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LITHOSTRATIGRAPHIC NOMENCLATURE OF THE OFFICER BASIN AND CORRELATIVE PARTS OF THE PATERSON OROGEN WESTERN AUSTRALIA

By K. Grey, R. M. Hocking, M. K. Stevens, L. Bagas, G. M. Carlsen, F. Irimies, F. Pirajno, P. W. Haines, and S. N. Apak

Geological Survey of Western Australia

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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Depot Camp, Townsend Range (photograph by E. de C. Clarke); originally published (1917) in 'A geological reconnaissance of the country between Laverton and the South Australian border (near latitude 26°S), including part of the Mount Margaret Goldfield', by H. W. B. Talbot and E. de C. Clarke (GSWA Bulletin 75). Townsend Quartzite is exposed in the bluff behind the camp, at Lillian Creek. Bulletin 75 reports on the first systematic geological investigations of the Officer Basin and Musgrave Complex

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Lithostratigraphic nomenclature of the Officer Basin and correlative parts of the Paterson Orogen, Western Australia

by

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Abstract

Recent work in the western Officer Basin, including stratigraphic drilling, has led to substantial revision of the lithostratigraphy, structural divisions, and extent of the basin. The Officer Basin as defined in Western Australia contains a Neoproterozoic and earliest Cambrian succession, the lithostratigraphy of which is considered here. The Middle to Late Cambrian Table Hill Volcanics and younger rocks are assigned to an overlying basin, the Gunbarrel Basin, and are not reviewed at length.

In the southwestern Officer Basin (the former Yowalga and Waigen Sub-basins, the Kingston Platform and the Neale Arch), the Buldya Group is a mixed carbonate–clastic–evaporite succession that comprises the Townsend Quartzite, Lefroy, Browne, Hussar, Kanpa, and Steptoe Formations, and probably the Ilma Formation and Mason Conglomerate. These units range in age from c. 830 to c. 700 Ma, and equate to Supersequence 1 of the Centralian Superbasin. An unconformity of about 100 million years duration separates the Buldya Group from rocks of Supersequence 3 age. No lateral equivalents of the Sturtian of central and South Australia (Supersequence 2) have been positively identified in Western Australia, but possible candidates are the Throssell Range (amended from Throssell) and Lamil Groups in the Paterson Orogen, and the Lupton and Turkey Hill Formations, the ages of which are virtually unconstrained. A diamictite-dominated unit, previously assigned to the Lupton Formation, is here defined as the Wahlgu Formation. This unit correlates with the Marinoan glaciation and cap dolomite included in Supersequence 3 of central and South Australia, and the Boondawari Formation of the northwestern Officer Basin. An uppermost Proterozoic – Lower Cambrian sandstone-dominated unit that extends through the southwestern and northern Officer Basin, previously referred to as 'McFadden Formation equivalent' and possibly equivalent to the Punkerri Sandstone, is here named the Lungkarta Formation. In Lancer 1 it is very similar to the McFadden Formation of the Disappointment Group. The Lungkarta Formation may correlate in part with the thick, conglomeratic Vines Formation in Vines 1.

In the northwestern Officer Basin (former 'Savory Basin', the largest part of the basin without extensive Phanerozoic cover) the Sunbeam Group (Buldya Group correlative), Boondawari Formation (Wahlgu Formation correlative), Disappointment Group (Lungkarta Formation partial correlative), and Durba Sandstone are recognized, following abandonment of the 'Savory Group'. Basal sandstone units were recently excised from the Sunbeam Group, as they are part of an older succession. The Tarcunyah Group of the Paterson Orogen correlates with the Buldya and Sunbeam Groups but is structurally separated from it and commonly more deformed. The Lamil and Throssell Range Groups of the Yeneena Basin are probably related to the Officer Basin succession, but are separated from the Officer Basin by the Vines–Southwest–McKay fault system, and are more deformed than the northern Officer Basin succession.

KEYWORDS: Officer Basin, Buldya Group, Sunbeam Group, Disappointment Group, Tarcunyah Group, Yeneena Basin, Throssell Range Group, Lamil Group, Paterson Orogen, lithostratigraphy, geochronology, biostratigraphy, petroleum geology, igneous petrology, regional geology, sedimentology, hydrocarbon potential.

Introduction

This publication presents a revised lithostratigraphic framework for the Officer Basin in Western Australia (Fig. 1), hereafter referred to as the western Officer Basin. The revisions arise from recent Geological Survey of Western Australia (GSWA) studies in the Officer Basin and adjacent Paterson Orogen. The stratigraphic nomenclature and geology of existing units in the main area of the western Officer Basin are reviewed, and a new group (the Buldya Group) is introduced. In addition, brief descriptions are given of the succession along the northwest margin of the basin where it is also part of the Paterson Orogen (Tarcunyah Group), and the Throssell Range (previously Throssell Group, which is invalid due to prior use of the name) and Lamil Groups of the related

Figure 1. Location, infrastructure, and surrounding tectonic units, western Officer Basin

Yeneena Basin. Most spatial data are presented as an accompanying Geoviewer dataset, rather than as figures or plates.

Within the report, Grey and Hocking coordinated the report overall; Grey contributed all biostratigraphy and palaeontology, and much of the lithostratigraphy; Hocking contributed sections on the northwest Officer Basin, other scattered areas, and the geological setting; Stevens contributed geological details for several areas; Bagas wrote the section on the Paterson Orogen (including igneous rocks in this region) and included comments on other parts of the report; Carlsen assembled the initial contribution on the Townsend Quartzite and some introductory sections; Irimies produced all the GIS background to the report; Pirajno wrote the initial sections on igneous rocks; Apak made various geological observations; and Haines and Stevens provided most interpretations regarding Lancer 1. Lancer 1 finished drilling as this report approached finalization and preliminary results have been incorporated, but all interpretation should be regarded as tentative and subject to amendment in the light of further work.

Earlier descriptions of the Officer Basin, its stratigraphic nomenclature, its structural development, correlation both within the the basin and to other basins, and possible connections to other parts of the Centralian Superbasin (Walter et al., 1995) are presented in Fitzpatrick (1966), Wells et al. (1970), Daniels (1974), Preiss (1976), Preiss et al. (1978), Jackson and van de Graaff (1981), Lambeck (1984), Phillips et al. (1985), Townson (1985), Cockbain and Hocking (1989), Preiss (1987, 1993, 2000), Iasky (1990), Korsch and Kennard (1991), Williams (1992, 1994), Baillie et al. (1994), Hocking (1994), Walter and Gorter (1994), Walter et al. (1994, 1995, 2000), Bagas et al. (1995, 1999), Hoskins and Lemon (1995), Levin and Lindsay (1995), Moussavi-Harami and Gravestock (1995), Lindsay and Levin (1996), Myers et al. (1996), Morton and Drexel (1997), Walter and Veevers (1997), Hill and Walter (2000), Hill et al. (2000a,b), and Walter (2000) and references therein. Publications arising from the present GSWA study are Perincek (1996a,b, 1998), Grey and Stevens (1997), Stevens and Grey (1997), Carlsen and Grey (1998), Stevens and Adamides (1998), Stevens and Carlsen (1998), Carlsen et al. (1999, 2003), Grey et al. (1999), Stevens and Apak (1999), Apak and Moors (2000a,b, 2001), Apak et al. (2002a,b), Moors and Apak (2002), Stevens et al. (2002a,b), Apak and Carlsen (2003), Hocking (2003), Hamilton et al. (2004), Haines et al. (2004), Simeonova and Iasky (2005), and D'Ercole et al. (2005).

The name Officer Basin, after Officer Creek in South Australia, was proposed by R. C. Sprigg (see Preiss, 1993), and used in the 1959–60 Annual Report of the South Australian Mines Department (O'Neill, 1997). Shiels (1960, 1961) and Wopfner (1961) outlined the extent of the basin in South Australia (Preiss, 1993). The basin (Fig. 2) covers a total area of about 525 000 km^2, of which some 300 000 km^2 is in Western Australia and 225 000 km^2 in South Australia (referred to as the eastern Officer Basin). These areas include estimates of the extent of the basin beneath the Eucla Basin, but do not allow for possible extensions northward under the Canning Basin, or include areas in the Paterson Orogen, part of which consists of dynamically metamorphosed sedimentary rocks of the Officer Basin succession.

Rationalization and revision of the nomenclature has become necessary for several reasons. Firstly, the areal extent of the western Officer Basin was increased in the mid-1990s (Bagas et al., 1995; Perincek, 1996a,b) and the stratigraphic range of the Officer Basin succession in Western Australia was restricted to the Neoproterozoic and Cambrian rocks that underlie the Table Hill Volcanics (Hocking, 1994; Hocking et al., 1994; Fig. 3). Overlying Palaeozoic rocks were placed in the Gunbarrel Basin. This restriction of the stratigraphic extent of the basin has not been applied in South Australia, where the eastern Officer Basin includes the whole Neoproterozoic and Palaeozoic succession (Preiss, 1993; Morton and Drexel, 1997).

Secondly, seismic interpretation, palaeontological, geochronological and stable isotope studies, stratigraphic drilling, sequence stratigraphic studies, and geological mapping in adjoining areas in the last decade have advanced understanding of the stratigraphy of the basin since the last regional overview by Jackson and van de Graaff (1981) and the summary by Iasky (1990). Correlations between several stratigraphic units have changed, with concomitant changes to geographical distribution, lithological description, and boundary criteria. Some stratigraphic names that are widely used were never formally defined, and other names have become obsolete. Several areas and names remain of uncertain affinity. Correlations between the major wells in the basin are shown in Figure 4.

Lastly, sub-basin terminology is also in the process of revision. The status of basin sub-divisions such as the 'Yowalga Sub-basin', originally identified from potential-field studies (Townson, 1985; Iasky, 1990), was cast into doubt by Apak and Moors (2000a,b), who did not recognize a clearly defined sub-basin in the Yowalga area. As an interim measure, most of the former tectonic units are referred to informally in a geographical sense only, as 'the Yowalga area' or 'the Savory area', when a need arises to refer separately to a geographical area. Apak et al. (2002a), Apak and Carlsen (2003) and Carlsen et al. (2003) outlined a tectonic framework with subdivisions based on halotectonic character, after work by JNOC (1997), for the central part of the western Officer Basin (Fig. 5).

Separate stratigraphic schemes have arisen in South Australia and Western Australia largely because the basin straddles a border remote from both Adelaide and Perth. The revisions proposed here have not been applied to the South Australian succession, but correlations have been suggested wherever possible. A more integrated stratigraphic framework for the whole Officer Basin may arise from future studies in South Australia.

Boundaries

The interpreted boundaries of the Officer Basin have been substantially revised from those proposed by Jackson

Figure 2. **Extent of the Officer Basin in Western and South Australia. Eucla Basin overlies the basin on the south, Gunbarrel Basin overlies most of the central part of the western Officer Basin but is included in the Officer Basin in South Australia. Informal areas or regions within Officer Basin shown here in italics**

and van de Graaff (1981). As presently defined, the basin includes Neoproterozoic and Lower Cambrian rocks in the region east of the Yilgarn and Pilbara Cratons, south of the Canning Basin, and south or west of the Paterson Orogen (Rudall and Musgrave Complexes; Fig. 1; Tyler et al., 1998; Tyler and Hocking, 2001). The term Musgrave Complex is used for the whole of the exposed part of the Paterson Orogen adjoining the Western Australia – South Australia border. In South Australia these rocks are referred to as the Musgrave Block (Major and Conor, 1993).

The western Officer Basin is onlapped and covered to the south by Cainozoic rocks of the Eucla Basin. The Neoproterozoic succession of the Officer Basin extends southward beneath the Eucla Basin, but shallows, and is absent in water bores along the Transcontinental Railway Line. These boreholes intersected granite and gneiss (Lowry, 1970) which, based on aeromagnetic imagery, correlate with the Coompana Block of South Australia.

To the west, Precambrian igneous, metamorphic, and sedimentary rocks of the Albany–Fraser Orogen, Yilgarn Craton, and Earaheedy Basin flank the Officer Basin. Carboniferous–Permian glacigene rocks obscure the boundary, the location of which is discussed in detail below. The basin onlaps the Mesoproterozoic Collier Basin and ?correlative Salvation Group (Hocking and Jones, 2002) in the northwest. To the north, the basin succession is faulted against, or onlaps, the Palaeoproterozoic Rudall Complex and subsurface extensions, southeast along the Warri Ridge to the Mesoproterozoic Musgrave Complex. Much of the north to northeastern margin is overlain by the Canning Basin succession, which is continuous into the Phanerozoic Gunbarrel Basin. The Officer Basin may have been connected to the Amadeus Basin in the east and perhaps to the Adelaide Rift Complex (Preiss, 1987; Walter and Gorter, 1994), at least in the early stages of deposition, although Camacho et al. (2003) have cast doubt on this hypothesis. South and east of the Musgrave Complex in South Australia, the basin presumably extends to the Gawler Craton, although the younger Eromanga and Arckaringa Basins conceal the easternmost extent (D'Ercole et al., 2005).

The Officer Basin now incorporates most of the former 'Savory Basin', which lies south and southwest of the Rudall Complex. Bagas et al. (1995) abandoned the term 'Savory Basin', and Bagas et al. (1999) split the 'Savory

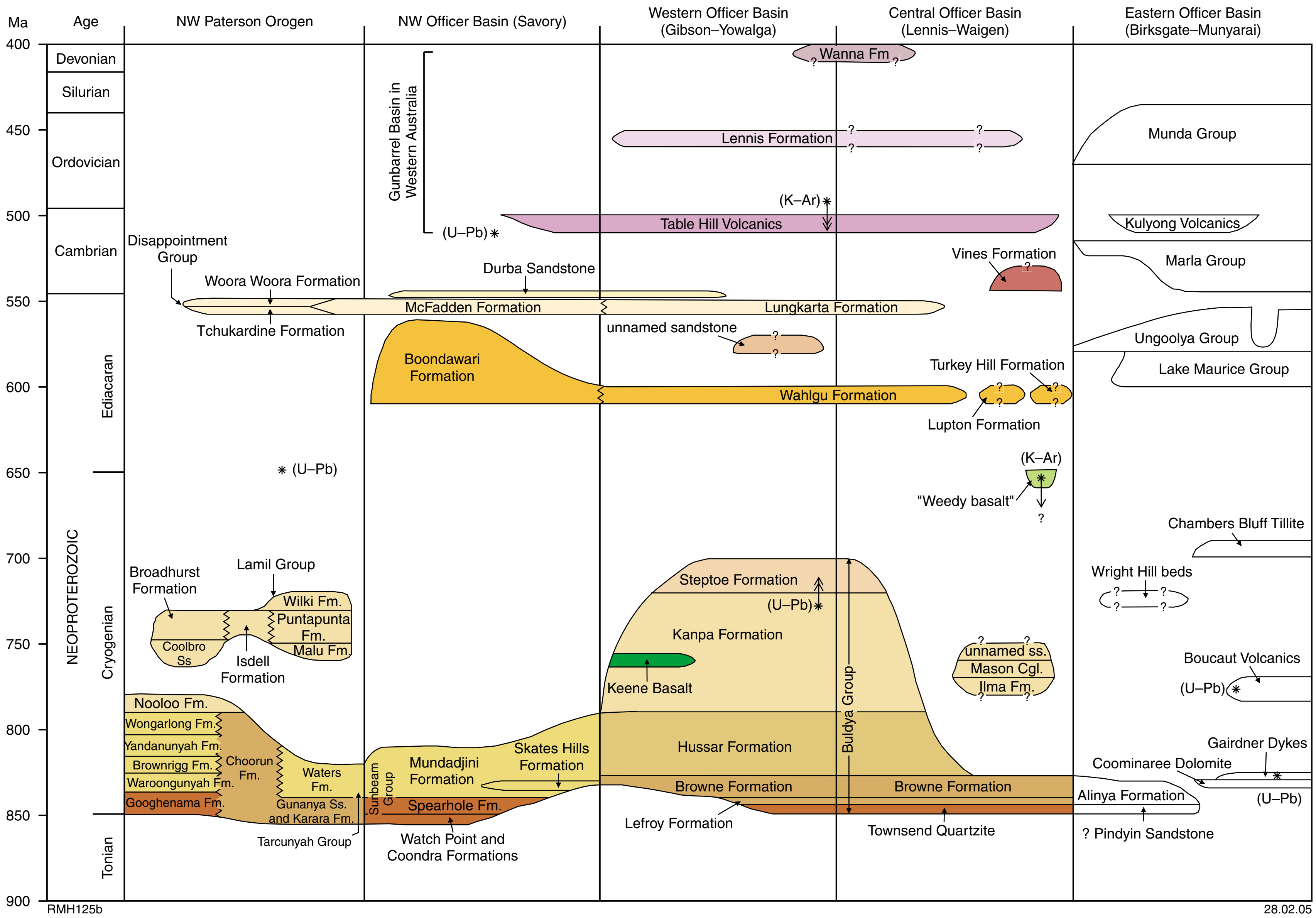


Figure 3. Stratigraphic succession, western Officer Basin, showing parallel stratigraphic frameworks in main part of basin, northwest Officer Basin, and Paterson Orogen

