Government of **Western Australia**
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Abstract

The Amadeus Basin is a large and economically important Neoproterozoic to Paleozoic depositional system in central Australia. The Western Australian (WA) portion of the basin is much less known and explored than its counterpart in the Northern Territory (NT), a function of remoteness, poor outcrop and historic perceptions of decreased prospectivity to the west. Most outcrops in WA comprise either the Tonian to lower Cryogenian basal section (the Heavitree Quartzite and overlying Bitter Springs Formation, and southern margin equivalents) or siliciclastic units now recognized to be of upper Ediacaran to lower Cambrian age deposited synchronously with the Petermann Orogeny (the Carnegie to Maurice Formations). Compared to the east, most of the intervening Neoproterozoic section (Cryogenian to lower Ediacaran) is rarely exposed, and most of the eastern units were once thought to be absent. Here we show that the stratigraphic section exposed in the Boord Ridges and adjacent Gordon Hills, most of which was previously referred to collectively as the 'Boord Formation', provides a unique semicontinuous window into the bulk of the Neoproterozoic stratigraphy of the western Amadeus Basin. Although of variable and often poor outcrop quality, the stratigraphy of this section is directly comparable to that known from outcrop and drilling in the eastern Amadeus Basin. Recognized units above the Bitter Springs Formation include an unnamed unit (c. 150 m), the Areyonga (c. 150 m), Aralka (c. 450 m), Olympic (≤ 100 m), Pertatataka (c. 300 m), Julie (c. 500 m) and Carnegie (> 70 m) Formations, and the Ellis Sandstone (c. 130 m) in ascending order. Based on stratigraphic position and stromatolite occurrences, the unnamed unit at the base is correlated with a unit that has been informally referred to as the 'Finke beds' in hydrocarbon exploration wells in the NT. Although the distribution of most of the units between the Bitter Springs and Carnegie Formations beyond the Boord Ridges area is speculative, we infer that they are widespread, at least in the northern half of the WA Amadeus Basin. In the south at least some, and locally all, may have been eroded during uplift associated with the Petermann Orogeny. The presence in WA of all formations bearing proven or probable Neoproterozoic hydrocarbon source rocks known in the NT increases the hydrocarbon prospectivity of the WA Amadeus Basin.

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

Introduction

The Amadeus Basin is a thick and economically important Neoproterozoic to Paleozoic basin in central Australia. While the north–central and northeastern parts of the basin in the Northern Territory (NT) are moderately well studied and have been part of a hydrocarbon-producing province since the 1980s, the southern and western parts are less well known due to poorer outcrop and accessibility. The portion in Western Australia (WA) has, until recently, been essentially ignored due to remoteness, poor access, extensive surficial sand cover, and perceptions of limited hydrocarbon and mineral prospectivity. The Geological Survey of Western Australia (GSWA) began fieldwork in this area in 2009 and it was quickly realized that significant revisions to stratigraphic correlations with the rest of the basin were required. Preliminary progress has been reported in Haines et al. (2010a,b, 2012a,b), Allen et al. (2012) and Grey et al. (2012). The proposed stratigraphic revisions provide the basis for a fresh discussion of the hydrocarbon prospectivity of the far western end of the basin.

Although often poorly and incompletely exposed, the outcrops around the Boord Ridges and adjacent Gordon Hills (Fig. 1, northeastern MACDONALD map sheet) are recognized as providing the key stratigraphic section for revising most of the Neoproterozoic stratigraphy of the far western Amadeus Basin. Direct correlation can now be made with the better known northeastern Amadeus Basin. This Record provides a description of the geology and revised stratigraphy of this key area.

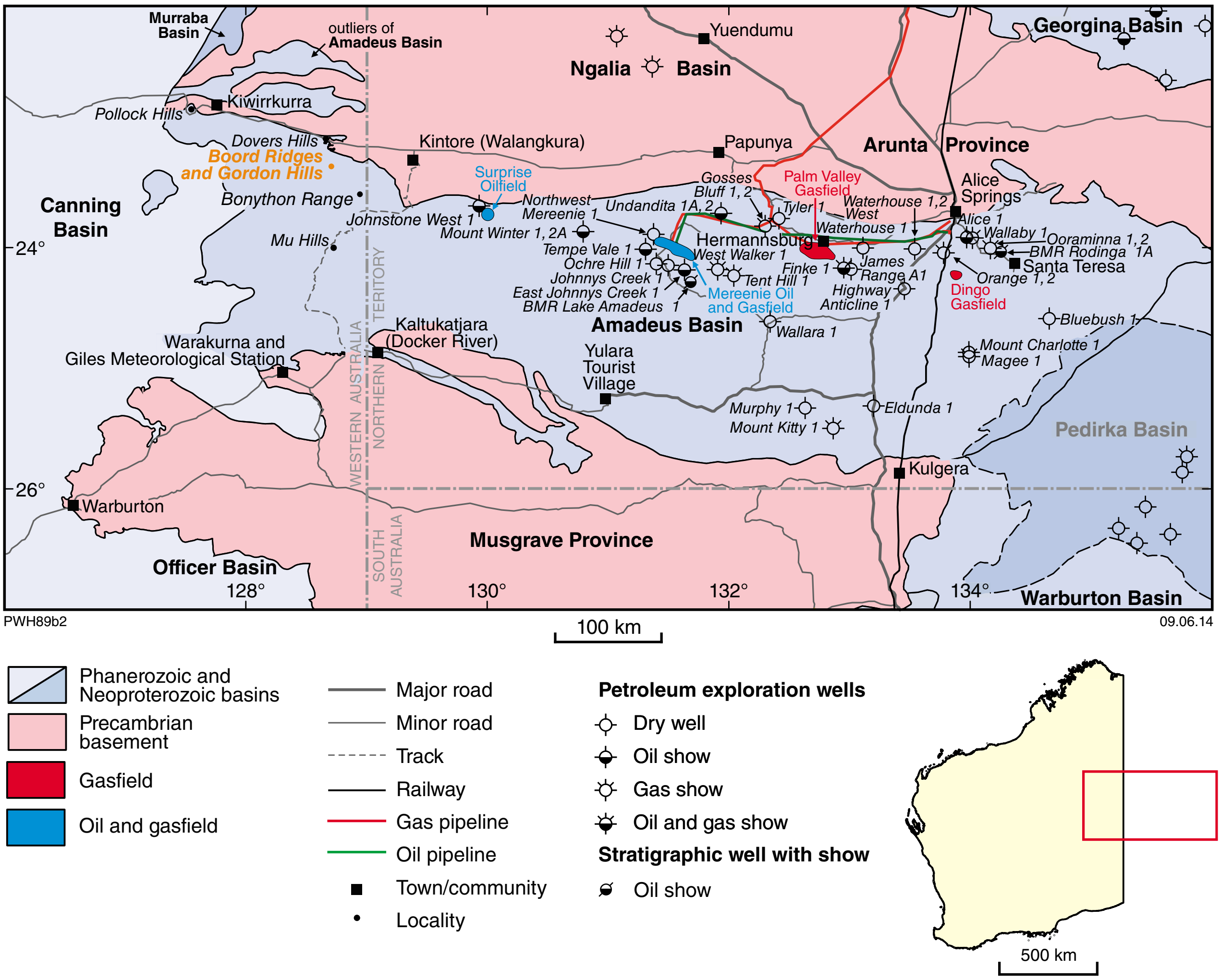

Figure 1. The Amadeus Basin showing hydrocarbon exploration wells, fields, and the location of the Boord Ridges and Gordon Hills

Regional geology

The Amadeus Basin (Wells et al., 1970; Korsch and Kennard, 1991; Edgoose, 2012, 2013) is exposed over approximately 170 000 km^2 in central Australia, mostly within the NT, with roughly one-fifth of the exposed basin extending into WA (Fig. 1). Its lower Neoproterozoic to upper Paleozoic fill (Fig. 2) locally reaches a thickness of about 12 km in the NT (Edgoose, 2013). The Neoproterozoic component is considered to be part of the former Centralian Superbasin (Walter et al., 1995), a large intracratonic depositional system that was linked to the Adelaide Rift Complex (Adelaide Geosyncline) along the continental margin. The Centralian Superbasin was progressively fragmented by Neoproterozoic and Paleozoic orogenic events to form the present Neoproterozoic to Paleozoic basins of central Australia. The current boundaries of the Amadeus Basin do not reflect depositional limits, but are either of tectonic origin, or placed where the basin is onlapped by younger depositional systems, such as the Canning Basin to the west.

The sedimentary fill is mainly of shallow-marine origin, apart from significant fluvial clastic wedges shed from the uplifted basin margins during orogenic events. Deposition began in the early Neoproterozoic with a widespread sand blanket, now comprising the Heavitree Quartzite in the north and the Kulail Sandstone and the Dean Quartzite in the south (Haines et al., 2012a). A widespread thick salt unit within the Gillen Member of the overlying Bitter Springs Formation is responsible for the halotectonic deformational style of the basin (Lindsay, 1987; Marshall and Dyson, 2007), although a more spatially restricted salt unit (the Chandler Formation) is also present in the Cambrian section in the east. Apart from evaporites, the Bitter Springs Formation is dominated by carbonate rocks and fine siliciclastic interbeds, with a local volcanic component near the top. The remainder of the Neoproterozoic succession comprises alternating carbonates and fine- to coarse-grained siliciclastics, including two widespread predominantly siliciclastic glacial phases that can be correlated throughout the Centralian Superbasin and Adelaide Rift Complex — the Sturt ('Sturtian') and Elatina ('Marinoan') glaciations, in ascending order (Hill et al., 2011). An immature deltaic to non-marine clastic package straddling the Neoproterozoic–Cambrian boundary is related to southern margin uplift during the Petermann Orogeny (see below).

The Neoproterozoic of the Amadeus Basin, and other components of the Centralian Superbasin, was subdivided into four supersequences by Walter et al. (1995) to facilitate regional correlation. The base of Supersequence 1 is marked by the unconformity at the base of the Heavitree Quartzite and equivalents. The bases of Supersequence 2 and 3 are marked by regional unconformities related mainly to the onset of the two Neoproterozoic glaciations. The base of Supersequence 4, which may be unconformable or conformable, depending on its position in the basin, is marked by the onset of the Petermann Orogeny and the base of the associated syntectonic siliciclastic package.

The eastern Amadeus Basin contains a thick Paleozoic section including mainly marine Cambrian and Ordovician strata, and non-marine Silurian to Devonian rocks. The Cambrian succession becomes progressively more terrestrial and exclusively siliciclastic to the west. Because these western siliciclastic units are unfossiliferous, it is unclear how much of the Cambrian section may be present in WA. Fossiliferous marine Ordovician rocks have been identified in WA (Wells et al., 1964; Haines et al., 2012a), but are localized and presumably thin. Possible Silurian–Devonian rocks in WA are restricted to one outcrop of the Mereenie Sandstone identified by Wells et al. (1964); other outcrops once considered Devonian are now demonstrated to be much older.

Two major tectonic events affected the basin during deposition. The first, the c. 580–530 Ma Petermann Orogeny (Forman, 1966; Aitken et al., 2009; Walsh et al., 2012; Howard et al., 2011) was focused on the Mesoproterozoic Musgrave Province to the south of the Amadeus Basin, but also strongly affected the southern margin of the basin, with deformation decreasing to the north. The Alice Springs Orogeny, focused on the Paleoproterozoic–Mesoproterozoic Arunta Province to the north, and the northern margin of the basin, was a series of compressive movements extending from the latest Ordovician to a culmination in the Devonian and Carboniferous (Forman et al., 1967; Haines et al., 2001). Structural style in the basin is strongly influenced by halotectonics and the timing of salt movement likely extended beyond the recognized orogenic events (Marshall and Dyson, 2007).

Previous studies

Although early European explorers and prospectors made some geological notes while traversing the WA Amadeus Basin, the first systematic geological mapping of the area was undertaken by the Bureau of Mineral Resources (BMR), starting in 1960 (Wells et al., 1961, 1964). The Boord Ridges area was mapped at this time and that data later compiled into the MACDONALD geological map (Wells, 1968). These authors mapped three Neoproterozoic units at the Boord Ridges: the Bitter Springs Formation, the ‘Boord Formation’ and the Ellis Sandstone in ascending order, with the Heavitree Quartzite exposed approximately 10 km to the north. Two partially measured sections of the ‘Boord Formation’ (MFX1 and MFX8) were presented in Wells et al. (1961, 1964). The ‘Boord Formation’ was interpreted as a correlative of the Areyonga Formation and the Inindia beds of the NT Amadeus Basin, and the Carnegie Formation to the south in WA (Wells, 1968; Wells et al., 1970). Note that the definition of the Areyonga Formation was subsequently revised by Preiss et al. (1978), but at the time of the early BMR work it included the current Areyonga Formation plus the Aralka Formation and overlying Pioneer Sandstone at its type area in the MacDonnell Ranges. The correlation with the old Areyonga Formation and the Inindia beds was based on lithological similarities, specifically the recognition of glacial diamictites in all three units. Glacial influence was not recognized in the Carnegie Formation; correlation with that unit was based on the belief that the ‘Boord’ and Carnegie Formations occupy the same stratigraphic position between the Bitter Springs Formation and the Ellis Sandstone, and on the apparent interfingering of the ‘Boord’ and Carnegie Formations at a location south of the Boord Ridges and west Bonython Range (Fig. 1). The area was covered by a reconnaissance gravity survey in 1962 (Lonsdale and Flavelle, 1968).

