic setting of the basin, is a first step in this direction. With very limited subsurface data, this reconnaissance examination is largely based on the incomplete stratigraphic record as revealed at select outcrops. The revised understanding of how the stratigraphy of this basin may fit the regional Centralian Superbasin stratigraphic framework, and specifically how it correlates to the nearby Amadeus Basin and its prospective Neoproterozoic hydrocarbon systems, permits a tentative discussion of the hydrocarbon exploration potential of this basin for the first time.

Background

Centralian Superbasin

The Centralian Superbasin (Walter and Gorter, 1994; Walter et al., 1995) is a term for an extensive, interconnected, intracratonic depositional system that occupied a large area of the central, western and northern Australian landmass during the Neoproterozoic to early Paleozoic. Tectonic events from the late Neoproterozoic to late Paleozoic sequentially fragmented this depositional system into the current configuration of structurally separate basins. As originally conceived, the superbasin was restricted to the Officer (including former 'Savory Basin'), Amadeus, Ngalia and southern Georgina Basins. Walter and Veevers (1997) tentatively included the younger components of the Birrindudu Basin (now Murraba Basin), while later workers further included the Yeneena Basin of the Paterson Orogen, and the Louisa, Wolfe and Victoria Basins of the Kimberly region (Fig. 1; Grey et al., 2005; Carson, 2013; Munson et al., 2013). The Irindina Province, between the Amadeus and Georgina Basins, is interpreted as a metamorphic remnant of the superbasin (Scrimgeour, 2013c). The superbasin is tentatively extended beneath the eastern part of the Canning Basin where petroleum wells have penetrated sedimentary and low-grade metasedimentary basement. Support for this interpretation comes from geochronology on detrital zircons from metasedimentary basement in petroleum well Acacia 2 (Fig. 1), which gives a maximum depositional age of c. 870 Ma, similar to the inferred initiation of the Centralian Superbasin (Haines et al., 2013). The Adelaide Rift Complex ('Adelaide Geosyncline') is excluded from the definition of the intracratonic Centralian Superbasin because it evolved into a passive continental margin succession following continental breakup during deposition. However, the two entities were presumably connected during deposition as they share clear lithostratigraphic and biostratigraphic links at many levels.

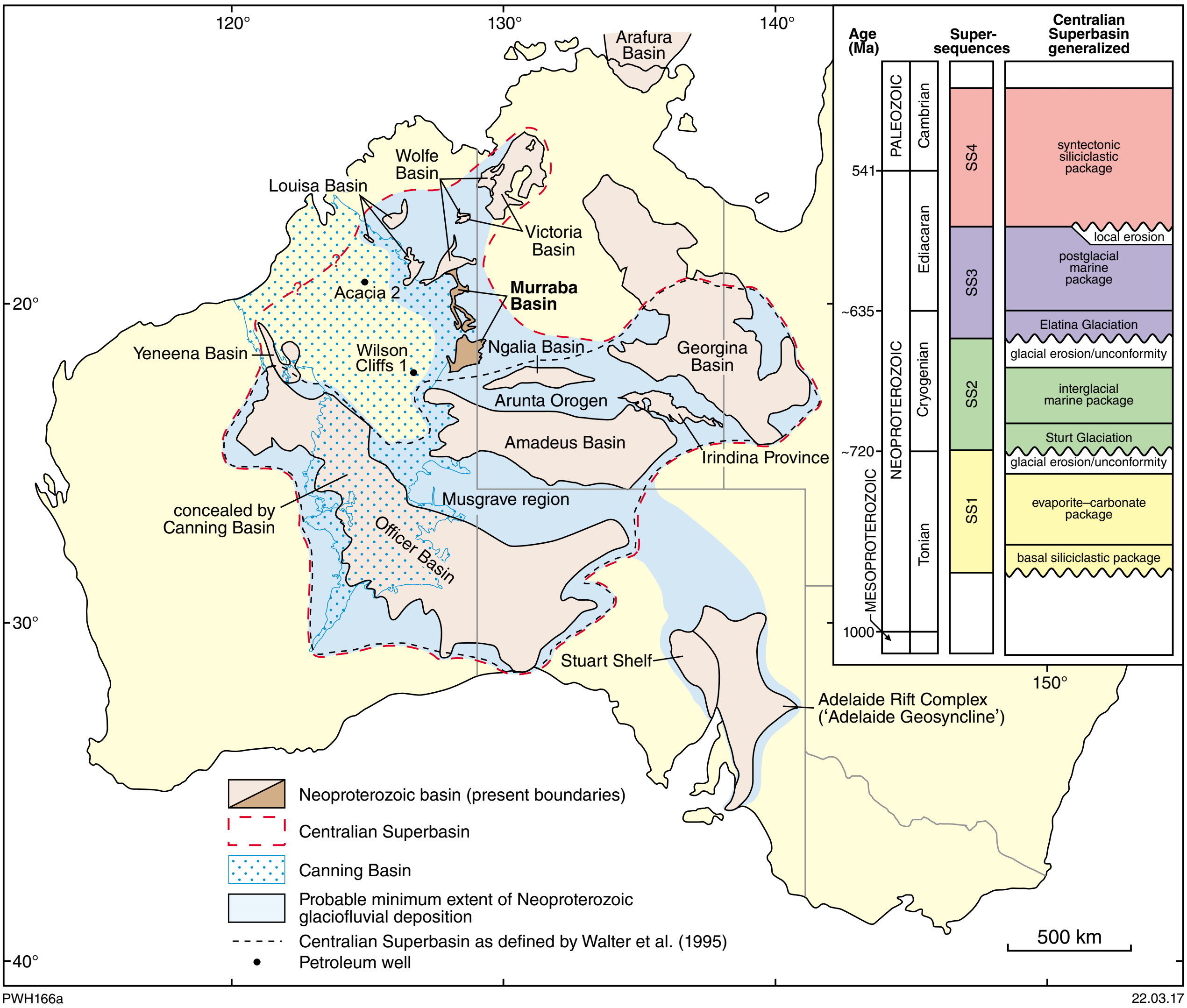

Figure 1. **Location map of components of the Centralian Superbasin modified after Munson et al. (2013). Murraba Basin highlighted. Generalized Centralian Superbasin stratigraphy shown in inset. Stippled area is concealed by the younger Canning Basin**

The superbasin model has been criticized because detrital zircon data indicate that late Mesoproterozoic zircons, generally assumed to be from magmatic sources in the Musgrave region now exposed between the Amadeus and Officer Basins, were supplied to the Amadeus Basin episodically throughout the Neoproterozoic (Camacho et al., 2002, 2015). Thus the Musgrave region could not have been totally covered by a thick blanket of sediment during this time, as implied by a simplistic Centralian Superbasin model. In our view this does not negate the entire superbasin concept, but if correct, only means that the superbasin may have had a more complex shape than originally envisaged, and surrounded local emergent basement highs. Alternatively, Haines et al. (2015) pointed to subtle variations in the age spectra of late Mesoproterozoic detrital zircons with the depositional age of sampled units through the Neoproterozoic succession of the Amadeus Basin. The implication is that the detrital zircon source, or sources, may have changed through time and that the Musgrave region may not have been the source, or sole source, of Mesoproterozoic zircons at all stratigraphic levels. Conclusive links between Amadeus Basin detrital zircons and the Musgrave region are only demonstrated during the transgression at basin initiation, and during later episodes of basement-involved tectonism. A more distal source of late Mesoproterozoic zircons, subtly different in age distribution from the Musgrave region, may have provided zircons to the sediments in the interim. Hf isotopes offer the promise of distinguishing those different source regions.

Supersequences

The Neoproterozoic to lower Cambrian stratigraphy of the Centralian Superbasin has been subdivided into four supersequences (Fig. 1), mostly separated by unconformities (Walter and Gorter, 1994; Walter et al., 1995). Although this scheme is believed to be applicable across the superbasin, certain supersequences may be missing due to nondeposition or erosion in some areas, and isolated successions may be difficult to assign to specific supersequences due to lack of biostratigraphic or other correlation information.

Supersequence 1

Supersequence 1 unconformably overlies crystalline basement or older sedimentary basins. It typically displays a basal fluvial to shallow-marine siliciclastic unit (conglomerate, sandstone, minor siltstone; locally metamorphosed) overlain by a thick succession of mudstone, stromatolitic carbonate, sandstone and evaporites. Significant accumulations of halite low in the succession are responsible for halotectonic deformation across parts of the Centralian Superbasin (Lindsay, 1987; Dyson and Marshall, 2007). The halite could potentially form a seal over a hydrocarbon system lower in the basin succession. Supersequence 1 is inferred to be largely or entirely of Tonian (early Neoproterozoic) age. This age assignment follows the recent amendment of the age of the Tonian–Cyrogenian boundary to c. 720 Ma (Shields-Zhou et al., 2016). Supersequence 1 typically contains disconformities of at least local extent.

Supersequence 2

The base of Supersequence 2 is marked by a regional unconformity at the base of the oldest Cryogenian glacial event, the Sturt (Sturtian) glaciation (Sturt Tillite and correlatives in the Adelaide Rift Complex). While the presence of an unconformity has led to the assumption there was a widespread tectonic event at this time (the ‘Areyonga Movement’ of Wells et al., 1970), it is more likely that in most areas the unconformity is simply related to significant erosion induced by lowering of sea level and possibly mild deformation related to ice sheet loading and movement over poorly consolidated sediments during the glaciation (an unconformity at the base of Cyrogenian glacial units is common worldwide). This does not negate the possibility that local tectonic events at around this time may have contributed in some areas. Siliciclastic glacial and periglacial facies (diamictite, conglomerate, sandstone) in the lower part of Supersequence 2 are overlain by postglacial, fine-grained marine siliciclastics and minor carbonates. The age of the supersequence is restricted to the Cyrogenian. Supersequence 2 is well developed in the Amadeus, Ngalia, Georgina, and central and eastern Officer Basins (Preiss et al., 1978; Walter et al., 1995; Haines et al., 2008). It appears to be absent in most of the western Officer and Yeneena Basins (Grey et al., 2005), and its presence in Neoproterozoic basins of the Kimberley region is controversial (Coats and Preiss, 1980; Corkeron, 2008).

Supersequence 3

The base of Supersequence 3 is another regional unconformity at the base of a second glacial interval, attributed to the Elatina (Marinoan) glaciation (see Williams et al., 2008 for discussion of terminology) first recognized in the Adelaide Rift Complex. The basal unit varies from glacial diamictite to periglacial sandstone, arkose or conglomerates, which are locally capped by a thin carbonate unit (postglacial ‘cap carbonate’). This is overlain by fine-grained marine siliciclastics, variable thicknesses of interbedded shallow-marine sandstone, capped finally by shallow-marine carbonates. If we assume it is valid to correlate the Elatina glaciation with radiometrically dated glacial successions overseas (Rooney et al., 2015), the age of Supersequence 3 ranges from late Cryogenian to Ediacaran.

Supersequence 4

Supersequence 4 is dominated by deltaic, fluvial and eolian siliciclastic strata coeval with the Petermann Orogeny and correlative events. Supersequence 4 straddles the Ediacaran–Cambrian boundary, as determined by body fossils and trace fossils preserved in areas with marine influence, such as the Georgina Basin and eastern Amadeus Basin (Walter et al., 1989; Haines et al., 1991; McIlroy et al., 1997). However, in many areas, such as the western Amadeus Basin, the Ediacaran–Cambrian boundary position cannot be determined due to the lack of suitable marine facies (Haines and Allen, 2014). The age of the syntectonic Supersequence 4 can be broadly constrained to the duration of the Petermann Orogeny, as determined from basement geochronology (580–520 Ma; Close, 2013; Howard et al., 2015). The base of Supersequence 4 may be unconformable, disconformable, or possibly locally conformable, depending on proximity to tectonic uplift. An internal unconformity or disconformity at or close to the Ediacaran–Cambrian boundary is recognized at least locally in the Georgina (Haines et al., 1991; Kruse et al., 2013), eastern Amadeus (McIlroy et al., 1997) and Ngalia Basins (Burek et al., 1979). In the eastern Amadeus and Georgina Basins, Supersequence 4 is succeeded, apparently conformably, by fossiliferous marine Cambrian strata (Edgoose, 2013; Kruse et al., 2013), but in many areas to the west it is followed by a large hiatus in sedimentation (Grey et al., 2005; Haines and Allen, 2014).

Murraba Basin

Location

The Murraba Basin underlies the Tanami Desert straddling the WA–NT border, although the majority of the basin lies within WA (Figs 1 and 2). The irregular remnants of the basin outcrop across seven 1:250 000-scale map sheets (Webb, Stansmore, Lucas, Billiluna in WA, and Lake Mackay, Highland Rocks and The Granites in the NT)*. Minor extensions into the Wilson and Gordon Downs areas are inferred under cover in WA.

Tectonic setting

The Murraba Basin unconformably overlies the Aileron Province (Arunta Orogen) in the south, the Granites–Tanami Orogen and Tanami Basin in central areas, and the Birrindudu Basin in the north. Contacts with coeval basins — the Amadeus Basin in the south and Wolfe Basin in the north — are not exposed, but are inferred to be faulted. The younger Canning Basin is in fault contact to the west and locally overlies the Murraba Basin as the Lucas Outlier and smaller remnants. The Murraba Basin is mostly gently folded and faulted, although there is tight folding locally near major fault zones. Most of the deformation occurred prior to deposition of Paleozoic Canning Basin rocks.

Previous investigations

The stratigraphy of Murraba Basin units has undergone at least two significant revisions since they were first mapped by the Bureau of Mineral Resources (BMR) in the 1950s and early 1960s. Initially, outcrops now included in the Murraba Basin were mostly assigned to the Gardiner, Phillipson and Kearney beds during first edition mapping of the Billiluna, Lucas and Stansmore 4-Mile Geological Series maps (Wells, 1962a,b,c; Casey and Wells, 1964). These units were considered to be upper Proterozoic, but were not assigned to any basin at this time. During second edition mapping for 1:250 000-scale maps of the same and adjacent areas by BMR and GSWA in the 1970s, the stratigraphy was substantially revised and the newly recognized stratigraphic units were assigned to the Birrindudu Basin (Blake et al., 1973, 1979).

This revised stratigraphy (Fig. 3) was dominated by the Redcliff Pound Group (redefined herein), comprising basal siliciclastic units, the Munyu Sandstone in the south, Lewis Range Sandstone in the north, and Muriel Range Sandstone in the east. The last of these is almost entirely contained within the NT. These basal units were considered to be lateral equivalents of each other. The remainder of the Redcliff Pound Group comprised the Murraba Formation and Erica Sandstone, in ascending order. Shallow stratigraphic drilling by BMR and Esso Australia Ltd (mostly not cored), over areas of extensively Cenozoic cover, was reported by Blake (1974). Blake et al. (1979) estimated that the true thickness of the Redcliff Pound Group, as originally defined, is at least 2000 m, and may be much greater because an unknown thickness of stratigraphy is concealed beneath Cenozoic deposits. The local Denison, Jawilga and Boee beds on second edition Billiluna were considered potential correlatives of the Lewis Range Sandstone, Murraba Formation and Erica Sandstone, respectively (Blake et al., 1977, 1979).

Blake et al. (1979) inferred an ‘Adelaidean’ (Neoproterozoic) age for the Redcliff Pound Group and correlated the basal siliciclastic units with the lithologically similar Heavitree Formation of the Amadeus Basin. The remainder of the group was correlated with the Bitter Springs Group that overlies the Heavitree Formation in the Amadeus Basin. The reasons for this correlation are not entirely clear as there is little resemblance between the exposed Murraba Formation to Erica Sandstone package (outcrop of which is dominated by sandstone), and the carbonate, siltstone and evaporite facies of the Bitter Springs Group. It is likely that the apparent absence of glacial facies (which lie above the Bitter Springs Group in the Amadeus Basin), and the assumption that the basal siliciclastic units are conformable with the Murraba Formation, played an important role in the correlation.

The siliciclastic-dominated Hidden Basin beds (Blake and Yeates, 1976; Blake et al., 1979) crop out to the west of exposures mapped as Redcliff Pound Group on Stansmore and central-north Webb. On regional structural evidence, it was inferred that the Hidden Basin beds overlie the Erica Sandstone (‘possibly conformably’; Blake et al., 1979, p. 51), and thus were considered potentially a younger unit of the Redcliff Pound Group, although the only exposed contact was described as faulted. The age was inferred to be ‘late Adelaidean’ (late Neoproterozoic). If correct, the Hidden Basin beds could be correlated with some or all of the Neoproterozoic or even Cambrian succession above the Bitter Springs Group in the Amadeus Basin, although there is a notable absence of characteristic lithofacies of that succession, such as glacial diamictites.

There has been very little work on these successions in WA since field mapping in the 1970s. Grey (1990) summarized the previous literature and maintained the suggested correlations that Blake et al. (1979) had made. Walter and Veevers (1997) were the first to tentatively

* Map names in small caps refer to second edition 1:250 000-scale Geological Series maps, unless otherwise specified

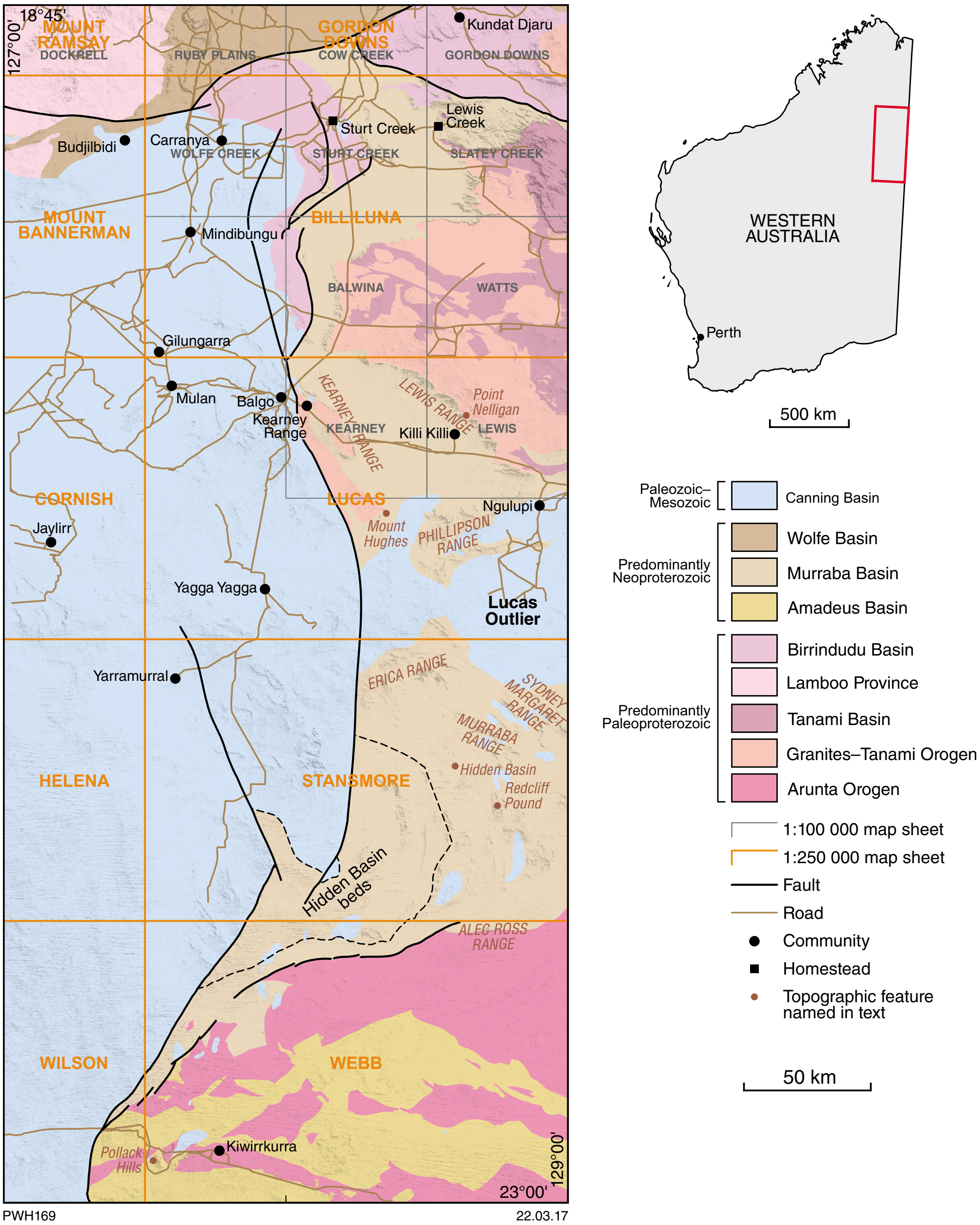

Figure 2. Location map of the Western Australian portion of the Murraba Basin with surrounding tectonic domains and indexes of published 1:250 000 and 1:100 000 Geological Series maps. Shading shows relief

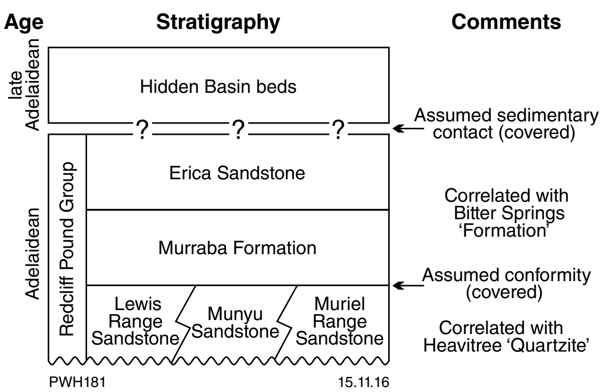

Figure 3. Original stratigraphy and inferred relationships of the Redcliff Pound Group and Hidden Basin beds, and regional correlations, as presented by Blake et al. (1979). Note that Bitter Springs 'Formation' is now a group and the name Heavitree 'Quartzite' has been revised to Heavitree Formation

include the Redcliff Pound Group in the Centralian Superbasin, using previous correlations to conclude that the Redcliff Pound Group was restricted to Supersequence 1. The name Murraba Basin was first applied to the Redcliff Pound Group and Hidden Basin beds by Grey et al. (2005) and Tyler (2005), who took the name from the Murraba Ranges in WA. The basin name was subsequently used on the second edition HIGHLAND ROCKS (Vandenberg et al., 2006), LAKE MACKAY (Edgoose et al., 2008) and THE GRANITES (Vandenberg and Crispe, 2014) in the NT (Ahmad, 2013). The redefined Birrindudu Basin is now restricted to sedimentary units of late Paleoproterozoic to possibly early Mesoproterozoic age (Dunster and Ahmad, 2013), of which the youngest stratigraphic component has a conservative maximum depositional age from detrital zircons of c. 1600 Ma (Carson, 2013). Recent evidence of links beneath surficial cover between the McArthur (northeast NT) and Birrindudu Basins, to jointly comprise the 'greater McArthur Basin', implies that the age of the Birrindudu Basin may extend significantly up into the Mesoproterozoic, at least in the NT (Munson, 2016).