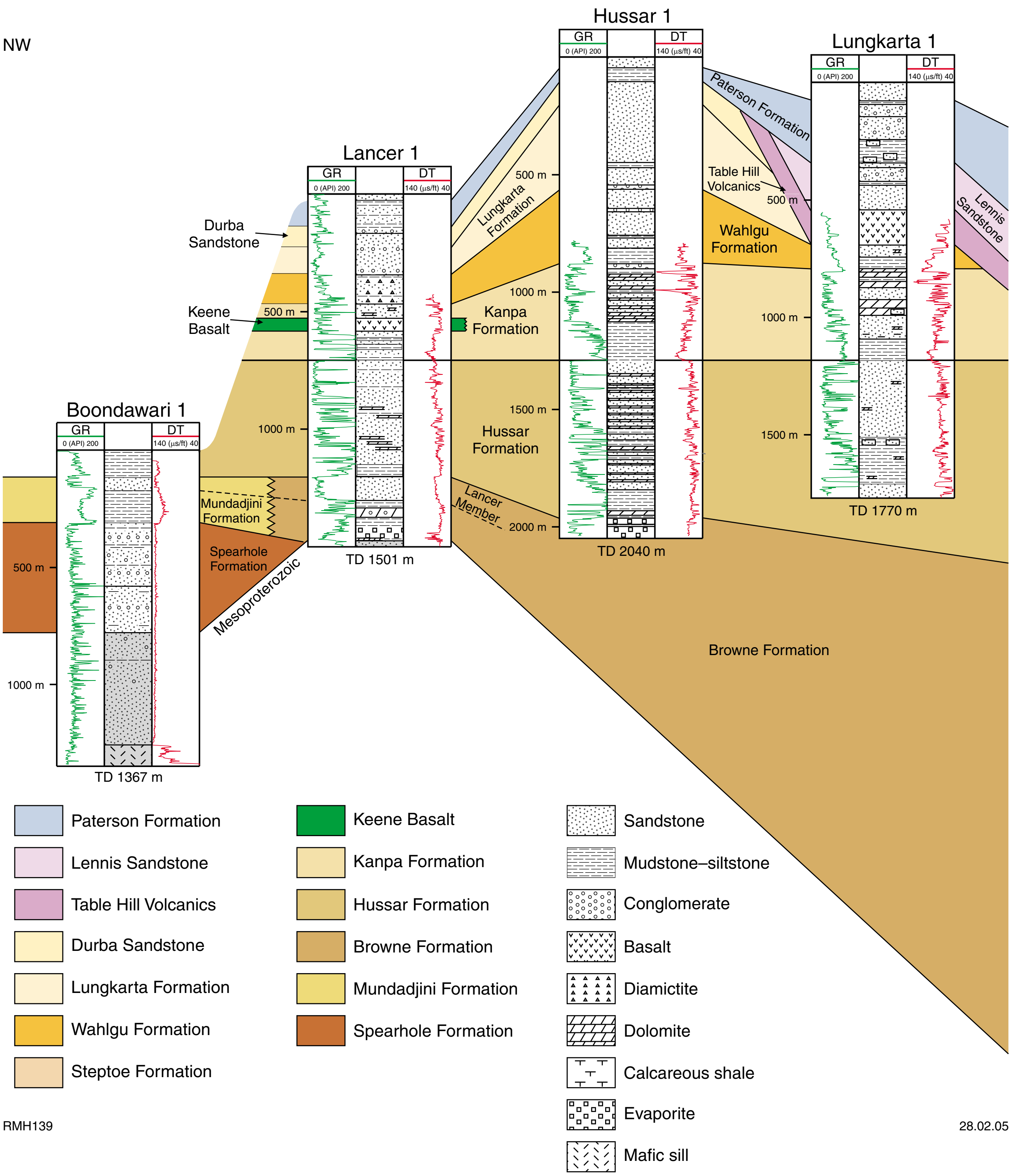
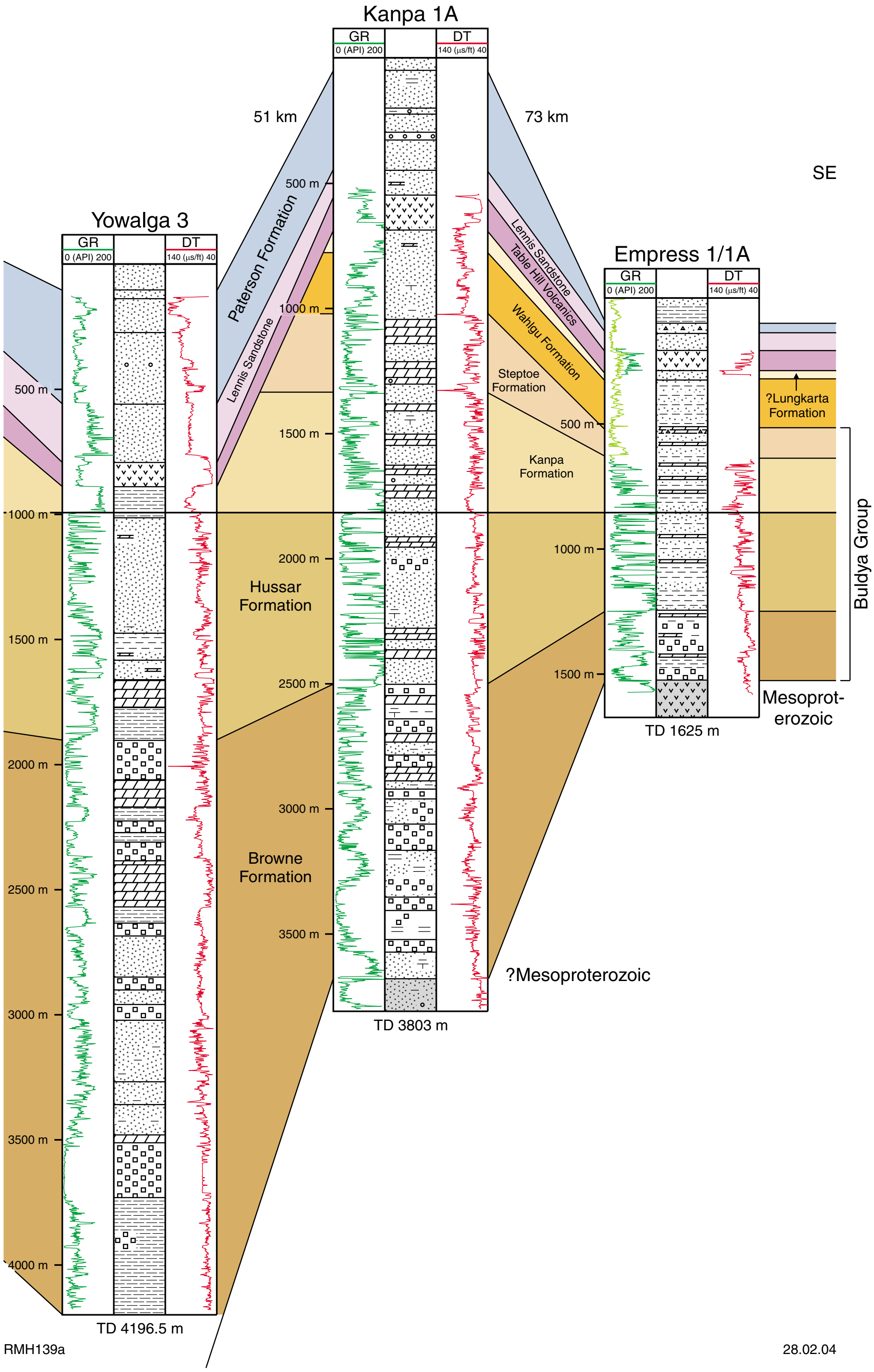


Figure 4. **Correlation between major wells in western Officer Basin. In this and subsequent figures: TD = Total Depth; GR = Gamma Ray, measured in API units; DT = Delta T (Compensated Sonic), measured in microseconds/foot**


Kanpa 1A
Yowalga 3
Empress 1/1A
GR
0 (API) 200
DT
140 (μs/ft) 40
51 km
73 km
SE
Paterson Formation
Lennis Sandstone
Table Hill Volcanics
Wahlgu Formation
Steptoe Formation
Kanpa Formation
Hussar Formation
Browne Formation
?Lungkarta Formation
Buldya Group
Mesoproterozoic
?Mesoproterozoic
500 m
1000 m
1500 m
2000 m
2500 m
3000 m
3500 m
4000 m
TD 4196.5 m
TD 3803 m
TD 1625 m
RMH139a
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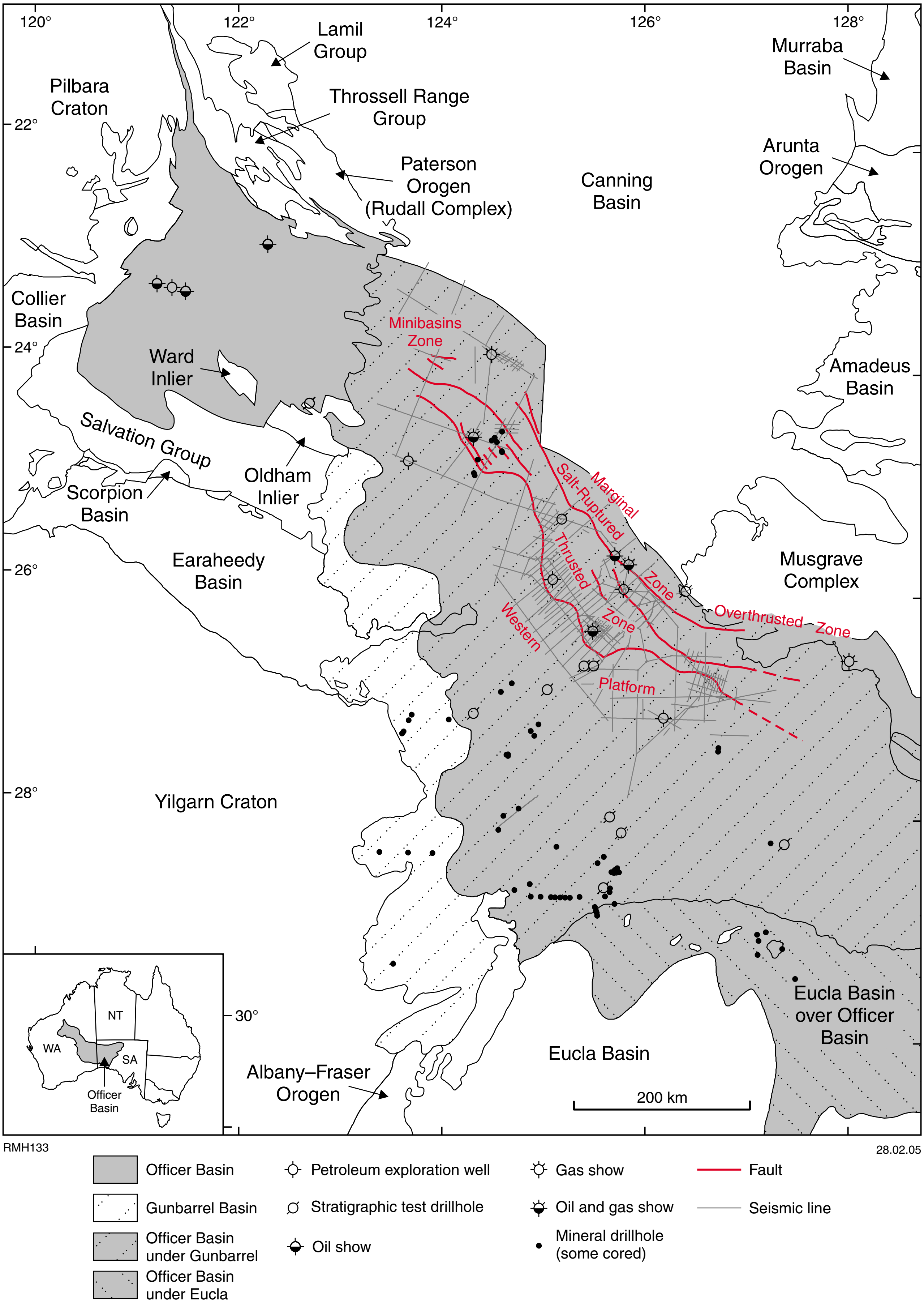

Figure 5. Halotectonic structural elements, central western Officer Basin, after Carlsen et al. (2003)

Group' into (in ascending order) the Sunbeam Group, Boondawari Formation, Disappointment Group, and Durba Sandstone. Hocking and Jones (2002) recognized that several units at the base of the Sunbeam Group should instead be placed in an older succession, the Salvation Group of Hocking et al. (2000).

Western limit of the Officer Basin

The western margin of the Officer Basin (excluding the northwestern Officer Basin) was originally taken as the western limit of continuous Permian outcrop, but this constraint no longer applies because in Western Australia nearly all the Phanerozoic succession is now incorporated in the Gunbarrel Basin (Hocking, 1994; Hocking et al., 1994). The Gunbarrel Basin contains the Table Hill Volcanics, which are currently thought to be Middle – Late Cambrian, and overlying rocks. Outcrops of Proterozoic rocks older than the Officer Basin succession are minimal near the basin margin. Some clues are provided by outcrop patterns and drillholes. Diamond drillholes TD 1, 2, 3, and 4, completed by Dampier Mining Co. Ltd (then a subsidiary of BHP Co. Ltd), intersected Carboniferous–Permian Paterson Formation and underlying Archaean or Mesoproterozoic crystalline basement rocks west of 124°E on central THROSSELL* (BHP Co. Ltd, 1979; Perincek, 1998). Permian rocks overlie crystalline rocks or banded iron-formation on RASON, MINIGWAL, and southern NEALE (Perincek, 1998), with the easternmost such intersection in BMR Rason 2 on RASON, a few kilometres east of 124°E.