Beach Petroleum NL held petroleum exploration tenement PE 153 H over much of the WA part of the Amadeus Basin, including the Boord Ridges area, in the 1960s. The tenement was farmed out to Australian Aquitaine Petroleum Pty Ltd in 1965. Available reports are restricted to an aeromagnetic survey and outcrop studies which included re-measurement of the BMR sections in the Boord Ridges (Wilson and Gates, 1965). Evidence of stratigraphic drilling along the eastern of these measured sections (MFX1), and elsewhere, was discovered during GSWA field studies in 2009. This drilling is believed to have taken place in 1967 and to be related to PE 153 H, although no reports of this activity are held by GSWA (Haines, 2010). The three marked drillholes located in the Boord Ridges (CD4: MGA 470851E 7421352N; CD5: MGA 470527E 7420274N; CD6: MGA 470385E 7419797N) apparently targeted very poorly exposed shaly sections of the ‘Boord Formation’ (now the upper Aralka and Julie Formations), and were likely aimed at obtaining lithological details of these units, possibly including source rock properties.

Walter et al. (1979) described a new stromatolite (*Tesca stewartii*) from carbonates in the ‘Boord Formation’ in the Boord Ridges, apparently from the lower part of the unit now recognized as the Julie Formation. Grey (1990) and Walter et al. (1995) tentatively assigned the ‘Boord Formation’ to Supersequence 3, rather than a combined Supersequence 2–3 as implied by earlier correlations.

Modern geophysical surveys over the area include an aeromagnetic and radiometric survey flown by the Australian Geological Survey Organisation in 1993 (400 m line spacing, 60 m mean terrain clearance), and an airborne gravity survey (5000 m line spacing, 1200 m mean terrain clearance) conducted by Merlin West Pty Ltd

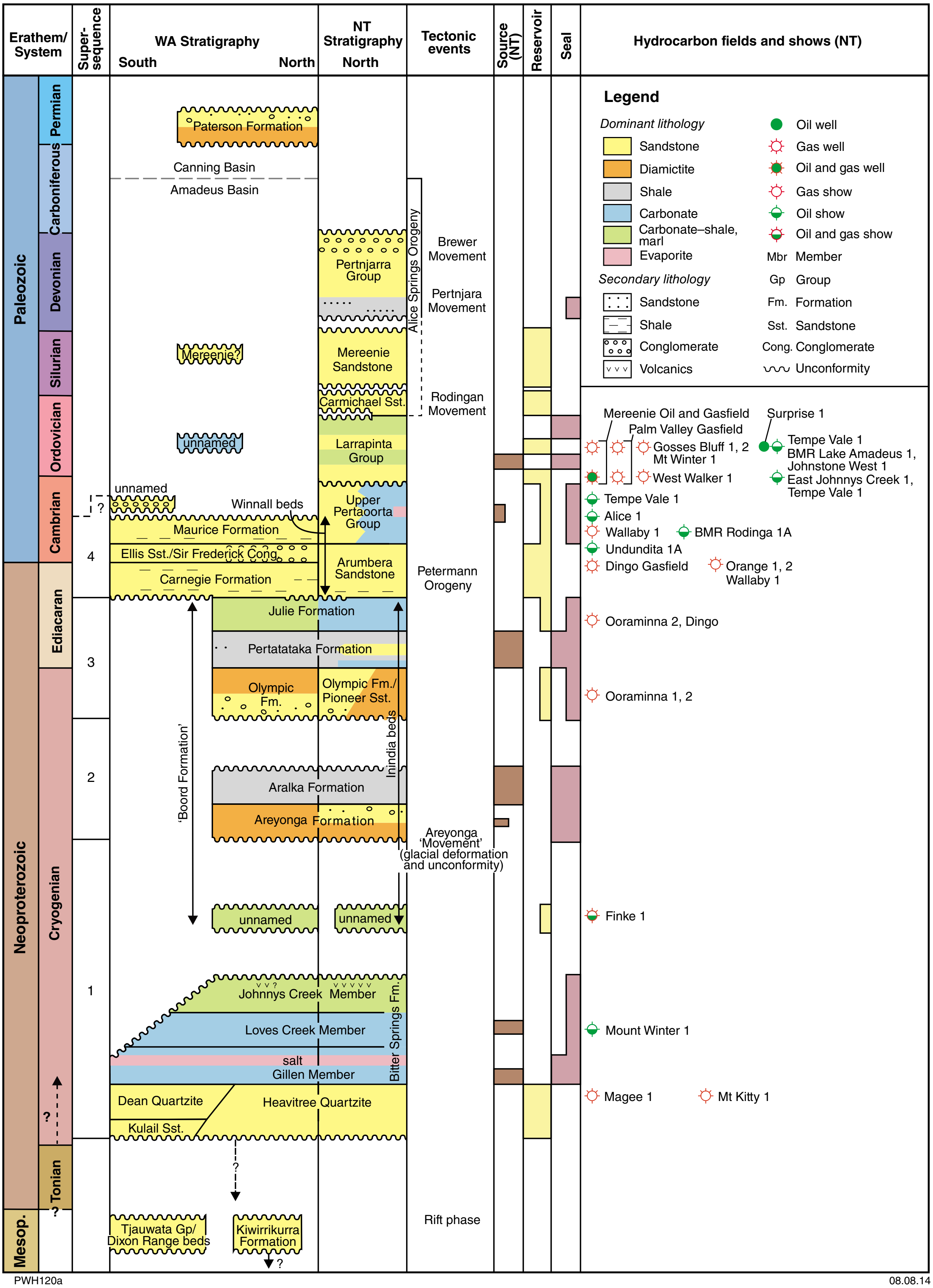

Figure 2. Simplified stratigraphy of the Western Australian and northern Northern Territory Amadeus Basin, showing petroleum systems and wells with hydrocarbon shows or production in the Northern Territory

in 2008 as a commitment to Special Prospecting Authority SPA 7/04–5 AO covering most of the WA Amadeus Basin. Combined interpretation of the aeromagnetic and gravity data is presented by Dentith and Cowan (2011).

Structure and topography

The Boord Ridges and Gordon Hills form the northern limb and hinge, respectively, of a doubly plunging asymmetric syncline (Fig. 3); the southern and western portions of which are mostly covered by Cenozoic deposits. Although outcrop is generally very poor along the synclinal axis east of the Gordon Hills, trend lines on aerial images suggest that the axis is either fault offset south of the central Boord Ridges, or that there are two separate axes, parallel but slightly offset in an en echelon manner. Despite this uncertainty, the term Boord Ridges Syncline refers to the combined structure throughout this Record. The Boord Ridges is a west-northwest-trending belt of south-southwest-dipping low strike ridges and rubbly rises about 20 km long. Dips are steep (c. 60 to 70°) at the northernmost outcrops, but decrease steadily towards the syncline hinge. The ridges lie to the northwest of Lake Macdonald salt lake system (a complex of small ephemeral lakes) which occupies the lowest topography in the area. The maximum relief is less than 40 m from the highest ridge tops to the usually dry lake floor to the south. The 6 km long Gordon Hills lie immediately to the west of the Boord Ridges and the highest point, Mount Greene, is elevated about 90 m above the lake floor. The southern limb of the syncline is very poorly exposed, apart from the southern flank of the Gordon Hills.

Stratigraphy

The stratigraphy exposed on the northern limb of the Boord Ridges Syncline includes the upper Bitter Springs Formation overlain by an unnamed unit, followed by the Areyonga, Aralka, Olympic, Pertatataka and Julie Formations, in ascending order, with the overlying Carnegie Formation and the Ellis Sandstone exposed in the synclinal hinge in the Gordon Hills (Figs 3 and 4). The Heavitree Quartzite at the base of the succession is exposed about 10 km to the north, beyond a covered interval that probably obscures, at least in part, halotectonically deformed lower Bitter Springs Formation (mostly Gillen Member). The combined section represents all units, or their equivalents, as recognized in the Neoproterozoic section of the northeast Amadeus Basin, with the addition of the unnamed unit. The Supersequence classification used below is that of Walter et al. (1995).

Thickness estimates are based on measured dips, which are approximate only due to the poor quality of many outcrops. The thickness estimates were derived from the central northern limb of the Boord Ridges Syncline, where units appear to be at their maximum thickness. The overall succession appears to thin significantly towards the western end of the structure, but due to extensive cover it is unclear if this thinning involves all units, or only some, and if any component of the thinning could have a structural explanation. It is possible that some units pinch out to the west. Such rapid thickness changes are consistent with active halotectonics during deposition.

Supersequence 1

Heavitree Quartzite

The Heavitree Quartzite is the basal unit of the Amadeus Basin in the north, and is exposed intermittently along the full length of its northern margin. The type section is in the NT (Heavitree Gap at Alice Springs; Joklik, 1955), and Wells et al. (1964) mapped the unit into WA. The assumed equivalent Dean Quartzite (Wells et al., 1964) is mapped along the southern boundary of the basin.

The unit does not crop out at the Boord Ridges, but is exposed as intermittent south-dipping strike ridges about 10 km north of the northernmost outcrops of the Boord Ridges where they overlie crystalline basement of the Arunta Province, although this contact is not exposed here. A thickness of about 120 m was measured in the nearby Dovers Hills (Fig. 1) by Wells et al. (1964). The lithology is dominated by variably silicified medium- to coarse-grained, blocky to flaggy quartz sandstone and conglomerate, with minor interbeds of green siltstone. The sandstone is commonly cross-bedded and sometimes displays wave and current ripple marks (Fig. 5a). Near the Pollock Hills (Fig. 1), 130 km to the west-northwest, the formation can be subdivided into a lower coarse to pebbly and conglomeratic fluvial facies, and an overlying finer and texturally more mature sandstone sequence of likely shallow marine origin (Haines et al., 2012a).

The age of the Heavitree Quartzite is poorly constrained. It is normally assigned a basal Cryogenian age (c. 850 Ma) based on the assumption of conformity with the Gillen Member and the further assumption that no long time breaks occurred between the beginning of sedimentation and the deposition of better age constrained upper Bitter Springs Formation. However, the maximum age constraints for the unit are latest Mesoproterozoic (c. 1040 Ma), based on the youngest units underlying the Heavitree Quartzite equivalents in the Musgrave Province (1041 ± 2 Ma Wankari Volcanics of the upper Tjauwata Group: Close et al., 2003). Where not heavily silicified, the Heavitree Quartzite is seen as a potential hydrocarbon reservoir to the ‘Gillen petroleum system’ (Wakelin-King, 1994; Young and Ambrose, 2007).

Bitter Springs Formation

The Heavitree Quartzite is overlain by the Bitter Springs Formation across the entire northern margin of the Amadeus Basin, with outcrops and drill intersections widespread in the NT. Originally defined by Joklik (1955) in the northeastern Amadeus Basin, the Bitter Springs Formation was mapped across the WA portion of the basin by Wells et al. (1964), although outcrops are sparse and all sections incomplete. The most recent subdivision recognizes three members, the Gillen, Loves Creek and Johnnys Creek in ascending order (Ambrose, 2006;