The northern part of the Murraba Basin is represented on recent GSWA 1:100 000 Geological Series maps BALWINA (Eacott et al., 2014a), SLATEY CREEK (Eacott et al., 2014b), WATTS (Eacott et al., 2014c), KEARNEY (Eacott and de Souza Kovacs, 2015a) and LEWIS (Eacott and de Souza Kovacs, 2015b). These maps incorporated new field mapping in the Granites–Tanami Orogen and Tanami Basin, but the stratigraphy of the Murraba Basin succession was not reassessed.

Stratigraphy

Original Redcliff Pound Group

Munyu Sandstone

The Munyu Sandstone (Blake and Yeates, 1976; Blake et al., 1979), named after Munyu Hills in the NT, is a basal unit to the southern Murraba Basin, and a basal unit of the original Redcliff Pound Group (Fig. 3 and see below for redefinition). It crops out on WEBB, STANSMORE and HIGHLAND ROCKS (NT) where it forms strike ridges trending east to northeast. The type section is an isolated strike ridge on southeastern STANSMORE (approximately MGA 491600E 7577100N), where the formation has its maximum exposed thickness of 400 m (Blake et al., 1979). The unit unconformably overlies basement of the Aileron Province of the Arunta Orogen on WEBB (Blake, 1977; Hollis et al., 2013). Blake et al. (1979) inferred that it is overlain conformably by the Murraba Formation. This inference is open to question, as mapped outcrops of the respective units are separated by at least 3 km of Cenozoic cover on HIGHLAND ROCKS in the NT (Vandenberg et al., 2006), and the minimum separation by Cenozoic cover is significantly greater in WA.

The following regional description of the Munyu Sandstone is summarized from Blake et al. (1979). The dominant rock type is medium- to very coarse-grained, thin- to medium-bedded, silicified quartz arenite. It commonly contains scattered pebbles and granular lenses and beds of quartz-pebble conglomerate, especially near the base. Feldspathic and micaceous sublithic arenite beds are also present locally near the base of the formation. Cross-bedding is common. Blake et al. (1979) also reported an interbedded limestone lens a few metres thick at one locality on STANSMORE, and limestone with chert laminae at or near the top of the Munyu Sandstone in the Alec Ross Range on WEBB. The limestone is described as crystalline with local laminar banding suggesting it may be stromatolitic. Blake et al. (1979) reported that samples of carbonate and chert were examined for microfossils, but found to be barren.

Lewis Range Sandstone

The Lewis Range Sandstone (Crowe and Muhling, 1977; Blake et al., 1979), named after Lewis Range on LUCAS, is restricted to BILLILUNA and LUCAS in WA. It is the basal unit in the northern Murraba Basin, and a basal unit of the originally defined Redcliff Pound Group. Blake et al. (1979, p. 46) specified the type section as 'the steep side of a cuesta 1.5 km southwest of Point Nelligan' (MGA 462100E 7765300N). This section is restricted to the base of the unit where it unconformably overlies the Lewis Granite and is only about 20 m thick. Elsewhere along the Lewis Range, southeast of the type section, the thickness of the formation is estimated to reach 400 m (Blake et al., 1979). According to Blake et al. (1979) the maximum exposed thickness of the unit is approximately 1000 m in the Kearney Range to the west; however, we consider the stratigraphy of the Kearney Range to be questionable, as discussed later.

The following regional description of the Lewis Range Sandstone is summarized from Blake et al. (1979). The unit is dominated by well-sorted, fine- to medium-grained, thin- to medium-bedded quartz arenite, with subordinate, poorly sorted, sublithic arenite, quartz arenite and conglomerate. The subordinate lithologies are mainly found near the base. Minor siltstone is present locally. The dominant quartz arenite is either white or iron stained to shades of brown or maroon, and has a clayey matrix. Cross-bedding and ripple marks are widespread. A basal conglomerate up to 3 m thick, in places interbedded with finer grained siliciclastic lithologies, is commonly present where the formation overlies granite and metamorphic rocks of the Granites–Tanami Orogen. The pebbles and cobbles mainly consist of quartz, but include various basement lithologies. The formation is generally friable, but is locally silicified in the Kearney Range (see later comments on the stratigraphy of the Kearney Range). Blake et al. (1979) interpreted the unit as a lateral equivalent of the Munyu Sandstone to the south and the Muriel Range Sandstone in the NT.

Muriel Range Sandstone

The Muriel Range Sandstone (Hodgson, 1976; Blake et al., 1979) is defined in the NT and restricted to the NT on current geological maps. According to Blake et al. (1979), the formation reaches 450 m in thickness and consists predominantly of sublithic arenite and quartz arenite, but also includes minor siltstone, shale, arkose, conglomerate, and breccia. The Muriel Range Sandstone lies unconformably on Granites–Tanami Orogen and Tanami Basin rocks, and has been correlated with both the Lewis Range Sandstone and Munyu Sandstone (Blake et al., 1979). The unit was said to be distinguished from its correlatives by its very thin to thin bedding and the abundance of shale pellets. Due to its restriction to the NT it has not been reassessed during this study.

Murraba Formation

The Murraba Formation (Blake and Yeates, 1976; Blake et al., 1979) was named after the Murraba Ranges on STANSMORE. According to Blake et al. (1979) the Murraba Formation is inferred to be conformable on the Lewis Range Sandstone in the northwest and the Munyu Sandstone in the south. However, in both areas there is a considerable separation by Cenozoic cover of even the closest mapped outcrops of the respective units (2.5 km in north, 7 km in the south, 3 km in the NT). This allows for a considerable thickness of hidden stratigraphy between the exposures of the respective units, which previous workers assumed to be Murraba Formation. Blake et al. (1979, p. 48) stated that 'in the type section on the east side of Redcliff Pound at 21°36'30"S 128°46'30"E, about 350 m is exposed, dipping west at about 25°'. No top or base coordinates are specified, but the stated location (approximately MGA 476700E 7610500N) roughly corresponds with the top contact as represented on STANSMORE. According to Blake et al. (1979, p. 48) the conformable contact with the overlying Erica Sandstone was 'taken at the top of the highest bed of chert-granule conglomerate'.

The following regional description of the Murraba Formation is summarized from Blake et al. (1979). The formation consists of interbedded chert-granule conglomerate, sublithic arenite, quartz arenite, siltstone, shale, pebble conglomerate and dolomite. The chert-granule conglomerate, which was considered the diagnostic lithology of the formation, comprises rounded to subangular granules, and less commonly pebbles, composed predominantly of chert, set in a matrix of medium-grained sublithic to quartz arenite, which has a quartz-overgrowth cement. The sublithic arenite and quartz arenite are mainly thin bedded and fine to medium grained, and commonly silicified. Some beds are micaceous and some contain scattered granules of quartz and chert. Siltstone and shale interbeds are present at some localities. Pinkish to purple and grey laminated dolomite was reported in the Redcliff Pound area on STANSMORE.

Shallow stratigraphic drillholes intersected the succession below outcropping Murraba Formation in northern LUCAS and southern BILLILUNA (Blake, 1974); locations of these drillholes are indicated on the second editions of these maps. The intersected lithologies (identified mostly from cuttings as very little core was drilled) include mudstone, shale, dolomite, calcareous sandstone, chert and conglomerate. This succession has been referred to by Blake et al. (1979) as the Murraba Formation.

Erica Sandstone

The Erica Sandstone (Crowe and Muhling, 1977; Blake et al., 1979) was named after Erica Range on northern STANSMORE, and is largely restricted to LUCAS and STANSMORE in WA, and HIGHLAND ROCKS in the NT. Outcrops originally assigned to the Erica Sandstone on BILLILUNA have been reassigned to other units on the BALWINA 1:100 000 Geological Series map by Eacott et al. (2014a). The type section of the Erica Sandstone is 'across the main cuesta of the Erica Range, from 21°05'50"S, 128°30'00"E, to 21°07'00"S, 128°29'00"E, where a sequence about 400 m thick dips 5–10° southwest' (Blake et al., 1979). No other units are mapped nearby and the Erica Range is surrounded by sand dunes; hence, no boundary criteria can be applied to the type section. Elsewhere, the contact with the underlying Murraba Formation was deemed conformable on chert-granule conglomerate at the top of the Murraba Formation (Blake et al., 1979). In WA, the Erica Sandstone is unconformably overlain by Paleozoic outliers of the Canning Basin. In the NT the unit is inferred to be overlain by the Antrim Plateau Volcanics of the Kalkarindji Large Igneous Province (Ahmed, 2013), which has an age of c. 510 Ma (Jourdan et al., 2014).

The following regional description of the Erica Sandstone is summarized from Blake et al. (1979). The predominant rock type is well-sorted, fine- to medium-grained, friable, sublithic arenite that has up to 10% clay matrix. It is mainly medium bedded and either white or iron stained to purple or reddish-brown. Cross-bedding is very common, with most foresets less than 1 m thick, but larger scale foresets are present locally; for example, in the western Erica Range (upper part of the type section). Ripple marks and bedding planes covered with shale pellets are common, and scattered shale clasts, very coarse quartz grains, and well-rounded pebbles of quartz and chert are present in places, mainly in the lower part of the formation.

Hidden Basin beds

The Hidden Basin beds were first differentiated by Blake et al. (1973) from the earlier 'Gardiner Beds' of Wells (1962c), with more detailed description in Blake et al. (1979). The name is derived from Hidden Basin, a large depression containing Lake Wills and Lake Hazlett east of the northern exposures of the unit. The unit was inferred to overlie the Erica Sandstone, although no unfaulted contact was observed (Blake et al., 1979). Outcrop is mostly restricted to south-central STANSMORE (Blake and Yeates, 1976), but extends to the northern edge of WEBB (Blake, 1977; Spaggiari et al., 2016). No type section was proposed, but Blake et al. (1979) nominated a reference area 23 km southwest of Lake Hazlett centred at 21°40'S, 128°25'E (MGA 439600E 7604000N) where a succession about 2000 m thick dips west. Blake et al. (1979) estimated a maximum exposed thickness of about 3000 m, but stated that the unit may be considerably thicker with much of it concealed beneath Cenozoic cover. The unit is expressed as low strike ridges alternating with recessive valleys, and is folded into open and tight folds.

The following regional description of the Hidden Basin beds is summarized from Blake et al. (1979). Outcrop is dominated by quartz arenite and sublithic arenite, but includes laminated shale and siltstone. The latter lithologies are recessive and mainly exposed in a few creek beds, but could be the main lithologies beneath cover in recessive valleys. The arenites are white to pale grey, where they are not iron stained, and are mainly well sorted and fine to medium grained. They commonly have a sparse, white clayey matrix. Low-angle cross-bedding is very common, and some ripple marks are present. The quartz arenite is very thin to medium bedded, and is very well silicified. In places it contains scattered quartz pebbles. The sublithic arenite is mainly medium bedded, but is locally very thin bedded to laminated. Some sublithic arenite is micaceous and displays abundant shale pellets. Near faults, the Hidden Basin beds are closely jointed, brecciated, and veined by quartz.

During a brief helicopter survey of the area at the time of drilling of petroleum well White Hills 1 in the eastern Canning Basin in 1982, Mobil Exploration (1983, appendix 10) reported ‘common vertical tubes, worm burrows’ from an outcrop of red-brown sandstone identified as Hidden Basin beds at their site H-5. No fossils were reported from two additional sites visited in this unit. If confirmed as bona fide vertical burrows, the observations would be consistent with a Phanerozoic age for the rocks.

Review of detrital zircon data

A detrital zircon sample of the Munyu Sandstone (GSWA 184342) from the Alec Ross Range on northeastern WEBB was previously dated by GSWA (Kirkland et al., 2009b; Hollis et al., 2013). The $^{207}Pb/^{206}Pb$ date of 1099 ± 40 Ma (1σ) for the youngest zircon is interpreted as the maximum depositional age for the sandstone, with a more conservative estimate provided by the weighted mean date of 1155 ± 14 Ma (MSWD = 0.96) for the youngest 15 analyses (Kirkland et al., 2009b). The detrital zircon age spectra (Fig. 4a) has a significant late Mesoproterozoic component (1250–1100 Ma, maxima at c. 1162 Ma), with other significant components ranging between late Paleoproterozoic and earliest Mesoproterozoic (maxima at c. 1744 Ma and c. 1575 Ma).

Two detrital zircon samples of the Lewis Range Sandstone (GSWA 178851, Wingate et al., 2008a; GSWA 178852, Wingate et al., 2008b) have previously been dated by GSWA. The samples were collected in the Bramall Hills on the northern edge of the SLATEY CREEK 1:100 000 Geological Series map sheet, well north of the area surveyed for this Record. GSWA 178851 was collected near the base of the unit where it unconformably overlies the Paleoproterozoic Slatey Creek Granite of the Granites–Tanami Orogen. GSWA 178852 was collected higher in the unit. Both samples yielded similar zircon age spectra (Fig. 4b,c), with a broad spread of late Paleoproterozoic to earliest Neoproterozoic ages, but late Mesoproterozoic ages are dominant. Samples 178851 and 178852 provide maximum depositional ages of 916 ± 43 Ma and 986 ± 55 Ma (1σ), respectively, based on the $^{207}Pb/^{206}Pb$ dates for the youngest concordant zircons (Wingate et al., 2008a,b).

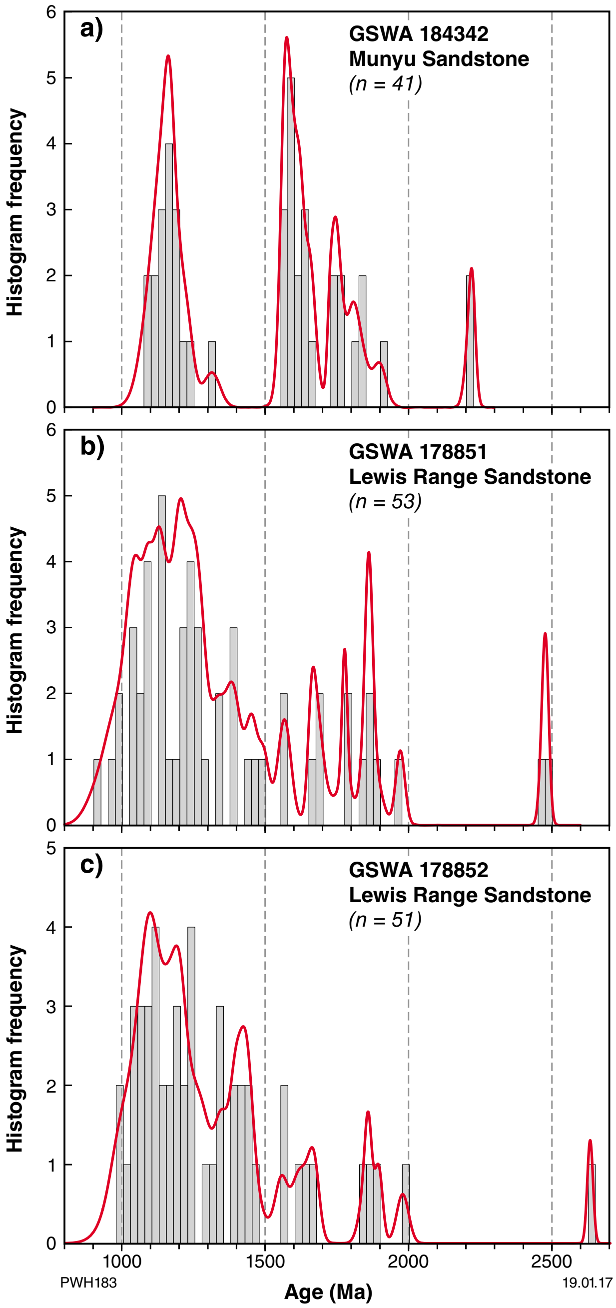

Figure 4. Probability density diagrams (red) and histograms (grey) of detrital zircon age data: a) Munyu Sandstone (Kirkland et al., 2009b); b) and c) Lewis Range Sandstone (Wingate et al., 2008a,b). Data >5% discordant excluded; n = the number of analyses displayed in each plot

Reconnaissance observations in 2015

Munyu Sandstone

Where examined around MGA 475000E 7570600N on southern STANSMORE, the Munyu Sandstone is typically a medium-grained, well-sorted quartz sandstone, varying from thin bedded and flaggy, to more commonly thick bedded and blocky (Fig. 5a). Fine-grained quartz-pebble conglomerate is present locally. Quartz grains are typically rounded, with minimal clay matrix visible between grains. Beds are massive to weakly bedded and cross-bedded. The rock often exhibits an orange-brown weathering skin, but is pale grey to white when freshly broken. The weathered surface is commonly silicified, but freshly broken surfaces may be slightly friable. The unit closely resembles the Heavitree Formation of the basal Amadeus Basin, with which it has long been correlated. No basal contact with Arunta Orogen basement is exposed in this area. Blake et al. (1979) reported a 'limestone' unit interbedded in the Munyu Sandstone at this locality, but we interpret this carbonate unit to be in fault contact with the Munyu Sandstone, and consider it most likely a separate younger unit (see below).

Lewis Range Sandstone

Outcrops mapped as Lewis Range Sandstone were examined within a 3 km radius of Mount Hughes (MGA 432860E 7727290N) on central LUCAS. These outcrops unconformably overlie weathered granitic basement of the Granites–Tanami Orogen (Fig. 5b). Only about 50 m of section is exposed in this area. Considering the thickness of the Lewis Range Sandstone reported elsewhere, this is interpreted to represent only the basal part of the formation, and may not be representative of the unit as a whole.

The basal few metres of the unit comprise poorly sorted, medium- to coarse-grained pebbly sandstone, with lenticular beds of granule to pebble conglomerate (Fig. 5c). Pebble clasts are almost exclusively white to grey quartz, and vary from angular to rounded. Pebbles are typically 1–3 cm in diameter, rarely up to 5 cm. The sandstone is quartz rich, but has a minor clay matrix. Higher in the unit, medium-grained, well-sorted, silicified sandstone alternates with more poorly sorted, medium- to coarse-grained and locally pebbly quartz sandstone. Trough cross-beds are commonly preserved where silicification is not too intense. Current ripples are locally common. The sandstone is typically white to pale brown or purple when freshly broken, but commonly has an orange-brown weathering skin (Fig. 5d).

Paleocurrents were determined largely from trough cross-beds, with minor data from current ripples. Although the full dataset includes a wide range of directions, there is a strong unimodal trend towards the west, with a mean flow vector towards 290° (Fig. 6a).

Unnamed carbonate unit

This unnamed carbonate unit is the 'limestone' unit described by Blake et al. (1979) as interbedded with the Munyu Sandstone. Where observed near the southern edge of STANSMORE (around MGA 475500E 7570200N) the outcrop is poor and mostly covered with soil, but consists of folded horizons of brown, partially silicified dolostone. The rock is typically coarsely recrystallized (sucrosic) and ferruginous, and there are poorly preserved microbial laminations and columnar stromatolites (Fig. 5e,f). There is no evidence that the unit is interbedded with the Munyu Sandstone; instead the field relationships strongly support a fault contact between the respective units. The carbonate unit at this location is likely to correlate with the lithologically similar carbonate unit of the Alec Ross Range described by Blake et al. (1979) as the topmost unit of the Munyu Sandstone. We infer that both outcrops represent a separate, as yet unnamed, unit stratigraphically above the Munyu Sandstone. The carbonate unit lithologically resembles components of the Bitter Springs Group, most notably the Gillen Formation at the base of the group, directly overlying the Heavitree Formation in the Amadeus Basin. The columnar stromatolites resemble *Tungussia erecta*, which is only known from the Gillen Formation in the central Amadeus Basin (Walter, 1972) and the Pollock Hills in the western Amadeus Basin (Allen et al., 2012). The latter site is only 160 km southwest of the current location. Unfortunately, the degree of recrystallization prevents conclusive identification.