Outcrops west of about 124°E contain rock types typical of the Earaheedy Group, in particular granular iron formation. They also contain stromatolites typical of this age (Grey, 1984a, 1994). Outcrops east of this area, between Lake Throssell and the Gunbarrel Highway, contain *Baicalia burra*† and other stromatolites from the *Baicalia burra* Stromatolite Assemblage of Stevens and Grey (1997), and so can be correlated with the upper Buldya Group. A fine-grained mafic igneous outcrop with basaltic texture east of Ida Range, located between exposures of the Earaheedy Basin to the west and Officer Basin to the east, has a Rb–Sr age of 1028 ± 50 Ma (Bunting, 1986, recalculated from Compston, 1974). Stratigraphic relationships at the outcrop are uncertain. A few undifferentiated quartzite outcrops east of Buldya Soak on Throssell, and intruded by a dolerite in drillhole CRAE 92 THAC 001 west of Lake Throssell (Clifford and Clydsdale, 1992), may be Townsend Quartzite, although the age is unconfirmed. Alternatively, they could be part of the Hussar Formation. It is equally possible that they are Mesoproterozoic, and that the Buldya Group onlaps basement progressively to the west.

On northeast Minigwal, a small northeast-trending outcrop of massive quartzite overlies strongly sheared and cleaved felsic rock (Bunting and Boegli, 1977). This outcrop was interpreted as being the same unit as a cross-bedded quartzite near Lindsay Hill on northwest PLUMRIDGE that was described by van de Graaff and Bunting (1977). Other outcrops of quartzite 10 km southeast of Bartlett Bluff on southwest NEALE and on CUNDEELEE (Bunting and van de Graaff, 1977) were described as cleaved and metasomatized. The age of these quartzite outcrops is unknown; they may be Townsend Quartzite, but probably are older.

* Capitalized names refer to standard 1:250 000 map sheets. The scale is appended where the reference is to a 1:100 000 map sheet.

† Full citations of fossil names and their authors are given in Appendix 3.

Centralian Superbasin

Walter et al. (1995) considered the Centralian Superbasin (Figs 6–8) to be a single Neoproterozoic intracratonic basin that covered an area of around 2 000 000 km^2. The superbasin was tectonically disrupted during the c. 550 Ma Paterson and Petermann Orogenies, and the mid-late Palaeozoic Alice Springs Orogeny, resulting in the development of numerous discrete basins, including the Amadeus and Officer Basins (Walter et al., 1995). Following the recognition of common stratigraphic successions in each of these basin, Walter et al. (1995, 2000) recognized depositional supersequences, which they called Supersequences 1 (early Cryogenian; Willouran, Torrensian, and early Sturtian), 2 (mid to late Cryogenian; mid-Sturtian to early Marinoan), 3 (late Cryogenian; early to mid-Marinoan), and 4 (Ediacaran, i.e. from the top of the Marinoan cap dolomite to the base of the Cambrian) (Figs 7, 8). Names in parentheses refer to IUGS chronometric divisions and Adelaide Rift Complex chronostratigraphic subdivisions respectively.

The Centralian Superbasin concept is based on an extensional model for initial basin formation, followed by a series of compressional and extensional events that deformed the superbasin and split it into the structural basins identified today. Proponents of the concept consider these structural basins shared a common depositional history, particularly in the early stages of formation (Walter et al., 1995; Hoskins and Lemon, 1995), and may have been a single extensive basin during the first phase of deposition. The superbasin is thought to have been largely cratonic in character, in contrast to the Adelaide Rift Complex, which appears to have developed as an intracratonic sag basin, but then progressed through breakup to a passive margin (Preiss, 2000; Preiss and Cowley, 1999). A series of recently published studies provide a framework for correlations both within the Centralian Superbasin and between the Centralian Superbasin and Adelaide Rift Complex, and place the successions in their global context (Walter, 2000). Stromatolite biostratigraphy, palynology, and isotope chemostratigraphy provide good tie points for correlation between Officer Basin units and other Neoproterozoic units in Australia (Hill and Walter, 2000; Hill et al., 2000a,b), and allow some age constraints to be placed on the succession.

Apak and Moors (2000a,b) rejected the intracratonic sag model for the western Officer Basin and its inclusion in the Centralian Superbasin, and interpreted the earliest stages of formation as a foreland basin forming against an

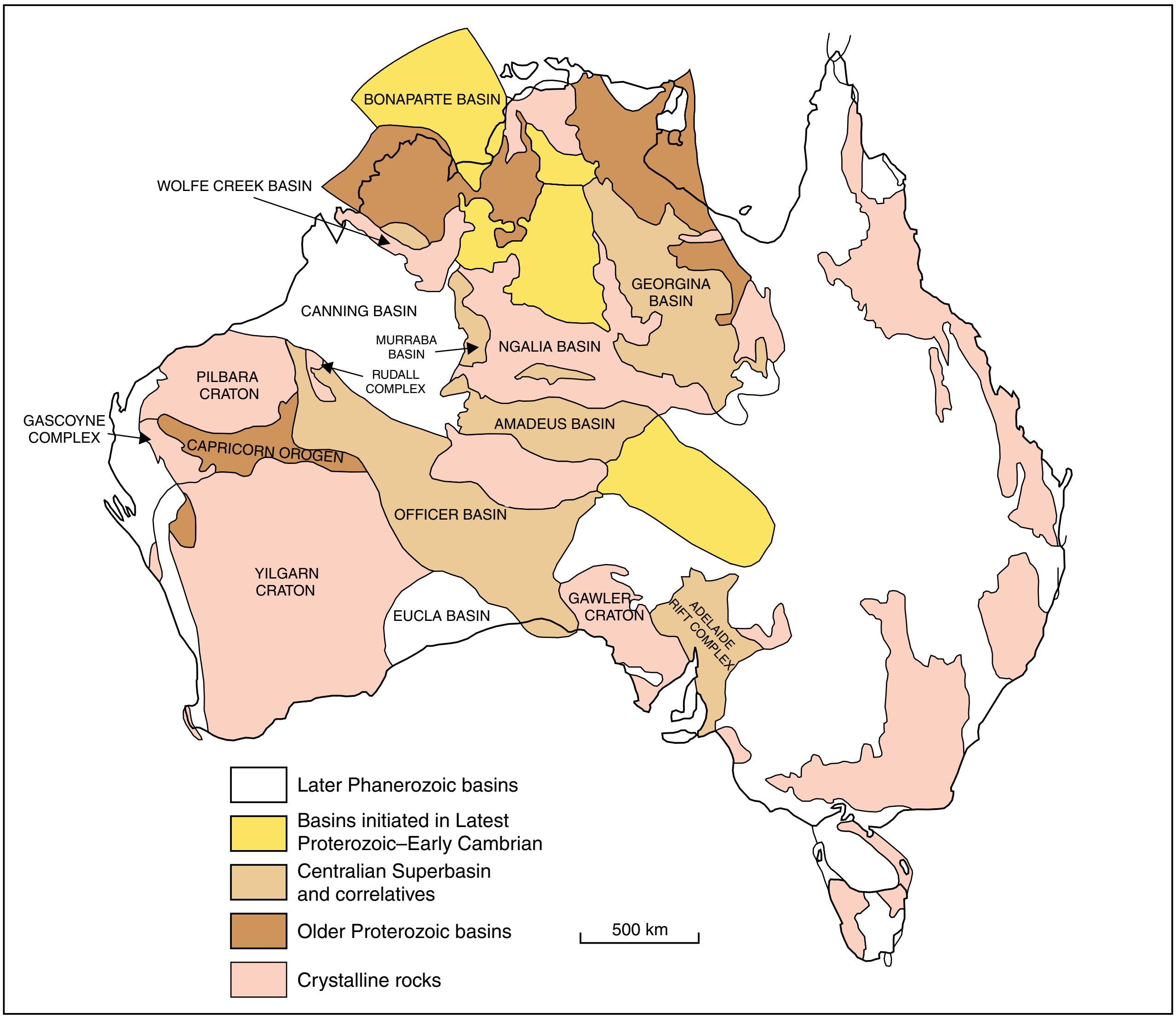

Figure 6. Component basins of the Centralian Superbasin of Walter et al. (1995, 2000), modified from Lindsay and Korsch (1991, fig. 1)

emergent Musgrave Complex, with significant tectonic movement during the Areyonga Movement.

Many of the models for the Centralian Superbasin suggest that major uplift and emergence of the Musgrave Complex was during the c. 550 Ma Petermann Orogeny (e.g. Lindsay and Korsch, 1991). However, Camacho et al. (2003) demonstrated that the complex was emergent and contributing sediment to the southern Amadeus Basin from at least 700 Ma, and probably during deposition of Supersequence 1 also. This suggests that while depositional style may have been similar throughout the Centralian Superbasin, there was always a series of related basins rather than a single entity. Camacho et al.'s (2003) model is also consistent with seismic lines in the western Officer Basin that show a significant angular unconformity at the top of Supersequence 1, and an increase in thickness of Supersequence 1 units towards the Musgrave Complex.

Southwestern Officer Basin

Buldya Group

Definition and nomenclature: The Buldya Group is here named after Buldya Soak on Rason, and defined herein. The succession included in the Buldya Group has not previously been assigned to a group, and has commonly been referred to as 'Supersequence 1' (Walter et al., 1995). The constituent formations are the Townsend Quartzite, and the Lefroy, Browne, Hussar, Kanpa, and Steptoe Formations. The Ilma Formation, Mason Conglomerate, and an unnamed sandstone formerly assigned to the Lungkarta Formation, are here tentatively assigned to the Buldya Group solely on the basis of lithology, but their position within the group is unknown. For simplicity, the Buldya Group is informally divided into the lower Buldya Group (Townsend Quartzite and Lefroy Formation), the middle Buldya Group (Browne

Formation), and the upper Buldya Group (Hussar, Kanpa, and Steptoe Formations). These divisions represent significant changes in sedimentary character, but do not by themselves indicate major breaks in the succession. An unequivocal contact between the lower and the middle Buldya Group has not been observed in the Officer Basin, so the relationship between these informal units is inferred. Southgate (1991) recognized a disconformity between the lower and upper Bitter Springs Formation in the eastern Amadeus Basin, but this has not been observed in the correlative Browne Formation. The contact between the middle and the upper Buldya Group is apparently conformable in drillcore in Empress 1A (Stevens and Apak, 1999).

Distribution and thickness: The Buldya Group is known from drillhole and seismic data, scattered isolated outcrops on BENTLEY, COOPER, MADLEY, NEALE, ROBERT, TALBOT, THROSSELL, and WARRI, and possibly minor outcrops on MINIGWAL, RASON, WESTWOOD, WAIGEN, YOWALGA, and MASON. The group underlies Phanerozoic rocks of the Gunbarrel Basin or Cainozoic cover throughout much of the southwestern Officer Basin, and was intersected in a series of petroleum and stratigraphic drillholes (Perincek, 1998) that include: Browne 1 and 2, Dragoon 1, Hussar 1, Kanpa 1A, Lungkarta 1, Yowalga 2 and 3; Bureau of Mineral Resources (BMR, now Geoscience Australia (GA)) drillholes Madley 1, Talbot 1, 3, and 4, Throssell 1, and Warri 20; GSWA Empress 1 and 1A, GSWA Lancer 1, and deep mineral drillholes Kennecott N1 1, WMC NJD 1, and 92 THAC 001. The stratigraphic relationships of parts of sections intersected in drillholes PNC EXP CA 5, 9, 13, and 15 (Perincek, 1998) remain uncertain.

It is difficult to estimate the thickness of the group because of the poor outcrop, and because it is deeply eroded in places. The group is at least 4500 m thick as estimated from maximum observed thicknesses of individual formations, mainly in drillholes.

Lithology: The Buldya Group comprises siltstone, mudstone, sandstone (in part quartzite), dolomite (commonly stromatolitic), and minor halite and other evaporite minerals (Fig. 4). In core, rocks of the group are commonly chocolate brown or light ferrous green, with pink and red-tinted evaporites. Further lithological descriptions are given under each formation.

Relationships and boundary criteria: Lower and upper contacts are rarely exposed, and are discussed in detail under the relevant formation. The lower contact is best observed along the southwest margin of the

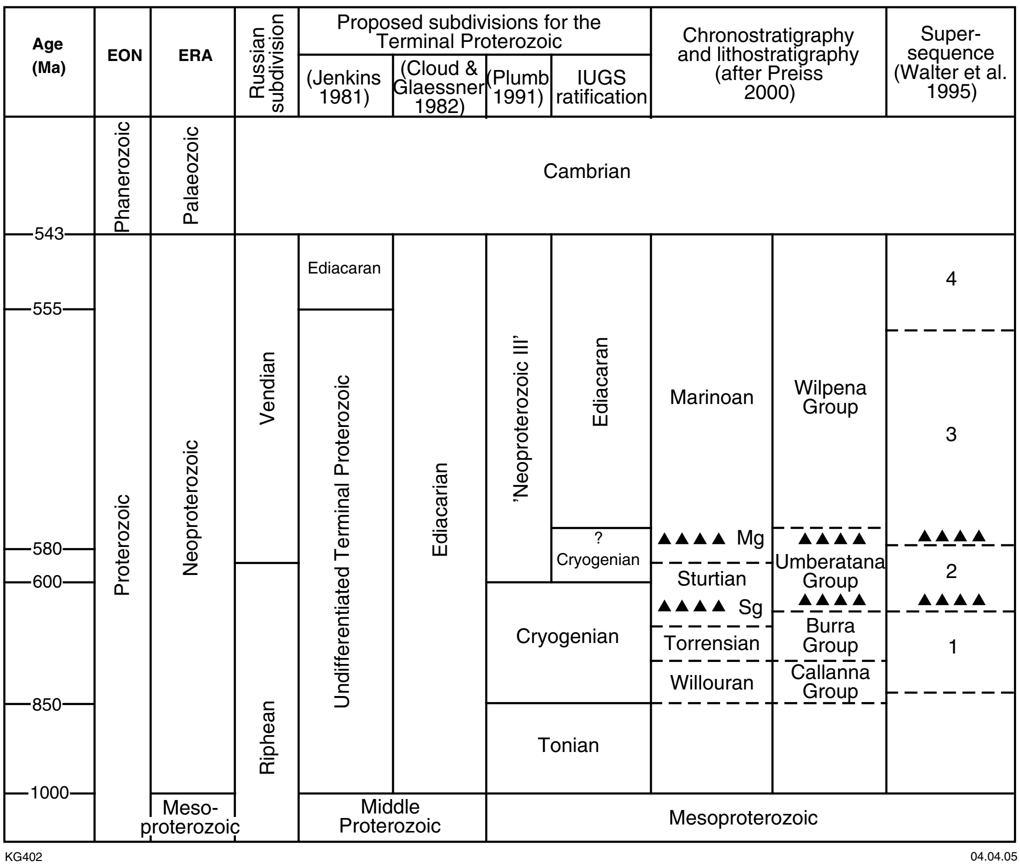

Figure 7. Subdivisions of the Neoproterozoic Era, historical Australian chronostratigraphic subdivisions, key lithostratigraphic groups for the Adelaide Rift Complex and super-sequence subdivisions of the Centralian Superbasin (modified after Preiss, 1987; Plumb, 1991; Walter et al., 1995; Calver, 1995)