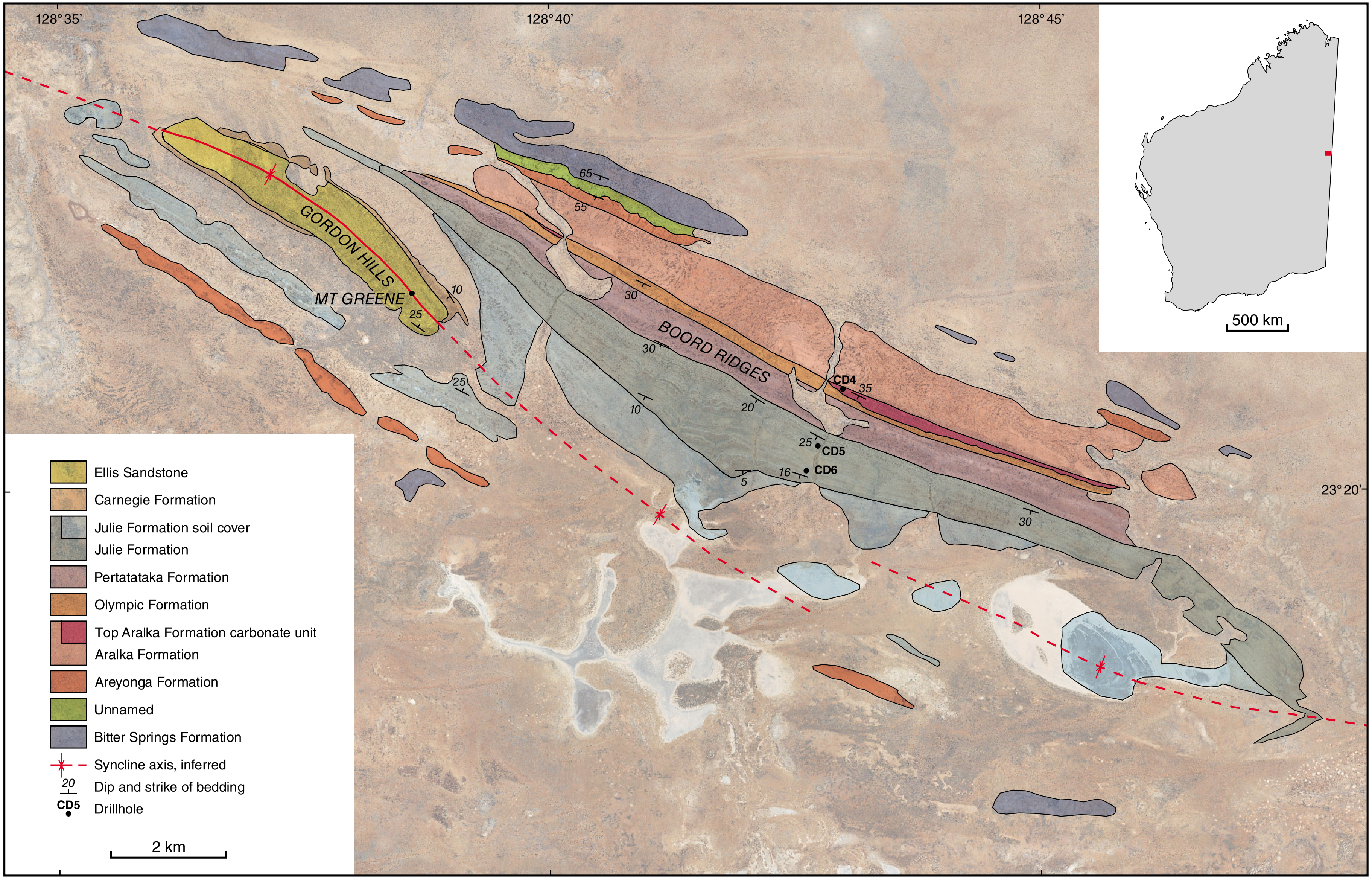

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Figure 3. Geological map of the Boord Ridges and Gordon Hills draped over aerial orthophoto. Cenozoic deposits are not represented. Julie Formation soil cover in the legend refers to areas with subtle bedding trends of Julie Formation on aerial images, but very little or no outcrop. Such bedding trends could include basal Carnegie Formation.

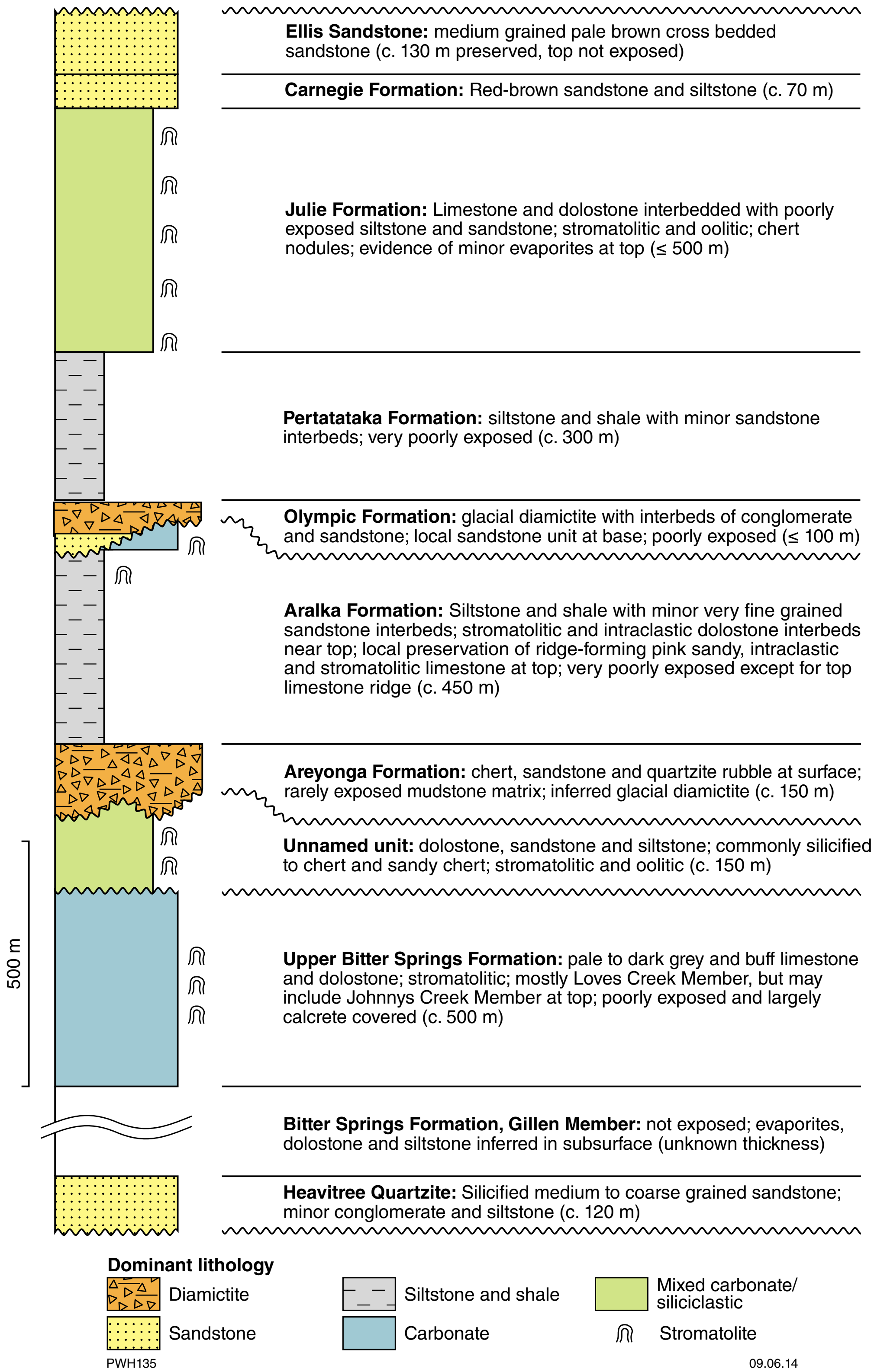


Figure 4. Schematic stratigraphic section across the Boord Ridges and Gordon Hills, including Heavitree Quartzite exposed 10 km to the north. Unit thicknesses are estimates from aerial photographs and measured dips. Some structural thickening is possible.

Edgoose, 2013). The Gillen Member comprises dolostone, siliciclastic rocks and significant thicknesses of evaporites in the subsurface, most notably halite. The halite content has driven halotectonics throughout the basin (Lindsay, 1987; Marshall and Dyson, 2007) and a salt seal is integral to the Gillen petroleum system which involves charge from basal Gillen Member organic-rich shales, and entrapment in a Heavitree Quartzite reservoir (Wakelin-King, 1994; Young and Ambrose, 2007). The overlying Loves Creek Member is dominated by grey limestone and dolostone, often stromatolitic, with subordinate siltstone and shale. The contact between these members has been locally described as disconformable or unconformable (Edgoose, 2013), but in many areas the relationship is unclear. The Johnnys Creek Member, formerly 'unit 3' or the 'lacustrine unit' of an earlier conception of the Loves Creek Member, is distinguished from the current Loves Creek Member by significant intervals of mottled red dolomitic mudstone with interbedded units of grey dolostone and limestone. The Johnnys Creek Member locally contains mafic volcanic interbeds in the NT, and Haines et al. (2012a) speculate that certain linear aeromagnetic anomalies in the southern part of the WA Amadeus Basin could represent such volcanics under cover. No such aeromagnetic anomalies are associated with the Boord Ridges outcrops.

All three members can be tentatively identified locally in WA, but in the Boord Ridges area it has not been possible to map boundaries between the members due to poor exposure. Outcrop is generally low and patchy, partially calcrete and sand covered, and confined to grey and buff-coloured chert-bearing dolostone and limestone. The carbonates are massive to laminated and locally intraclastic and oolitic, and there are horizons of locally abundant and well-preserved stromatolites. These stromatolites comprise a range of taxa, all belonging to the *Acaciella australica* Stromatolite Assemblage (Fig. 5b–d) characteristic of the Loves Creek Member (Allen et al., 2012; Grey et al., 2012). Sparse outcrops below and above the zone of stromatolites could belong to the top of the Gillen Member, or the Johnnys Creek Member, respectively. The poor outcrop would likely hide the distinctive, but recessive red mudstone intervals of the Johnnys Creek Member, if present.

No exposure of the contact between the Bitter Springs Formation and the Heavitree Quartzite was seen north of the Boord Ridges. The c. 10 km sand-covered interval between the south-dipping Heavitree Quartzite and the northernmost Bitter Springs Formations outcrops of the Boord Ridges is assumed to be largely underlain by Gillen Member, very likely convoluted due to salt tectonics, and possibly entraining some younger members, or even younger formations. The contact between the Heavitree Quartzite and the Gillen Member is exposed, though poorly, in the Pollock Hills area 130 km to the west-northwest (Fig. 1), where it appears to be gradational (Haines et al., 2012a).

No thickness for the Bitter Springs Formation as a whole can be given in the Boord Ridges area, or elsewhere in WA. The exposed upper Bitter Springs Formation (mostly the Loves Creek Member, but possibly including the Johnnys Creek Member) is estimated to be about 400 m thick on the central northern limb of the Boord Ridges Syncline.

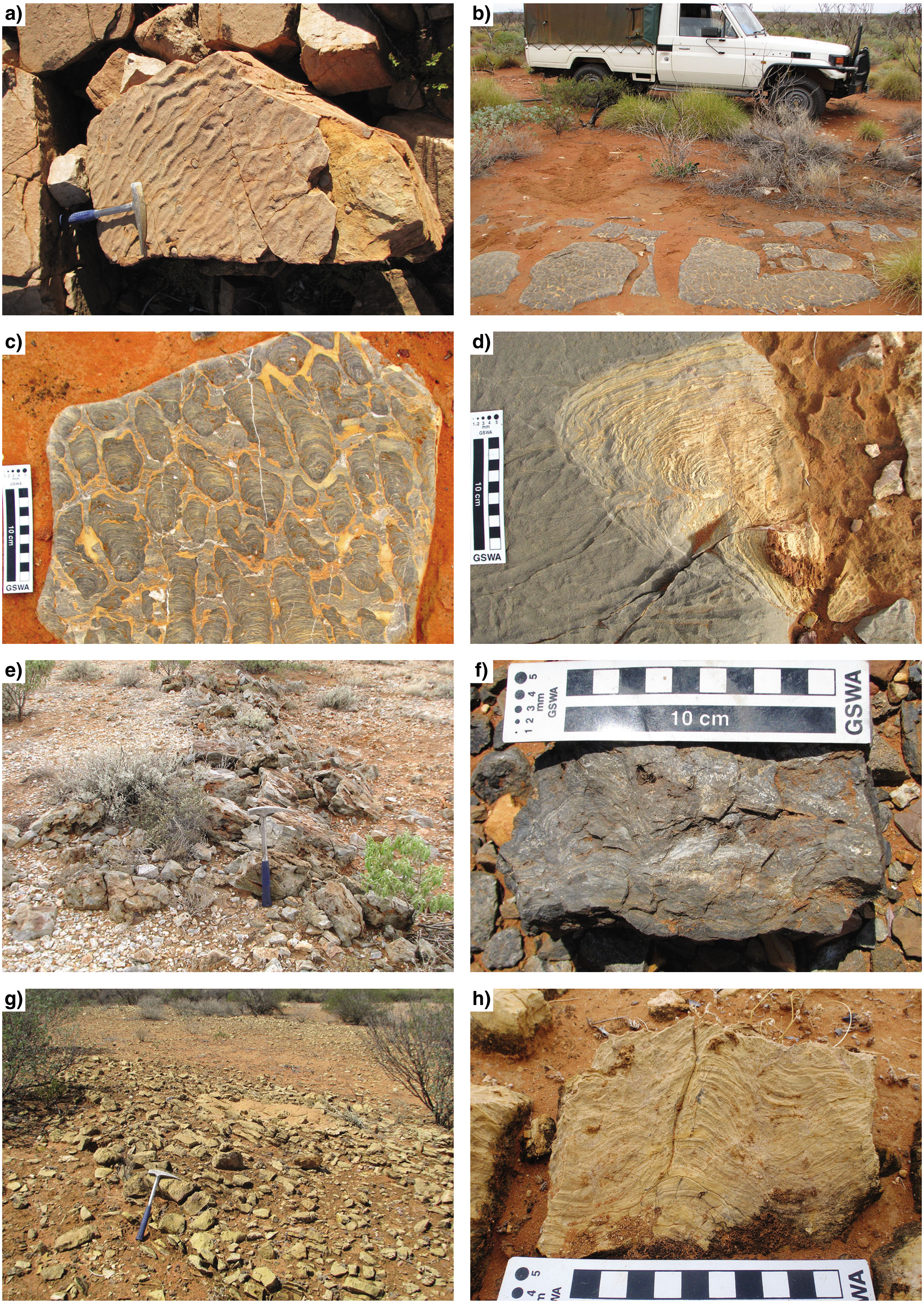
Unnamed unit

A probable disconformity separates the Bitter Springs Formation carbonates from a poorly exposed mixed carbonate–siliciclastic succession up to about 150 m thick that is mostly silicified. Outcrop of the unit is largely restricted to a 4 km-long strip on the northern edge of the Boord Ridges. The base is coincident with the base of the old 'Boord Formation', defined as the base of a unit of 'chert breccia' by Wells et al. (1964).