Concealed stratigraphy below Murraba Formation

Previous workers assumed a downward continuation of the Murraba Formation under cover to rest conformably on the Munyu, Lewis Range or Muriel Range Sandstones, in their respective areas of distribution. To evaluate the nature of the covered succession, a traverse was walked from east to west across the plain southeast of Redcliff Pound (between approximately MGA 486100E 7613500N and 484600E 7613000N) in an area that displays distinct soil trend lines that are parallel to bedding trends in outcropping lower Murraba Formation farther west (Fig. 7). No in situ outcrop was found during this traverse, but the lithology of common float clasts was noted to change with changing soil patterns. Considering the very flat topography and absence of significant drainage channels, the clasts are considered indicative of underlying lithologies, rather than being significantly transported. Three distinct 'float clast units', labelled units 1 to 3 (Fig. 7) in assumed stratigraphic order, were distinguished.

Unit 1 (MGA 486100E 7613500N to 485300E 7613200N) is characterized by scattered calcrete (Fig. 8a), in places forming low mounds, associated with clasts of chert and carbonate rocks. The carbonate is mostly limestone, and is typically micritic and grey to purple-grey (Fig. 8b), but includes partially silicified and dolomitized ooid grainstones that are commonly a buff-yellow colour (Fig. 8c). Although no well-formed columnar

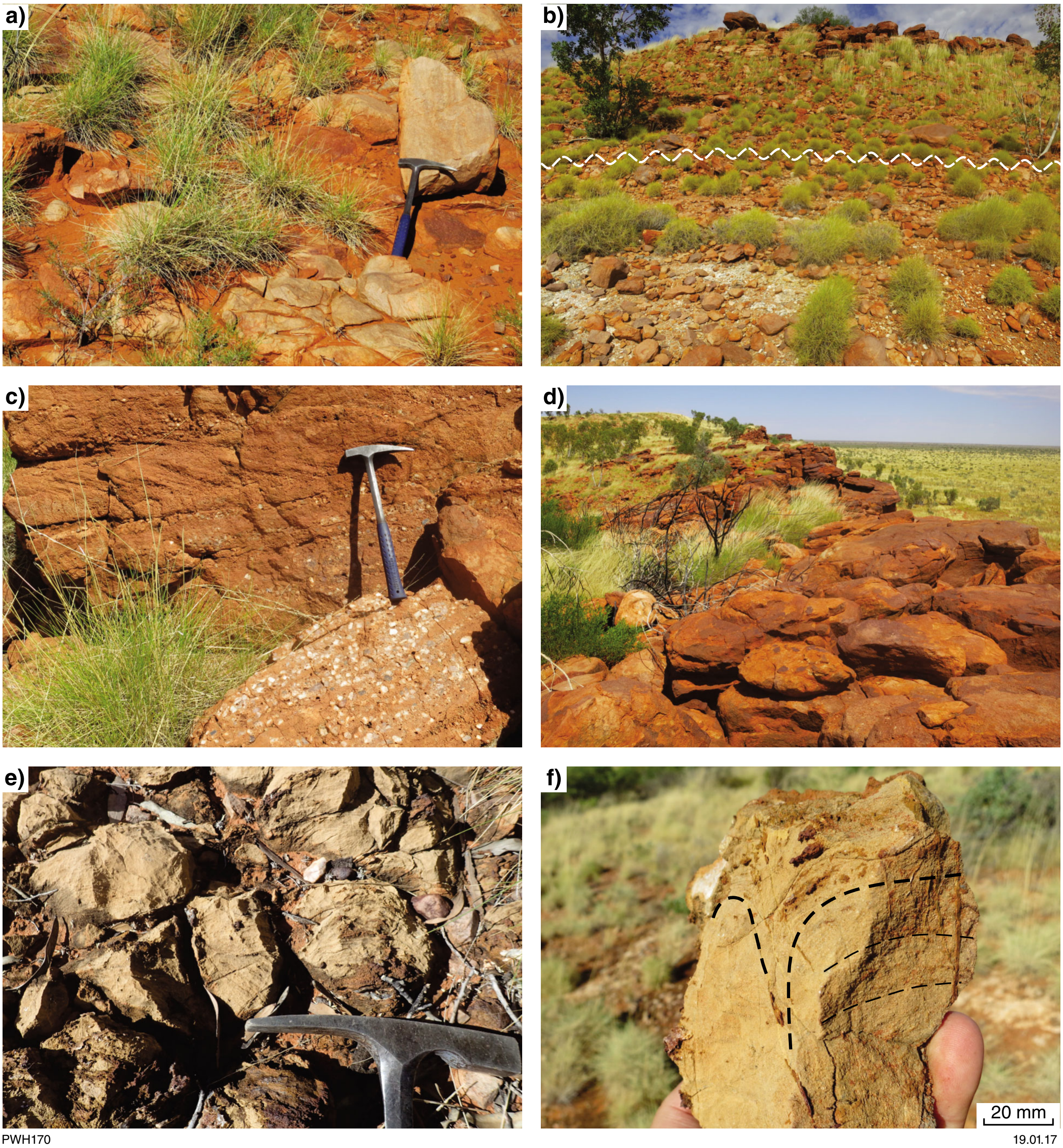

Figure 5. **Field photographs of lower Murraba Basin succession: a) typical outcrop of Munyu Sandstone; white, medium-grained, silicified sandstone (MGA 475029E 7570622N); b) Lewis Range Sandstone unconformably (dashed line) overlying weathered granitic basement exposed in foreground (MGA 431231E 7726835N); c) quartz-pebble conglomerate and coarse-grained, cross-bedded sandstone typical of the basal Lewis Range Sandstone (MGA 431081E 7727090N); d) southern-most outcrops of Lewis Range Sandstone in the Mount Hughes area (MGA 431000E 7727000N); e) recrystallized dolostone with poorly preserved stromatolites in fault contact with Munyu Sandstone (MGA 475326E 7570291N); f) same unit as e) with highlighted stromatolite column margins (heavy dashed lines) and laminae (light dashed lines) (MGA 475449E 7570250N)**

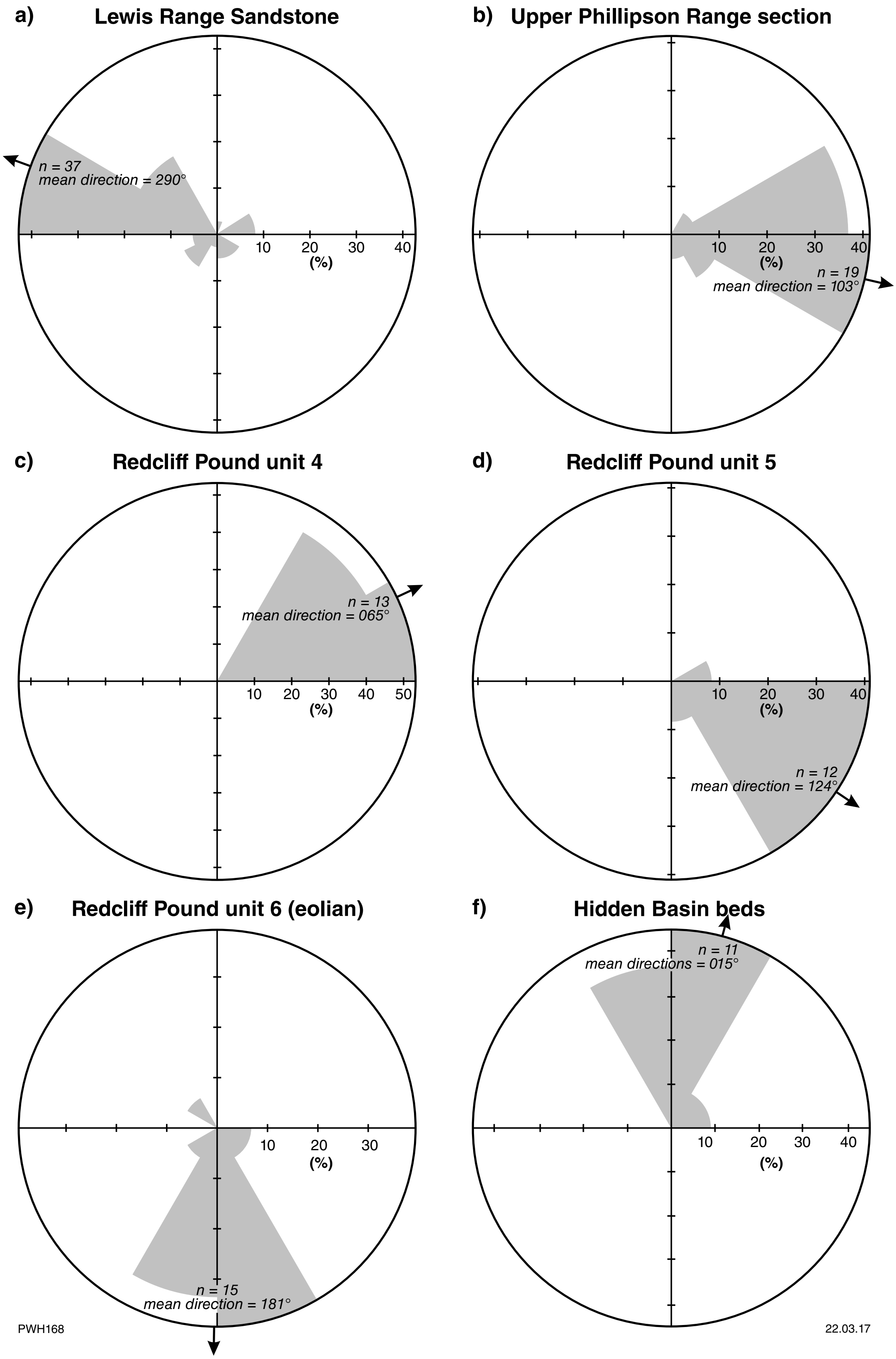

Figure 6. Paleocurrent rose diagrams for cross-bed data: a) Lewis Range Sandstone near Mount Hughes; b) to e) Murraba Formation and Erica Sandstone; see text for discussion of local units; f) Hidden Basin beds at reference section. The plotting interval is 30°, n = number of measurements, and arrows indicate mean direction

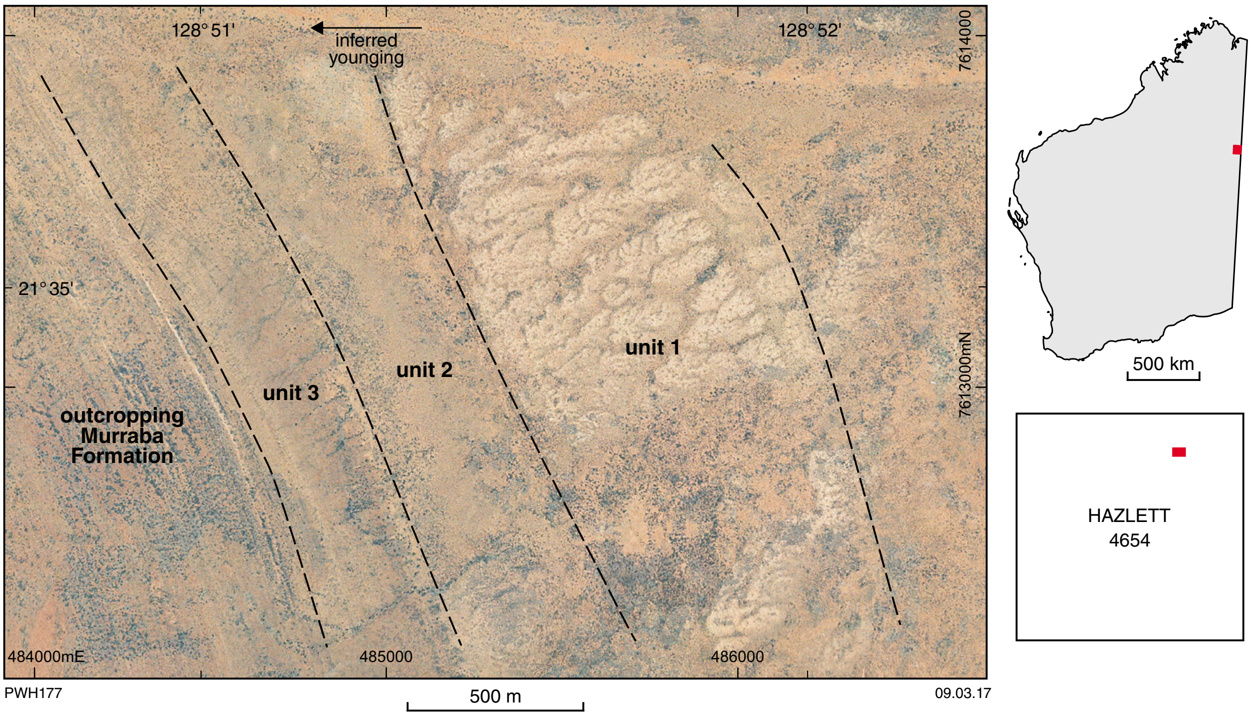

Figure 7. **Orthophoto image within HAZLETT 1:100 000 map tile, showing regolith trends east of Redcliff Pound; regolith units are described in text**

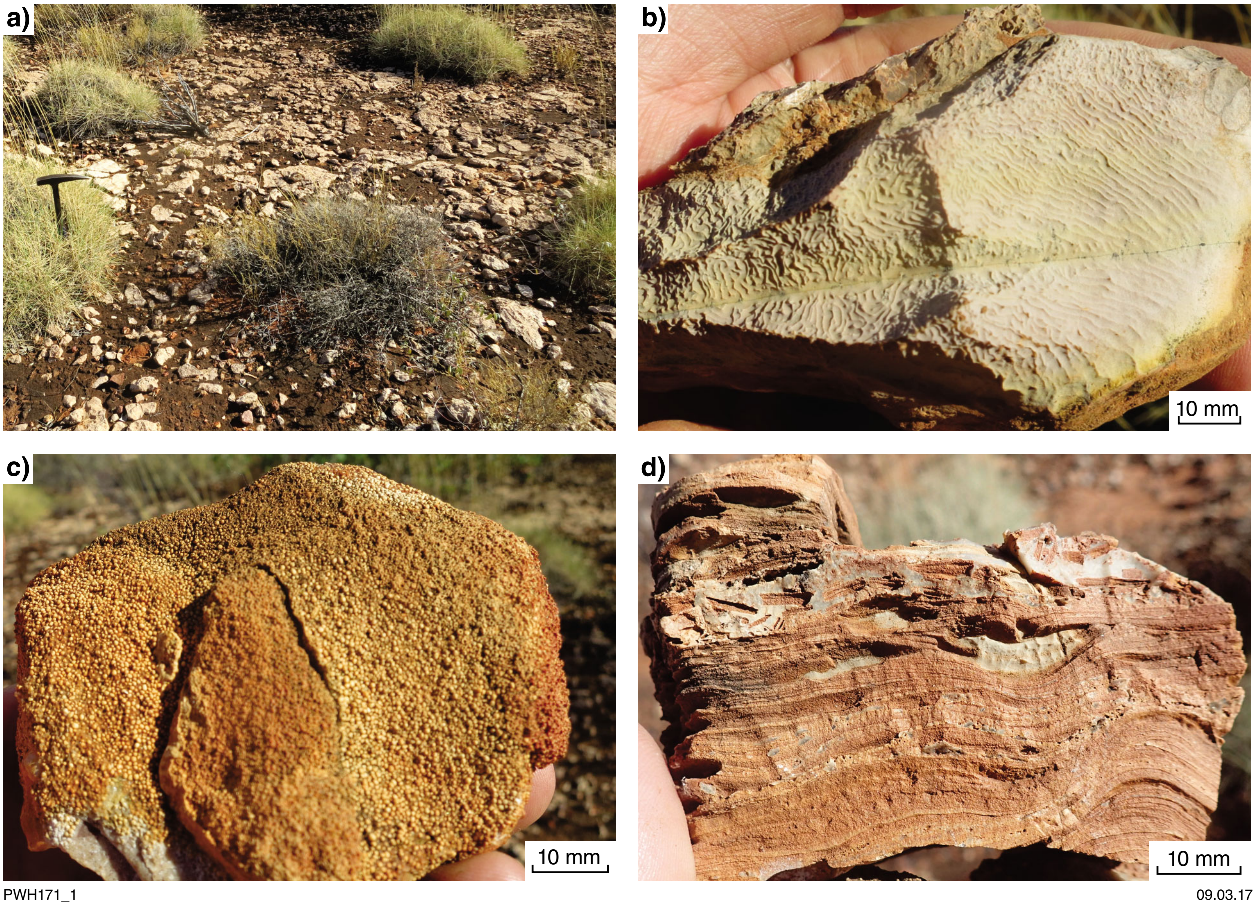

Figure 8. **Field photographs of regolith over concealed interval: a) typical clast-bearing calcrete (MGA 485500E 7613300N); b) grey micritic limestone clast (MGA 485500E 7613300N); c) oolitic dolostone clast (MGA 485500E 7613300N); d) silty carbonate clasts showing domical lamination and intraclasts (MGA 485500E 7613300N)**

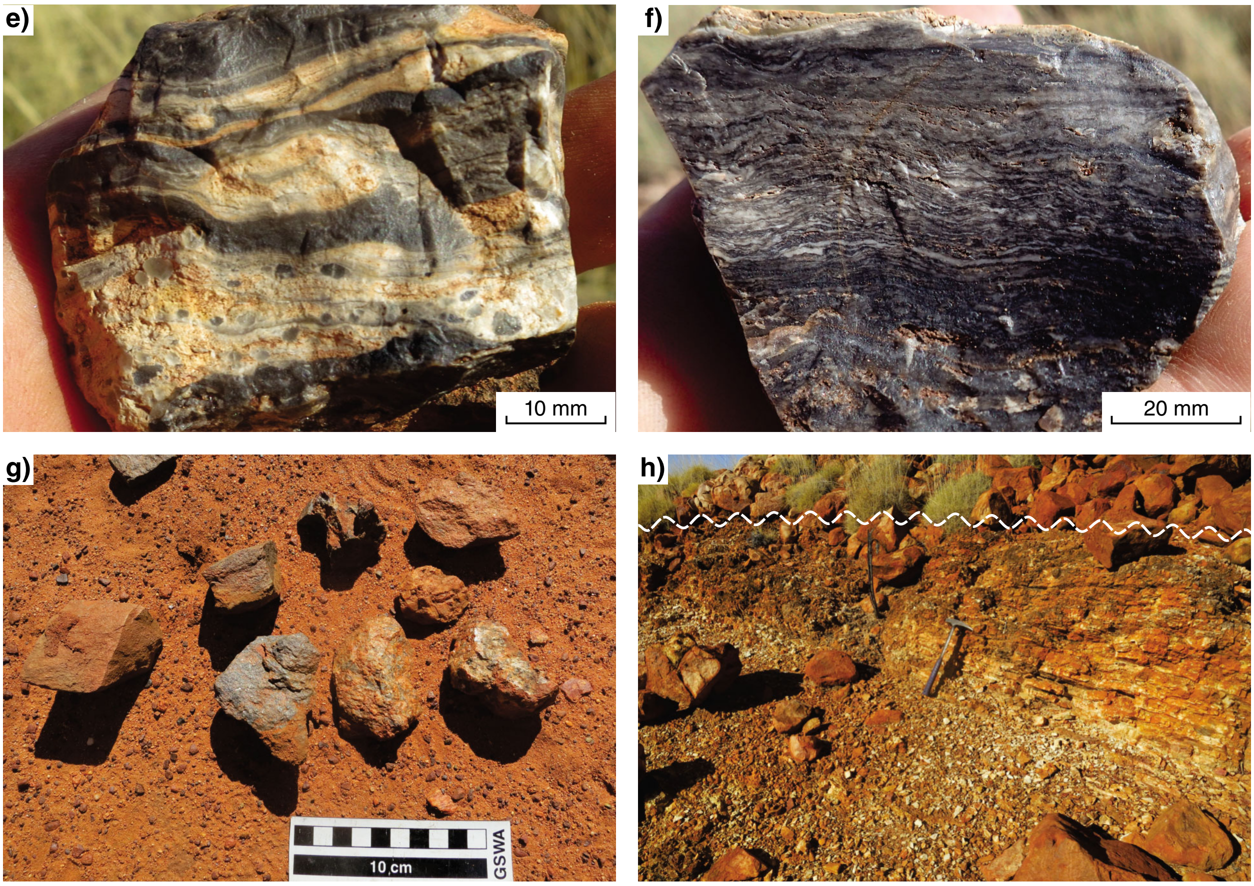

Figure 8. **(continued) e) clast of black and white banded chert (MGA 485500E 7613300N); f) black and white banded chert showing microbial lamination (MGA 485500E 7613300N); g) relatively fresh clasts of crystalline basement (MGA 485100E 7613150N); h) deeply weathered and leached silty carbonate below disconformity or unconformity (wavy dashed line), overlain by pebbly quartz sandstone of basal Murraba Formation; locality indicated in Figure 9 (MGA 445819E 7720478N)**

stromatolites were observed, some clasts have wavy microbial laminations that may be incipient stromatolite development (Fig. 8d). The chert is white to black, and is typically banded with relict structures such as ooids and microbial laminations that indicate silicification of carbonate rocks (Fig. 8e,f).

Unit 2 (MGA 485300E 7613200N to 484950E 7613100N) is devoid of calcrete and contains sparse float clasts of diverse lithologies, most notably crystalline basement rocks including granite, pegmatite, micaceous metamorphic rocks (psammites to pelites), quartzite and vein quartz (Fig. 8g). Labile minerals appear relatively fresh. Some clasts show relics of rounded outer surfaces, suggesting these are broken fragments of larger clasts that were at least partly rounded. Shallow basement is not expected in this area, where aeromagnetic data indicate thick basin cover.

Unit 3 (MGA 484950E 7613100N to MGA 484600E 7613000N) is characterized by ferruginous gravel with clasts of fine-grained flaggy sandstone and minor weathered siltstone. Float of coarse sandstone with rounded chert and quartz granules is also present, but this may be transported from low outcrops of Murraba Formation to the west.