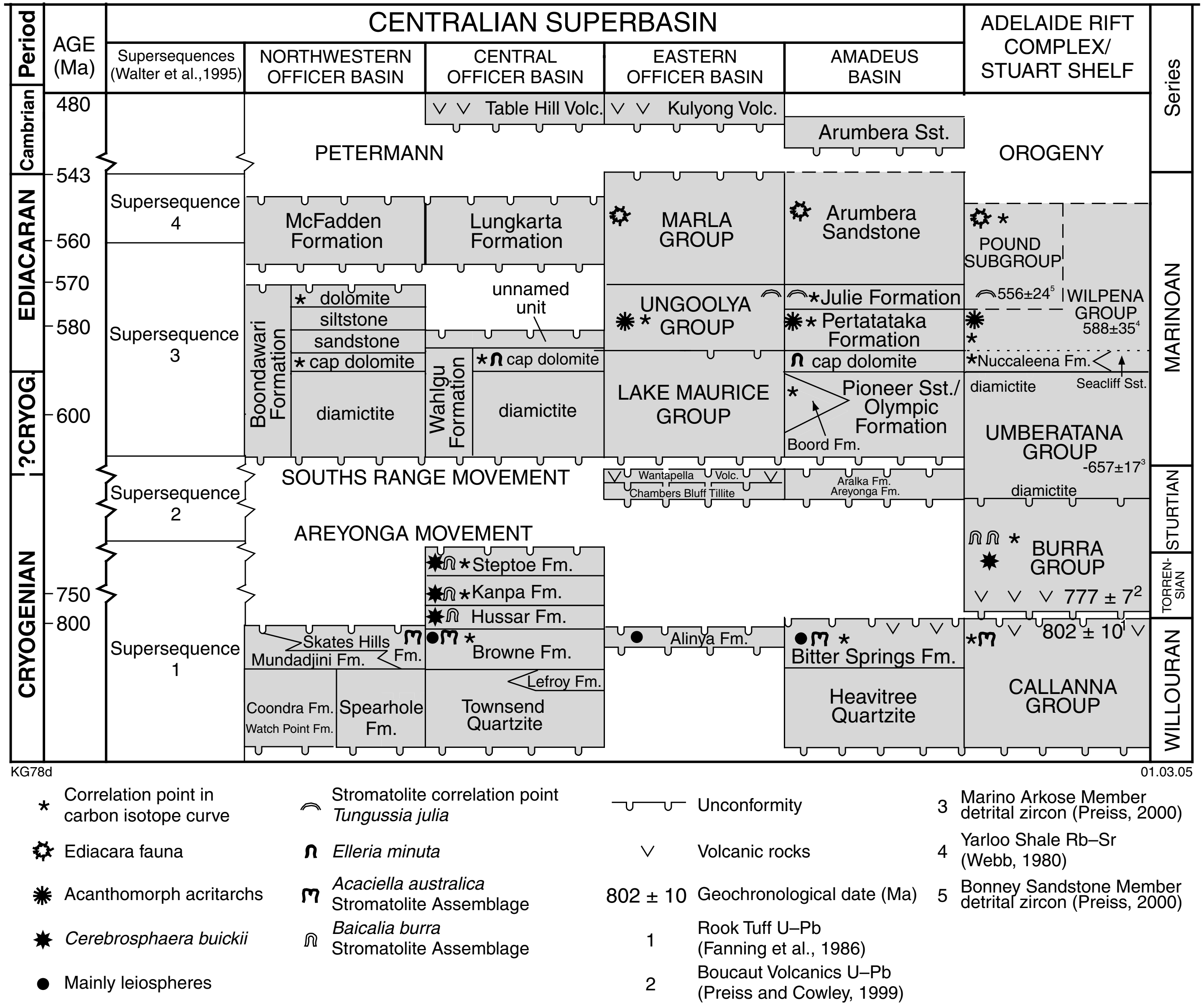

Figure 8. Comparison of successions, Officer Basin and other components of Centralian Superbasin.

Musgrave Complex, where there is an inferred angular unconformity between the Townsend Quartzite and Mesoproterozoic basement rocks. From sections in drillholes towards the western margin of the basin, it appears that the unit immediately above the basal contact becomes progressively younger towards the basin margin. The Townsend Quartzite, Lefroy, and lower Browne Formations are absent in Empress 1A (Stevens and Apak, 1999; Morris and Pirajno, 2002) and Lancer 1. Farther to the southwest in NJD 1, all the section below the upper Hussar Formation may be absent (Hocking, 2003), although a revised correlation based on comparison with Lancer 1 (Haines et al., 2004) would allow a thin sandy interval of Browne Formation overlain by thinner sections of Hussar and lower Kanpa Formation. Stromatolites in outcrops along the western margin of the basin are characteristic of the Kanpa Formation, but it is difficult to determine whether there might be some older Buldya Group between the basement and the Kanpa Formation. Exposures mapped as Townsend Quartzite along the western margin are possibly an older Mesoproterozoic sandstone, or Hussar or Kanpa Formation. On the southern basin margin, the Ilma Formation may be part of the Buldya Group, but its position within the group relative to other formations is unknown. It contains stromatolites similar to those found in the Woolnough Member, but preservation is too poor for this to be determined with any certainty.

Age and correlation: The Buldya Group is younger than steeply dipping late Mesoproterozoic sedimentary and volcanic rocks of the Musgrave Complex, which was deformed prior to c. 824 Ma, the age of an undeformed dyke that cuts the complex in the Michael Hills (Glikson et al., 1996). In Empress 1A, the Browne Formation is unconformable on a predominantly volcanic succession that yielded a K–Ar age of 1058 ± 13 Ma (Amdel, 1999; Stevens and Apak, 1999). Along the margins of the Musgrave Complex, the Townsend Quartzite unconformably overlies deformed and metamorphosed greenschist facies rocks of the Bentley Supergroup. Acid volcanic rocks from the Tollu Group have a whole rock Rb–Sr isochron age of 1060 ± 140 Ma (Compston and Nesbitt, 1967). If correlations between the Buldya Group and successions in the Amadeus Basin and Adelaide Rift Complex are correct, then deposition of the Buldya Group began before about 827 Ma, possibly as early as 850 Ma (see below, under **Townsend Quartzite** and **Browne Formation**). Deposition continued beyond 725 Ma, which is the age of a detrital zircon in the upper Kanpa Formation.

Stromatolites and carbon isotopes provide a tie between the stromatolitic carbonate horizon in the Browne Formation in Empress 1A and the Coominaree Dolomite of the Denison Range in the Adelaide Rift Complex (Hill and Walter, 2000; Hill et al., 2000b) and the Bitter Springs Formation of the Amadeus Basin. The Coominaree Dolomite is older than the Rook Tuff, which has a U–Pb SHRIMP zircon age of 802 ± 10 Ma (Fanning et al., 1986). It is also older than the Cadlareena Volcanics, which is correlated with the Wooltanna Volcanics and Gairdner Dyke Swarm (Preiss, 2000), and is therefore probably older than 827 Ma.

Palynomorphs, stromatolites, and carbon isotope chemostratigraphy in the Hussar Formation support correlation with part of the Burra Group of South Australia (Cotter, 1999; Hill et al., 2000b; Preiss and Cowley, 1999). The Boucaut Volcanics at or below the base of the Burra Group has a U–Pb SHRIMP zircon age of 777 ± 7 Ma (Preiss, 2000), implying that the Hussar Formation is of a similar age. The Kanpa Formation can be tied to the Burra Group and to successions in Canada, Spitsbergen, and Namibia using a combination of isotope chemostratigraphy, stromatolites and palynology (Hill and Walter, 2000; Hill et al., 2000b). The heaviest known mid-Neoproterozoic $\delta^{13}C$ values link the Kanpa Formation to the middle Ombombo Subgroup of Namibia, from which a volcanic-ash layer has provided a U–Pb zircon date of 758 ± 3.5 Ma (Hoffman et al., 1996).

The Buldya Group is overlain by diamictites that in Empress 1A have been correlated with the Marinoan glaciation at about 600 Ma based on the recognition of a cap dolomite, and using carbon isotopes and stromatolites (Walter and Hill, 1999; Grey et al., 1999). Regional considerations suggest that there is a considerable hiatus at the disconformity between the known top of the Buldya Group and the base of the diamictite succession. Detrital zircons with a SHRIMP U–Pb age of 725 ± 11 Ma are present in the Kanpa Formation in Empress 1A (Nelson, D. R., 2002, written comm.), so deposition of the group extended at least until about 725 Ma. The origin of the zircons is uncertain, and therefore the time between formation of the grains and deposition in the Kanpa Formation is unknown. In South Australia, the upper Burra Group correlates with the upper Buldya Group. In the Amadeus Basin succession, the section that correlates with the upper Buldya Group is not recorded, and erosion has commonly extended down to the level of the middle Browne Formation. The top of the group in Empress 1A, although stratigraphically higher than most other occurrences of the top Buldya Group, is a karstified surface as well (Preiss, W. V., 1998, written comm.). These aspects suggest a major erosional episode rather than mere non-deposition, and there is a major time break in the succession between the uppermost Buldya Group and the base of the Wahlgu Formation.

Notes: The succession in Empress 1A appears to show more or less continuous deposition from the Browne Formation through to the Steptoe Formation, with no apparent major breaks or sharp changes in character. The contact between the Lefroy Formation and the Browne Formation has not been observed at any location. Rocks initially tentatively assigned to the Lefroy Formation in Empress 1A are actually Mesoproterozoic mafic igneous rocks (Morris and Pirajno, 2002), so the Browne Formation rests directly on basement to the Officer Basin in this drillhole. Jackson and van de Graaff (1981) reported that the Lefroy Formation conformably overlies the Townsend Quartzite in the Townsend Ridges, but Apak and Moors (2000a,b) interpreted the two units as lateral equivalents. Kanpa 1A was interpreted as bottoming in Townsend Quartzite, disconformable beneath Browne Formation (Perincek, 1998), but this sandstone could be Mesoproterozoic in age, as in NJD 1 and Lancer 1.

Townsend Quartzite

Definition and nomenclature: The Townsend Quartzite was named after the Townsend Ridges by Sofoulis (1962) and was formally defined by Jackson and van de Graaff (1981). Previous usage is 'Townsend Range Series' (Horwitz, 1968), 'Townsend Formation' (Gee, 1974), 'Townsend quartzite' (Preiss and Forbes, 1981). This unit is the basal sandstone of the Officer Basin succession in Western Australia, where the basin overlies the Musgrave Complex. As discussed below, a series of unnamed quartz sandstone to quartzite units in the Officer Basin, mainly assigned to undifferentiated Proterozoic, may be Townsend Quartzite equivalents. Equally, some Townsend Quartzite as presently recognized may be older Mesoproterozoic sandstone rather than part of the Officer Basin succession.

Type section or area: Daniels (1974, table 6) referred to an 840 feet (256 m)-thick section 3½ miles (5.6 km) east of Lilian Creek gorge (informal topographic name) in the Townsend Ridges as the type section, and gave descriptions of the section from unpublished work by R. A. Farbridge. Jackson and van de Graaff (1981, fig. 13) noted Daniels' section, and presented a reference section about 370 m thick in Ainslie Gorge. As far as can be determined, their section extends from a base at about MGA Zone 52 265700E 7095600N southward to the stratigraphically youngest exposure at 265200E 7095200N. In South Australia, the type section of the laterally equivalent Pindyin Sandstone is at Pindyin Hills on LINDSAY (Major, 1973a). A reference section for the Pindyin Sandstone was designated in Giles 1, between 1289 and 1326.8 m (Morton, 1997).

Distribution and thickness: The Townsend Quartzite is exposed mainly along the western and southern margins of the Musgrave Complex, on BENTLEY, TALBOT, WAIGEN, and COOPER (Sofoulis, 1962; Daniels, 1970, 1971a,b, 1974; Jackson et al., 1975; Jackson, 1978a; Jackson and van de Graaff, 1981; Grigson, 1982; Watts, 1982). Sporadic outcrops of quartzite can be traced eastward along the southern margin of the Musgrave Complex to near the Stuart Highway in South Australia, where some is assigned to the Pindyin Sandstone (Major, 1973a; Krieg, 1973; Zang, 1995a; Morton, 1997) or, in places, undifferentiated Burra Group. It is uncertain which outcrops may correlate with the Townsend Quartzite. Some may be much younger, such as the early Torrensian Mount Margaret Quartzite of the Peake and Denison Ranges (Preiss, W. V., 2004, written comm.).

The northernmost outcrop of the Townsend Quartzite near the Musgrave Complex is near Mount Harvest on southern BENTLEY. Just to the south, near the western edge of the Musgrave Complex on TALBOT, BMR Talbot 1 penetrated 5.06 m of Townsend Quartzite before terminating at 33.06 m (Jackson et al., 1975; Jackson and van de Graaff, 1981, appendix 15). Nearby drillholes (BMR Talbot 2–5) did not reach the Townsend Quartzite. The Townsend Quartzite outcrops as a prominent, broken ridge around the southwestern margin of the Musgrave Complex on TALBOT, from Brown Range in the west to Hocking Range in the east. Possible lateral equivalents outcrop about 35 km south of Hocking Range. Jackson (1978a) assigned a west-trending ridge of silicified sandstone in the extreme northeast corner of WAIGEN to the Townsend Quartzite.

The silicified sandstone ('quartzite') unit appears to continue eastward on to BIRKSGATE and LINDSAY in South Australia via discontinuous outcrops that have been assigned to the lower part of the Pindyin Sandstone (Major, 1973a, Preiss, 1993; Zang 1995a,b; Morton, 1997). Morton (1997) noted that the Townsend Quartzite and Pindyin Sandstone are probable synonyms. Originally, the 'Pindyin Beds' were defined to include a basal quartz sandstone and overlying siltstone, sandstone, and evaporite (Major, 1973a). Zang (1995b) restricted the name Pindyin to the basal quartzite unit, renamed it Pindyin Sandstone, and assigned the overlying units to the Alinya Formation. Grey (1999a) reassessed the palynology in drillhole Birksgate 1 in South Australia, and considered that the Pindyin Sandstone probably lies just below TD, contrary to previous interpretations (Lindsay and Reine, 1995; Lindsay, 1995). Its base probably coincides with a seismic reflector at a depth of about 2 km, previously assigned to base Karlaya Limestone (Lindsay, 1995, plates 10, 12, 13), on an Australian Geological Survey Organisation (AGSO, now Geoscience Australia (GA)) deep seismic line. Reinterpretation of the line would provide significant data about the subcrop of the unit in Western Australia.

Daniels (1974) described the Townsend Quartzite type section as being 256 m thick. Grigson (1982) and Watts (1982) measured a series of sections in the Townsend Ridges, the thickest of which is about 300 m. From his diagrams, Grigson's (1982) Section 2 is located close to the type section but is a slightly thicker 298 m. The formation decreases in thickness to about 110 m near Lilian Creek gorge (informal name, Jackson and van de Graaff, 1981), 5.6 km west of the type section, and then thickens to 370 m in the reference section at Ainslie Gorge (Fig. 9), about 33 km farther west. The stratigraphic top of the formation and its contact with the overlying Lefroy Formation is exposed only near Ainslie Gorge.