The base of the unnamed unit is marked by poorly exposed lithic sandstone with chert clasts. Outcrops above the base are composed mostly of grey-bedded chert and cherty sandstone (Fig. 5e). The chert clearly represents silicified sedimentary carbonate as it contains common relic ooids, stromatolites (Fig. 5f), and other carbonate textures. Lenticular bodies of buff-coloured stromatolitic dolostone that have escaped the extensive silicification are present locally near the middle of the unit (Fig. 5g,h). Stromatolites in both silicified carbonates and dolostone have been identified as *Bacalia burra* (Allen et al., 2012; Grey et al., 2012).

The upper contact with the Areyonga Formation is an irregular unconformity surface that can be mapped on orthophotos, but is not well defined on the ground. This surface downcuts at least 50 m into the underlying strata in what appears to be channels. Based on lithology, stratigraphic relationships, and stromatolite content, this interval is interpreted as a direct correlative of the informal 'Finke beds' previously recognized in Finke 1 (Gorter, 1983) and Wallara 1 (Indigo Oil and Sirgo Exploration,

Figure 5. (facing) Field photographs: a) typical Heavitree Quartzite north of the Boord Ridges showing wave ripples on top surface of medium-grained quartz sandstone (MGA 477880E 7443625N); b) flat pavement providing oblique cross-section of steeply dipping stromatolitic limestone typical of exposures of Loves Creek Member in the central northern limb of Boord Ridges Syncline (MGA 468033E 7424527N); c) close-up view of oblique section through Loves Creek Member stromatolite *Linella avis* at same locality; d) near vertical cross-section through large club-shaped columnar stromatolite *Basisphaera irregularis*, steeply dipping Loves Creek Member (MGA 459748E 7427386N); e) bedded chert representing silicified ooid and stromatolitic carbonate in unnamed unit between Bitter Springs Formation and Areyonga Formation (MGA 466352E 7424786N); f) chert replacing stromatolitic carbonate (cf. *Bacalia burra*) in unnamed unit between Bitter Springs Formation and Areyonga Formation (MGA 466556E 7424802N); g) buff-coloured stromatolitic dolostone in unnamed unit between Bitter Springs Formation and Areyonga Formation (MGA 466750E 7424666N); h) stromatolite *Bacalia burra* in dolostone in unnamed unit between Bitter Springs Formation and Areyonga Formation (MGA 467315E 7424376N)



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1990) in the NT (Fig. 1), but not previously reported in outcrop east of the state border. The term 'Finke beds' is inappropriate because the Devonian Finke Group is an established stratigraphic name in the same basin; formal definition and naming of this interval is pending in the NT (CJ Edgoose, 2014, written comm.). The argument for a separate formation is based on evidence for a basal disconformity, overlying unconformity, distinct lithofacies and biostratigraphy. In Wallara 1 the unit contains the distinctive acritarch *Cerebrosphaera buickii* and the stromatolite *Bacalia burra* indicating correlation with the Burra Group of the Adelaide Rift Complex and the upper Buldya Group of the western Officer Basin (Grey et al., 2011; Edgoose, 2013). In drillcore the unit consists of interbedded sandstone, ooid and stromatolitic carbonate (mainly dolostone) and red, green and black siltstone, and shale. Chert is common in carbonate units. The unit has a distinctive cyclical wireline log signature that can be identified in other wells in the upper part of an interval traditionally assigned to the Bitter Springs Formation. Based on published descriptions, this unit is probably present at the base of the Inindia beds in the western NT Amadeus Basin; specifically, descriptions of bedded ooid chert in Ranford et al. (1965).

Supersequence 2

Areyonga Formation

The Areyonga Formation (Prichard and Quinlan, 1962; revised by Preiss et al., 1978) is a widespread glacigene unit in the central and eastern Amadeus Basin, correlated with the Cryogenian Sturt glaciation of the Adelaide Rift Complex and elsewhere (Hill et al., 2011). It is characterized by glacial diamictite, but includes interbeds of sandstone, conglomerate and carbonate (Hill et al., 2011). The unit is presumed to be included within the poorly exposed Inindia beds of the southern and western NT Amadeus Basin.

In the Boord Ridges the unnamed unit is unconformably overlain by a very poorly exposed interval predominantly expressed at surface by low rises covered by loose clasts of chert and minor sandstone and quartzite (Fig. 6a). It supports little vegetation except along minor drainage channels. The lower contact can be mapped on orthophotos for several kilometres and is notably irregular, with apparent channels cutting down at least 50 m into underlying stratigraphy, as noted above. The estimated average thickness is about 150 m based on dips lower in the stratigraphy, increasing in thickness over the basal channels. The unit is best developed along the central northern edge of the Boord Ridges, but it can be traced intermittently elsewhere around the Boord Ridges Syncline and around the unnamed syncline that lies about 15 km to the west.

The chert clasts are typically pebble sized and angular, while the sparser sandstone and quartzite clasts reach cobble and boulder size, and display various degrees of rounding, facets and, rarely, striations and chatter marks indicative of glacial transport (Fig. 6b,c). Rare exposures in erosion gullies show pebble-sized angular chert clasts embedded in a pale grey mudstone matrix. Thus it appears that the rubble at surface is the expression of an underlying glacial diamictite dominated by chert clasts derived from the underlying unnamed silicified unit and Bitter Springs Formation. The quartzite and sandstone are likely derived from the Heavitree Quartzite. Evidence for a glacial origin and stratigraphic position identify the unit as the Areyonga Formation, which likewise contains diamictite with common chert clasts further east, although a more diverse clast assemblage and other lithologies including conglomerate and sandstone are usually present.

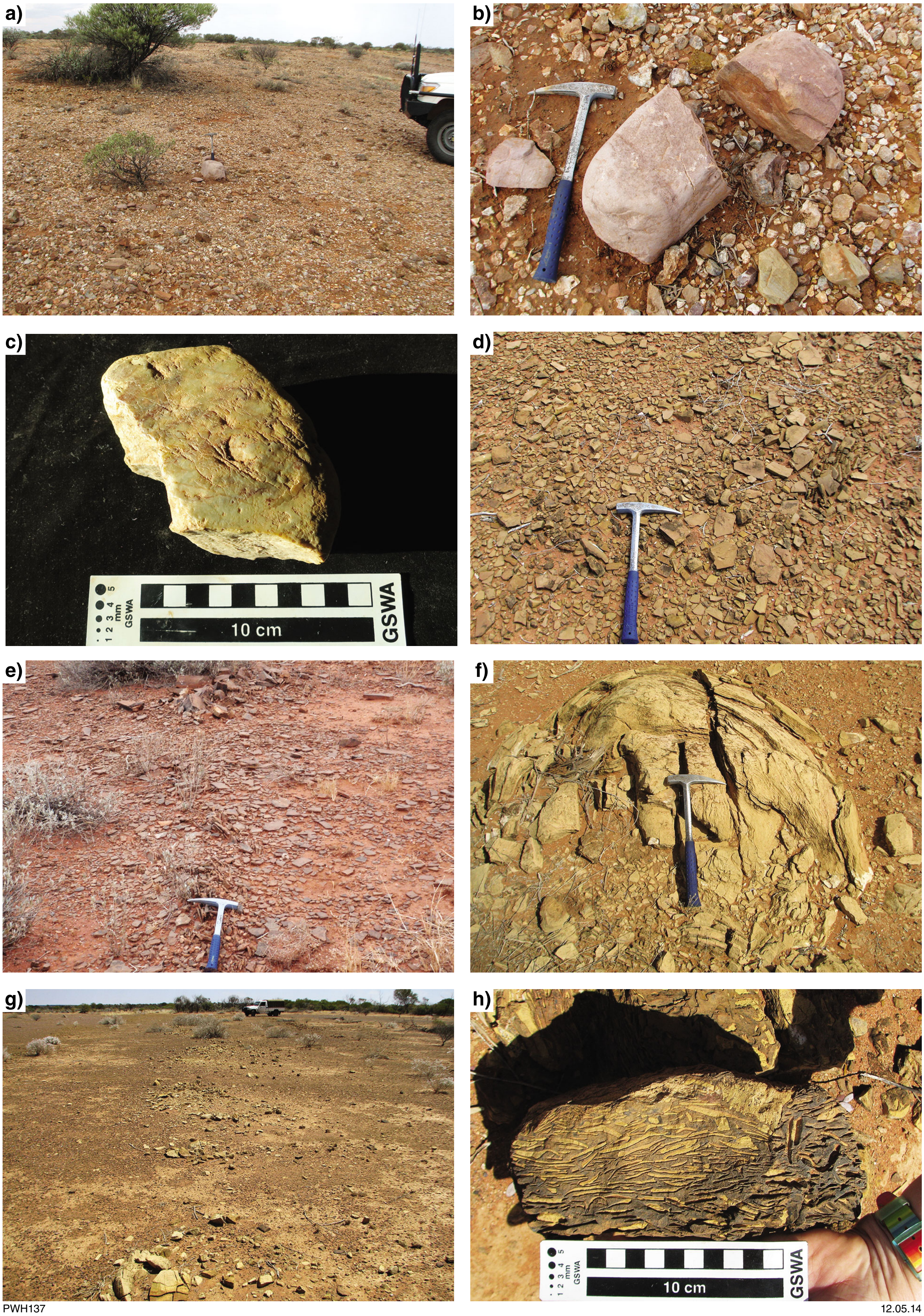
The interval now recognized as the Areyonga Formation was previously included, along with the underlying 'unnamed unit' in the basal chert breccia unit of the old 'Boord Formation' of Wells et al. (1964). Glacigene influence at this level in the 'Boord Formation' was not previously recognized, although the presence of glacial diamictite at a higher stratigraphic level was instrumental in the original correlation of the entire 'Boord Formation' with the Areyonga Formation (Wells et al., 1970).

Aralka Formation

The siltstone and shale-dominated Aralka Formation was defined in the northeastern Amadeus Basin during a major redefinition of the Neoproterozoic stratigraphy by Preiss et al. (1978). The corresponding interval was previously included, inconsistently, in earlier definitions of the Pertatataka and Areyonga Formations in the northeast and north–central parts of the basin, respectively. The unit's distribution has been extended well beyond these outcrop areas using well data (e.g. Ambrose et al., 2012) and it is presumed to be included within the poorly exposed Inindia beds of the southern and western NT Amadeus Basin.

On the northern limb of the Boord Ridges Syncline, the chert rubble of the Areyonga Formation is replaced up-section by a broad flat interval of clayey soils, locally

Figure 6. (facing) Field photographs: a) typical exposure of disaggregated Areyonga Formation comprising chert rubble with sparse cobble and boulder clasts of sandstone and quartzite (MGA 465941E 7425028N); b) close-up view of quartzite boulder in disaggregated Areyonga Formation at previous location; c) quartzite clast showing polished and striated facet with crude chatter marks indicative of glacial transport, basal Areyonga Formation (GSWA 143752; MGA 467640E 7424195N); d) typical weathered rubbly exposure of Aralka Formation (MGA 470600E 7421830N); e) fine-grained flaggy sandstone interbeds in the central Aralka Formation (MGA 467257E 7423643N); f) large isolated hemispherical domical stromatolite in the upper Aralka Formation (MGA 470654E 7421705N); g) spaced piles for stromatolitic dolostone rubble following bedding trends are interpreted as remnants of isolated domical stromatolites within a siltstone-dominated succession, upper Aralka Formation (MGA 470600E 7421830N); h) flat-pebble dolostone intraclast bed, upper Aralka Formation (MGA 470600E 7421830N)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displaying weak trend lines on aerial imagery. Over the lower two-thirds of the interval, sparse outcrop is restricted to very weathered brown to greenish siltstone (Fig. 6d) and rarer fine grained sandstone (Fig. 6e). Bands of stromatolitic and intraclastic dolostone crop out intermittently along with very weathered siltstone rubble in the upper third of the formation. The formation is locally capped by a low strike ridge of stromatolitic sandy limestone, except where this unit has been removed by erosion beneath the unconformably overlying Olympic Formation. The maximum thickness is estimated from sparse dip information at approximately 450 m. The contact with the underlying Areyonga Formation is not exposed. The assignment of this interval to the Aralka Formation is based on the stratigraphic position between the Areyonga and Olympic Formations, lithological similarity to the Aralka Formation type area of the eastern Amadeus Basin (Preiss et al., 1978), and similarity of the stromatolite assemblage.