The lowest exposed beds of the Murraba Formation west of regolith unit 3 are composed of silicified sandstone, some beds with abundant heavy minerals, and interbeds of chert-granule conglomerate. The contact with the stratigraphic units underlying the covered interval is not exposed here, although the presence of the chert clasts suggests erosion and reworking of older silicified carbonates. This is consistent with observations from the lowest exposed beds of the Murraba Formation at the western end of Phillipson Range (at and along strike from MGA 445819E 7720478N) that appear to reveal a disconformity or unconformity. At this point, pebbly, medium-grained sandstone (chert and quartz pebbles) sharply overlies a few metres of deeply weathered, fine-grained sedimentary rocks (Fig. 8h). The degree and style of weathering is distinctly different from other fine-grained sedimentary rocks in the overlying succession, and is interpreted to indicate a paleo-weathering profile pre-dating deposition of the pebbly sandstone, indicating a significant hiatus in deposition. The original lithologies of the underlying succession probably included carbonates and calcareous or dolomitic siltstones, but these are now heavily leached. The chert pebbles, which are also common higher in the Murraba Formation, were likely derived from the erosion of a silicified carbonate-bearing terrain. Such silicification suggests a long period of exposure. The evidence for a disconformity or unconformity at this point suggests that the covered succession below the mapped Murraba Formation is not a lower recessive component of that unit, but a distinct, older succession or series of successions.

Murraba Formation and Erica Sandstone

These units will be discussed together because we believe the contact between these formations has been mapped inconsistently on LUCAS and STANSMORE. The cause of this is possibly the definition of the Murraba Formation – Erica Sandstone contact 'at the top of the highest bed of chert-granule conglomerate' (Blake et al., 1979, p. 48). Field observations suggest the chert-granule conglomerate is not laterally persistent, but is expressed as local interbeds, and in general decreases in abundance gradually upsection. Much of the chert-granule conglomerate is seen as float in areas of poor outcrop, and it may be over representative of the true content of this lithology in the succession as it tends to be more resistant than associated siltstone and fine-grained sandstone. Picking the highest bed is fraught with difficulty, and is affected by the quality of outcrop and observation time. The criteria cannot be applied to remote mapping from aerial images or geophysics. Minor beds of chert-granule conglomerate have been observed well above the mapped boundary. We believe that there may be significant stratigraphic overlap between the type sections of the Murraba Formation and the Erica Sandstone. The definitions of both the Murraba Formation and Erica Sandstone need revision to select boundary criteria that can be utilized more consistently for regional mapping. Observations during 2015 fieldwork were concentrated in two main areas — the western end of the Phillipson Range on LUCAS (Fig. 9), and the Redcliff Pound area on STANSMORE (Fig. 11).

Western end of Phillipson Range

This section from approximately MGA 444950E 7719680N (base) to 446730E 7719270N (top) mostly dips east-southeast at approximately 10°, with dip angle decreasing near the top (i.e. towards the southeast; Fig. 9). As depicted on LUCAS, the section is dominated by Murraba Formation and concludes in the lower Erica Sandstone. Based on outcrop widths and measured dips, the mapped Murraba Formation is estimated to be about 220 m thick. The lowest exposed unit (unit 1 on Fig. 9) forms a low scarp comprising thick-bedded, medium-grained quartz sandstone (Fig. 10a). This unit contains thin lenticular interbeds of chert and quartz granules, as well as rare chert and quartz pebbles. Lenticular chert-pebble conglomerate beds are present at this level along strike and at nearby outcrops (Fig. 10b). The unit has a patchy orange-brown weathering skin, but is typically white when freshly broken. It is massive to weakly bedded, with common soft-sediment deformation. The base of the unit is not exposed in the section, but a sharp contact with an older, mostly concealed unit is poorly exposed about 1.2 km along strike to the northeast (MGA 445819E 7720478N; Fig. 8h).

Above the basal massive sandstone unit, the remainder of the interval assigned to the Murraba Formation is dominated by white to purple-brown, flaggy, very thin- to thin-bedded, mostly fine-grained sandstone interbedded with minor siltstone (unit 2 in Fig. 9). A few thicker, blocky, medium-grained sandstone beds are present. Outcrop is generally poor, and most of the surface is covered by scree. The upper third of unit 2 is particularly poorly exposed and the top is covered. It is likely that the siltstone content is higher in this interval. Gutter casts are locally abundant, particularly near the base (Fig. 10c). Microbially induced sedimentary structures (MISS), expressed as lineated bedding surfaces, are locally common (see below). Horizons rich in heavy minerals were observed near the top of the unit, giving some beds a dark-grey colour. The facies is consistent with a shallow-marine depositional environment, below fair-weather, but above storm-wave base.

The mapped base of the Erica Sandstone (approximately MGA 446100E, 7719350N) is marked by a significant facies and colour change (unit 3 in Fig. 9). The contact itself is covered, and thus may lie somewhat below the lowest exposed beds. These comprise fine-grained to more commonly medium-grained, red-brown sandstone. Ripple marks are common, and wave-formed symmetrical ripples are more abundant than asymmetrical current ripples. Up-section, recessive, largely scree-covered horizons that appear to be thinner bedded and finer grained alternate with more resistant, scarp-forming units of medium-grained, blockier, cross-bedded sandstone. The sandstone is poorly sorted, typically feldspathic and micaceous, and some clay matrix is common. Paleocurrents measured from trough cross-beds indicate unimodal flow from the west (mean direction towards 103°; Fig. 6b). Depositional conditions were very shallow and desiccation cracks indicate intermittent subaerial exposure (Fig. 10d). A deltaic depositional environment is envisaged, with sediment sourced from uplifted terrain to the west. MISS are locally common (see below).

Redcliff Pound area

The Redcliff Pound area (centred around MGA 474500E, 7614000N) contains some of the better exposures of the upper Murraba Basin succession within a series of north–south trending folds (Fig. 11). Redcliff Pound itself is the eroded core of an anticline (Fig. 12a) developed within Murraba Formation and Erica Sandstone. The Redcliff Pound area contains the type section of the Murraba Formation on the east flank of a syncline to the east of the Redcliff Pound anticline. The exposed succession of the Redcliff Pound area is dominated by sandstone throughout, but the description is facilitated by subdividing this into six local informal units. On STANSMORE the boundary between Murraba Formation and Erica Sandstone coincides with the unit 5–6 boundary in the Redcliff Pound anticline, but was taken at the unit 4–5 boundary within the second syncline to the east.

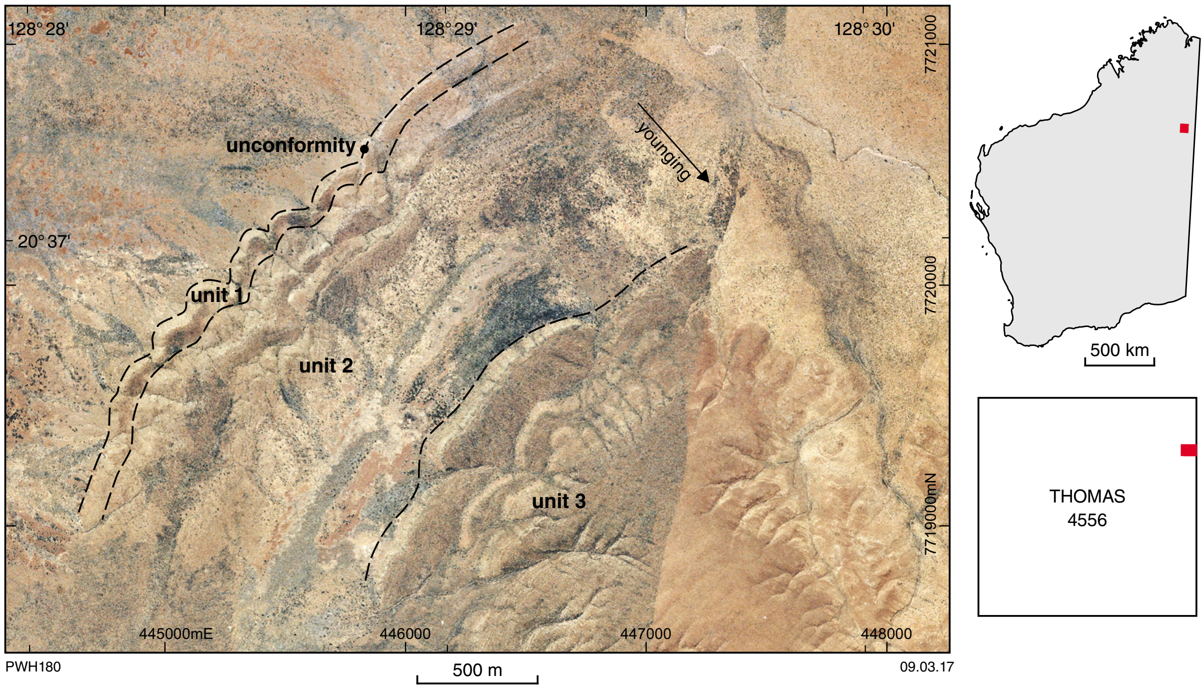

Figure 9. **Orthophoto image within Thomas 1:100 000 map tile, showing western end of Phillipson Range; local informal units are described in text. Base of Erica Sandstone, as mapped on Lucas, corresponds with base unit 3. Location labelled 'unconformity' is shown in Figure 8h**

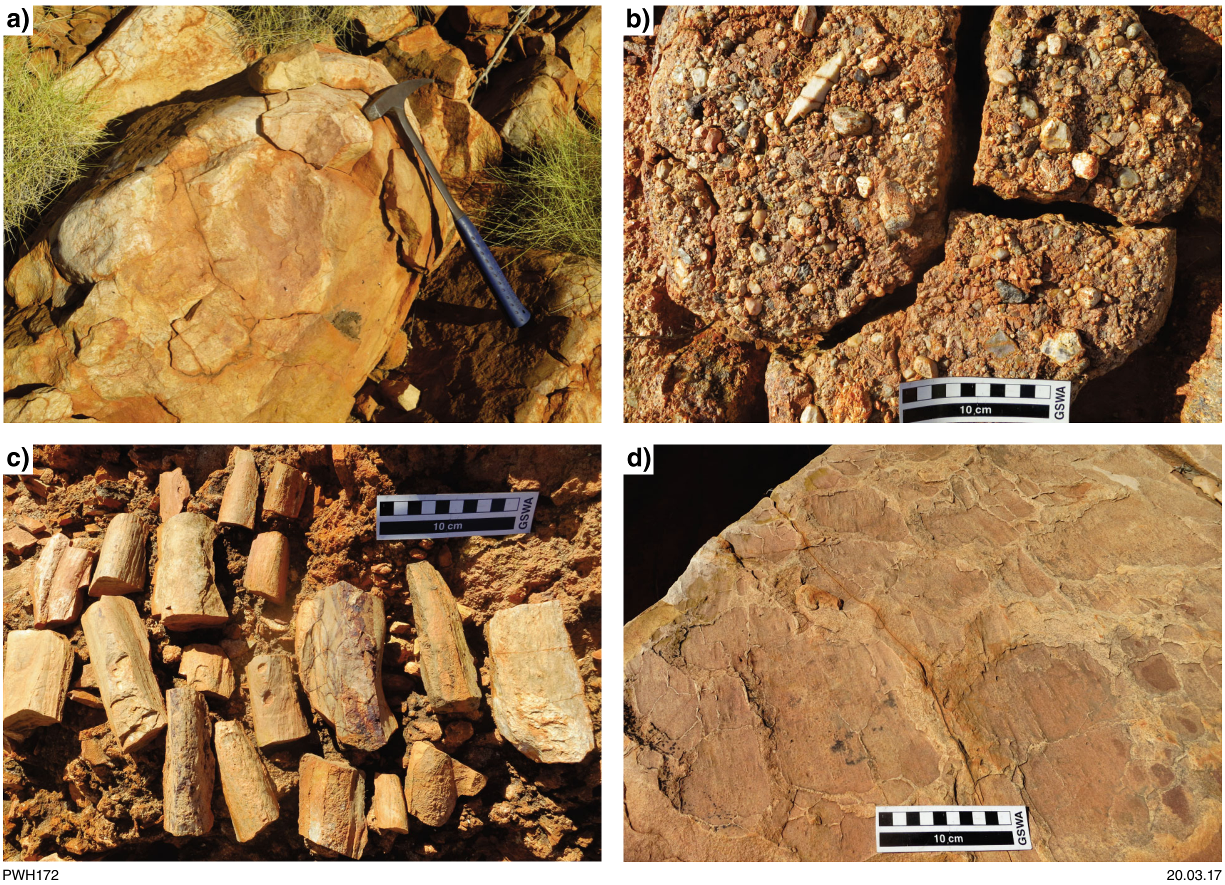

Figure 10. **Field photographs of Murraba Formation and Erica Sandstone, Phillipson Range area: a) white, medium-grained, massive quartz sandstone at local base, western Phillipson Range (MGA 444947E 7719685N); b) chert-pebble conglomerate near local base, southwest of Phillipson Range (MGA 443497E 7711194N); c) inverted gutter-cast fragments, western Phillipson Range (MGA 445040E 7719627N); d) desiccation cracks disrupting microbial mat surface, western Phillipson Range (MGA 446167E 7719341N)**

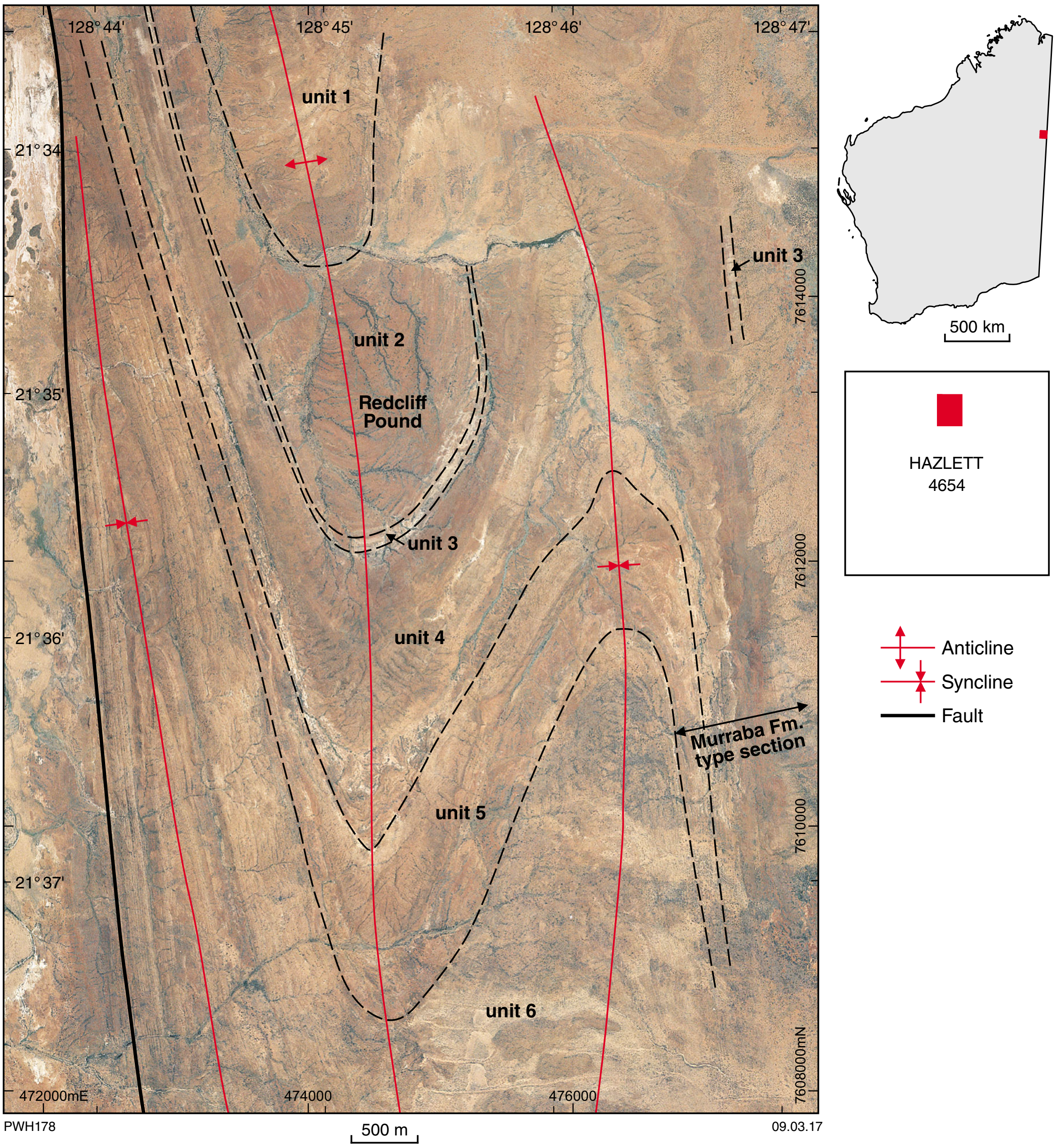

Figure 11. Orthophoto image within HAZLETT 1:100 000 map tile, showing Redcliff Pound area; local informal units are described in text

These inconsistencies in mapping of the boundary between the Murraba Formation and Erica Sandstone are discussed in a later section.

The lowest exposed stratigraphy in the Redcliff Pound area (unit 1 in Fig. 11) is dominated by tan to brown, fine-grained, thin-bedded, flaggy sandstone and minor siltstone (Fig. 12b). Sandstone beds typically have sharp, erosive bases. Thicker and blockier beds commonly have coarser grain size (reaching medium sand) and are typically well silicified. Some beds are dark grey due to the presence of abundant heavy minerals. The sandstones are generally well sorted, but include interbeds of poorly sorted, coarse-grained sandstone to granule conglomerate containing abundant chert clasts. Coarser, very poorly sorted pebble conglomerate was also observed locally, containing clasts of chert, quartzite and vein quartz. Pebble clasts vary from subangular to well-rounded. A shallow-marine, storm-dominated shelf setting is considered the likely depositional environment based on the assemblage of sedimentary structures. These include wave-induced sedimentary laminae and ripples associated with weakly graded, sharp-based beds (i.e. they are tempestites).

Outcrop of unit 2 is largely restricted to the core of the anticline within Redcliff Pound, and is mostly covered by sand elsewhere. The base appears to be transitional from unit 1. The unit comprises red-brown, ferruginous, micaceous, fine- to medium-grained sandstone and siltstone. Beds with chert granules are still present, but are less common. Coarse arkosic beds occur locally and mud-pellet intraclast horizons are common. We noted MISS and *Arumberia* is common at one locality (see 'Biogenic structures'). The unit represents a change of depositional environment from shallow-marine shelf to a probable deltaic setting (see discussion for unit 4).

Unit 3 is carbonate bearing and forms a discontinuously exposed marker horizon about 20 m thick separating otherwise similar red-brown sandstone facies above and below. The best exposures are within Redcliff Pound near the anticlinal axis (MGA 474600E 7612100N) and on the east flank of the syncline to the east (MGA 477190E 7614180N). The outcrop in the lower part of the unit is dominated by grey-pink dolostone, which typically weathers to buff, grey and brown (Fig. 12c,d). Manganese oxide dendrites are common, and are best seen on freshly broken surfaces. The rock is massive to weakly laminated and in part microbial, but well-developed stromatolites were not observed. Silty to fine-grained sandy dolostone at the top of the unit displays current structures including planar laminations and low-angle cross-beds with current lineations, tool marks and flutes on sharp soles (Fig. 12e,f). Poorly exposed interbeds of grey-green siltstone separate the carbonate beds.

Unit 4 is lithologically similar to unit 2, but parts of the unit are better exposed as a series of low strike ridges, the most prominent of which forms the walls of Redcliff Pound (Fig. 12a,g). The strike ridges are dominated by medium-grained, red-brown, ferruginous sandstone. Trough cross-beds and ripples are common, and desiccation cracks (Fig. 12h) were observed locally. Sandstone ridges have the appearance of channel complexes. Locally common MISS and possible tubular body fossils were observed at several localities at approximately the same horizon (see 'Biogenic structures'). The valleys between strike ridges are poorly exposed or covered by sand. Paleocurrent directions measured from trough cross-beds indicate unimodal flow from the southwest (mean direction towards 065°; Fig. 6c). The unit was deposited under a depositional environment similar to unit 2. The immature sediment, channel-complex sandstone units, evidence for desiccation, and unidirectional paleocurrents are typical of fluvial facies, but the presence of biogenic structures suggests marine influence, therefore a deltaic environment is envisaged. The probable delta complex was fed by sediment sourced from uplifted terrain to the west or southwest.

The base of unit 5 coincides with a prominent sandstone ridge and a colour change from pervasive red-brown on both freshly broken and weathered surfaces below the contact, to white or pale brown on broken surfaces above. The prominent basal part of the unit exhibits a distinctive porcellanous silicification (Fig. 12i). Weathered surfaces typically retain a red-brown or orange-brown weathering skin, but the colour is superficial. This sandstone is typically medium grained, blocky to flaggy and relatively well sorted with common trough cross-beds. Wave and current ripples (Fig. 12j), desiccation cracks and MISS were also noted. The upper part of the unit is recessive and poorly exposed. Outcrop consists mainly of friable, medium-grained brown sandstone. Ferruginized siltstone and minor, thin, pink and grey manganiferous dolostone beds were observed in float. Paleocurrent directions measured from trough cross-beds indicate unimodal flow from the northwest (mean direction towards 124°; Fig. 6d).