Apart from Talbot 1, the only other drillhole that possibly penetrated the Townsend Quartzite is Kanpa 1A (see *Disputed occurrences*, below). The Townsend Quartzite is absent in Empress 1A, NJD 1, and Lancer 1 which, together with the absence of the Lefroy Formation and part of the Browne Formation in these drillholes (Stevens and Apak, 1999; Apak and Moors, 2000a,b; Hocking, 2003), suggests overstepping near the southern and western basin margins. Otherwise, seismic data in the central part of the western Officer Basin show gradual thickening of many Buldya Group units towards the Musgrave Complex.

Disputed occurrences: Daniels (1971b, 1974) mapped numerous outcrops on COOPER as the Townsend Quartzite. He described outcrops in the Livesay Range on southwest COOPER and about 20 km to the west on eastern TALBOT as containing 'well bedded sandstones with occasional thin bands of grey to black silicified oolite' (Daniels, 1974, p. 83). Jackson and van de Graaff (1981) assigned these outcrops to the Punkerri Sandstone, but oolitic limestone is more typical of both the upper Buldya Group and the correlative Burra Group of South Australia rather than of the Punkerri Sandstone or the Townsend Quartzite. Jackson and van de Graaff (1981) also subdivided outcrops in central COOPER, 27 km west-southwest of South Hill, into the Townsend Quartzite and Punkerri Formation. Some of these outcrops consist of dolomite and interbedded sandstone, and contain poorly preserved specimens of the stromatolite *Basisphaera irregularis*, indicating that they are probably part of the Browne Formation. Farther south, about 4 km west of Pirrilyungka, sandstone and lesser dolomite contain *Baicalia burra*, a stromatolite characteristic of the upper Buldya Group. These features are more consistent with the Hussar, Kanpa, or Steptoe Formations than the Townsend Quartzite. Only unconsolidated boulder gravel of unknown age was found at a series of narrow strike ridges about 10 km southeast of Pirrilyungka when visited by MKS, GMC and SNA in 1998. All the outcrops listed above are now excluded from the Townsend Quartzite.

In the central and western parts of the western Officer Basin, sandstone in the vicinity of Lake Throssell was previously assigned to the 'Robert Beds' (Jackson and van de Graaff, 1981; amended to 'Robert Formation' by Cockbain and Hocking, 1989) and considered to be a lateral equivalent of the Townsend Quartzite (Jackson and van de Graaff, 1981). However, stromatolites of the *Baicalia burra* Stromatolite Assemblage (Stevens and Grey, 1997) have been found to the west of the sandstone in carbonate outcrops previously mapped as Earaheedy Group (Jackson and van de Graaff, 1981), and are here assigned to the Kanpa Formation. The 'Robert Beds' may therefore be equivalent to the Hussar Formation (see below). Several quartzite outcrops near the western basin margin are probably Mesoproterozoic in age, but some could be Neoproterozoic.

In Kanpa 1A, an intensely silicified sandstone interval from 3671 to 3701 m (TD) was interpreted as Townsend Quartzite by Townson (1985). Dipmeter data for this interval are poor but may indicate structural dips of up to 62°. The high angles recorded could also be joints or bad data due to the quartzitic, highly resistive rock type. Dips in all overlying units are less than 5°, and no Lefroy Formation is present. This appears similar to NJD 1, where shallow-dipping Buldya Group (probably Hussar Formation) rests on steeply dipping, silicified and cleaved sandstone of probable Mesoproterozoic age (Hocking, 2003), part of which was initially considered as possibly Townsend Quartzite. The same interpretation is made here, that the section previously assigned to the Townsend Quartzite is probably an older, ?Mesoproterozoic sandstone. At the time of writing, the identification of the silicified sandstone at the base of Lancer 1 as Mesoproterozoic is tentative, but is more probable on regional grounds than identification as Townsend Quartzite.

Lithology: The Townsend Quartzite is predominantly medium- to coarse-grained, in part pebbly, sandstone ranging in composition from quartz sandstone to feldspathic sandstone. Intense silica cementation has almost obliterated the porosity (Jackson and van de Graaff, 1981), although silicification may decrease basinward at depth as suggested for the lithologically similar Heavitree Quartzite of the Amadeus Basin (Lindsay, 1999). Daniels (1974), Jackson and van de Graaff (1981), Grigson (1982), and Watts (1982) recognized two major units in the Townsend Quartzite. The lower unit is dominated by flaggy, thin- to thick-bedded micaceous sandstone, with planar and trough cross-bedding, whereas the upper unit consists of coarse- to very coarse grained sandstone with conglomeratic intercalations and minor shale-flake beds, and large-scale (up to 3 m) cross-beds.

Relationships and boundary criteria: The lower boundary of the Townsend Quartzite is not exposed, but fairly complete sections appear to be present in the Townsend Ridges (Grigson, 1982; Watts, 1982), particularly in the vicinity of the type section. Regional relationships indicate that the Townsend Quartzite unconformably overlies various units of the Musgrave Complex.

The upper part of the Townsend Quartzite and the contact with the overlying Lefroy Formation is exposed only in the Brown Range near Ainslie Gorge, where the contact is gradational and conformable according to Jackson and van de Graaff (1981). Elsewhere, variable amounts of Townsend Quartzite have been eroded, and Phanerozoic rocks commonly overlie the unit.

Age and correlation: The age of the Townsend Quartzite is inferred from relative stratigraphic position, regional correlations based on biostratigraphy, and stable isotope analysis of overlying formations. Maximum-age constraints are provided by dating of underlying Mesoproterozoic successions and dyke swarms that are both widespread and apparently pre-date either the Officer Basin succession or equivalent successions in the Adelaide Rift Complex and Centralian Superbasin.

The Bentley Supergroup (Mission, Cassidy, Tollu, and Pussy Cat Groups) of the Musgrave Complex underlies the Townsend Quartzite and has been dated at c. 1080–1060 Ma (Glikson et al., 1996; U–Pb zircon age of 1078 ± 5 Ma on the Tollu Group, Sun et al., 1996). The supergroup is associated with the c. 1080–1050 Ma Stuart and Kulgera/Alcurra Dyke Swarms (Myers et al., 1996; Rb–Sr age of 1054 ± 14 Ma, Camacho et al., 1991; Sm–Nd age of 1090 ± 32 Ma, Zhao and McCulloch, 1993). These provide a maximum age for the onset of sedimentation of the Townsend Quartzite.

Younger mafic dykes, the Gairdner Dyke Swarm (Goode, 1970), intrude the Musgrave Complex and, in South Australia, the Gawler Craton and Mesoproterozoic Pandurra Formation, and appear to be related to major northeast–southwest directed extension during the early tectonic evolution of the Adelaide Rift Complex and the Centralian Superbasin (Mason et al., 1978; Goode, 1975; Parker et al., 1987; Preiss, 1987; Cowley and Flint, 1993). A Gairdner dyke on the Stuart Shelf (South Australia) has a SHRIMP U–Pb baddeleyite age of 827 ± 6 Ma, and the Little Broken Hill Gabbro in the Broken Hill Inlier of the Curnamona Province (east of the Adelaide Rift Complex) has a SHRIMP U–Pb baddeleyite age of 827 ± 9 Ma (Wingate et al., 1998). Sm–Nd isochrons of 867 ± 47 and 802 ± 35 Ma (Zhao and McCulloch, 1993; Zhao et al., 1994) were obtained from a dyke in the Gawler Craton (South Australia) included in the Gairdner Dyke Swarm (Glikson et al., 1996; and see references in Preiss, 2000). The dykes are accepted as feeders for volcanic rocks at the base of the Neoproterozoic succession in the Adelaide

Rift Complex (Mason et al., 1978) and were intruded during initial sedimentation (Preiss, 2000; Preiss, W. V., 2004, written comm.). If correlation across to the Adelaide Rift Complex is accepted, the Townsend Quartzite has a probable maximum age of about 830 Ma, and may be younger than 825 Ma.

A dyke at Michael Hills on northeast COOPER has the same trend as the Gairdner Dyke Swarm, crosscuts Mesoproterozoic units in the western Musgrave Complex, is undeformed, and has a zircon ^{207}Pb–^{206}Pb age of 824 ± 4 Ma (Glikson et al., 1996). The Mission Group, the youngest component of the Musgrave Complex, is deformed, so deformation is older than c. 824 Ma. The nearest outcrops of Pindyin Sandstone lie 40 km south of the dyke, and close examination of whether dykes underlie or disrupt these outcrops could resolve the age of the Pindyin Sandstone and Townsend Quartzite.

Unnamed volcanic units intruding the Bitter Springs Formation in the Amadeus Basin are thought to be co-magmatic with the Gairdner Dyke Swarm (Walter et al., 2000). The Bitter Springs Formation correlates with the Browne Formation, which from comparison with exposed successions in the northwest Officer and Amadeus Basins should overlie the Townsend Quartzite, so it is possible that the Townsend Quartzite is slightly older than c. 825 Ma. Close et al. (2003) give an age of 850 Ma for the correlative Dean Quartzite on the northern margin of the Musgrave Complex, based on an age of 820 Ma for spilites that are present near the top of the overlying Bitter Springs Formation (Close et al., 2003; Close, D. F., 2003, written comm.).

A minimum age of greater than 800 Ma can be inferred for the Townsend Quartzite from biostratigraphic and stable isotopic correlations of the overlying Browne Formation with part of the Callanna Group of the Adelaide Rift Complex (see **Browne Formation** for discussion). The Rook Tuff, from near the top of the Callanna Group, overlies the Coominaree Dolomite (a Browne Formation equivalent) and has a U–Pb SHRIMP zircon age of 802 ± 10 Ma (Fanning et al., 1986).

Correlation within basin: The Townsend Quartzite may correlate with the Watch Point and Coondra Formations, or with the Spearhole Formation and siliciclastic units at the base of the Skates Hills Formation in the northwestern Officer Basin (see below, and Williams, 1992, 1994; Bagas et al., 1999). The Jilyili, Glass Springs and Brassey Range Formations, which underlie the Spearhole Formation, are now recognized as part of an older succession that correlates with the Collier Group (Hocking and Jones, 2002). The Townsend Quartzite is also probably equivalent to the Googhenama Formation and possibly part of the Waroongunyah Formation (basal Tarcunyah Group) along the northeast margin of the Officer Basin, based on palynology and limited stromatolite biostratigraphy of overlying units (Bagas et al., 1995; Grey and Stevens, 1997; Stevens and Grey, 1997).

Regional Correlations: Correlation between the various basal sandstone units in the Centralian Superbasin has been widely proposed by, for example, Lambeck (1983, 1984), Shaw (1991), Walter and Gorter (1994), Walter et al. (1995, 2000), Walter and Veevers (1997), Morton (1997), Lindsay (1999), and Preiss (2000). These authors thought that deposition took place synchronously and more or less continuously over a wide area in a slowly subsiding sag basin. Walter et al. (1995) described the basal sandstone as part of a thick sand sheet that covered much of Neoproterozoic Australia. Thus, the Townsend Quartzite could be a correlative of (if not contiguous with) the Dean and Heavitree Quartzites of the Amadeus Basin (Walter and Gorter, 1994; Walter et al., 1995). The Townsend Quartzite shows a similar pattern of a fluvial lower part beneath a marine upper part as the newly defined Kukial Sandstone (deltaic) and the overlying Dean Quartzite (marine) on the southern margin of the Amadeus Basin (Close et al., 2003). Other possible correlative basal units are the Vaughan Springs Quartzite of the Ngalia Basin (Preiss and Forbes, 1981; Lambeck, 1983, 1984; Shaw, 1991; Walter and Gorter, 1994; Walter et al., 1995; Hoskins and Lemon, 1995), possibly part of the Yackah beds of the Georgina Basin (Walter, 1980; Preiss and Forbes, 1981), the Lewis Range, Muriel Range, and Munyu Sandstones of the Murraba (formerly Birrindudu) Basin (Blake et al., 1979), and the Mount Kinahan Sandstone of the Wolfe Creek Basin (Blake et al., 1999; Grey and Blake, 1999).

Correlation with the Adelaide Rift Complex is indirect. Stable isotope analyses and biostratigraphy (Hill and Walter, 2000; Hill et al., 2000a,b) indicate that the Bitter Springs Formation of the Amadeus Basin (a probable Browne Formation equivalent) correlates with the Callanna Group of the Adelaide Rift Complex (Preiss, 2000). The Younghusband Conglomerate at the base of the Callana Group thus may be a correlative of the Townsend Quartzite.

Correlations between these formations throughout the Centralian Superbasin are based on their position at the base of the succession, reinforced by biostratigraphic and stable isotopic correlations of overlying formations, and a probable absolute age of less than 830 Ma because of the age of dyke swarms discussed above. Moreover, in every basin, the basal sandstone is overlain by dolomite, limestone, evaporite, and fine-grained siliciclastic rocks. Alternatively, deposition may have been in separate basins, but of very similar style due to global-scale climate controls and an intracratonic setting for all basins.

By contrast, Apak and Moors (2000b, p. 9), in a study of the Yowalga area of the Western Officer Basin, stated that 'there is no direct evidence to support the previous model of a single sandsheet forming a basal transgressive unit over the entire Centralian Superbasin'. Apak and Moors (2000b) further suggested that deposition in the western Officer Basin took place in a foreland basin adjacent to the Musgrave Complex. Glikson et al. (1996) documented a thrust fault for the basin against the Musgrave Complex, but did not propose a foreland basin model with contemporaneous movement and thrust control of the basin. The most comprehensive palaeocurrent studies are by Grigson (1982) and Watts (1982), who showed an unequivocal westward to northward trend, implying derivation from the (now buried) Coompana Block or Antarctica. This could reflect derivation from a foreland bulge. Although his dataset was presumably much smaller, Daniels (1974) noted flow to the southwest and southeast, with some east–west flow that he attributed to longshore drift or local currents.

The absence of Townsend Quartzite in Empress 1A, Lancer 1, and probably Kanpa 1A and NJD 1, does not support the sandsheet model. However, the pronounced similarity between basal sandstone units across the Centralian Superbasin does support common regional climatic and possibly tectonic controls through a series of basins.

Depositional setting: The lower part of the Townsend Quartzite was deposited in fluvial to possibly deltaic environments, based on lithology and bedding (Grigson, 1982; Watts, 1982), and corresponds to the Kulail Sandstone defined by Close et al. (2003) at the base of the Amadeus Basin succession north of the Musgrave Complex. The upper Townsend Quartzite is a shallow-marine, near-shore deposit (Grigson, 1982; Watts, 1982), which appears to grade at the very top into lower energy, more distal marine deposits assigned to the Lefroy Formation.

References: Sofoulis (1962), Lowry et al. (1972), Kennewell (1974, 1977a,b), Daniels (1970, 1971a,b, 1974, 1975), Bunting and Boegli (1977), Bunting et al. (1978), Jackson (1978a), Jackson and van de Graaff (1981), Preiss and Forbes (1981), Grigson (1982), Watts (1982), Townson (1985), Phillips et al. (1985), Walter et al. (1994, 1995).

Lefroy Formation

Definition and nomenclature: Lowry et al. (1972) proposed the name 'Lefroy Beds', for a mixed siltstone and sandstone unit conformable on the Townsend Quartzite, after Point Lefroy, 11 km east-southeast of the type locality. Jackson (1966a) and Daniels (1969) earlier included this sequence in the informal 'Brown Range Siltstone', and Daniels (1971a, 1974) included it in the Townsend Quartzite. Jackson and van de Graaff (1981) defined the 'Lefroy Beds', and Cockbain and Hocking (1989) upgraded the name to Lefroy Formation.