The stratigraphically lower stromatolite horizons display isolated domical stromatolites ranging in diameter from several tens of centimetres to over 1 metre (Fig. 6f). The stromatolites are rarely intact; most commonly expressed as isolated piles of buff-coloured stromatolitic dolostone rubble spaced out in bedding-parallel trends surrounded by weathered siltstone float (Fig. 6g). The stromatolite horizons are commonly associated with beds of intraclastic dolostone (Fig. 6h) and some stromatolites have clearly nucleated on clusters of such intraclasts. The parallel trends of isolated stromatolites are suggestive of multiple shallowing-upward cycles where the cycle tops coincide with water depths permitting stromatolite growth in a predominantly muddy substrate. At least 10, and possibly 12, cycles are present at the best exposed locality on the central northern limb of the Boord Ridges Syncline (between MGA 470687E 7421785N and 470612E 7421634N). These stromatolites have not been named, but are considered to occur also at a similar stratigraphic level near Fenn Gap and Mount Conner in the north–central and southern NT Amadeus Basin, respectively (Grey, 2005; Grey et al., 2012; Allen et al., 2012).

The ridge-forming limestone unit locally marking the top of the Aralka Formation is up to c. 50 m thick in the eastern Boord Ridges, but thins westward and disappears (around MGA 470740E 7421430N) as the unconformity with overlying strata cuts down through the ridge to lie over the more recessive siltstone-dominated portion of the upper Aralka Formation. A small remnant of the carbonate unit is locally preserved further west. Large boulders derived from this carbonate unit are incorporated into the overlying Olympic Formation. The unit mainly comprises pink sandy and intraclastic limestone (Fig. 7a), usually partly obscured by surface calcrete. Microbial laminations are common and elongate aligned bioherms typically 2 m long (Fig. 7b) display irregularly branching stromatolites (Fig. 7c). Haines et al. (2012a) tentatively correlated this carbonate unit with the Limbla Member of the eastern Amadeus Basin, but a recent examination of the Aralka Formation type section and other sections in the eastern Amadeus Basin reveals closer lithological and stromatolite affinities to the older Ringwood Member. If this correlation is correct, only the lower half of the Aralka Formation, with respect to the most complete eastern Amadeus Basin sections, is preserved at the Boord Ridges.

In WA the Aralka Formation is currently known only from the Boord Ridges, but is likely widespread in the subsurface, at least in the north. The Aralka Formation is considered to have hydrocarbon source potential in the NT (Marshall, 2005; Ambrose et al., 2012; Munson, 2014), but deep-surface weathering precludes any assessment of its source potential or maturity from the Boord Ridges outcrops.

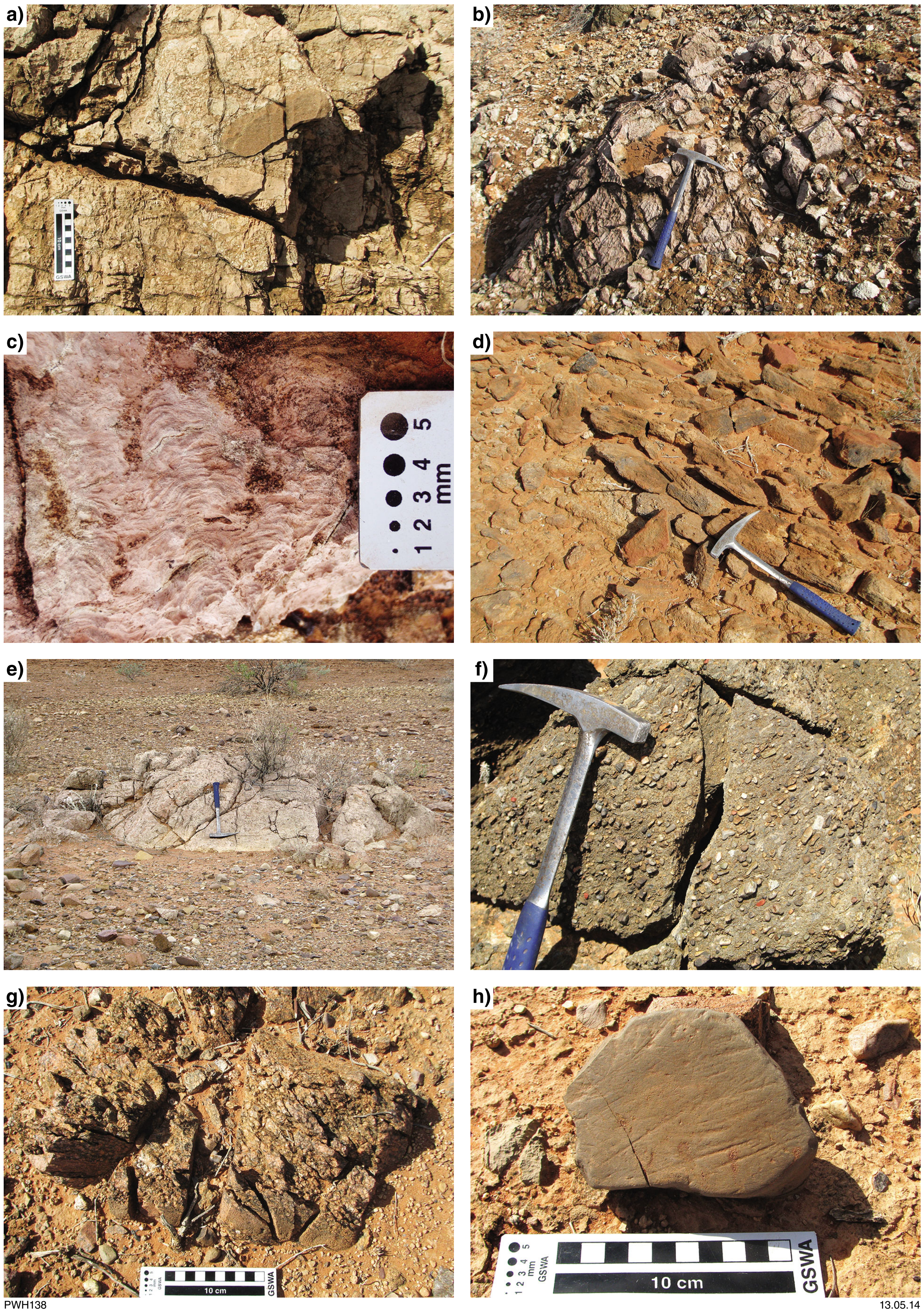
Supersequence 3

Olympic Formation

The Olympic Formation (‘Olympic Member’ of Wells et al., 1967; revised by Preiss et al., 1978) is a glacigene unit previously defined and mapped only in the northeastern Amadeus Basin. The unit is characterized by the presence of reddish diamictite with faceted and striated clasts, but the dominant lithology is commonly siltstone with interbedded sandstone, while conglomerate and dolostone are also present. Where the same stratigraphic interval is replaced by a predominantly sandstone facies the term Pioneer Sandstone is applied, although the units are inferred to be lateral equivalents (Preiss et al., 1978). While the Pioneer Sandstone often lacks definitive evidence of glacial influences, both units are considered to have been deposited during the latest Cryogenian Elatina (‘Marinoan’) glaciation (Hill et al., 2011). Both formations are commonly capped by a lenticular and locally stromatolitic dolostone unit interpreted as a post-glacial ‘cap carbonate’ (Hill et al., 2011).

On the northern limb of the Boord Ridges Syncline the Aralka Formation is unconformably overlain by a glacigene unit with a notably angular unconformable contact. Due to this irregular base the interval varies significantly in thickness, with a maximum of about

Figure 7. (facing) Field photographs: a) sandy intraclastic limestone, top Aralka Formation carbonate ridge (MGA 470860E 7421355N); b) elongate stromatolitic bioherm composed of pink sandy intraclast-rich limestone, top Aralka Formation carbonate ridge (MGA 470938E 7421298N); c) branching columnar stromatolites (cf. *Tungussia*) in bioherm, top Aralka Formation carbonate ridge (MGA 470938E 7421298S); d) poorly sorted, lithic, medium to coarse grained pebbly sandstone, basal Olympic Formation (MGA 468231E 7422736S); e) large erratic (c. 2 m long) derived from top Aralka Formation carbonate unit, within disaggregated Olympic Formation diamictite (MGA 465915E 7424016N); f) lenticular body (probably channel fill) of polymict pebble conglomerate with clasts of chert, fine quartzite and carbonate in a grey sandy limestone matrix, Olympic Formation (MGA 470902E 7421238N); g) fractured granite erratic in disaggregated diamictite, Olympic Formation (MGA 467410E 7423160N); h) striated mudstone clast from disaggregated diamictite, Olympic Formation (MGA 467410E 7423160N)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100 m in the area of maximum downcutting. In this zone of maximum downcutting the lower part of the formation comprises a local, lenticular, poorly sorted, pebbly sandstone unit up to about 30 m in thickness (Fig. 7d). A more widespread upper unit consists of poorly exposed diamictite (Fig. 7e) with interbeds of sandstone and conglomerate (Fig. 7f). This upper unit onlaps the unconformity surface over the top Aralka Formation carbonate ridge east of the downcut, the base being often marked by a poorly exposed and partly calcrete covered boulder conglomerate of pink limestone derived from below.

Clasts in the diamictite include granitic (Fig. 7g) and felsic volcanic igneous rocks, schistose and gneissic metamorphic rocks, quartzite, sandstone, mudstone (Fig. 7h), dolostone, limestone and chert. Some stromatolitic carbonate clasts can be matched to the Loves Creek Member and the two stromatolitic horizons of the upper Aralka Formation. The largest erratics, some exceeding 2 m in length, consist of banded pink sandy limestone clearly derived from the ridge-forming carbonate unit of the underlying Aralka Formation (Fig. 7e). Many clasts, particularly those composed of quartzite, sandstone, and mudstone show well-developed facets and striations (Fig. 7h) indicative of glacial transportation. The sandy mudstone matrix of the diamictite is rarely preserved.

Haines et al. (2010a, 2012a) referred to this interval as an unnamed equivalent of the Olympic Formation/Pioneer Sandstone. In this Record we propose using the name Olympic Formation for this interval. This is because diamictite is the dominant lithology and the range of lithologies present is similar to the Olympic Formation in the northeastern Amadeus Basin. It is anticipated that a future subdivision of the disparate units currently encompassed by the Inindia beds in the southern NT Amadeus Basin will allow the Olympic Formation and the Pioneer Sandstone to be identified in the intervening area. A 'cap carbonate', typical of the Olympic Formation and Pioneer Sandstone elsewhere, has not been recognized in the Boord Ridges area, but this may be a function of poor outcrop, as the contact between the Olympic Formation and overlying Pertatataka Formation is not exposed.

Pertatataka Formation

The Pertatataka Formation (Prichard and Quinlan, 1962; revised by Preiss et al., 1978) is a unit of red and green (commonly black in subsurface) siltstone, shale, and minor sandstone that lies above the glacially influenced Pioneer Sandstone or Olympic Formation and is overlain by the carbonate-dominated Julie Formation in the north–central and northeast Amadeus Basin. The age is early Ediacaran (Edgoose, 2013). Along the northern margin of the Amadeus Basin the interval containing the Pertatataka Formation is not exposed west of about 131° 50'E until the Boord Ridges. Previous correlation schemes (e.g. Wells et al., 1970) equated the Pertatataka Formation with the reddish siliciclastic sequence of the Winnall beds in the southern Amadeus Basin, and thence to the Ellis Sandstone and Maurice Formation along and west of the WA border. Haines et al. (2012a) argued for a revision to the stratigraphic position and relationships of the Winnall beds, interpreting them as younger than the Pertatataka Formation. The Pertatataka interval is instead considered to lie within the Inindia beds of the southern and western NT Amadeus Basin, but has likely been removed by Petermann Orogeny uplift and erosion in the far south.

In the Boord Ridges the recessive and mostly covered interval between the Olympic Formation and carbonates now placed in the Julie Formation is assigned to the Pertatataka Formation based on stratigraphic position and limited lithological data. Outcrop is very sparse, consisting mainly of very weathered brown siltstone (Fig. 8a,b) and interbedded fine-grained sandstone. A band of pale medium-grained flaggy sandstone is intermittently exposed in the upper half of the formation. Thin flaggy beds of poorly sorted, medium- to coarse-grained feldspathic and lithic sandstone are poorly exposed near the top of the unit. The basal contact with the Olympic Formation is not exposed. The upper contact with the Julie Formation is very poorly exposed, and appears to be gradational. Based on measured dips above and below, the Pertatataka Formation is estimated to be of the order of 300 m in thickness, similar to that of its type area in the north–central Amadeus Basin.