Unit 6 is mostly composed of very well-sorted, well-rounded, medium-grained sandstone that is typically white to pale brown or yellowish when broken, but with a thin, orange-brown weathering skin. Cross-beds are abundant and reach very large sizes, with foresets exceeding 5 m in thickness (Fig. 12k,l). The scale of the foresets, locally steep foreset dips, and high degree of sorting and rounding of sand grains support an eolian origin for at least part of the unit, although water-deposited intervals are also present. Rare chert-granule beds were noted in the lower part. The top of the unit is not exposed. Dip directions were determined on 15 large-scale cross-beds which are probably of eolian origin, with most varying from southeast to southwest, and a mean direction towards 181° (Fig. 6e). These directions are likely related to prevailing winds, and should not be seen as indicating paleoslope or having a direct bearing on ultimate provenance.

Biogenic structures

The Murraba Formation and Erica Sandstone display a variety of structures that we think are biogenic in origin. The majority may be classified as microbially induced sedimentary structures (MISS), and include 'textured organic surfaces' (TOS). The latter term covers a diverse assemblage of organic bedding surface structures that may have discrete morphological characters, but commonly do not have a defined shape or size that might enable taxonomic description (Gehling and Droser, 2009).

One of the most common forms of MISS is expressed as straight to wavy, parallel to subparallel ridges and grooves on fine-grained flaggy sandstone beds (Fig. 13a,b). In some instances, the textured area shows sharp edges (Fig. 13c). Examples are particularly common in the lower part of the western Phillipson Range traverse, in lower unit 2 around MGA 445000E 7719600N (Fig. 9), but were also seen in higher parts of the section.

Bedding plane structures referable to *Arumberia banksi* (Glaessner and Walter, 1975) are locally common in fine- to medium-grained, flaggy, red-brown sandstone around MGA 474990E 7614130N. On lower surfaces, *Arumberia* is characterized by long, narrow, straight to slightly curved grooves, which are commonly subparallel, but locally radiate away from mounds and may show acute branching in both directions (Fig. 13d). Although the biogenicity of *Arumberia* has sometimes been questioned (McIlroy and Walter, 1997), most authors accept that it is an organic structure, perhaps related to MISS, although its affinities are poorly understood (Kolesnikov et al., 2012; Davies, et al., 2016). *Arumberia* has been reported worldwide, but mainly from shallow water siliciclastic successions deposited close to the Ediacaran–Cambrian transition, leading to discussion of its potential use in biostratigraphy (Bland, 1984).

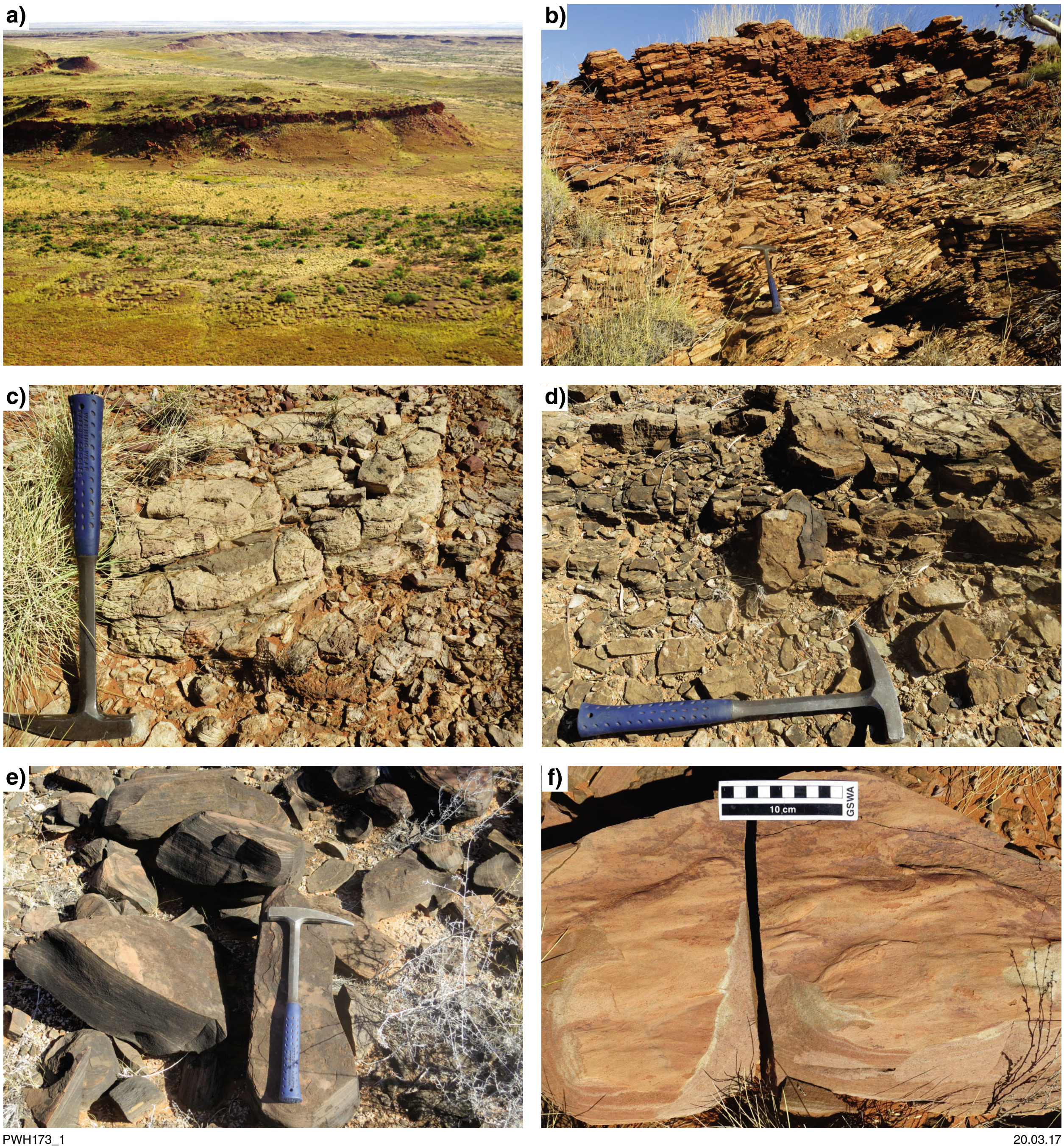

Figure 12. Field photographs of Murraba Formation and Erica Sandstone, Redcliff Pound area: a) aerial view looking west of cliff-forming red-brown sandstone defining the anticlinal structure of Redcliff Pound (approximate position MGA 477600E 7613500N); b) thin-bedded, fine-grained sandstone facies north of Redcliff Pound (MGA 474401E 7616769N); c) buff and grey dolostone in carbonate unit, east of Redcliff Pound (MGA 477195E 7614185N); d) brown dolostone unit in Redcliff Pound (MGA 474530E 7612060N); e) current-laminated dolostone at top of carbonate unit in Redcliff Pound (MGA 474617E 7612032N); f) flutes on sole of pink silty dolostone, top of carbonate unit east of Redcliff Pound (MGA 477197E 7614201N)

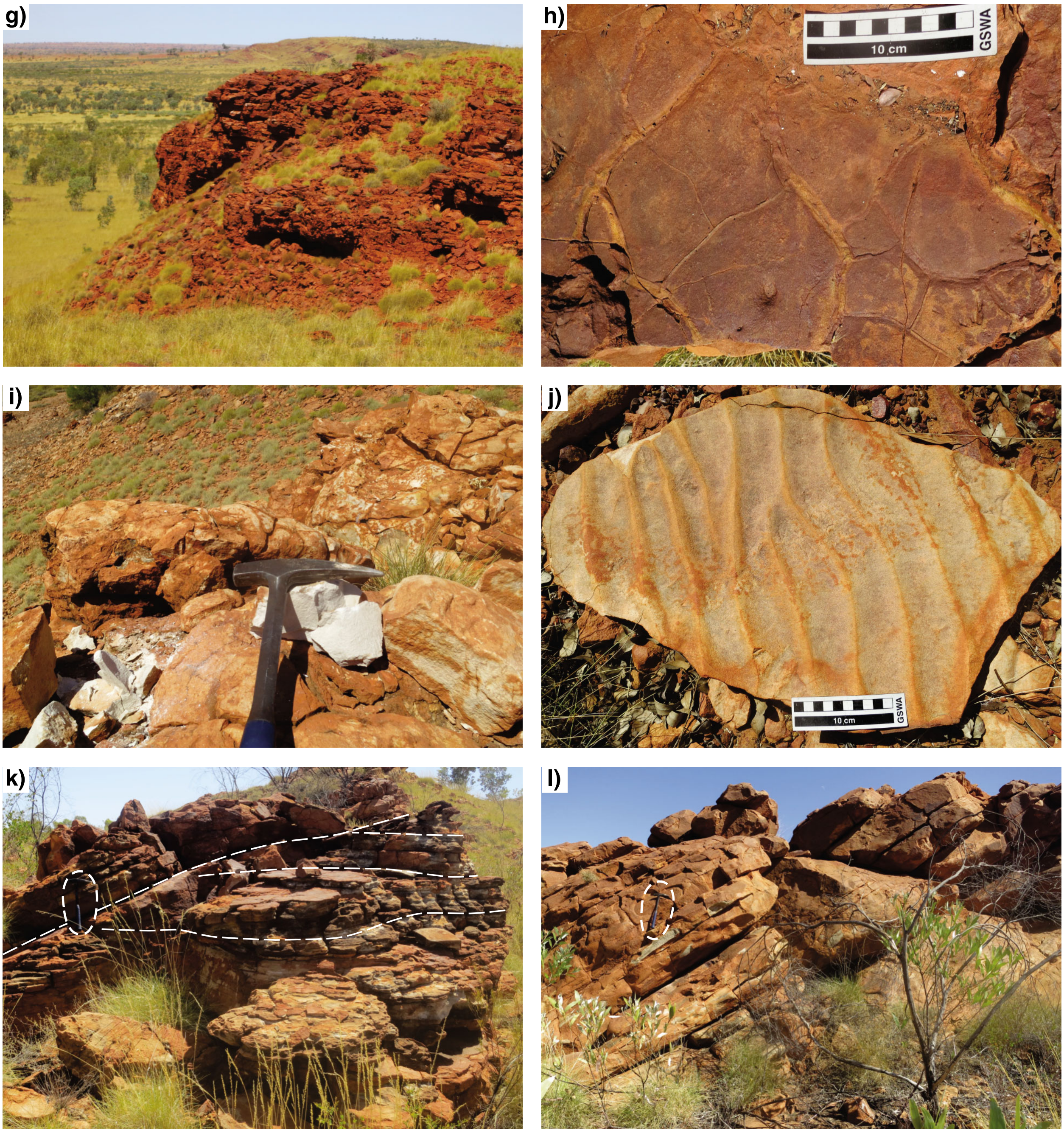

Figure 12. (continued) g) typical outcrop of red-brown deltaic sandstone package, east of Redcliff Pound (MGA 482828E 7612358N); h) polygonal desiccation cracks in red-brown deltaic sandstone, southern rim of Redcliff Pound (MGA 474365E 7611379N); i) white porcellanous sandstone, south of Redcliff Pound (MGA 474417E 7609833N); j) symmetrical wave ripples in white, medium-grained sandstone, east of Redcliff Pound (MGA 481108E 7611184N); k) large-scale cross-beds (bedding highlighted by dashed lines) in medium-grained well-sorted sandstone, probably of eolian origin, south of Redcliff Pound (hammer circled for scale, MGA 473833E 7609079N); l) dipping beds of medium-grained, well-sorted sandstone, interpreted as very large-scale eolian foresets that extend below photograph (structural attitude inferred to be nearly horizontal), south of Redcliff Pound (hammer circled for scale, MGA 473318E 7608501N)

In other basins, adjacent to the Murraba Basin, *Arumberia* is locally common in the Arumbera Sandstone (Glaessner and Walter, 1975) and correlative Carnegie Formation (Haines et al., 2010) of the Amadeus Basin, and Central Mount Stuart Formation of the Georgina Basin (Haines et al., 1991). These occurrences are all interpreted to be in the lower part of Supersequence 4 and thus considered to be of approximately the same age, and are locally associated with an Ediacaran soft-bodied fossil fauna.

Reticulated structures on bedding surfaces are locally common, and are best seen on bed soles of flaggy, fine-grained sandstone. There are abundant examples around MGA 446400E 7719300N in the western Phillipson Range area, but similar structures were also observed at a broadly similar stratigraphic position in the Redcliff Pound area. This form displays low relief bulges, resembling incipient load structures, which are separated by a network of fine, branching grooves (Fig. 13e,f). The grooves locally form radiating dendritic patterns. Another form displays small dimples connected by a network of grooves (Fig. 13g). Such surfaces have been referred to as 'elephant skin' texture (Gehling, 1999; Gehling and Droser, 2009), a term covering various grades of TOS from coarse to very fine networks of reticulating ridges or groves on bedding surfaces. The 'elephant skin' TOS described here is similar to forms common in Ediacaran siliciclastic shallow-marine successions where it is sometimes associated with soft-bodied metazoan faunas and ichnofaunas.

Tool marks on bed soles are common in fine-grained sandstone facies of the Redcliff Pound Group. Most are short spindle-shaped structures that could be produced by inorganic mud pellets or small pebbles impacting the cohesive seabed during current transport. Less commonly, the structures consist of long, fine ridges (casts of original grooves) that may be solitary or occur in parallel to slightly diverging clusters (Fig. 13h). Such structures resemble those described by Haines (1997) and suggest the presence of flexible filaments, or connected clusters of filaments that were passively dragged across the substrate by currents. These filaments are likely to have been organic, but the nature of the organisms is speculative.

Haines and Allen (2016a) described the discovery of 'simple cylindrical trace fossils (*Planolites*)' in red deltaic facies of the upper Redcliff Pound Group. These structures, shown in Figure 14a–d, are expressed as straight to gently curved or sinuous rounded ridges on what are interpreted as soles (all specimens were observed in float) of flaggy, fine- to medium-grained sandstone beds. The ridges are typically 1–3 mm in width, commonly appear to taper towards one or both ends, and are up to 6 cm long. Some examples appear to branch at acute angles. Although orientation varies, separate ridges on the same surface are often aligned in the same general direction. The structures may be aligned at a high angle to current lineations on the same surface. A collected specimen (GSWA 220010) shows poorly preserved

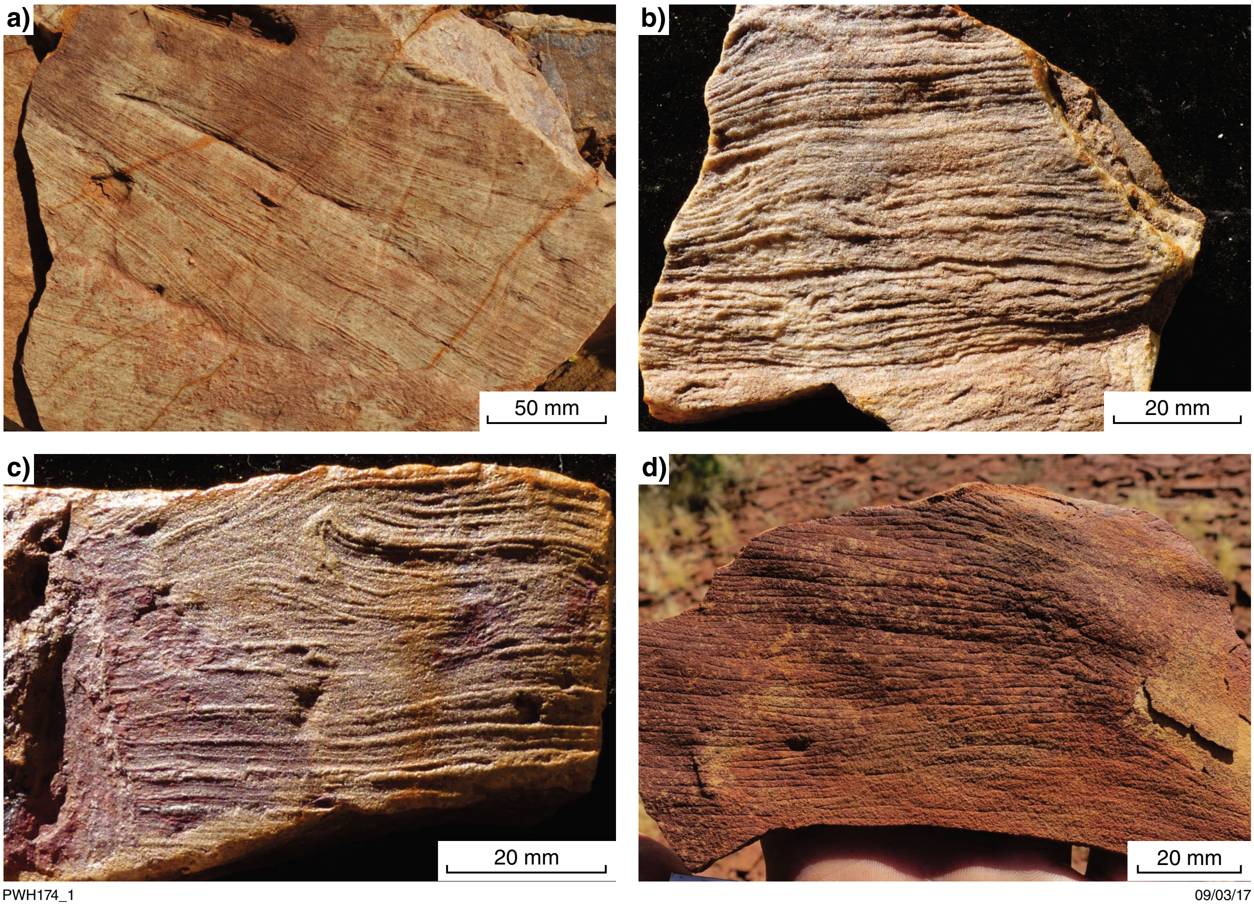

Figure 13. Biogenic structures: a), b), c) lineated microbial bedding surface structures, western Phillipson Range (MGA 445040E 7719627N; 445671E 7719490N; 445671E 7719490N, respectively); d) *Arumberia*, Redcliff Pound (MGA 474987E 7614132N)

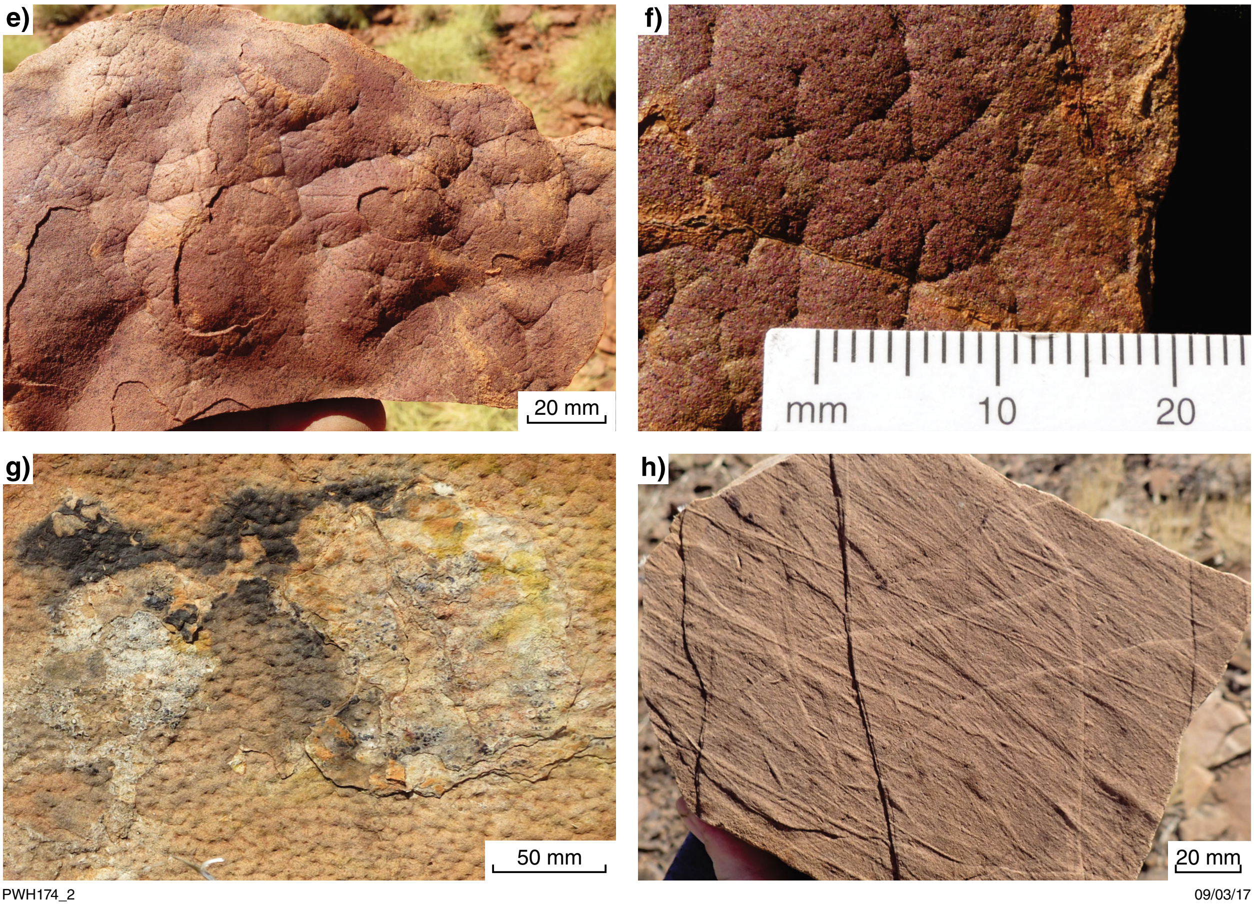

Figure 13. (continued) e) 'elephant skin' textured organic surface, western Phillipson Range (MGA 446499E 7719324N); f) close-up of 'elephant skin' textured organic surface from same locality; g) 'elephant skin' textured organic surface, east of Redcliff Pound (MGA 481108E 7611184N); h) sole of bed showing clusters of fine elongate tool marks, probably produced by drifting organic (algal?) filaments, Redcliff Pound (MGA 474613E 7612080N)

grooves of similar dimension in the opposite (upper?) surface. Examples were found at four locations in the Redcliff Pound area (MGA 482977E 7612411N; 476900E 7614400N; 482977E 7612411N; 474400E 7611450N), all interpreted to be at approximately the same stratigraphic level within what was mapped as Murraba Formation by Blake and Yeates (1976). Although similar structures in Ediacaran successions have traditionally been interpreted as trace fossils (e.g. Glaessner, 1969), it is now realized that the characteristics of many such features are better interpreted as tubular body fossils, although the affinities are unknown (Droser and Gehling, 2008; Sappenfield et al., 2011). Sappenfield et al. (2011) reinterpreted 'trace fossil' Form E and F of Glaessner (1969) from the Ediacara Member of the Rawnsley Quartzite in South Australia as body fossils of a single, unidentified tubular organism *Somatohelix sinuosus*. While the Murraba Basin specimens are generally smaller and not identical to this taxon, a similar tubular body fossil interpretation is now considered more likely than a trace fossil explanation. Further support for a body fossil origin is provided by apparent twisting and kinking of some specimens (Fig. 14a) suggesting that they had walls made of a flexible material.