Synonymy: 'Brown Range Siltstone' (Jackson, 1966a; Daniels, 1969), part of Townsend Quartzite of Daniels (1974), 'Lefroy Beds' of Lowry et al. (1972) and Jackson and van de Graaff (1981), 'Lefroy beds' of Wells and Moss (1983).

Distribution and thickness: The Lefroy Formation is part of a southwesterly dipping succession exposed on the southwest side of the Brown Range along the southern margin of the Musgrave Complex on TALBOT. The formation is about 250 m thick at its type locality, and possibly thickens eastward. BMR Talbot 3 and 4 intersected about 25 m and 15 m respectively of siltstone and claystone that may be Lefroy Formation, beneath probable Permian rocks. Daniels (1971b) reported minor shales in the Townsend Quartzite on COOPER that may be Lefroy Formation. It was not recognized on WAIGEN (Jackson, 1978a). The lower Alinya Formation in South Australia is a probable correlative (see below).

Re-examination of the interval between 1521.8 m and 1540.2 m in Empress 1A, originally thought to be Lefroy Formation (Stevens and Apak, 1999) based on the presence of an 0.6 m-thick conglomerate with rounded quartz pebbles at 1540.2 m, shows it is mainly fine-grained mafic igneous rocks, which are considered to be part of the underlying Mesoproterozoic succession (Morris and Pirajno, 2002). The contact with the overlying Browne Formation is disconformable, with consolidated mudstone clasts from the unit below incorporated into the basal bed of the Browne Formation. Based on seismic correlation, the lower Browne Formation is absent, presumably as a result of overstepping. The Lefroy Formation is also absent in Kanpa 1A, where the Browne Formation appears to unconformably overlie a quartzite that Townson (1985) referred to as 'assumed Townsend Quartzite', an interpretation followed by Perincek (1998) and Apak and Moors (2000a), but which is more probably a Mesoproterozoic sandstone. Farther west in WMC NJD 1, the Lefroy Formation may be present in a very condensed section of the Buldya Group, but the relevant interval is more likely to be lower Kanpa Formation based on comparison with Empress 1A (Hocking, 2003).

Type section or area: The type section of the Lefroy Formation is near Ainslie Gorge (at MGA Zone 52, 263500E 7096500N on TALBOT; Jackson and van de Graaff, 1981, fig. 13; Fig. 9). The top of the type section is taken at the 600 m mark in this section, rather than at 610 m as was done by Jackson and van de Graaff (1981), and the contact with the overlying Lupton Formation is inferred to be unconformable (see below).

Lithology: The Lefroy Formation consists of white to purple-weathering, grey to maroon, shaly, very argillaceous, evenly and continuously bedded, laminated to thin-bedded micaceous siltstone, with intercalations of medium- to thick-bedded quartz sandstone (Jackson and van de Graaff, 1981).

Relationships and boundary criteria: The lower boundary of the Lefroy Formation is poorly exposed in the type section, but is inferred to be a gradational, conformable contact with the Townsend Quartzite. Jackson and van de Graaff (1981) noted a well-exposed contact at their locality BMR 21 on TALBOT, where there is a transition zone of interbedded siltstone and fine-grained sandstone a few metres thick. Major (1973a) described the contact between the lower and upper Pindyin Beds (now the contact between the Pindyin Sandstone and Alinya Formation; Zang, 1995b) as transitional over a few metres at the type locality in South Australia.

The upper boundary of the Lefroy Formation is commonly eroded, except in the vicinity of Ainslie Gorge where, although exposure is poor, Jackson and van de Graaff (1981) considered the upper boundary to be transitional into Lupton Formation above. We consider the upper boundary to be 10 m lower, and unconformable. In the TALBOT BMR 21 section, which was not re-examined in the present study, Jackson and van de Graaff (1981) noted that the upper Lefroy Formation appeared to grade upward into Lupton Formation. A conformable relationship is unlikely, as the Browne, Hussar, Kanpa, and Steptoe Formations are missing.

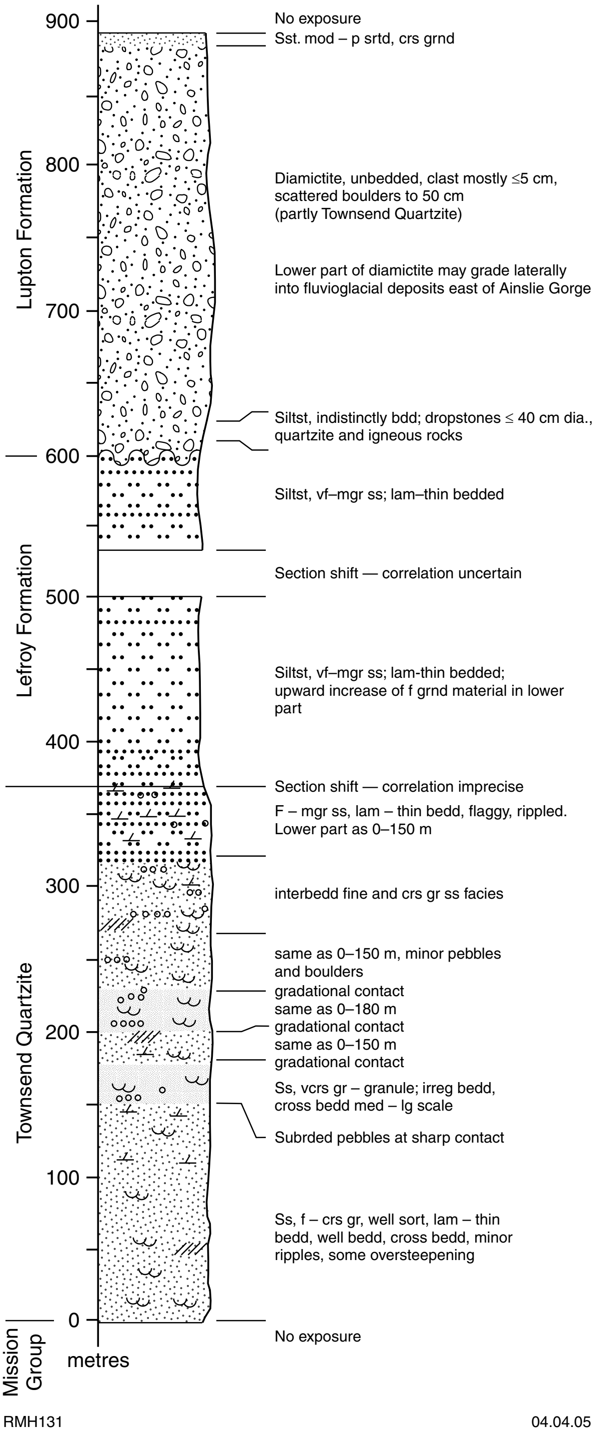

Figure 9. Reference section of Townsend Quartzite, Lefroy Formation, and Lupton Formation; after Jackson and van de Graaff (1981, fig. 13)

Age and correlation: The inferred age of between about 825 and 800 Ma for the Lefroy Formation is based on relative stratigraphic position and palynomorphs in the correlative Alinya Formation of the eastern Officer Basin (Zang, 1995a). Apart from its apparent continuity with the basal Alinya Formation (previously upper Pindyin Sandstone) eastward, the unit is too poorly known to allow good correlation with other units in the Centralian Superbasin.

Correlation: Jackson and van de Graaff (1981) suggested that the Lefroy Formation was a lateral equivalent of the Wright Hill beds, but the presence of oolites suggests that at least part of the latter unit correlates with younger formations in the upper Buldya Group. The Lefroy Formation may correlate with the finer grained section in the upper Spearhole Formation (Williams, 1992) in the Sunbeam Group of the northwestern Officer Basin, or with the lower Mundadjini Formation if the Spearhole Formation is part of an older succession (see discussion in **Spearhole Formation**).

In South Australia, a white-weathering shaly unit that may be a lateral equivalent of the Lefroy Formation is exposed at Pindyin Hills (the Pindyin Sandstone type section) on LINDSAY (Jackson and van de Graaff, 1981; Morton, 1997). This was originally regarded as an upper, shaly part of the 'Pindyin Beds' by Major (1973a), but more recently was interpreted as a lower unit of the Alinya Formation (Zang, 1995a). The unit is 200 m thick, a thickness comparable with that of the type section of the Lefroy Formation.

Depositional setting: The depositional environment of the Lefroy Formation as exposed south of the Musgrave Complex was probably a low-energy, subwavebase marine shelf. Boulders and cobbles near the top of the type section that were interpreted as dropstones from melting ice and precursors of the overlying 'tillite' (Jackson and van de Graaff, 1981) are here considered to overlie a major hiatus and be unrelated to the Lefroy Formation. They belong to the overlying Lupton Formation.

References: Lowry et al. (1972), Jackson and van de Graaff (1981), Cockbain and Hocking (1989), Kennewell (1977a,b), Perincek (1998), Stevens and Apak (1999), Apak and Moors (2000a,b).

Browne Formation

Definition and nomenclature: Jackson (1966b) proposed the name 'Browne Evaporites' for an evaporitic succession intersected in drillholes on southeast BROWNE. The name was published but not defined by Peers and Trendall (1968). Lowry et al. (1972) modified the name to 'Browne Beds' and defined the formation. Jackson and van de Graaff (1981) published a more detailed description, and Cockbain and Hocking (1989) revised the name to Browne Formation. Wells and Moss (1983) referred to the 'Browne beds'.

Proterozoic rocks previously assigned to the 'Woolnough' and 'Madley' Formations (Jackson and van de Graaff, 1981; Cockbain and Hocking, 1989) are best placed in the Browne Formation. The name 'Madley' is abandoned not only because Browne Formation has priority but also because the 'Madley Formation' constitutes only a part of the Browne Formation, and dolomitic rocks previously assigned to the 'Madley Formation' are here included in the Woolnough Member. As originally defined (Jackson and van de Graaff, 1981), the 'Woolnough Formation' was narrower in concept than the Browne Formation. In its type area in the Woolnough Diapir, the 'Woolnough Formation' forms a distinctive, stromatolite-rich unit within the Browne Formation, so it is herein given member status within the Browne Formation (see ***Woolnough Member*** below).

In GSWA Lancer 1, the upper Browne Formation is a thick, eolian sandstone instead of the evaporitic facies seen elsewhere (Fig. 10). This is named the Lancer Member (Haines et al., 2004).

Synonymy: 'Browne Beds', 'Browne beds', 'Browne Evaporite', 'Browne Evaporites'; 'Madley Formation' and synonyms (here abandoned); 'Woolnough Formation' and synonyms, now Woolnough Member.

Distribution and thickness: The Browne Formation was originally named for intersections in drillholes Hunt Oil Browne 1 (between 132.59 and 386.79 m) and Browne 2 (between 262.13 and 292.79 m) in the southeast corner of BROWNE. There were no known surface outcrops (Lowry et al., 1972) because, at the time, rocks exposed in the Woolnough and Madley Diapirs were assigned to the Woolnough or Madley Formations (see below). The Browne Formation was subsequently intersected in BMR Madley 1, BMR Warri 20, Kanpa 1A, Yowalga 3, Dragoon 1, Hussar 1, GSWA Empress 1A, and GSWA Lancer 1 (Jackson et al., 1984; Phillips et al., 1985; Townson, 1985; Stevens and Apak, 1999; Perincek, 1998). Perincek (1998) interpreted parts of Kennecott N1 1 and WMC NJD 1 as Browne Formation, but these intervals are more likely to be Hussar and Kanpa Formations.

Exposures of dolomite and sandstone containing poorly preserved *Basisphaera irregularis* on COOPER were assigned to Townsend Quartzite or Punkerri Sandstone by Jackson and van de Graaff (1981). These are probably Browne Formation, based on the presence of *B. irregularis*.

The Browne Formation is more than 254 m thick in the type section in Browne 1 (which bottomed in the formation), but this does not indicate true stratigraphic thickness, as this is the core of the Browne Diapir, with a section of brecciated evaporites beneath Palaeozoic rocks. Seismic line Hunt Oil 13-C shows a thick, mobilized halite succession piercing the Table Hill Volcanics (Jackson and van de Graaff, 1981, fig. 68). Hussar 1 bottomed in Browne Formation after penetrating 75 m of evaporites. Dragoon 1 penetrated at least 1596 m of Browne Formation, but the drillhole was sited on a diapiric structure (Phillips et al., 1985). Farther south, the Browne Formation thickens from Empress 1A through Kanpa 1 to Yowalga 3 (Fig. 11). In Empress 1A it is 275 m thick (Stevens and Apak, 1999), but the lower Browne Formation is absent. Kanpa 1A intersected a 1156 m-thick section, complete except for the lower part of parasequence set B1 (Fig. 12), based on seismic data. At least 2304 m of Browne Formation was intersected in Yowalga 3 (Townson, 1985), and seismic interpretations suggest that at least 4000 m of Browne Formation may be present in the Yowalga area (Townson, 1985; Apak and Moors, 2000a,b).

On lithology alone, the Browne Formation shows remarkable lateral continuity of thickness with limited lateral facies changes (Figs 4, 12). Between Empress 1A and Lancer 1 (260 km distance), the thickness is similar, and there is a change from a section of evaporites in the upper Browne Formation to eolian sandstone in Lancer 1. The lower Browne Formation is slightly sandier but otherwise very similar. Between Lancer 1 and Boondawari 1 (about 300 km distance), there is a similar persistence of thickness and broad lithology. The lower Browne Formation in Lancer 1 can be correlated with the lower Mundadjini Formation in Boondawari 1, the Lancer Member with the middle sandstone and overlying sandy siltstone of the Mundadjini Formation in Boondawari 1, and the lower Hussar Formation with the mudstone at the top of both Boondawari 1 and Mundadjini 1. This is discussed further under **Mundadjini Formation**.

Field examinations of the Madley and Woolnough Diapirs (MADLEY and WARRI) by MKS, KG, and GMC in 1996 indicated that the 'Madley' and 'Woolnough' Formations are better described as Browne Formation (Fig. 13), and in fact represent most of the known outcrops of the formation. The 'Madley Formation' was originally defined as a thick evaporite succession with a gypsum caprock that outcrops in the core of the Woolnough and Madley Diapirs (Jackson and van de Graaff, 1981).

The 'Woolnough Formation' was defined by Jackson and van de Graaff (1981) as a succession of sandstone, stromatolitic dolomite, dolomite, siltstone, and chert exposed both as part of the Woolnough Diapir rim, and as (in their judgement) poorly preserved rafts of carbonate resting on 'Madley Formation' evaporites within the diapir core. Re-examination of the carbonate by KG suggests it is largely in situ rather than being exotic rafts. The stromatolitic dolomite is distinctive, and equates with parasequence set B5 of Apak and Moors (2000a,b). A pink dolomite-dominated unit in Empress 1A (between 1365 and 1386.3 m), Yowalga 3 at 2390 m, and Lancer 1 (1323–1358 m) contains the same suite of stromatolites as at Woolnough Diapir (Grey, 1995a, 1999b). The lack of surface expression makes it difficult to determine whether the stromatolitic dolomite forms a continuous horizon or consists of several lensoidal carbonates, but nonetheless the dolomite appears to be an important marker horizon within the Browne Formation. Consequently, this stromatolite-dominated carbonate unit is here downgraded to member status as the Woolnough Member of the Browne Formation.