Although very poorly exposed, the Boord Ridges provides the only known exposure of the Pertatataka Formation in WA. However, it is likely to be widely present in the subsurface in at least the northern half of the WA Amadeus Basin, but is possibly removed, if ever present, by Petermann Orogeny erosion in the south. The Pertatataka Formation is considered to have some gas- and oil-prone hydrocarbon source potential in the eastern part of the basin (Marshall, 2005; Ambrose et al., 2012), but deep weathering precludes any assessment of such potential from the Boord Ridges outcrops.

Julie Formation

The Julie Formation ('Julie Member' of Wells et al., 1967; revised to formation status by Preiss et al., 1978) is a carbonate-dominated unit originally recognized in the north–central and northeast Amadeus Basin where it lies between the Pertatataka Formation (below) and Arumbera Sandstone. The age is Ediacaran based on stratigraphic position and stromatolite biostratigraphy (Grey et al., 2012). Along the northern margin of the Amadeus Basin the interval containing the Julie Formation is not known in outcrop west of the Gardiner Range (c. 132°E) except for the exposures at the Boord Ridges and west of Bonython Range in WA. In the southern and western NT Amadeus Basin the interval occupied by the Julie Formation is interpreted to lie within the upper Inindia beds (Haines et al., 2012a), although it was probably eroded by Petermann Orogeny uplift in most southern areas.

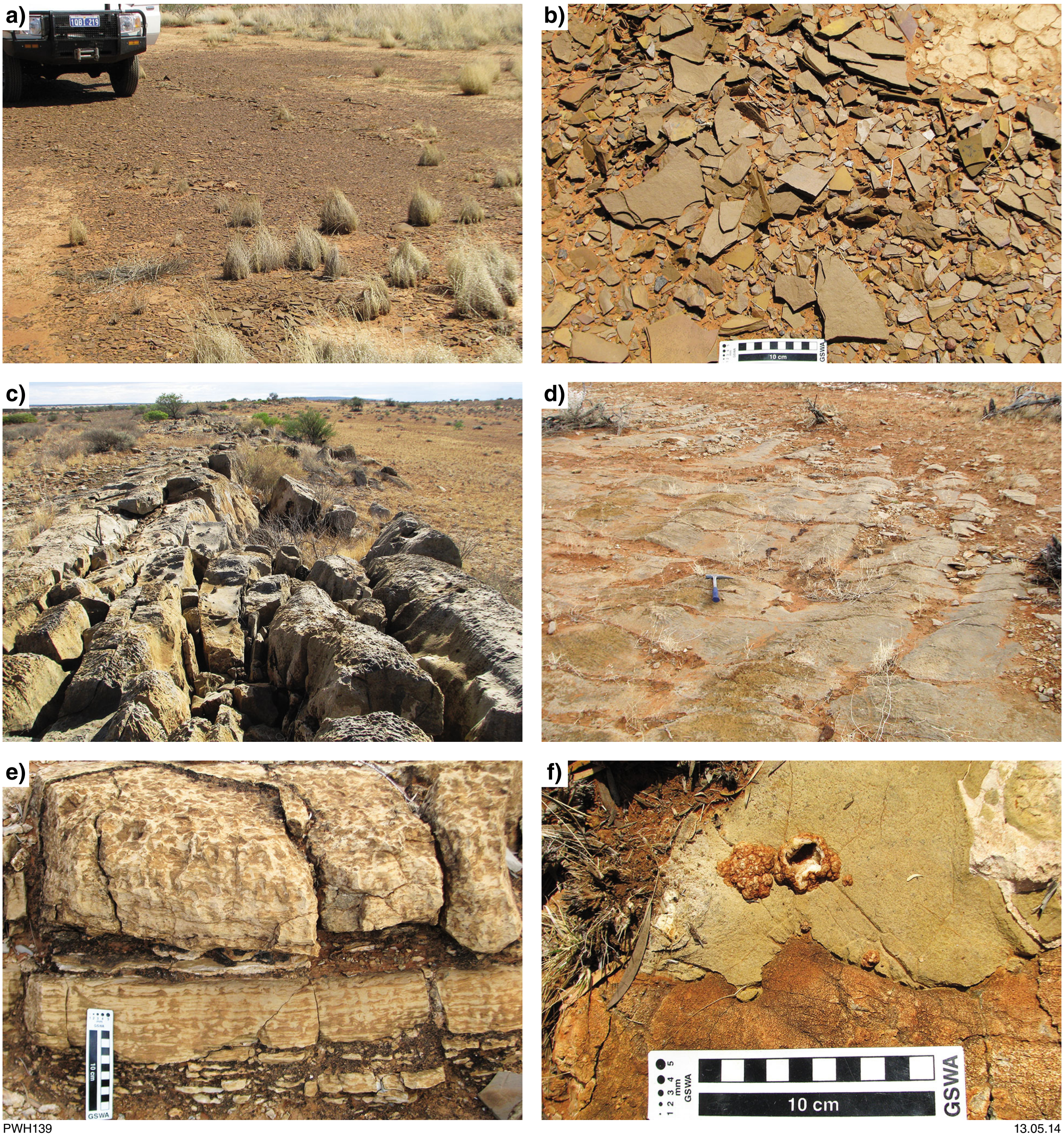

Figure 8. Field photographs: a) typical rubbly exposure of deeply weathered Pertatataka Formation siltstone (MGA 473179E 7420078N); b) close-up view of deeply weathered Pertatataka Formation siltstone in previous photo; c) typical carbonate strike ridge in the upper Julie Formation (MGA 470343E 7419794N); d) megaripples in calcarenite, upper Julie Formation (MGA 468847E 7419973N); e) stromatolitic carbonate in the lower Julie Formation (MGA 469577E 7421126N); f) cauliflower chert nodules after sulphate evaporite minerals, upper Julie Formation (MGA 469070E 7420524N)

In the Boord Ridges the Julie Formation is exposed as a cyclical series of low strike ridges of limestone and dolostone (Fig. 8c,d), separated by broader recessive intervals that are either covered or display poor outcrop of siltstone, thin-bedded limestone or dolostone, and friable sandstone. The carbonate ridges vary from about one to 10 m in thickness and comprise light to dark grey limestone or buff-coloured dolostone. Occasionally limestone and dolostone are interbedded. Both carbonates vary from micritic, to ooid and peloidal packstones and grainstones. Stromatolites and microbially laminated boundstone are common (Fig. 8e). Patchy diagenetic silicification is common, with chert often showing replacement of original carbonate textures, such as ooids. Occasional black chert nodules probably formed during very early diagenesis. In the upper part of the formation some chert nodules show ‘cauliflower’ textures interpreted as a replacement of sulphate evaporites such as anhydrite or gypsum (Fig. 8f).

The stromatolite assemblage is diverse and includes *Tungussia julia*, *Tesca stewartii*, possible *Georgina howchini* and undescribed taxa (Allen et al., 2012). The presence of *Tungussia julia* is particularly significant as it provides a biostratigraphic link to the Julie Formation in the eastern Amadeus Basin, where it was first described, and to related Ediacaran carbonate units across the Centralian Superbasin and the Adelaide Rift Complex (Grey et al., 2012). The Boord Ridges outcrop is the type locality for *Tesca stewartii* (Walter et al., 1979).

The Julie Formation overlies the Pertatataka Formation with an apparently conformable and gradational relationship, but the contact is very poorly exposed. The base was placed at the first in situ carbonate bed. The main outcrops have a calculated thickness of 420 m, although this should be taken as approximate as the low angles of dip and extensive covered intervals in the upper part make accurate thickness measurements impossible. There is also the possibility of some structural thickening. There is a covered interval between the last semicontinuous carbonate ridge of the Julie Formation and outcrops of the Carnegie Formation. This interval often displays weak trend lines on orthophotos, and rare outcrops of carbonate, mainly ooid limestone and dolostone suggest that the interval mainly represents the Julie Formation. These areas are mapped as Julie Formation soil cover on Figure 3, but may include some soil covered lower Carnegie Formation. Thus the full thickness of the Julie Formation in the Boord Ridges is likely greater than the figure given above, possibly up to 500 m, unless the angle of dip is very shallow in the upper part of the formation.

Supersequence 4

Carnegie Formation

The Carnegie Formation is a thick siliciclastic unit recognized in the Rawlinson, Macdonald and western Mount Rennie (NT) map sheet areas of the western Amadeus Basin (Wells et al., 1964, 1965). No type section was nominated. As originally conceived, the formation was considered to lie conformably between the Bitter Springs Formation and the Ellis Sandstone, and to laterally interfinger with the ‘Boord Formation’ (Wells et al., 1964). The stratigraphic relationships were reassessed by Haines et al. (2010a,b) who concluded that the unit overlies the collective package of the old ‘Boord Formation’, where present, or unconformably overlies the Bitter Springs Formation where intervening units have been removed by erosion. The Carnegie Formation was not previously recognized in the Boord Ridges/Gordon Hills area, where all strata overlying the ‘Boord Formation’ were mapped as the Ellis Sandstone by Wells et al. (1964). As reinterpreted, the siliciclastic package making up the Gordon Hills is now subdivided into relatively thin Carnegie Formation overlain by incomplete Ellis Sandstone in the core of the syncline (Haines et al., 2010a,b). The Carnegie Formation overlies the Julie Formation in the revised Boord Ridges stratigraphy, but the contact is covered. It is possible that minor interdigitation of the top Julie Formation and basal Carnegie Formation is present in the poor exposure west of Bonython Range (Fig. 1; Haines et al., 2010a).

The revised stratigraphic relationships suggest correlation of the Carnegie Formation with the lithologically similar lower Arumbera Sandstone of the north–central and north-eastern Amadeus Basin and the lower Winnall beds (unit 1) in the southern and southwestern NT Amadeus Basin (Haines et al., 2012a). The age is inferred to be late Ediacaran, but could extend into the earliest Cambrian. Problematic organic remains, including *Arumberia* originally described from the lower Arumbera Sandstone (Glaessner and Walter, 1975), were identified in outcrops of Carnegie Formation further south (Haines et al., 2010a), but were not seen at the Gordon Hills.

In the Gordon Hills the exposed part of the Carnegie Formation is estimated to be about 70 m thick, but as the base is not exposed, the complete thickness may be somewhat greater. The lower part of the formation consists of red-brown to rarely grey-green, fine- to medium-grained, flaggy, micaceous sandstone and poorly exposed sandy siltstone (Fig. 9a). Thin sandstone beds commonly display erosive sole marks, includes flute casts (Fig. 9b). A bench-forming central unit comprises red-brown medium-grained sandstone with common trough cross-beds, current ripples, mud pellets and possible desiccation cracks. Some beds at this level have a lenticular channel-like morphology. The upper part of the formation is similar, but more recessive, comprising red-brown, medium-grained, friable, cross-bedded sandstone. Sandstone throughout the unit is feldspathic/lithic and relatively immature. The apparently conformable contact with the Ellis Sandstone is marked by the appearance of lighter brown, cleaner and better cemented sandstone that forms a prominent bench.

The Carnegie Formation is interpreted to be of deltaic origin. Although no paleocurrent measurements were made at this locality, regional information suggests currents were mainly from the south, as with the overlying Ellis Sandstone (see below). Detrital zircon age data from a sample of the Carnegie Formation collected further south in the Mu Hills (Fig. 1; Wingate et al., 2013a) is consistent with derivation from uplifted Musgrave Province during the Petermann Orogeny (Haines et al., 2012b), as inferred by Haines et al. (2010a,b).

Ellis Sandstone

The Ellis Sandstone is recognized in the RAWLINSON, MACDONALD and western MOUNT RENNIE (NT) map sheet areas of the western Amadeus Basin (Wells et al., 1964, 1965). No type section was nominated. Further south the unit forms prominent strike ridges with an average thickness of about 500 m. It is inferred to interfinger with the Sir Frederick Conglomerate in that area (Wells et al., 1964), although the field relationships are not entirely clear (Haines et al., 2012a).

The entire outcrop of the Gordon Hills was previously mapped as the Ellis Sandstone (Wells et al., 1964; Wells, 1968) but a comparison with other sections in the western Amadeus Basin indicates that comparatively thin underlying Carnegie Formation is also present, mainly exposed on the northern limb of the syncline. The contact between the more silty and immature Carnegie Formation and somewhat 'cleaner' Ellis Sandstone is not well exposed, but there is no evidence of any angular discordance. The Ellis Sandstone is dominated by pale brown to pale purple medium-grained sandstone, commonly with an orange-brown weathering skin (Fig. 9c). Trough and tabular cross-bedding (Fig. 9d) and current lineations are common and mud pellets are abundant in some beds. Unlike thicker sections further south, the Ellis Sandstone is not notably pebbly at this location, perhaps indicating a more distal setting with respect to the source area. The preserved thickness, east of Mount Greene, is estimated at about 130 m, with the top eroded. Elsewhere the Ellis Sandstone is overlain by siltstone and sandstone of the Maurice Formation.