Hidden Basin beds

Field observations of the Hidden Basin beds were mostly restricted to an across-strike 3.2 km traverse of west-dipping strata of the reference area nominated by Blake et al. (1979; MGA 441480E 7604250N to 438330E 7603900N; Figs 15 and 16a). Additional observations were made near the base of the exposed succession about 19 km farther north (MGA 435820E 7622730N to 435290E 7622450N) to investigate putative trace fossils reported by Mobil Exploration (1983). To facilitate description, the reference area was subdivided into five local informal units (Fig. 15).

The lower (eastern) part of the reference section is dominated by red-brown ferruginous sandstone (unit 1; Fig. 16b,c). Most is medium-grained and massive to weakly bedded, with ripples and cross-bedding preserved locally. It is mostly very well silicified. There is a strike valley of recessive, fine- to medium-grained, flaggy micaceous sandstone near the top of the lower interval. The central part of the section is marked by a covered interval 150–200 m wide (unit 2). The upper section is dominated by white to grey, medium-grained, very well-

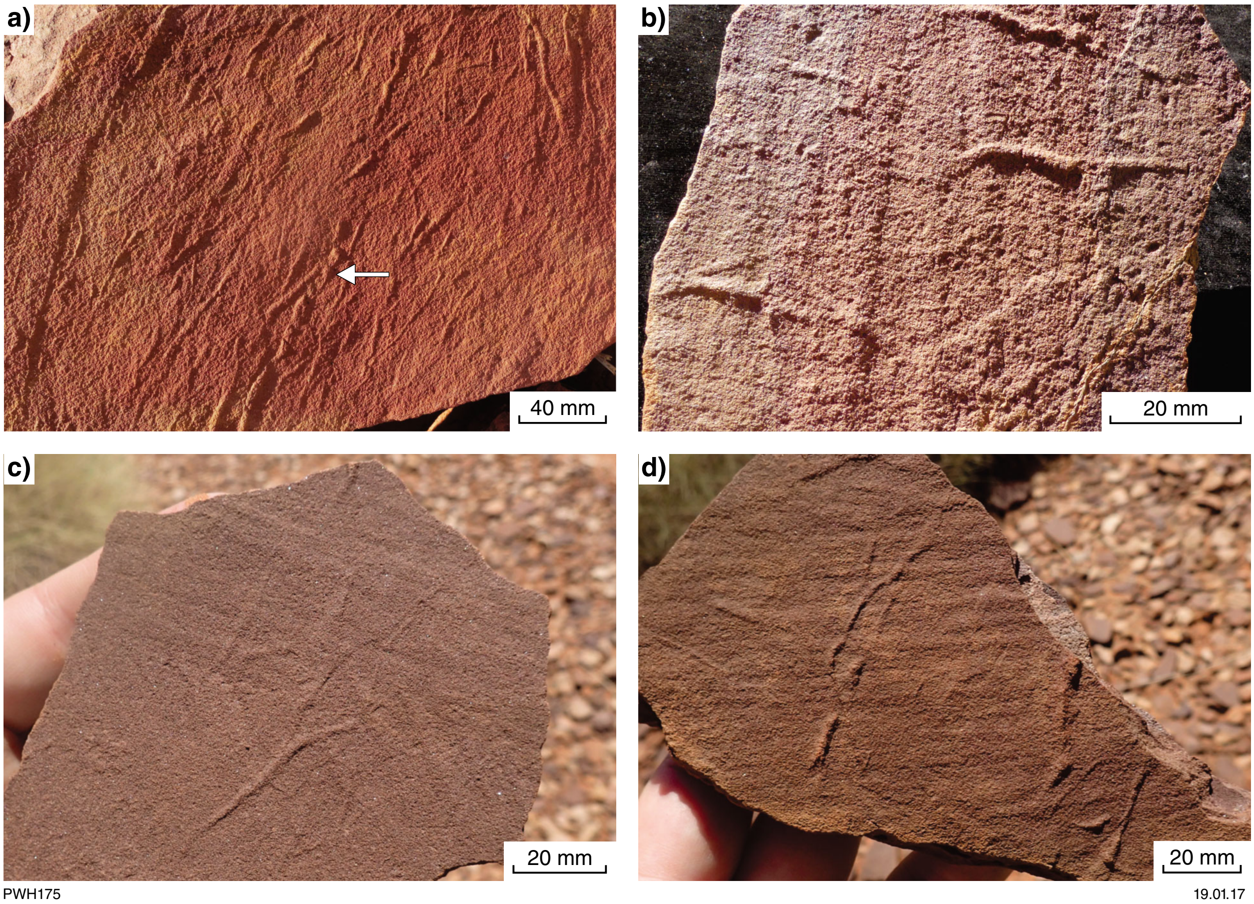

Figure 14. Possible tubular body fossils: a) east of Redcliff Pound (MGA 482977E 7612411N), with arrow indicating twisted tube; b) Redcliff Pound (MGA 475525E 7614280N); c) Redcliff Pound area (MGA 475525E 7614280N); d) Redcliff Pound area (MGA 475525E 7614280N)

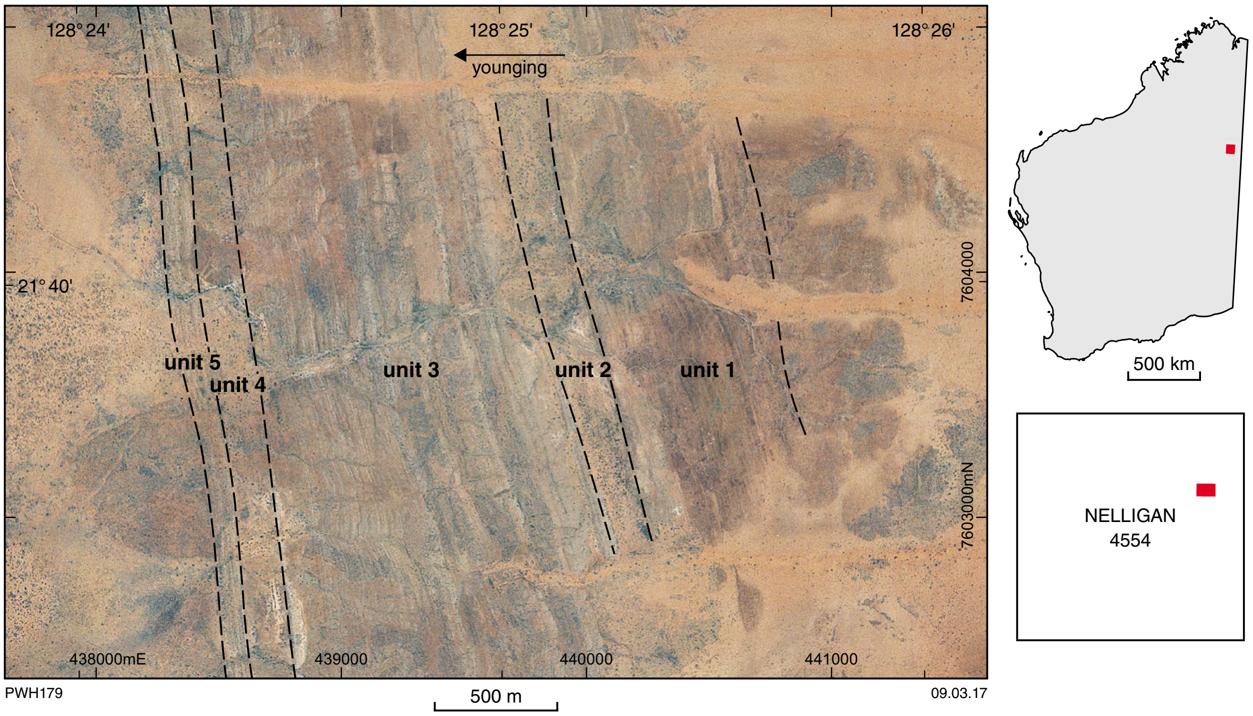

Figure 15. Orthophoto image within Nelligan 1:100 000 map tile, showing Hidden Basin beds reference section; local informal units are described in text

silicified quartz sandstone (orthoquartzite) (units 3, 5; Fig. 16d,e). There is a cyclical alternation between thick-bedded massive sandstone intervals and thinner bedded, flaggy and slightly more recessive intervals. A recessive valley about 200 m wide near the top of the section is largely covered in scree except for creek bank exposures of weathered, pale-grey to white, fissile siltstone with red-brown ferruginous stringers and bands (unit 4; Fig. 16f). The white weathering suggests a black siltstone at depth. Paleocurrent measurements were made from cross-beds at several intervals through the reference section. The limited dataset is unimodal with flow towards the north (mean direction 015°; Fig. 6f).

The site of putative trace fossils ('vertical worm burrows') reported by Mobil Exploration (1983, appendix 10) is dominated by red-brown, mostly medium-grained, variably silicified sandstone that is similar to the lower part of the reference section. Some fine-grained, rippled, micaceous beds are present near the base. No trace fossils were observed, and thus the report remains unconfirmed. Small round concretions were noted to be locally common in the area (Fig. 16c). It is possible that such structures when viewed on bedding planes could be confused with the plan view expression of vertical burrows.

Discussion

Lewis Range Sandstone and Munyu Sandstone

Based on lithology, facies and stratigraphic relationships the Munyu Sandstone is correlated with the Heavitree Formation of the northern Amadeus Basin, consistent with previous interpretations of Blake et al. (1979) and Grey (1990). It is thus also correlated with the Dean Quartzite and Kulail Sandstone of the southern Amadeus Basin, and Vaughan Springs Quartzite of the Ngalia Basin that are well-established correlatives of the Heavitree Formation. The age of the Heavitree Formation is not tightly constrained, but must be younger than the Central Desert Dolerite Suite (976 ± 3 Ma; Wyborn et al., 1998), which it unconformably overlies. The younger Loves Creek Formation of the overlying Bitter Springs Group is inferred to be older than c. 827 Ma based on a biostratigraphic (stromatolite assemblage) correlation to a unit in South Australia, which is overlain by volcanics of this age (Grey et al., 2005). The Munyu Sandstone is thus inferred to have similar Tonian age constraints.

The late Mesoproterozoic detrital zircon maximum depositional age (1099 ± 40 Ma) previously reported for Munyu Sandstone sample GSWA 184342 is significantly older than the above constraints. However, the detrital zircon maximum depositional ages reported for the Heavitree Formation (Zhao et al., 1992; Maidment et al., 2007; Kositcin et al., 2014), the Dean Quartzite (Haines et al., 2016; Camacho et al., 2015) and Kulail Sandstone (Haines et al., 2016) of the basal Amadeus Basin are similar to that of the Munyu Sandstone, and suggest that zircons close in age to the start of deposition of the Amadeus and Murraba Basins were not available in the collective source areas. The age also confirms a large hiatus above the redefined Birrindudu Basin succession, and justifies inclusion of the Murraba Basin in the Centralian Superbasin.

The significant late Mesoproterozoic zircon age component (maxima at c. 1162 Ma) in sample GSWA 184342 (Kirkland et al., 2009b; Fig. 17a) is consistent in both age and Hf isotope signature with the Musgrave Province, while earliest Mesoproterozoic and late Paleoproterozoic (maxima at c. 1575 Ma and c. 1744 Ma) components correspond with events in the Warumpi and Aileron Provinces of the Arunta Orogen (Hollis et al., 2013). The full zircon age spectrum is similar to a sample of Heavitree Formation published by Maidment et al. (2007) (Fig. 17b); both samples show a dominance of Warumpi-aged components over Aileron-aged components, as well as a late Mesoproterozoic Musgrave-aged component, although in this Heavitree sample, the late Mesoproterozoic component is minor. In contrast, other Heavitree Formation detrital zircon samples reported by Zhao et al. (1992), Kirkland et al. (2009a) (Fig. 17c) and Kositcin et al. (2014) (Fig. 17d), as well as a sample from the correlative Vaughan Springs Quartzite of the Ngalia Basin (Worden et al., 2008) (Fig. 17f), all show a strong dominance of ages consistent with an Aileron Province source, with few or no zircons of late Mesoproterozoic age.

The abundance of zircons linked to the Musgrave Province in the Munyu Sandstone sample is similar to results from the Kulail Sandstone and Dean Quartzite (Wingate et al., 2015; Haines et al., 2016; Fig. 17e), which were deposited much closer to the Musgrave Province. There are several possible explanations for the anomalous abundance of Musgrave detritus in the more distal Munyu Sandstone. Firstly, it is possible that components of the Musgrave Province, now buried beneath younger basins such as the southeastern Canning Basin, were exposed near the depositional site of the Munyu Sandstone. It is also possible that there was provenance stratification within the original sand body related to changing topography in the hinterland and changing paleocurrent patterns. In this regard, it is interesting to note that both GSWA 184342 and the Heavitree Formation sample of Maidment et al. (2007) were apparently collected near the top of the respective formations; the other Heavitree Formation and Vaughan Springs Quartzite samples appear to have been collected from the lower to middle parts of the units. A more systematic sampling approach would be required to test whether there is a significant shift in detrital zircon provenance through these units.

The two previously reported GSWA detrital zircon samples for different stratigraphic levels within the Lewis Range Sandstone have closely matching age spectra (Fig. 18a,b), suggesting that the unit is relatively homogeneous with respect to zircon provenance. However, the Lewis Range Sandstone age spectra are significantly different from that of its presumed correlative, the Munyu Sandstone, or the Heavitree Formation (Fig. 17) and its correlatives farther to the south. Specifically, the Lewis Range Sandstone displays only minor Paleoproterozoic age components, despite the

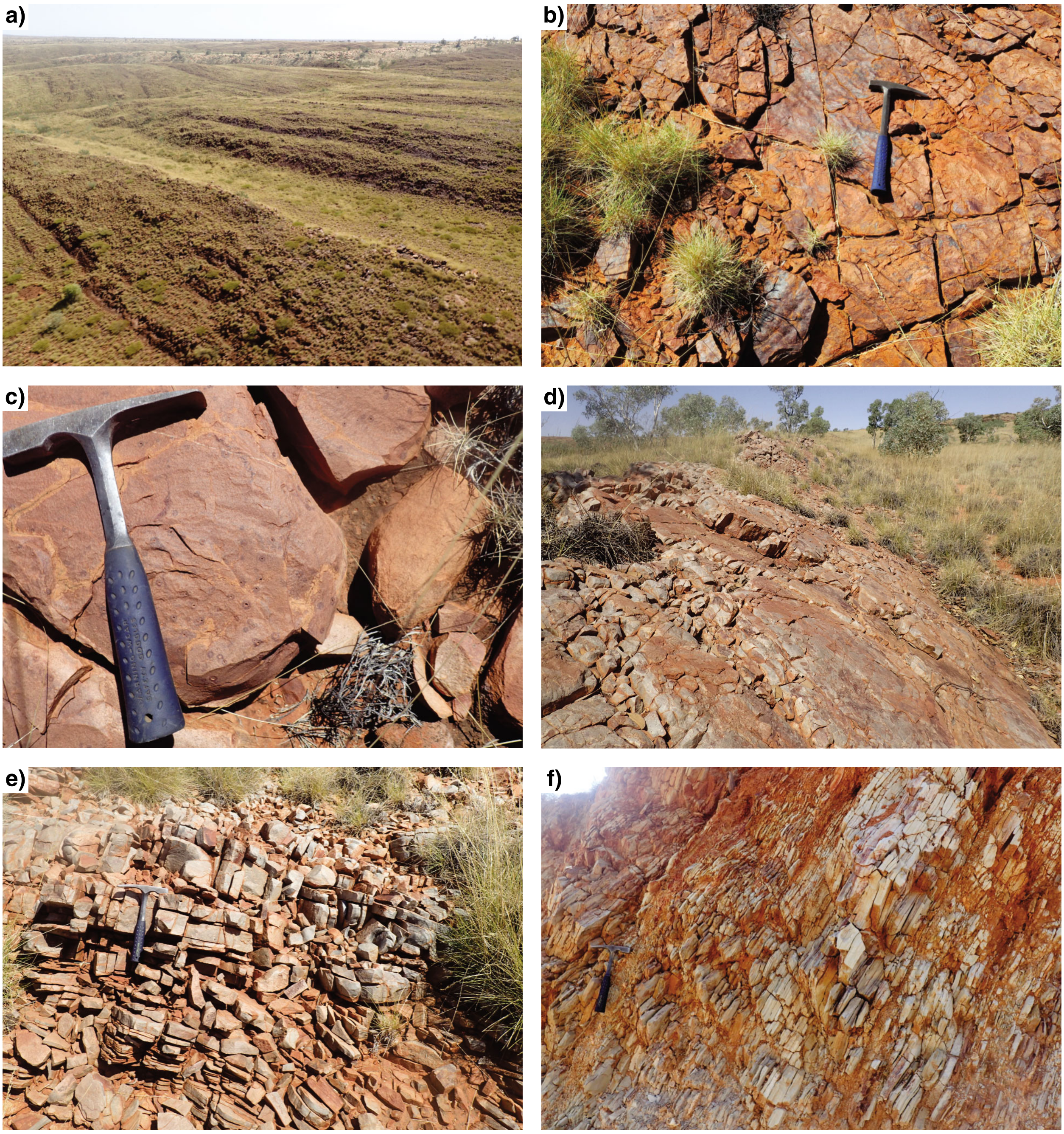

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Figure 16. Field photographs of Hidden Basin beds: a) aerial view looking northeast of cyclical ridges of red-brown silicified sandstone, lower part of reference section (approximate position MGA 440200E 7603200N); b) well-indurated, fine-grained, micaceous rippled sandstone, lower part of unit north of reference section (MGA 435824E 7622731N); c) red-brown silicified sandstone with small circular concretions, lower part of unit north of reference section (MGA 435438E 7622680N); d) grey-white, very well-silicified quartz sandstone, middle of reference section (MGA 439900E 7603553N); e) strongly jointed, grey-white, very well-silicified quartz sandstone, upper reference section (MGA 439539E 7603596N); f) white-weathering siltstone exposed in creek bank, reference area (MGA 438545E 7603935N)

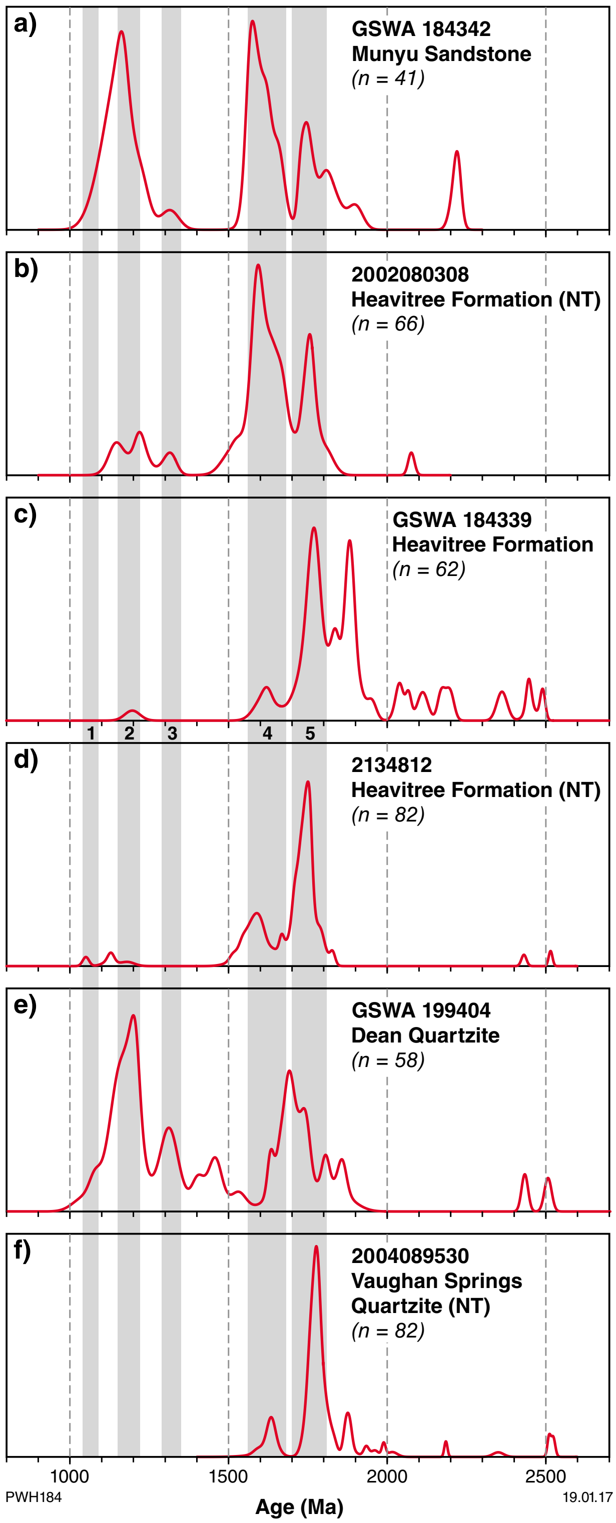

Figure 17. Comparison of detrital zircon age spectra (probability density diagrams) of the Munyu Sandstone and likely correlatives in the Amadeus (Heavitree Formation and Dean Quartzite) and Ngalia (Vaughan Springs Quartzite) Basins. Vertical grey bars indicate zircon-crystalizing tectonic and magmatic events in the likely source areas: 1. Giles Event (1090–1040 Ma) in Musgrave region (Howard et al., 2015); 2. Musgrave Orogeny (1220–1150 Ma) in Musgrave region (Howard et al., 2015); 3. Mount West Orogeny (1350–1290 Ma) in Musgrave region (Howard et al., 2015); 4. Warumpi Province events and Chewings Orogeny (1680–1560 Ma) in Arunta Orogen (Scrimgeour, 2013b); 5. Aileron Province events (1810–1690 Ma) in Arunta Orogen (Scrimgeour, 2013a). a) Munyu Sandstone data from Kirkland et al. (2009b); b) Heavitree Formation data from Maidment et al. (2007); c) Heavitree Formation data from Kirkland et al. (2009a); d) Heavitree Formation data from Kositcin et al. (2014); e) Dean Quartzite data from Wingate et al. (2015); f) Vaughan Springs Quartzite data from Worden et al. (2008). n = the number of analyses displayed in each plot

underlying Paleoproterozoic crystalline basement and the predominance of Paleoproterozoic rocks in the surrounding North Australian Craton. The zircon age spectra are instead dominated by Mesoproterozoic zircons, known sources for which are very limited in the North Australian Craton, suggesting that most of the sediment is allochthonous. Furthermore, a Musgrave Province source (the nearest obvious source of voluminous Mesoproterozoic magmatic rocks) is not well supported by the broad spread of zircon ages that extend outside recognized Musgrave events (Fig. 18), nor by a comparison of Hf isotope data from the detrital zircons from the Musgrave Province.