Type section: Lowry et al. (1972) designated the interval from 132.6 to 386.8 m in Browne 1 as the type section. This section has been affected by diapirism. Early descriptions were supplemented by data from Browne 2 (Lowry et al., 1972; Jackson and van de Graaff, 1981), where the interval between 262.1 and 292.8 m provides an important reference section.

The cored section through the Browne Formation in Empress 1A (Stevens and Apak, 1999), between 1247.1 and 1521.8 m (1249.1 and 1524.0 m log depth) is here designated as an additional reference section (Fig. 10), with the comment that it spans only the upper part of the formation, from sequence B3 (Fig. 12) of Apak and Moors (2000a,b) upward. The cored section in Lancer 1 between 1202 and 1479 m contains an eolian sandstone facies, the Lancer Member, in place of the evaporitic rocks in other holes. Yowalga 3 between 3320 and 3744 m (TD) and

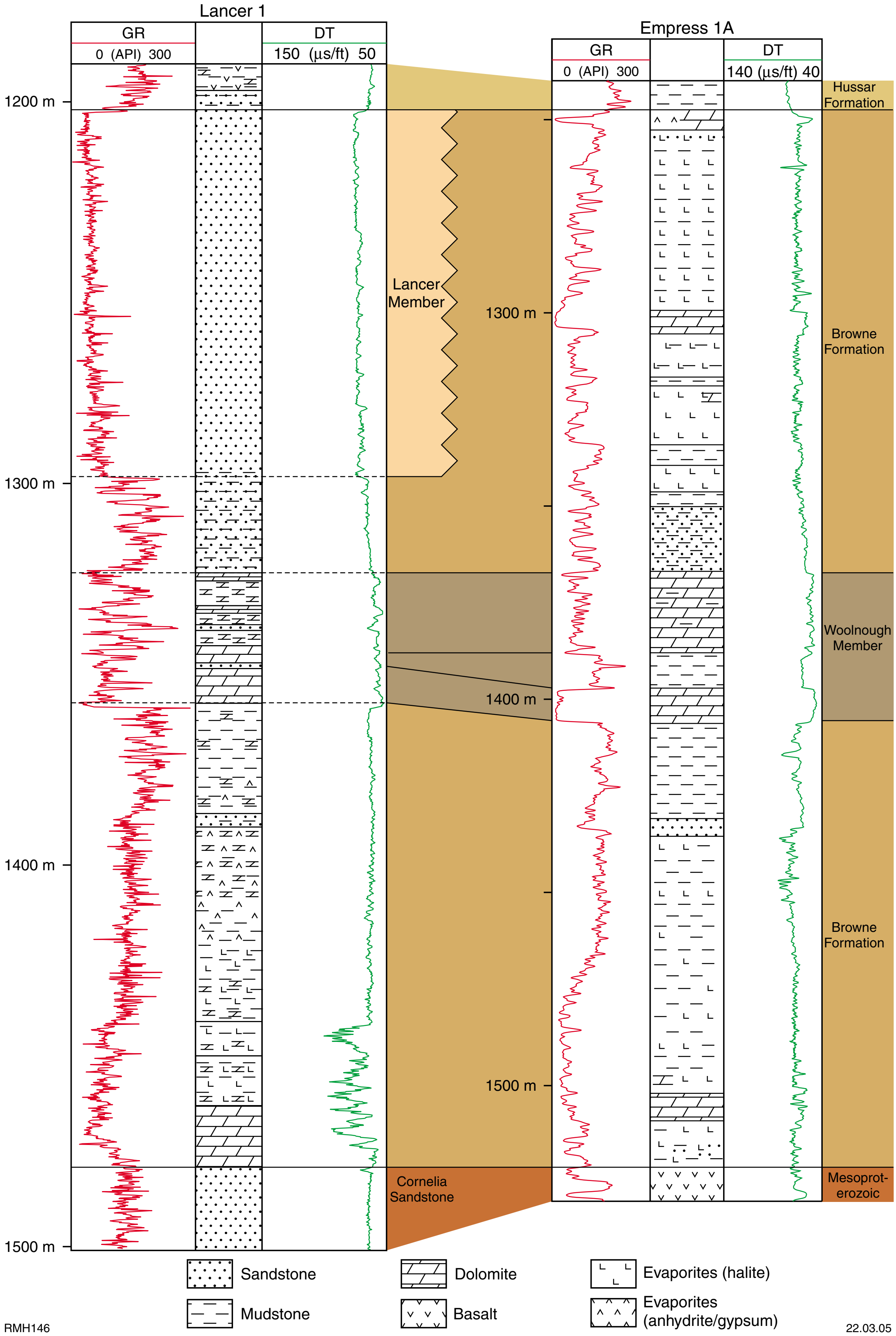

Figure 10. Reference sections of Browne Formation, Empress 1A, 1247.1 to 1521.8 m drilled depth (note log depth is 2 m deeper than drilled depth) and Lancer 1, 1202 to 1479 m, and type section of Lancer Member, Lancer 1, 1201.9 to 1297.7 m drilled depth. Section also includes reference section of Woolnough Member in Empress 1A, from 1365 to 1403.9 m drilled depth

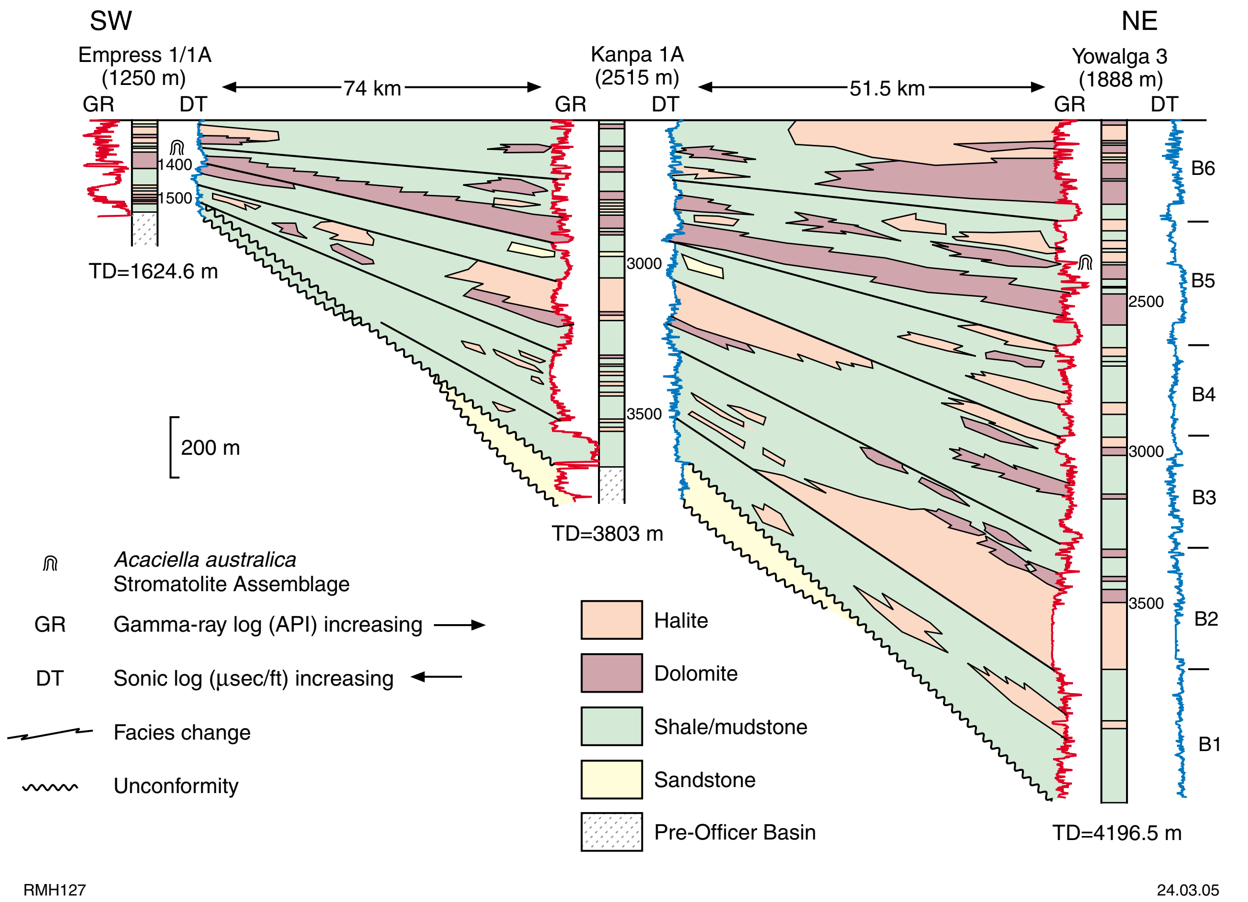

Figure 11. Cross section from Empress 1A through Kanpa 1A to Yowalga 3, showing thickening of Browne Formation into basin and onlap and younging of basal Officer Basin westwards, after Apak and Moors (2000a, fig. 7b)

Kanpa 1A from 3288 and 3671 m (the contact with an underlying sandstone, either Townsend Quartzite or more probably an older Mesoproterozoic sandstone) provide reference sections for the lower Browne Formation.

Lithology: The Browne Formation is a mixed sequence of fine-grained dolomite or dolomitic limestone, anhydrite, gypsum, halite, siltstone, and shale, in part calcareous. The formation is commonly brecciated and contorted in the vicinity of diapirs, and secondary recrystallization and evaporite inclusions are widespread. Diapiric structures throughout the basin indicate the presence of abundant halite. Apak and Moors (2000a,b) recognized six parasequence sets, separated by flooding surfaces, in the Browne Formation in the Yowalga area. These consist of varying mixtures of shale, siltstone, dolomite, halite and anhydrite, with proportions of each component varying both between parasequence sets and between holes. The dolomite is commonly silty, and the proportion of evaporites may increase upwards. Re-examination of the core in Empress 1A reveals metre-scale cyclicity, here interpreted as reflecting repeated shallowing-upward episodes. These cycles have not yet been related to Apak and Moors' (2000a,b) parasequence sets.

Relationships and boundary criteria: In outcrop, the Browne Formation has been recognized only in diapir cores, where most contacts are intrusive. The contact between the Browne Formation and the underlying Lefroy Formation or Townsend Quartzite has not been unequivocally identified anywhere. Most drillholes that intersect the Browne Formation bottom within it. Where a lower contact is present, as in Kanpa 1A, Empress 1A, and Lancer 1, the lower part of the formation is absent. In several drillholes near the Musgrave Complex (Talbot 1, 3, 4, and 5), younger units (such as the Paterson Formation) rest directly on older formations (Townsend Quartzite or Lefroy Formation), and the Browne Formation is absent. This may be because some of these intersections are on the hangingwall of a thrust fault, so that most of the Buldya Group has been eroded.

In Hussar 1, Kanpa 1A, Yowalga 3, and Empress 1A, the Browne Formation is conformably overlain by Hussar Formation. In Browne 1 and 2, the top of the Browne Formation is eroded, a feature common in the crests of diapirs and salt walls throughout the basin, and Permian Paterson Formation rests directly on parasequence set B5 (Apak and Moors, 2000a,b). Seismic lines in the Yowalga and Lennis areas show that the formation is commonly overlain with angular unconformity by younger Neoproterozoic units, such as the Lupton or Lungkarta Formations, or Phanerozoic units (Apak and Moors, 2000a,b, 2001).

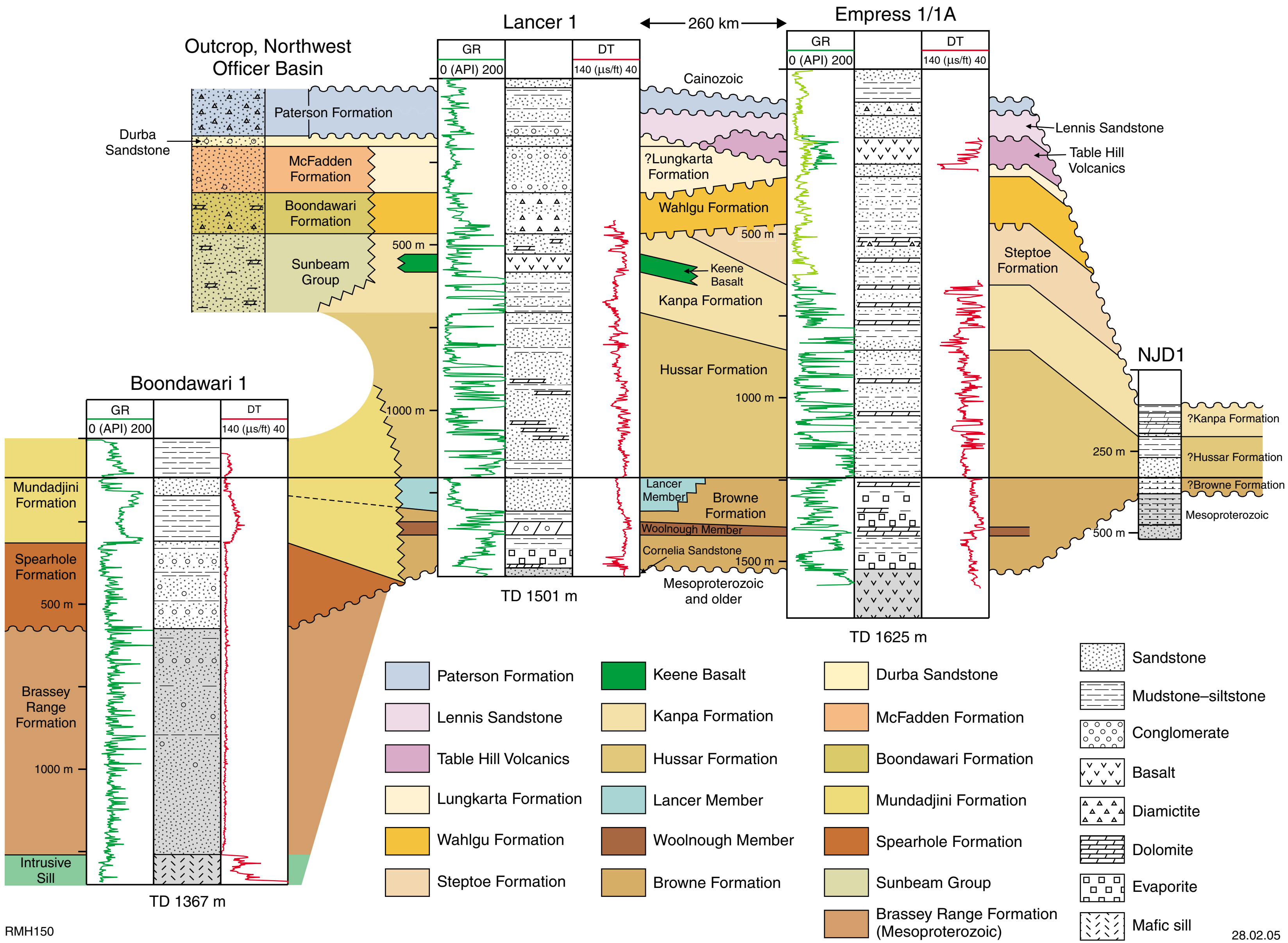

Figure 12. Cross section Empress 1A– Lancer 1 – Boondawari 1, showing lateral continuity of facies and thickness in the Browne Fromation and lower Hussar Formation, over about 560 km lateral extent