The Ellis Sandstone is interpreted to be of fluvial origin. Paleocurrent directions determined from trough and tabular cross-beds at the eastern end of the Gordon Hills are unimodal with the average direction towards the north-northeast (Fig. 10). This paleocurrent data is consistent with the directions measured elsewhere in the Ellis Sandstone. Detrital zircon age data from a sample collected to the south (Wingate et al. 2013b) is similar to that of the underlying Carnegie Formation, likewise consistent with derivation from uplifted Musgrave Province to the south during the Petermann Orogeny (Haines et al., 2012b).

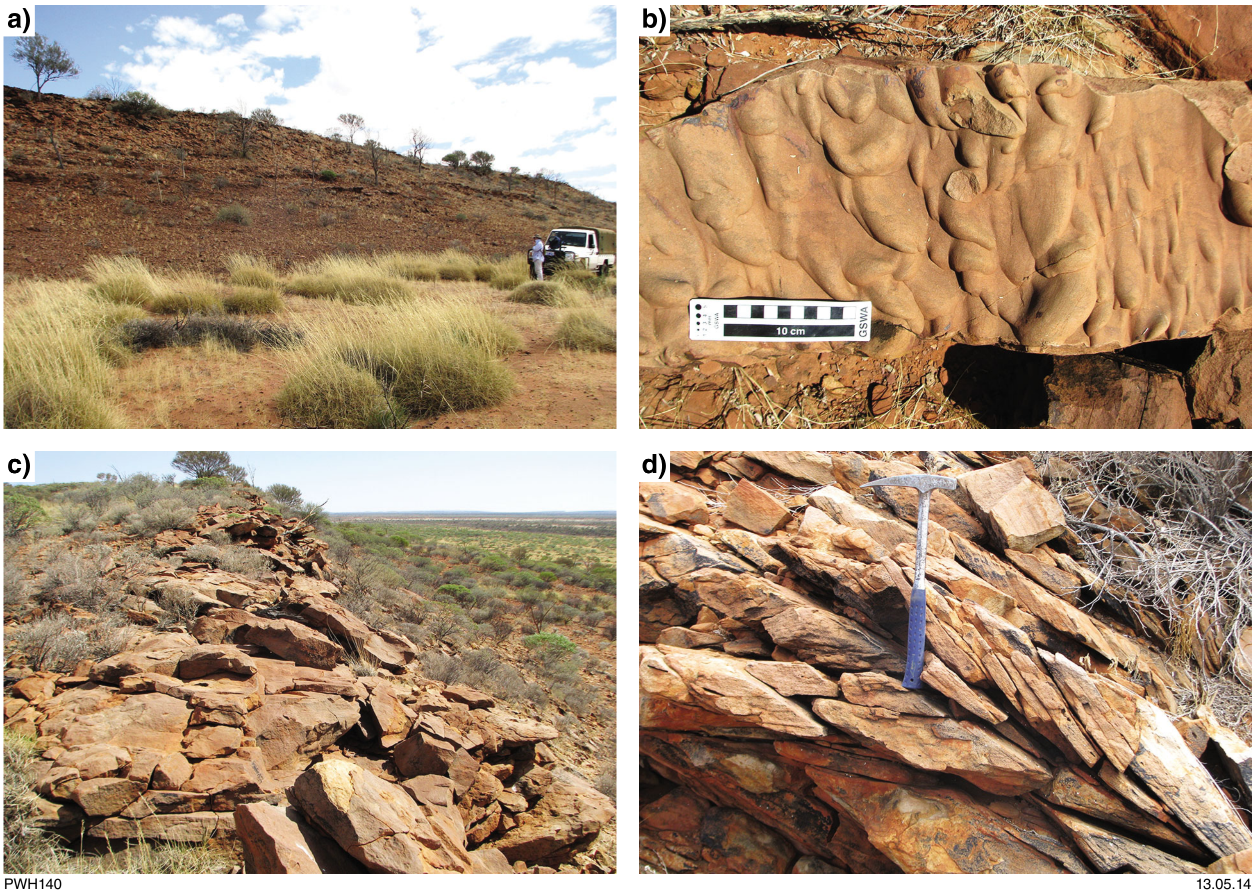

Figure 9. Field photographs: a) typical exposure of Carnegie Formation, eastern Gordon Hills (MGA 464440E 7422670N); b) flute-marked sole of fine-grained sandstone, lower Carnegie Formation, eastern Gordon Hills (MGA 464359E 7422675N); c) basal Ellis Sandstone overlying Carnegie Formation below scarp, eastern Gordon Hills (MGA 464143E 7422645N); d) cross-bedded Ellis Sandstone, eastern Gordon Hills (MGA 463684E 7422310N)

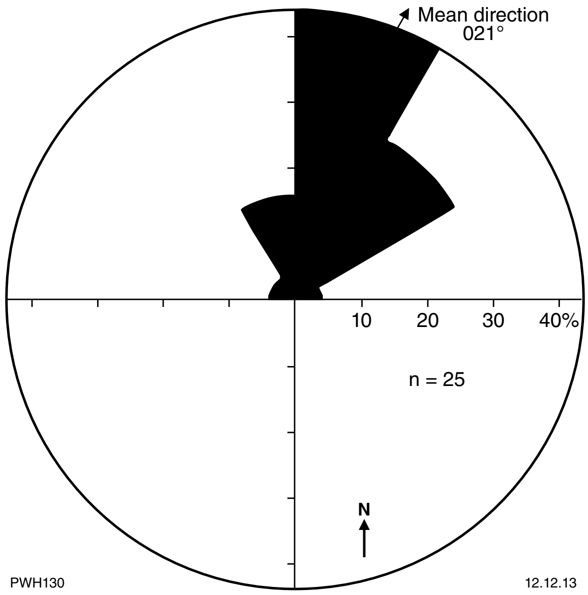

Figure 10. Paleocurrent rose diagram based on cross-bed measurements in the Ellis Sandstone, eastern Gordon Hills

Haines et al. (2012a) correlate the Ellis Sandstone with unit 2 of the Winnall beds in the southwestern NT Amadeus Basin. Based on stratigraphic position, its age could range from late Ediacaran to early Cambrian. No biostratigraphic evidence for age has been found in WA. Ranford et al. (1965) mention 'numerous indeterminate fossil tracks and trails' in Winnall beds unit 2 in the south–central part of the NT Amadeus Basin, additionally referring to a form comparable with the lower Cambrian *Syringomorpha* at one locality. Such occurrences, if confirmed, could allow a refined age for the unit.

Canning Basin and Cenozoic

Small flat-lying outcrops of glacial diamictite, conglomerate, sandstone and siltstone, originally mapped as 'Buck Formation' by Wells et al. (1964) and Wells (1968), are scattered over the WA Amadeus Basin. These are now referable to the more regionally used name, Paterson Formation, and are considered outliers of the Canning Basin. A latest Carboniferous to early Permian age is assumed from data elsewhere. Small outcrops of this unit were mapped near the southern edge of the Boord Ridges Syncline by Wells (1968), but have not been revisited during this project.

Scattered small outcrops of silcrete, presumably of Cenozoic age, occur across the area and represent relics of an old silicified land surface. Other presumed Cenozoic units of poorly constrained age include old calcareous lake sediments (chalcedonic limestone) to the west, east and southeast of the Boord Ridges outcrops. Weakly lithified old lake sediments are closely associated with modern playa lakes. Surficial calcrete deposits partially obscure most of the Neoproterozoic carbonate units. Recent eolian sand and alluvium cover much of the area.

Relevance to hydrocarbon prospectivity

The NT Amadeus Basin has been intermittently explored for hydrocarbons since the 1950s with drilling starting in 1963. Success came early with the Mereenie oil- and gasfield discovered in 1964 and the Palm Valley gasfield in 1965, both commercially producing hydrocarbons from Ordovician strata since 1984 (Ozimic et al., 1986). The recently discovered Surprise oilfield, also associated with the Ordovician hydrocarbon system, was brought into production in early 2014. The Neoproterozoic section has also been targeted since the inception of exploration, and has resulted in a number of significant gas and oil shows, and the discovery of the yet-to-be-commercialized Dingo gasfield (Fig. 2). In the NT, potential Neoproterozoic source rocks are present in all members of the Bitter Springs Formation (particularly the basal Gillen Member), and the Aralka and Pertatataka Formations (Marshall, 2005; Munson, 2014).

In comparison to the NT activity, hydrocarbon exploration in the WA Amadeus Basin has been very limited; a consequence of remoteness, difficult access and historic perceptions of very limited prospectivity at the western end of the basin. No hydrocarbon exploration wells have been drilled and there is no useful seismic data. However, structures can be mapped under cover, to some degree with aeromagnetic data, which show extensive synclines and anticlines probably influenced by halotectonic processes during orogenesis (Dentith and Cowan, 2011). A summary of the limited hydrocarbon exploration in the WA portion of the basin is provided under **Previous studies**. The revised stratigraphy summarized herein requires a reconsideration of the hydrocarbon potential in WA, because all potential Neoproterozoic source units recognized further east are now known to be present, at least locally. However, it must be stressed that in the absence of fresh subsurface samples, the source and reservoir potential, and maturity level within the WA Amadeus Basin remains speculative.

Gillen petroleum system

The Gillen petroleum system involves source rocks in the shaly basal Gillen Member, a Heavitree Quartzite reservoir, and an overlying salt seal in the upper Gillen Member (Wakelin-King, 1994; Marshall et al., 2007; Young and Ambrose, 2007; Munson, 2014). Only two wells (Magee 1 and Mount Kitty 1) have tested this play, both delivering measurable gas flows from the relatively tight Heavitree Quartzite with additional high content of basement-sourced helium (He), attesting to the high sealing quality of the salt. The Gillen Member is identified in outcrop in WA from its stromatolite content (Allen et al., 2012), although it is not exposed in the immediate Boord Ridges area. It is inferred to be widespread in the subsurface based on the halotectonic deformation style, because salt is not expected at other stratigraphic levels in the west. This petroleum system could thus be applicable to most of the WA Amadeus Basin, wherever salt is preserved, assuming the continuity of the basal Gillen Member source unit into the area. Even in the absence of a source rock, the reservoir may accumulate basement-sourced He. Preservation of porosity in the Heavitree Quartzite (and the Dean Quartzite in the south) is problematic, but is more likely to be better preserved beneath cover away from the basin margin thrust systems.

Upper Bitter Springs petroleum system

Source intervals in the Loves Creek Member of the eastern Amadeus Basin have oil-prone source characteristics with Total Organic Carbon (TOC) ≤1.1% (Marshall, 2005; Munson, 2014). The Johnnys Creek Member also has some preserved kerogens (Munson, 2014). Oil shows have been found in the Johnnys Creek Member and in the locally overlying unnamed unit ('Finke beds') and these are likely derived from below, potentially the Loves Creek Member. In Finke 1 a probable paleo-oil column has been identified in the unnamed unit based on grain fluorescence studies (Marshall et al., 2007). The presence of all of these units in WA is positive for hydrocarbon prospectivity. The sandstone cycles of the unnamed unit may have reservoir potential away from surface silicification, and the mudstone-dominated diamictites of the Areyonga Formation have potential as an overlying seal.

Aralka petroleum system

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 likely responsible for significant gas flows in Pioneer Sandstone reservoir in Ooraminna 1 and 2 south of Alice Springs.

The discovery of thick Aralka Formation in the Boord Ridges thus provides another potential hydrocarbon system for the WA Amadeus Basin. However, its distribution and thickness away from the only known exposure is unknown. The overlying Olympic Formation contains a local lenticular basal sandstone unit up to 30 m thick which appears porous in surface outcrops, although this may be a function of weathering. Such clastic units could provide a reservoir for any Aralka Formation-sourced hydrocarbons, although the distribution and reservoir characteristics of this unit in the subsurface are speculative. The lenticular nature of the overlying sandstone may support stratigraphic traps. Diamictites of the upper Olympic Formation, and shales and siltstones of the Pertatataka Formation could provide a seal.

Pertatataka petroleum system

The youngest Neoproterozoic hydrocarbon source recognized in the NT involves black shales in the Pertatataka Formation, with gas and oil-prone characteristics and TOC ≤1% (Marshall, 2005; Marshall et al., 2007; Munson, 2014). This system is most convincingly demonstrated in the four wells of the yet-to-be-commercialized Dingo gasfield south of Alice Springs (Fig. 1), where the Arumbera Sandstone acts as a reservoir, and significant gas shows at the same level in nearby Orange 1 and 2 (Marshall, 2005; Marshall et al., 2007). In these cases, a seal is provided by Cambrian shales and salt.

The presence of average thickness Pertatataka Formation in the Boord Ridges provides a final possibility for a Neoproterozoic hydrocarbon system in WA, if source rock characteristics extend to the west. As with the Aralka Formation, its distribution and thickness away from the only known exposure is speculative. Possible reservoirs include sandstone interbeds within the unit itself and in the overlying Julie and Carnegie formations, and higher in the succession, but the existence of an adequate seal above the Pertatataka Formation itself is problematic in the western Amadeus Basin.