The detrital zircon maximum depositional ages of the Lewis Range Sandstone samples are also notably younger than those of the Munyu Sandstone and its correlatives in the south (compare Fig. 17a and Fig. 18a,b). This allows, but does not conclusively demonstrate, that the Lewis Range Sandstone is younger than the Munyu Sandstone. If the two are direct correlatives, different parts of the Murraba Basin must have had a different provenance at this time, with little regional mixing. Detrital zircon data from the Victoria Basin in the NT (Carson, 2013) lends some support to the suggestion that the Lewis Range Sandstone is younger than the Munyu Sandstone. The basal unit of the Victoria Basin, the Jasper Gorge Sandstone (Supersequence 1), is dominated by late Paleoproterozoic detrital zircons, with minimal Mesoproterozoic detritus, similar to most Heavitree Formation samples. A significant late Mesoproterozoic component emerges at a higher stratigraphic level in the Black Point Sandstone Member of the Bullo River Sandstone (Carson, 2013).

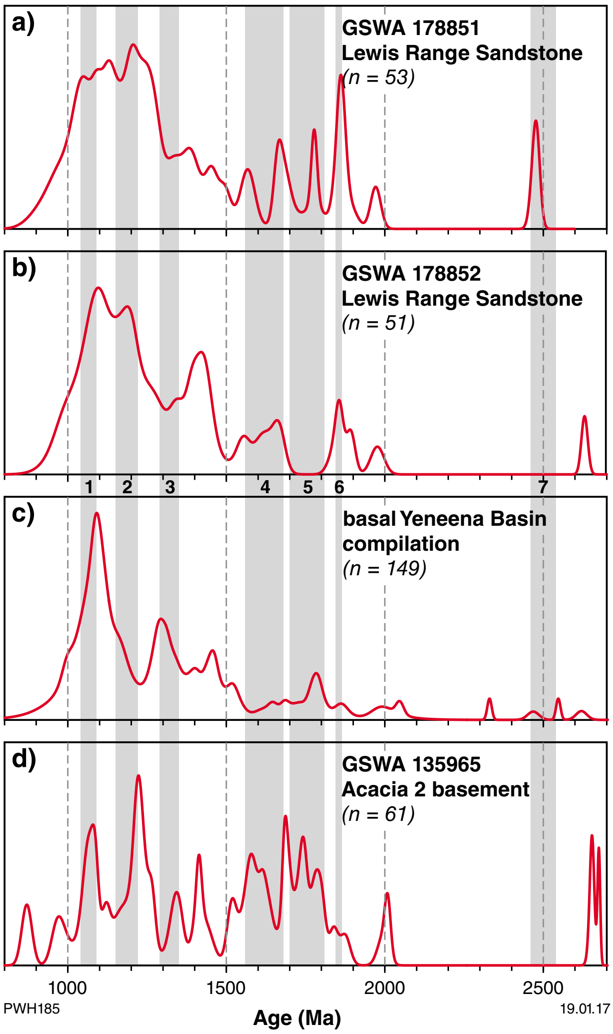

Figure 18. Comparison of detrital zircon age spectra (probability density diagrams) of the Lewis Range Sandstone with basal units of the Yeneena Basin and metasedimentary basement in Acacia 2. Vertical grey bars indicate zircon-crystallizing tectonic and magmatic events, and detrital zircon populations in select basement regions: 1–5 as for Figure 17; 6–7 are detrital zircon populations in Tanami Basin (1844–1864 Ma, c. 2500 Ma, respectively). a) Lewis Range Sandstone data from Wingate et al. (2008a); b) Lewis Range Sandstone data from Wingate et al. (2008b); c) compilation of data from samples of Coolbro Sandstone (GSWA 167117, 167118, 167119, 167120) and Malu Formation (GSWA 137655, 137657) of the basal Yeneena Basin (data from Nelson, 2000, 2001a,b, 2002a,b,c); d) Acacia 2 metasedimentary basement data from Wingate and Haines (2009). Data >5% discordant excluded; n = the number of analyses displayed in each plot

While the provenance of the Lewis Range Sandstone remains uncertain, we note close similarities between the detrital zircon age spectra for this formation and the age spectrum from probable Tonian rocks of the lower Yeneena Basin (Fig. 17c), located west of the Canning Basin (Fig. 1). Available Yeneena Basin samples are from the Coolbro Sandstone and Malu Formation of the Throssell Range and Lamil Groups, respectively, reported by Bagas and Nelson (2007) (data in Nelson, 2000, 2001a,b, 2002a,b,c). Although the ages of the Throssell Range and Lamil Groups are not firmly established, they are generally considered to be younger than the basal succession of the Centralian Superbasin, but still within Supersequence 1 (Grey et al., 2005). This suggests a connection (or at least shared sediment source) between the Yeneena Basin and northern Murraba Basin during the early history of the Centralian Superbasin. Such a connection, if preserved, is now covered by the Canning Basin. In this regard, we note some similarity between the detrital zircon age spectra of the Lewis Range Sandstone and a metasedimentary basement sample from Acacia 2 in the central Canning Basin (Figs 1 and 18d).

The succession in Kearney Range (KEARNEY 1:100 000 map sheet) was previously considered the thickest section of Lewis Range Sandstone, reaching 1000 m. The section was also noted to be anomalous as the only area where the Lewis Range Sandstone is steeply dipping, sheared, strongly silicified and cut by quartz veins (Blake et al., 1979). Although the Kearney Range section was not examined in the field during this project, we note that it is directly along strike from a lithologically and structurally similar package of rocks on BILLILUNA (BALWINA 1:100 000 map sheet) that are mapped as Birrindudu Group. Therefore, it is possible the rocks of the Kearney Range are not Lewis Range Sandstone, nor are they part of the Murraba Basin, but are instead a component of the Birrindudu Basin and are possible equivalents to the Hidden Basin beds (as discussed later).

Unnamed carbonate and concealed stratigraphy

The unnamed carbonate in fault contact with Munyu Sandstone resembles ferruginous and recrystallized dolostone that is common in the Gillen Formation (basal Bitter Springs Group) overlying the Heavitree Formation in the Amadeus Basin. The tentative identification of the stromatolite *Tungussia erecta* (only known from the Gillen Formation; Allen et al., 2012) is consistent with this correlation. In the Amadeus Basin the Gillen Formation contains a widespread upper salt interval that is responsible for the halotectonic deformation style of the basin and forms a salt seal over the 'Heavitree–Gillen petroleum system'. Gillen Formation salt is tentatively inferred in outliers of the western Amadeus Basin closest to the Murraba Basin based on geophysical modelling (Joly et al., 2013). It is possible that salt is present at this level in the Murraba Basin, but this cannot be confirmed without subsurface information. One observation that favours the presence of subsurface salt is the irregularity and inconsistency of fold axial tends in some parts of the basin — for, example in the Sydney Margaret Range in eastern STANSMORE (MGA 492000E 7645000N — which might be explained by halotectonics.

The carbonate and chert clast lithologies observed in the lower part of the concealed stratigraphy east of Redcliff Pound resemble lithologies common in the upper Bitter Springs Group and Wallara Formation (upper Supersequence 1) of the Amadeus Basin. In the poorly exposed western Amadeus Basin, outcrops of these units can be traced laterally into areas with similar clast-bearing calcrete regolith expression. The lithologies described from shallow drillholes by Blake (1974) are also consistent with such Amadeus Basin correlatives occupying this covered interval.

Clasts of basement lithologies (Fig. 8g) observed at what is interpreted to be a higher stratigraphic level east of Redcliff Pound might signify the presence of a glacial diamictite in the subsurface. Cryogenian glacial diamictites at the base of Supersequence 2 (Areyonga Formation) and Supersequence 3 (Olympic Formation) in the Amadeus Basin locally contain fresh basement clasts, transported by ice from beyond the basin margin or from basement inliers. These may survive in regolith after friable diamictite matrix has been removed by erosion. Fresh basement clasts are also found in glacial units within the Wolfe Basin to the north, and in other components of the Centralian Superbasin. No nearby basement inliers are visible on aeromagnetic images, and no significant drainage channels or paleochannels are known in the area. Instead, the clasts appear to be confined to an elongate soil pattern that is interpreted as the regolith expression of an underlying stratigraphic unit.

Murraba Formation and Erica Sandstone

The Murraba Formation and Erica Sandstone appear to have been previously mapped inconsistently between LUCAS and STANSMORE, and to a lesser extent between separate outcrops in the same areas (Fig. 19). In the section at the western end of Phillipson Range, the mapped formation boundary separates generally fine-grained, thin-bedded mature sandstone and siltstone, mapped as Murraba Formation, from red-brown, immature, ferruginous sandstone and siltstone of the lower Erica Sandstone. The actual contact is likely hidden beneath a concealed interval. As such, the boundary in this area is marked by a significant change of depositional environment from a shallow-marine, siliciclastic, storm-dominated shelf environment, to a deltaic depositional environment, fed by immature sediment coming from the west. In the Redcliff Pound area, a very similar red-brown deltaic succession (Fig. 10; units 2 and 4) is mapped entirely within the Murraba Formation. We consider the deltaic successions in the respective areas to be correlatives. Furthermore, the deltaic succession closely resembles distal components of Supersequence 4 in the Amadeus, Georgina and Ngalia Basins. The carbonate marker (Fig. 10; unit 3), which is only intermittently exposed in the Redcliff Pound area, was not observed at Phillipson Range; if present it is likely to lie in the covered interval below the mapped boundary, along with the equivalent of recessive unit 2. The prominent ridge-forming sandstone marking the exposed base of the Erica Sandstone at Phillipson Range is a potential correlative of the prominent cliff-forming ridge within unit 4 that creates the walls of Redcliff Pound. The onset of deltaic conditions was probably a response to tectonics in the source area, which lay to the west (based on paleocurrent data) and is now covered by the younger Canning Basin.

The Murraba Formation and Erica Sandstone show physical similarities to Supersequences 3 and 4 of the Amadeus, Georgina and Ngalia Basins to the south and east. Furthermore, the abundance of biogenic structures (MISS, TOS, *Arumberia* and tubular body fossils) is consistent with the assignment of the Murraba Formation and Erica Sandstone to Supersequences 3 and 4. The shift from relatively mature, shallow-marine siliciclastics to immature deltaic red beds matches the onset of Supersequence 4 syntectonic sedimentation in adjacent basins. The paleocurrent trends are different from the consistent north to northeast transport directions of Supersequence 4 in the Amadeus Basin (Haines et al., 2015), but are more consistent with the southeast trends reported by Haines et al. (1991) from the western Georgina Basin. The transport directions in the Amadeus Basin are consistent with sediment being derived from the Petermann Orogen in the Musgrave region, further supported by detrital zircon provenance data (Haines et al., 2015). The sediment transport direction for the Murraba Basin suggests a tectonically elevated source region to the west, which is now covered by the Canning Basin. This provides support for previous interpretations (e.g. Bagas et al., 1996) that the Petermann, Paterson and King Leopold Orogens, present exposures of which are separated by Canning Basin cover, are linked in the subsurface (Haines and Allen, 2016b).

Redefinition of Redcliff Pound Group

Previous workers placed the entire succession from Munyu Sandstone (and its presumed laterally equivalent Lewis Range and Muriel Range Sandstones) to Erica Sandstone into the Redcliff Pound Group. This was logical under the former view that the successive component formations were conformable with each other, and that deposition was accomplished in a single episode restricted in time to Supersequence 1 of the Centralian Superbasin. In this Record we reinterpret the succession to contain components of all four supersequences of the Centralian Superbasin, with deposition of diverse facies (not all exposed), separated by probable hiatuses, and deposited episodically during much of the Neoproterozoic, and possibly into early Cambrian time. This prolonged and fragmented depositional history is inconsistent with the lithostratigraphic concept of a group ('a succession of two or more contiguous or associated formations with significant and diagnostic lithologic properties in common'; Murphy and Salvador, 1999, p. 260). Therefore, we have revised the definition of the Redcliff Pound

Group to include only the mapped Murraba Formation and Erica Sandstone (Fig. 20; see Appendix). The base is a disconformity or unconformity at the bottom of mapped Murraba Formation, and the new definition excludes covered successions below this stratigraphic break that were originally assumed to be a downward extension of the Murraba Formation to the top of the Lewis Range and Munyu Sandstones. As redefined, the Redcliff Pound Group includes the succession that crops out around the Redcliff Pound area, from where the name was derived.

New regional correlations restrict the revised Redcliff Pound Group to Supersequences 3 and 4, and are thus mainly of Ediacaran age, possibly extending into the Cambrian. However, the eolian depositional environment inferred for the upper part of the succession is unlikely to yield biostratigraphically useful information to aid this interpretation.

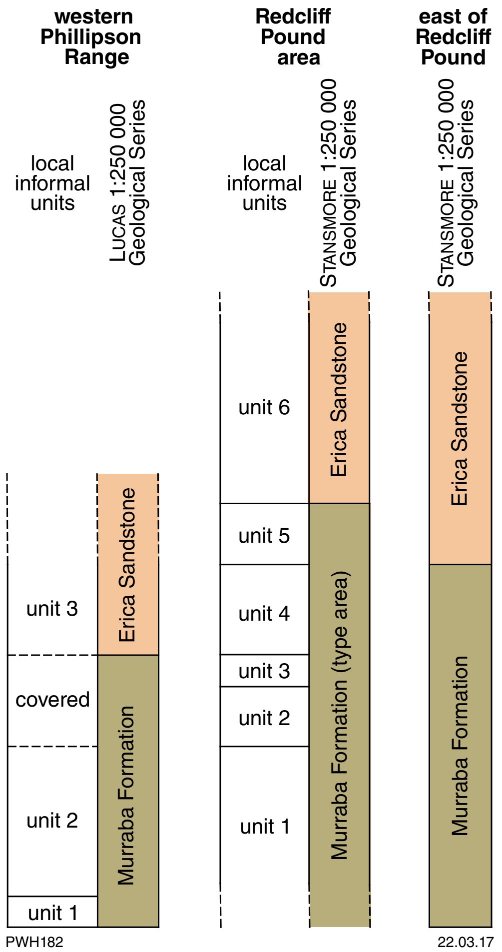

Figure 19. Correlation of local informal units (see text) between the western Phillipson Range section and the Redcliff Pound area. Note the inconsistent position of the boundary between Murraba Formation and Erica Sandstone as mapped on the Lucas and Stansmore 1:250 000 Geological Series maps. No thickness scale is implied

Hidden Basin beds are pre-Murraba Basin?

The age and stratigraphic relationships of the Hidden Basin beds remain uncertain; however, several field and geophysical observations may be pertinent to resolving these questions. Firstly, the exposed components of the Hidden Basin beds are strongly indurated, mostly well-silicified sandstone and orthoquartzite. The degree of induration is typically greater than that of the upper Redcliff Pound Group, which this unit was previously thought to overlie. The tightness of folding and steepness of dips in the Hidden Basin beds is also greater than that of most Redcliff Pound Group outcrops (with the exception of outcrops adjacent to some major fault zones). A gravity high over the Hidden Basin beds, and high-frequency aeromagnetic anomalies over the northern part of its exposed range, are not consistent with a thick basin beneath the Hidden Basin beds, as would be expected if the unit overlies the Erica Sandstone. Purported trace fossils in the Hidden Basin beds could not be relocated, and may have been inorganic. For these reasons we conclude that the Hidden Basin beds are more likely to be older than the Redcliff Pound Group (as redefined), and probably older than the Munyu Sandstone and Lewis Range Sandstone. The contact with the Murraba Basin succession is at least partly faulted, as indicated by previous mapping and aeromagnetic data.

The exposed Hidden Basin beds bear lithological, structural and geomorphological similarities to exposed units of the Birrindudu Basin surrounding the northern part of the Murraba Basin, mainly on Billiluna. They may also be equivalent to the succession in the Kearney Range currently mapped as Lewis Range Sandstone. The Hidden Basin beds should, therefore, be tentatively removed from the Murraba Basin succession, pending the results of detrital zircon dating which should provide improved constraints on depositional age.

Petroleum prospectivity

There has been no petroleum or mineral exploration drilling in the southern Murraba Basin. There are no seismic data, apart from the ends of several poor-quality Canning Basin seismic lines that terminate slightly beyond the faulted eastern edge of that basin, over covered Murraba Basin. Outcrops, particularly of fine-grained units that could act as petroleum source rocks, are limited, and in all instances are deeply weathered. Likewise, surface weathering and silicification make assessment of potential reservoirs problematic. Salt-bearing units that could act as excellent long-term seals may be present, but cannot be confirmed from poor outcrops. For these reasons it is not possible to directly assess the petroleum potential of specific units within the basin, but correlations with other parts of the Centralian Superbasin, particularly with the nearby petroleum-prospective Amadeus Basin, allow a general discussion of hypothetical prospectivity.