Summary and conclusion

Although outcrop quality is poor, the Boord Ridges and Gordon Hills area provides the key section to understand the Neoproterozoic stratigraphy in the WA portion of the Amadeus Basin. This section demonstrates that Neoproterozoic stratigraphy of this area is more complete than previously thought, and is directly comparable to the better exposed areas of the northeastern Amadeus Basin. In most cases the same formation names can be applied and the use of the term 'Boord Formation' for what is now demonstrated to be a complex of units, spanning over 200 Ma of Neoproterozoic history, can be discontinued. By analogy, the equivalent, or near equivalent Inindia beds of the poorly exposed southern and western NT Amadeus Basin can probably be similarly subdivided with careful mapping.

It remains unclear how far some particular units of the Boord Ridges stratigraphy extend under cover beyond this area. Between 30 and 80 km to the south and southwest of the Boord Ridges, respectively, the Carnegie Formation appears to lie unconformably on Bitter Springs Formation, a likely consequence of uplift and erosion early in the Petermann Orogeny, and probably also involving halotectonics. Such extreme erosion may be localized around salt-cored structures, and varying proportions of the intervening stratigraphy may be preserved elsewhere.

The stratigraphic revisions allow a revised appraisal of the hydrocarbon potential of the WA Amadeus Basin. Although the highly prospective Ordovician (Larapintine) petroleum system is unlikely to extend into WA owing to the thinness of known Ordovician rocks west of the state border, all of the Neoproterozoic hydrocarbon systems recognized in the eastern Amadeus Basin have potential to be present, based on lithostratigraphic comparisons. Of these, the subsalt Gillen petroleum system is likely to be the most widespread, assuming the continuation of a subsalt source rock and preservation of a salt seal over traps in the area.

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References

Aitken, ARA, Betts, PG and Ailleres, L 2009, The architecture, kinematics, and lithospheric processes of a compressional intraplate orogen occurring under Gondwana assembly: The Petermann orogeny, central Australia: Lithosphere, v. 1, p. 343–357.

Allen, HJ, Grey, K and Haines, PW 2012, Neoproterozoic stromatolite biostratigraphy in the western Amadeus, *in* Central Australian Basin Symposium III *edited by* GJ Ambrose and J Scott: Petroleum Exploration Society of Australia, Special Publication, CD-ROM, 11p.

Ambrose, G 2006, Northern Territory of Australia, onshore hydrocarbon potential, 2006: Northern Territory Geological Survey, Record 2006–003, 69p.

Ambrose, GJ, Heugh, JP and Shortt, T 2012, Ooraminna-2, a gas discovery in the Neoproterozoic Pioneer Sandstone, eastern Amadeus Basin, *in* Central Australian Basin Symposium III *edited by* GJ Ambrose and J Scott: Petroleum Exploration Society of Australia, Special Publication, CD-ROM, 9p.

Close, DF, Edgoose, CJ and Scrimgeour, IR 2003, Hull and Bloods Range, N.T.: Northern Territory Geological Survey, 1:100 000 Geological Map Series Explanatory Notes, 46p.

Dentith, MC and Cowan, D 2011, Using potential field data for petroleum exploration targeting, Amadeus Basin, Australia: Exploration Geophysics, v. 42, p. 190–198.

Edgoose, CJ 2012, The Amadeus Basin, central Australia: Episodes, v. 35, p. 256–263.

Edgoose, CJ 2013, Chapter 23: Amadeus Basin, *in* Geology and mineral resources of the Northern Territory *compiled by* M Ahmad and TJ Munson: Northern Territory Geological Survey, Special Publication 5, p. 23.1–23.70.

Forman, DJ 1966, The geology of the south-western margin of the Amadeus Basin, central Australia: Australia BMR, Report 87, 54p.

Forman, DJ, Milligan, EN and McCarthy, WR 1967, Regional geology and structure of the northeast margin of the Amadeus Basin, Northern Territory: Australia BMR, Report 103, 69p.

Glaessner, MF and Walter, MR 1975, New Precambrian fossils from the Arumbera Sandstone, Northern Territory, Australia: Alcheringa, v. 1, p. 59–69.

Gorter, JD 1983, Finke No.1 well completion report, Pancontinental Petroleum Ltd, PPL Report 96: Northern Territory Geological Survey, Open File Petroleum Report PR1984–0015 (unpublished).

Grey, K 1990, Amadeus Basin, *in* Geology and mineral resources of Western Australia: Geological Survey of Western Australia, Memoir 3, p. 335–349.

Grey, K 2005, Ediacaran palynology of Australia: Association of Australasian Palaeontologists, Memoir 31, 439p.

Grey, K, Hill, AC and Calver, C 2011, Biostratigraphy and stratigraphic subdivision of Cryogenian successions of Australia in a global context, *in* The Geological Record of Neoproterozoic Glaciations *edited by* E Arnaud, GP Halverson and G Shields-Zhou: Geological Society, London, Memoirs, no. 36, p. 113–134.

Grey, K, Allen, H-J, Hill, A and Haines, PW 2012, Neoproterozoic biostratigraphy of the Amadeus Basin, *in* Central Australian Basin Symposium III *edited by* GJ Ambrose and J Scott: Petroleum Exploration Society of Australia, Special Publication, CD-ROM, 18p.

Haines, P 2010, Message on a bottle: Fieldnotes, Geological Survey of Western Australia Newsletter, April 2010, no. 54, p. 3.

Haines, PW, Allen, HJ and Grey, K 2010a, The Amadeus Basin in Western Australia: a forgotten corner of the Centralian Superbasin: Geological Survey of Western Australia Annual Review 2008–09, p. 49–57.

Haines, PW, Allen, HJ and Grey, K 2010b, Reassessment of the geology and exploration potential of the Western Australian Amadeus Basin: GSWA 2010 extended abstracts p. 27–29.

Haines, PW, Allen, HJ, Grey, K and Edgoose, C 2012a, The western Amadeus Basin: revised stratigraphy and correlations, *in* Central Australian Basin Symposium III *edited by* GJ Ambrose and J Scott: Petroleum Exploration Society of Australia, Special Publication, CD-ROM, 6p.

Haines, PW, Allen, HJ, Wingate, MTD, Kirkland, CL and Edgoose, C 2012b, Syn-tectonic (Petermann Orogeny) deposition tracked through detrital zircon geochronology, western Amadeus Basin, central Australia: 34th International Geological Congress, Abstracts, 1091.

Haines, PW, Hand, M and Sandiford, M 2001, Palaeozoic synorogenic sedimentation in central and northern Australia: a review of distribution and timing with implications for the evolution of intracratonic orogens: Australian Journal of Earth Sciences, v. 48, p. 911–928.

Hill, AC, Haines, PW and Grey K 2011, Neoproterozoic glacial deposits of central Australia, *in* The Geological Record of Neoproterozoic Glaciations *edited by* E Arnaud, GP Halverson and G Shields-Zhou: Geological Society, London, Memoirs, no. 36, p. 677–691.

Howard, HM, Smithies, RH, Evins, PM, Kirkland, CL, Werner, M, Wingate, MTD and Pirajno, F 2011, Explanatory notes for the west Musgrave Province: Geological Survey of Western Australia, Record 2011/4, 349p.

Indigo Oil and Sirgo Exploration 1990, Wallara No. 1 well completion report, Indigo Oil Pty Ltd and Sirgo Exploration Inc.: Northern Territory Geological Survey, Open File Petroleum Report PR1990–0101 (unpublished).

Joklik, GF 1955, The geology and mica-fields of the Harts Range, central Australia: Australia BMR, Bulletin 26, 226p.

Korsch, RJ and Kennard, JM (editors) 1991, Geological and geophysical studies in the Amadeus Basin, central Australia: Australia BMR, Bulletin 236, 594p.

Lindsay, JF 1987, Upper Proterozoic evaporites in the Amadeus basin, central Australia, and their role in basin tectonics: Geological Society of America Bulletin, v. 99, p. 852–865.

Lonsdale, GF and Flavelle, AJ 1968, Amadeus and south Canning Basins gravity survey, Northern Territory and Western Australia 1962: Australia BMR, Report 133, 27p.

Marshall, TR 2005, Review of source rocks in the Amadeus Basin: Northern Territory Geological Survey, Record 2004–008, 42p.

Marshall, TR and Dyson, IA 2007, Halotectonics – a key element of Amadeus Basin development and prospectivity, *in* Proceedings of the Central Australian Basins Symposium (CABS) *edited by* TJ Munson and GJ Ambrose: Northern Territory Geological Survey, Central Australian Basins Symposium, Alice Springs, Northern Territory, 16–18 August, 2005, Proceedings; Special Publication, no. 2, p. 119–135.

Marshall, TR, Dyson, IA and Liu, K 2007, Petroleum systems in the Amadeus Basin, central Australia: Were they all oil prone?, *in* Proceedings of the Central Australian Basins Symposium (CABS) *edited by* TJ Munson and GJ Ambrose: Northern Territory Geological Survey, Central Australian Basins Symposium, Alice Springs, Northern Territory, 16–18 August 2005, Proceedings; Special Publication, no. 2, p. 136–146.

Munson, TJ 2014, Petroleum geology and potential of the onshore Northern Territory: Northern Territory Geological Survey, Report 22, 242p.

Ozimic, S, Passmore, VL, Pain, L and Lavering, IH 1986, Amadeus Basin, central Australia: Australia BMR, Australian Petroleum Accumulations Report 1, 64p.

Preiss, WV, Walter, MR, Coats, RP and Wells, AT 1978, Lithological correlations of Adelaidean glaciogenic rocks in parts of the Amadeus, Ngalia and Georgina Basins: BMR Journal of Australian Geology & Geophysics, v. 3, p. 43–53.

Prichard, CE and Quinlan, T 1962, The geology of the southern half of the Hermannsburg 1:250,000 sheet: Australia BMR, Report 61, 39p.

Ranford, LC, Cook, PJ and Wells, AT 1965, The geology of the central part of the Amadeus Basin, Northern Territory: Australia BMR, Report 86, 48p.

Wakelin-King, G 1994, Proterozoic play challenges Amadeus basin explorers: Oil and Gas Journal, v. 92, p. 52–55.

Walsh, AK, Raimondo, T, Kelsey, DE, Hand, M, Pfitzner, HL and Clark, C 2012, Duration of high-pressure metamorphism and cooling during the intraplate Petermann Orogeny: Gondwana Research , v. 24, p. 969–983.

Walter, MR, Krylov, IN and Preiss, WV 1979, Stromatolites from Adelaidean (late Proterozoic) sequences in central and South Australia: Alcheringa, v. 3, p. 287–305.

Walter, MR, Veevers, JJ, Calver, CR and Grey, K 1995, Neoproterozoic stratigraphy of the Centralian Superbasin, Australia: Precambrian Research, v. 73, p. 173–195.

Wells, AT, Forman, DJ and Ranford, LC 1961, Geological reconnaissance of the Rawlinson–MacDonald area, Western Australia: Australia BMR, Record 1961/59, 44p.

Wells, AT, Forman, DJ and Ranford, LC 1964, Geological reconnaissance of the Rawlinson and MacDonald 1:250 000 sheet areas: Australia BMR, Report 65, 35p.

Wells, AT, Forman, DJ and Ranford, LC 1965, The geology of the north-western part of the Amadeus Basin, Northern Territory: Australia BMR, Report 85, 45p.

Wells, AT, Ranford, LC, Stewart, AJ, Cook, PJ and Shaw, RD 1967, Geology of the north-eastern part of the Amadeus Basin, Northern Territory: Australia BMR, Report 113, 93p.

Wells, AT 1968, Macdonald, W.A.: Australia BMR, 1:250 000 Geological Series Explanatory Notes, 10p.

Wells, AT, Forman, DJ, Ranford, LC and Cook, PJ 1970, Geology of the Amadeus Basin, central Australia: Australia BMR, Bulletin 100, 222p.

Wilson, RB and Gates, A 1965, Field report on the geology of P.E. 153H, Western Australia; Australian Aquitaine Petroleum Pty Ltd: S8153 A2 (unpublished).

Wingate, MTD, Kirkland, CL and Haines, PW 2013a, 143783: sandstone, Mu Hills; Geochronology Record 1108: Geological Survey of Western Australia, 5p.

Wingate, MTD, Kirkland, CL and Haines, PW 2013b, 143800: sandstone, Dinner Hill; Geochronology Record 1111: Geological Survey of Western Australia, 6p.

Young, IF and Ambrose, GJ 2007, Petroleum geology of the southeastern Amadeus Basin: the search for sub-salt hydrocarbons, *in* Proceedings of the Central Australian Basins Symposium (CABS) *edited by* TJ Munson and GJ Ambrose: Northern Territory Geological Survey; Central Australian Basins Symposium, Alice Springs, Northern Territory, 16–18 August 2005, Special Publication, no. 2, p. 183–204.

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