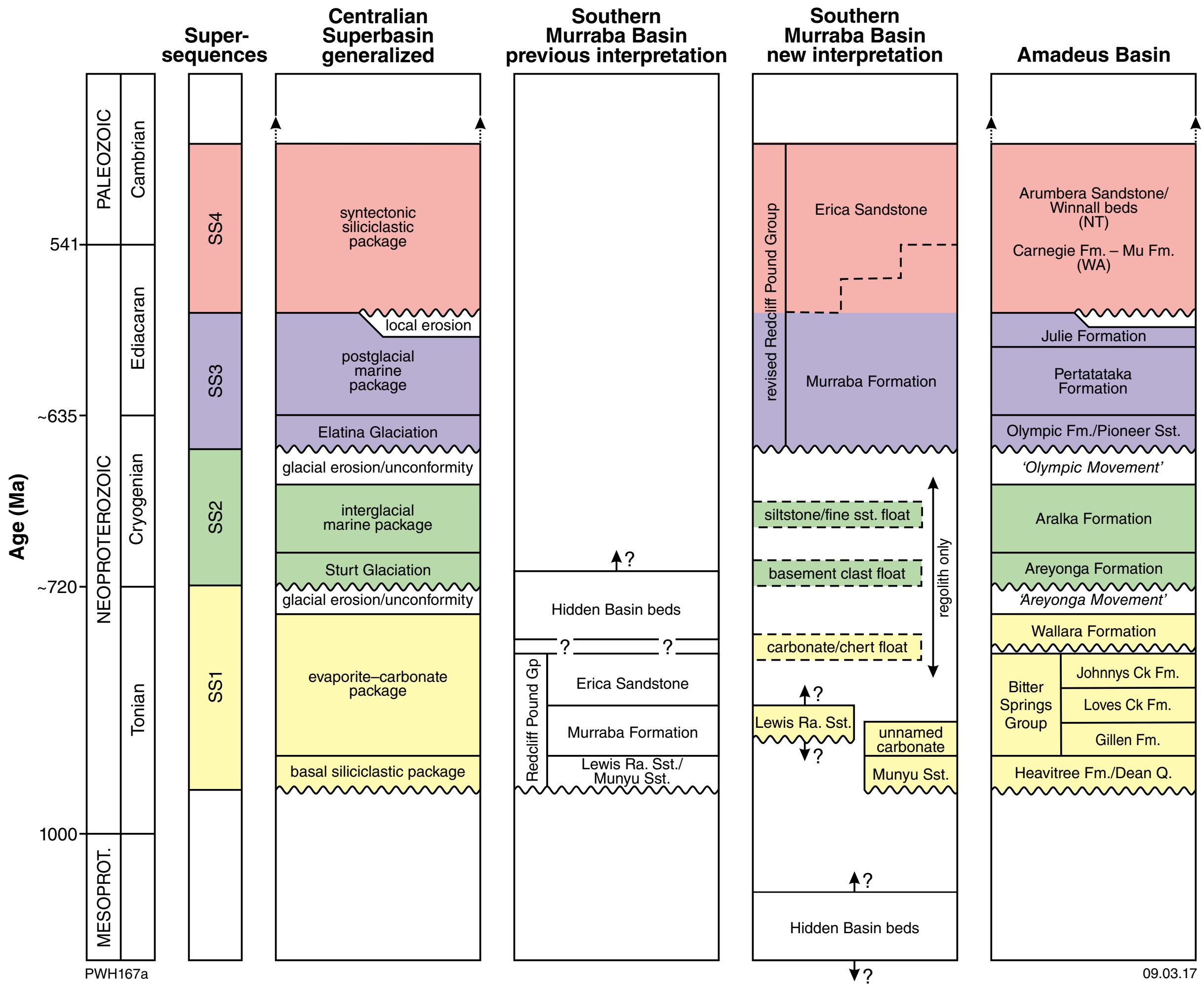

Figure 20. Comparison between the previous and revised stratigraphy of the southern Murraba Basin with respect to generalized Centralian Superbasin and Amadeus Basin Neoproterozoic stratigraphy; timescale follows International Chronostratigraphic Chart v. 2016/12 (Cohen et al., 2013, updated). sst., sandstone; Fm., Formation; Q., Quartzite; Ck, Creek; Ra., Range

Comparison to Amadeus Basin Neoproterozoic petroleum systems

The Amadeus Basin has several proven or probable petroleum systems ranging in age from early Neoproterozoic (Tonian) to Ordovician (Carr et al., 2016). Simplified basin stratigraphy, petroleum systems and selected wells are presented in Figure 21. The Ordovician system has been the target of most exploration and all historic oil and gas production, but is not relevant here as no Ordovician rocks are known in the Murraba Basin. However, multiple petroleum systems are also known from the Neoproterozoic of the Amadeus Basin and gas production from the Neoproterozoic-sourced Dingo Gas Field near Alice Springs has recently commenced (Department of Mines and Energy, Energy Directorate, 2016). The inference that the Murraba and Amadeus Basins were once joined, and the similarity of Neoproterozoic stratigraphy between the respective areas, provides encouragement that similar petroleum systems could be present in the Murraba Basin.

Gillen–Heavitree petroleum system

As originally conceived, the 'Gillen–Heavitree petroleum system' involves an intraformational salt seal in the upper Gillen Formation over source rocks in the shaly lower Gillen Formation, and a sandstone reservoir in the underlying Heavitree Formation (Young and Ambrose, 2007). Local intraformational sandstone could also provide reservoirs within the Gillen Formation. The system has been tested by only two exploration wells in the NT Amadeus Basin (Magee 1, Mt Kitty 1), both technical successes with gas flows to surface from subsalt reservoirs. In the case of Mt Kitty 1, there was no subsalt sandstone reservoir (no Heavitree Formation) and the gas flowed from fractured granitic basement (Clarke et al., 2014; Plummer, 2015; Debacker et al., 2016). In both wells the gas had high helium contents of 6.2% (Wakelin-King, 1994; Clarke et al., 2014) and 9% (Clarke et al., 2014; Debacker et al., 2016), respectively, increasing the commercial possibilities of the play and demonstrating the excellent sealing capacity of Gillen Formation salt.

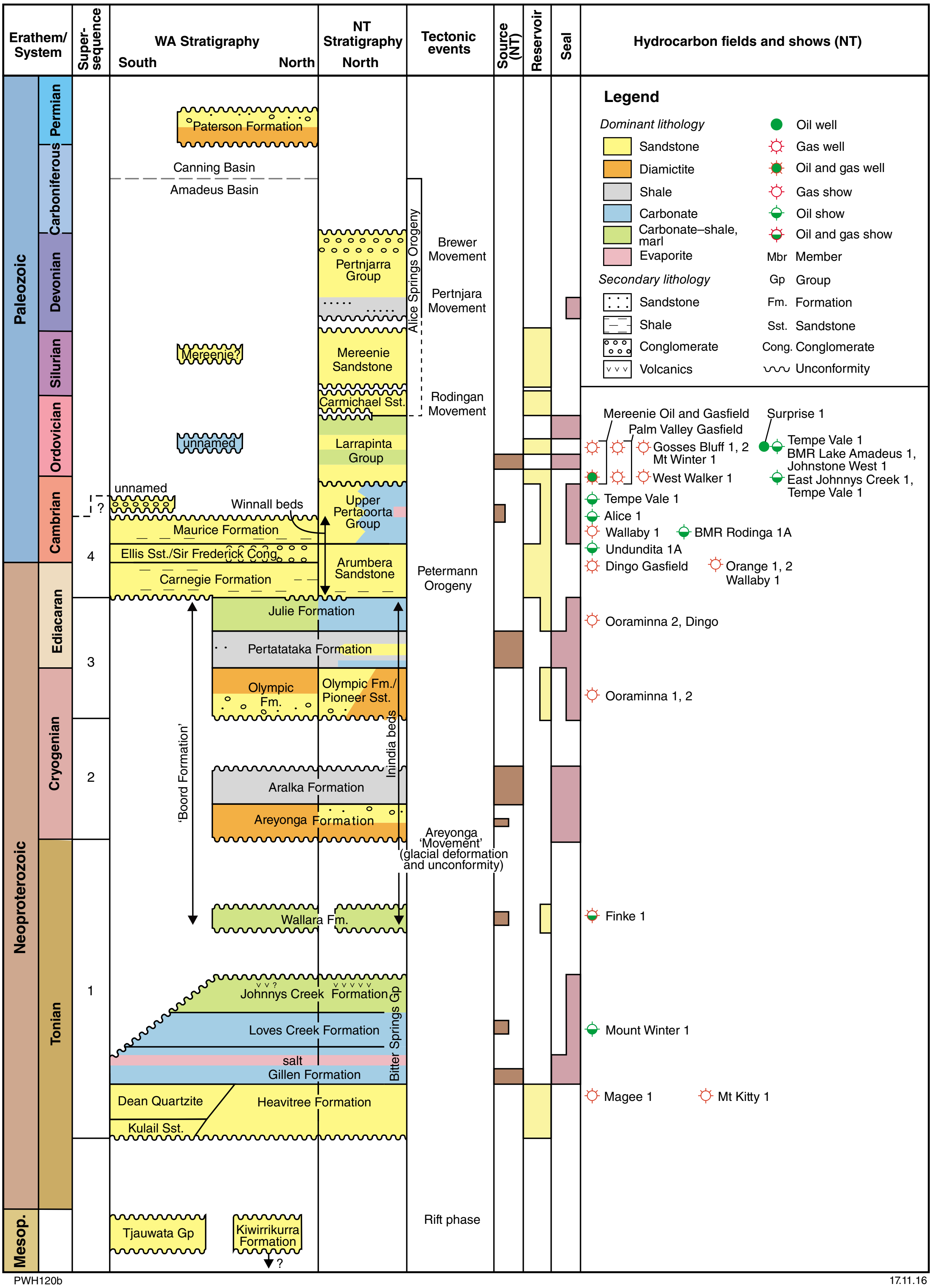

Figure 21. Amadeus Basin stratigraphy and petroleum systems

Although organic geochemical data on subsalt black shales in the Gillen Formation are sparse, the unit is inferred to have fair to good generating potential in the eastern Amadeus Basin (Munson, 2014) with total organic carbon (TOC) values locally up to about 1.8% (Jarrett et al., 2016). However, there is an absence of full Rock-Eval data for the unit.

Equivalent units in the Murraba Basin include the basal Munyu Sandstone and potentially the Lewis Range Sandstone, and the largely concealed overlying section, which is inferred to include a correlative of the Gillen Formation, at least in the south. The presence of organic-rich shaly facies or a salt seal cannot be assessed from the limited and very weathered surface outcrop. However, it is likely there is salt at this level in the Murraba Basin. If salt is present and does provide an effective seal, an equivalent of this petroleum system is considered the most prospective in the Murraba Basin, where burial depths have been sufficient for maturation. However, considering the large number of unknowns the exploration risk is very high.

Post-Gillen Neoproterozoic petroleum systems

In the Amadeus Basin, potential Neoproterozoic source rocks have been identified in the upper Bitter Springs Group and the Wallara, Aralka and Pertatataka Formations, and possibly at other levels (Marshall, 2005; Munson, 2014; Carr et al., 2016; Jarrett et al., 2016). The Wallara Formation has only recently been recognized (Normington et al., 2015) and this unit was previously referred to as ‘Finke beds’ or included in the Johnnys Creek Formation (previously Johnnys Creek ‘beds’). The lower part of this stratigraphy, up to and including Wallara Formation, has been associated with minor oil shows in several wells; most notably Finke 1 where a probable paleo-oil column has been identified in the Wallara Formation based on grain fluorescence studies (Marshall et al., 2007).

Black shales in the Aralka Formation are considered to have gas-prone source-rock characteristics in a number of wells in the eastern Amadeus Basin, with TOC ≤3.4% (Marshall, 2005; Marshall et al., 2007; Munson, 2014). This system is probably responsible for significant gas flows in a Pioneer Sandstone reservoir in Ooraminna 1 and 2. The Aralka Formation correlative in the Ngalia Basin, the Rinkabeena Shale, is a grey to black shale locally more than 900 m thick (Wells and Moss, 1983; Deckelman and Davidson, 1994). The formation was penetrated in only one well, Davis 1, which flared gas for several hours from what are interpreted as fractures in the Rinkabeena Shale (Deckelman and Davidson, 1994). Black shales in the Pertatataka Formation in the eastern Amadeus Basin have gas-prone characteristics with relatively low TOC (≤1%), but are considered the most probable source of gas in the Dingo Gas Field (Marshall, 2005; Marshall et al., 2007; Munson, 2014). Dingo gas is extracted from a reservoir in the Arumbera Sandstone, sealed by local Cambrian salt. Correlatives of all these source units are known to extend into the northern part of the WA Amadeus Basin, close to the tectonically separated Murraba Basin, but source potential cannot be directly assessed at the western end of the basin due to the absence of subsurface data (Haines and Allen, 2014).

Based on our revisions to the Murraba Basin stratigraphy, correlatives of Amadeus Basin units discussed above can be tentatively inferred in the Murraba Basin; however, only correlatives of the Pertatataka Formation are known to be exposed at the surface. The correlative interval of the Pertatataka Formation in the lower Redcliff Pound Group is generally much sandier than in the Amadeus Basin, but significant shaly units could be present beneath covered intervals. However, it is uncertain if this level of the stratigraphy has ever been buried deeply enough for petroleum maturation, or that an adequate seal is present over any conceivable reservoir units. The presence of a thick Paleozoic section is important in this regard in the eastern Amadeus Basin. While significant Paleozoic rocks are absent from the Murraba Basin itself, the Murraba Basin does extend beneath the poorly known Lucas Outlier of the Canning Basin (Fig. 2). It is also inferred to extend beneath the main Canning Basin to the west. Southeastern Canning Basin petroleum exploration well Wilson Cliffs 1 (Fig. 1) intersected carbonaceous black shales at 3578–3722 m (total depth) below the Canning Basin Ordovician succession (Creevey, 1969). The age of this succession is unknown, but it could be a buried component of the Murraba or Amadeus Basin, or of the older Birrindudu Basin. These shales contain a mixture of micronized amorphous kerogen and solid hydrocarbons, have TOC values up to 3.21%, and contain evidence that the unit has generated hydrocarbons but is now post-mature for oil and gas (Castaño, 1980; Buiskool Toxopeus and van Lieshout, 1979). Thus it is possible that pre-Canning sedimentary basins, conceivably the Murraba Basin, could have provided hydrocarbon charge to this younger rock package.

Conclusions

The Murraba Basin is a remnant of the Centralian Superbasin, with stratigraphic similarities to other Neoproterozoic components, particularly the Amadeus, Ngalia and Georgina Basins to the south and east. It contains a significantly greater age range of Neoproterozoic strata than previously thought. Components of basal Supersequence 1 and Supersequences 3 and 4 are confirmed from outcrop, while further units, potentially upper Supersequence 1 and Supersequence 2, can be inferred from regolith and historic shallow drilling. The thickness of the succession is difficult to determine because of the concealed intervals, but is probably significantly greater than the minimum 2000 m estimated for the original Redcliff Pound Group by Blake et al. (1979). It may be comparable in thickness to the Neoproterozoic successions in other components of the Centralian Superbasin.

Based on existing detrital zircon data, the basal siliciclastic units of the Murraba Basin have significant differences in provenance from the north (Lewis Range Sandstone) to south (Munyu Sandstone) of the basin, and may not be direct correlatives. Whereas the Munyu Sandstone was mainly sourced from rocks of, or similar to, the Musgrave region and Arunta Orogen, the source of the Lewis Range Sandstone is unknown, but detrital zircon age spectra are similar to those from the Yeneena Basin exposed southwest of the Canning Basin.

Because of the significantly increased time span now ascribed to the Murraba Basin, and probable internal unconformities, we have redefined the Redcliff Pound Group to include only those units exposed in the Redcliff Pound area — Murraba Formation and Erica Sandstone. The redefined group is mainly of Ediacaran age and includes components of both Supersequence 3 and 4. It is possible that Supersequence 4 extends into the Cambrian, as demonstrated elsewhere on biostratigraphic grounds, but nonmarine facies at the top of the succession preclude biostratigraphic analysis. The Murraba Formation and Erica Sandstone do not appear to have been consistently mapped between LUCAS and STANSMORE, probably due to the way the units have been defined; thus, the boundary criteria of these units are in need of reassessment. Paleocurrent data from deltaic facies in the Redcliff Pound Group indicate a tectonically active sediment source to the west, currently covered by the Canning Basin.

The stratigraphic position of the Hidden Basin beds remains uncertain. However, the previous interpretation that this package overlies the Erica Sandstone is unlikely, and it is more probable that the unit pre-dates the Murraba Basin. It may have affinity with the much older Birrindudu Basin succession, with which it shares notable lithological similarity. Some areas currently mapped as lower Murraba Basin, such as sections in the Kearney Range, may also belong to this potentially older package.

While the petroleum potential of the Murraba Basin cannot be directly assessed from weathered outcrop, similarities to the Neoproterozoic stratigraphy of the other components of the Centralian Superbasin with proven petroleum systems, most importantly to the Amadeus Basin, mean it is possible that similar petroleum systems could be present. Any potential source rocks in the upper part of the basin are unlikely to have reached sufficient burial depths for maturation, and the presence of an adequate seal is problematic, except perhaps where the Murraba Basin lies beneath younger cover of the Canning Basin. The lower part of the basin succession (particularly Supersequence 1) may have locally attained sufficient burial for maturation, and if a salt seal is present, plays analogous to the 'Gillen–Heavitree petroleum system' of the Amadeus Basin are possible.

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Appendix

Revised lithostratigraphic definition, Redcliff Pound Group

DEFINITION CARD	
NAME OF UNIT: Redcliff Pound Group	**STATE(S):** WA and NT
STATUS OF UNIT: Redefinition of formal unit	**RANK:** Group
PROPOSER: Peter Haines and Heidi Allen (GSWA); originally Blake et al. (1979).	**DATE:** 23 January 2017
IN STRATIGRAPHIC UNITS DATABASE: Yes	
PROPOSED PUBLICATION: GSWA Record 2017/4 (Haines and Allen, 2017)	

DERIVATION OF NAME: Redcliff Pound, WA (21º 35'S, 128º 45'E)

SYNONYMY, UNIT NAME HISTORY: The term Redcliff Pound Group was first used by Blake et al. (1973), and defined and described in more detail by Blake et al. (1979). The group was originally part of the Birrindudu Basin succession, but later moved to the Centralian Superbasin by Tyler and Hocking (2001). This part of the Centralian Superbasin was given the name Murraba Basin by Tyler (2005) and Grey et al. (2005). As originally conceived, the group comprised the correlative Lewis Range, Muriel Range and Munyu Sandstones at the base, overlain successively by the Murraba Formation and Erica Sandstone. The original correlations to the Amadeus Basin suggested by Blake et al. (1979), if correct, would restrict the original Redcliff Pound Group to Supersequence 1 of the Centralian Superbasin (supersequence terminology after Walter et al., 1995). The correlation of this succession to the rest of the Centralian Superbasin was substantially revised by Haines and Allen (2016, 2017), who assigned the Lewis Range, Muriel Range and Munyu Sandstones to lower Supersequence 1, and the Murraba Formation and Erica Sandstone to Supersequence 3–4. The base of the exposed Murraba Formation is inferred to be an unconformity over a mostly concealed succession (inferred from regolith) likely belonging to upper Supersequence 1 and Supersequence 2. The original Redcliff Pound Group no longer fits the lithostratigraphic definition of a group (‘a succession of two or more contiguous or associated formations with significant and diagnostic lithologic properties in common’) as it contains significant unconformities and hiatuses in deposition, and was deposited episodically over much of the Neoproterozoic. The definition of the Redcliff Pound Group is herein revised to include only the conformable Murraba Formation and Erica Sandstone, and exclude all lower units of the Murraba Basin. It includes all of the units exposed in the Redcliff Pound area where the name was derived.

CONSTITUENT UNITS: Murraba Formation and Erica Sandstone.

PARENT UNIT: None

TYPE LOCALITY: Not required for groups. Type localities of constituent units are near Redcliff Pound (Murraba Formation) and Erica Range (Erica Sandstone), as nominated by Blake et al. (1979). The Redcliff Pound area (centred around 21º 35'S, 128º 45'E) forms a useful Reference Locality for the group as a whole.

CONFIDENTIAL TYPE LOCALITY?: No

DESCRIPTION AT TYPE LOCALITY:
LITHOLOGY: Murraba Formation: Sandstone, siltstone, and minor carbonate and conglomerate deposited in shallow marine to deltaic environments. Erica Sandstone: predominantly sandstone deposited in deltaic, fluvial and eolian environments.
THICKNESS: c. 1500 m in the Redcliff Pound area (Blake et al., 1979).
FOSSILS: *Arumberia* and probable tubular body fossils are present in the lower part of the group.
DIASTEMS OR HIATUSES: None observed.
RELATIONSHIPS & BOUNDARY CRITERIA: Unconformable over mostly concealed unnamed units (likely Supersequence 1–2 of Centralian Superbasin). Top (Erica Sandstone) is youngest unit of the Murraba Basin and is unconformably overlain by Paleozoic outliers of the Canning Basin in WA and the Antrim Plateau Volcanics in NT.
DISTINGUISHING OR IDENTIFYING FEATURES: More resistant than underlying succession presumably due to dominant sandstone lithologies in Redcliff Pound Group. Underlying succession inferred to be mainly diamictite, siltstone and carbonates, which are either absent (diamictite) or subordinate in the Redcliff Pound Group.
AGE & EVIDENCE: Inferred to be mainly of Ediacaran age, but the age could potentially extend from the late Cyrogenian to early Cambrian. The age is inferred from regional correlations to the Amadeus and Georgina Basins. The problematical fossil *Arumberia* and probable tubular body fossils, both present in the late Ediacaran of the Amadeus and Georgina Basins, are present in the middle of the group. The age of the top is older than the c. 510 Ma Antrim Plateau Volcanics, which are inferred to locally overlie the Erica Sandstone in the NT (Ahmed, 2013).
CORRELATION WITH OTHER UNITS: Regionally correlated with Supersequence 3 and 4 of the Centralian Superbasin (supersequence scheme of Walter et al., 1995).
REGIONAL ASPECTS/GENERAL GEOLOGICAL DESCRIPTION
EXTENT: Outcrops are restricted to the eastern STANSMORE and southeastern LUCAS 1:250 000 map sheet areas in WA, and western HIGHLAND ROCKS in the NT.
GEOMORPHIC EXPRESSION: Low strike ridges and strike valleys.
THICKNESS VARIATIONS: Not well constrained due to poor outcrop; c. 1500 m in the Redcliff Pound area (Blake et al., 1979).
STRUCTURE AND METAMORPHISM: Gently to tightly folded and faulted, but not metamorphosed.
ALTERATION AND MINERALISATION: None observed.
GEOPHYSICAL EXPRESSION: Not distinguished on geophysical datasets.
GEOCHEMISTRY: No data.
GENESIS/DEPOSITIONAL ENVIRONMENT: Changes up-section from shallow marine, to deltaic and fluvial, with eolian facies near the top.
COMMENTS:

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RECORD 2017/4

GEOLOGICAL RECONNAISSANCE OF THE SOUTHERN MURRABA BASIN, WESTERN AUSTRALIA: REVISED STRATIGRAPHIC POSITION WITHIN THE CENTRALIAN SUPERBASIN AND HYDROCARBON POTENTIAL

Haines and Allen

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