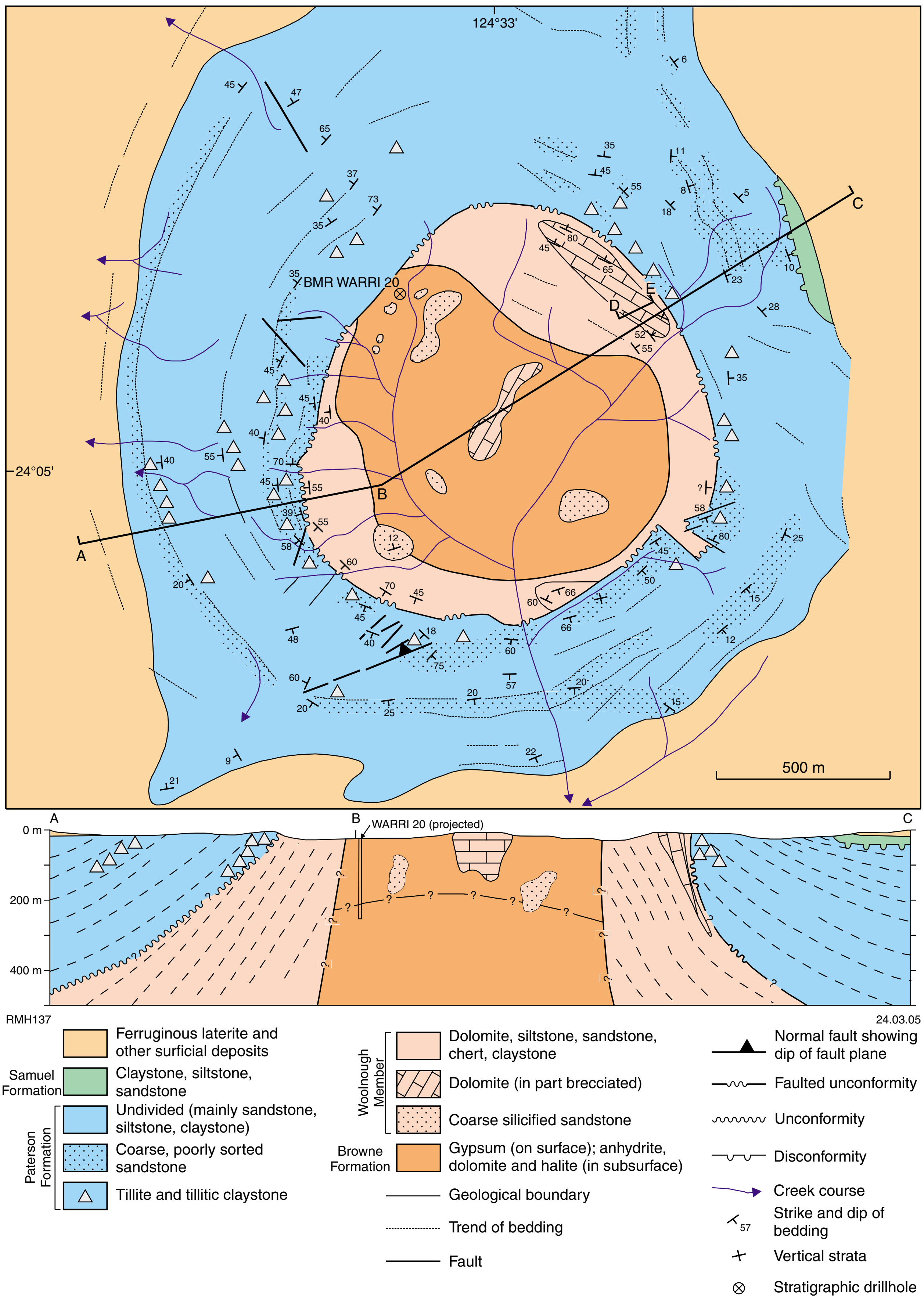

Figure 13. Woolnough Diapir, after Jackson and van de Graaff (1981, fig. 19), with revised stratigraphic interpretation shown. Line D–E shows section measured by MKS in Figure 14

In some diapirs, for example at Woolnough Diapir as intersected in Dragoon 1, the Browne Formation intrudes the Phanerozoic succession.

Age and correlation: From stromatolite and acritarch biostratigraphy and secular-isotope curves (Hill et al., 2000a,b; Hill and Walter, 2000; Walter et al., 2000), the Browne Formation can be correlated with the Bitter Springs Formation of the Amadeus Basin and the Coominaree Dolomite in the Callanna Group of the Adelaide Rift Complex. The Coominaree Dolomite underlies the Rook Tuff, which has a concordant U–Pb date of 802 ± 10 Ma on single zircon grains (Fanning et al., 1986). The dolomite is older than the Wooltana Volcanics and the correlative Cadlareena Volcanic Swarm and Beda Volcanics, the extrusive equivalents of the Gairdner Dyke Swarm (Preiss, 2000). The Browne Formation is therefore inferred to be older than about 800 Ma, and possibly older than about 827 Ma — the age of the Gairdner Dyke Swarm.

Stromatolite biostratigraphy indicates that the Browne Formation can be correlated with at least part of the Skates Hills Formation of the northwestern Officer Basin, the Bitter Springs Formation of the Amadeus Basin, the Coominaree Dolomite of the Adelaide Rift Complex, and the Yackah beds of the Georgina Basin (Grey, 1995a). This correlation is based on the presence of the *Acaciella australica* Stromatolite Assemblage. The key taxon, *Acaciella australica,* has been identified at Woolnough Hills, and at a depth of 2390 m in Yowalga 3. *A. australica* and *Basisphaera irregularis* are present between 1365 and 1386.3 m in Empress 1A, and *B. irregularis* has been found in outcrop in central COOPER.

Acritarchs and microfossils are also present in the Browne Formation, and have been studied extensively (M. R. Walter, *in* Jackson and van de Graaff, 1981; Grey and Cotter, 1996; Cotter, 1997, 1999; Grey and Stevens, 1997; Grey 1999c,d) since early reports of ‘primitive algal cysts and filaments with very little diversity of types’ (Phillips et al., 1985) in Hussar 1 and Dragoon 1. A similar assemblage was recorded from the Alinya Formation of South Australia (Zang, 1995a), supporting a correlation with the Browne Formation based on stratigraphic position.

Well-preserved microfossils are present in chert units of the ‘Madley Formation’ (here placed in the Browne Formation) at the Madley Diapirs (M. R. Walter, *in* Jackson and van de Graaff, 1981, p. 34; Cotter, 1997). Species diversity is low in the chert units, and they apparently represent a rapidly mineralized cyanobacterial mat. Two species of coccoid bacteria, *Myxococcoides cantabrigiensis* and *M. inornata*, and two filamentous bacteria, *Siphonophycus robustum* and *S. septatum*, were identified. Cotter (1997, 1999) identified the following palynomorphs from the Browne Formation in Browne 1 and 2, Kanpa 1A, Dragoon 1, and Yowalga 2 and 3: *Eoentophysalis croxfordii* Butterfield 1994, *Eomicrocystis malgica*, *Eomicrocystis* sp. cf. *elegans*, *Leiosphaeridia crassa*, *L. jacutica*, *L. minutissima*, *L. tenuissima*, *L. ternata*, *Pterospermopsimorpha granulata*, *Skiagia* cf. *pusilla*, *Synsphaeridium* sp., *Obruchevella* sp., *Siphonophycus kestron*, *S. solidum*, *S. robustum*, *S. septatum*, *S. typicum*, *Heliconema* sp., ?*Trachyhystrichosphaera* spp., and ?*Pterospermopsimorpha* sp. Pending further study, Grey and Cotter (1996) informally referred to this palynoflora as ‘Assemblage 1’. They noted that many species are long ranging and have been recorded from younger and older successions, and that species diversity is lower than in younger Neoproterozoic assemblages. Assemblage 1 has many species in common with assemblages from the Gillen Member of the Bitter Springs Formation (Zang and Walter, 1992), and the Alinya Formation of South Australia (Zang, 1995a). This is consistent with all three formations being of similar age.

Variations in the carbon and strontium isotope curves also support the correlations discussed above (Hill et al., 2000a,b; Hill and Walter, 2000; Walter et al., 2000). A distinct positive peak in the $\delta^{13}C_{carbonate}$ in the lower of two carbonate units in Empress 1A matches one at the contact between the Gillen and Loves Creek Members in the Bitter Springs Formation of the Amadeus Basin. It is followed by a major negative spike in the overlying stromatolitic carbonate (*A. australica* Stromatolite Assemblage) that is consistent with a similar spike in the stromatolitic carbonate of the Loves Creek Member of the Bitter Springs Formation, and the Coominaree Dolomite of the northern Adelaide Rift Complex and lateral equivalent in the eastern Officer Basin. The same sections are characterized by extremely low $^{87}Sr/^{86}Sr$ ratios. Both carbon and strontium isotope patterns are consistent with the global isotope curves. Southgate (1991) recognized a disconformity to ?angular unconformity at this level in the eastern Amadeus Basin.

Depositional setting: The Browne Formation contains abundant evaporites, and was deposited in a strongly evaporitic restricted marine, peritidal to intertidal or lagoonal environments with strong oxidizing influences. From the core in Empress 1A, there is no indication of any deep-water environments.

References: Veevers and Wells (1959a,b), Leslie (1961), Wells (1963, 1980), Wilson (1964, 1967), Mack and Herrmann (1965), Peers and Trendall (1968), Lowry et al. (1972), Wells and Kennewell (1974), Playford et al. (1975), Jackson (1976), Kennewell (1977a,b), Jackson and van de Graaff (1981), Jackson and Muir (1981), Cockbain and Hocking (1989), Walter et al. (1995), Grey (1995a), Stevens and Apak (1999), Hill and Walter (2000), Hill et al. (2000a,b), Walter et al. (2000).

Woolnough Member

Definition and nomenclature: The stromatolitic carbonate that is here defined as the Woolnough Member of the Browne Formation was first described by Veevers and Wells (1959a,b), followed by Leslie (1961), Wells (1963), Wilson (1964, 1967), and Mack and Herrmann (1965). Jackson and van de Graaff (1981) named the carbonate and underlying sandstone the ‘Woolnough Beds’, which Cockbain and Hocking (1989) upgraded to the ‘Woolnough Formation’.

Based on the succession in Empress 1A (Stevens and Apak, 1999), and re-examination of outcrops at Woolnough Hills by MKS, GMC, and KG in 1996, the stromatolitic carbonate is better considered as a distinctive unit within the Browne Formation. It is equivalent to parasequence set B5 of Apak and Moors (2000a,b), and units above and below the carbonate appear similar. Although the unit is widespread, it may be lenticular, rather than continuous throughout the basin. For these reasons, the stromatolitic carbonate is here given member status, as the Woolnough Member, within the Browne Formation.

The sandstone included within Jackson and van de Graaff's (1981) 'Woolnough Beds' is excluded from the member, and is regarded as an unnamed intra-Browne Formation sandstone. Alternatively, it could be a part of the Hussar Formation that has been caught up in diapiric uplift. Field relationships are equivocal at both the Madley and Woolnough Diapirs.

Synonymy: 'Woolnough beds', 'Woolnough Beds', 'Woolnough Formation'.

Distribution: The Woolnough Member forms the carbonate rim of the diapir at Woolnough Hills on Warri (Fig. 13). Although earlier workers suggested that the carbonate was a raft floating on the exhumed evaporitic core, a reconnaissance visit to Woolnough Diapir by MKS, GMC, and KG in 1996 led them to conclude that the rim is more or less in situ, and so in its correct stratigraphic position. However, rafts of poorly preserved stromatolitic carbonate are present as blocks within the evaporites in the diapir core. Jackson and van de Graaff (1981, fig. 20) measured 210 m of 'Woolnough Beds' at Woolnough Diapir, with 54 m of dolomite near the top of their section, but a section measured in 2001 revealed only 23.7 m of dolomite (see *Type section*, below).

Pink stromatolitic dolomite containing *Acaciella australica* and *Basisphaera irregularis* is present over 21.3 m in GSWA Empress 1A, from 1365 to 1386.3 m drilled depth (Grey, 1999b), and a pink stromatolitic dolomite containing *A. australica* is also present at 2390 m in Yowalga 3 (Grey, 1995a). These carbonate units are here assigned to the Woolnough Member because of their similarity to the stromatolitic carbonate at Woolnough Hills.

About 150 m of sandstone at Madley No. 2 Diapir, previously included in the Woolnough Formation (Jackson and van de Graaff, 1981), is here considered as undifferentiated Browne Formation. It may be Hussar Formation, although its stratigraphic position is uncertain.

Type section: Jackson and van de Graaff (1981) did not designate a type section, but illustrated a measured section at Woolnough Diapir (their figs 19 and 20), which is here designated as the type locality. The exact location of their section was not shown on their figure 19. A 51.9-m section through the Woolnough Member in the diapir was measured in 2001 (Fig. 14). There is very little outcrop in the basal 28.2 m of this section. The boundaries of the Woolnough Member are taken at the base and top of the lowest and highest stromatolitic dolomite exposures, giving a thickness of 23.7 m for the member. This compares with 34.3 m in Lancer 1 (1323.4 to 1357.7 m) and 38.7 m in Empress 1A (1365 and 1403.87 m drilled depth, including both dolomite intervals), both of which are fully cored reference sections.

Lithology: At Woolnough Hills, the Woolnough Member consists predominantly of a cream-weathering pink micritic dolomite, with interbedded siltstone, silicified dolomite, and minor limestone, and is in part oolitic. The carbonate probably forms discrete lenticular bodies that grade laterally into siltstone. The siltstone contains pseudomorphs after gypsum and halite. Rare sandstone interbeds consist of well-sorted, fine- to medium-grained quartz. The diapir-rim carbonate is pinkish, and contains stromatolites of the *Acaciella australica* Stromatolite Assemblage (Jackson and van de Graaff, 1981; Preiss, 1976; Stevens and Grey, 1997; Grey, 1995a, and unpublished data; Hill et al., 2000b). Two taxa, *Acaciella australica* and *Basisphaera irregularis*, are common (in the lower and middle parts, and the upper part of the member, respectively), and other forms tentatively identified by Grey (unpublished data) as *Boxonia pertaknurra*, *Inzeria intia*, and *Jurusania nisvensis* are also present. Very poorly preserved specimens of possible *A. australica* were found as float above the rafted dolomite in the diapir core.

In Empress 1A, the Woolnough Member consists predominantly of banded and bedded dolomite with 50-cm to 1-m stromatolitic bioherms, interbedded with mudstone and brecciated stromatolitic clasts. The member is evaporitic in places and becomes sandy in the upper few metres.

Relationships and boundary criteria: The Woolnough Member is part of the Woolnough Diapir rim, and is intruded by the salt core of the diapir (previously 'Madley Formation', here reassigned to the Browne Formation). The rim carbonate appears still to be in its stratigraphic context, but most contacts, particularly along the lower boundary, are faulted as a result of the intrusion. The upper contact at Woolnough Hills is not seen, but a sandstone bed outcrops a few metres above the dolomite. This may be part of the Browne Formation or may be part of the overlying Hussar Formation.

In Empress 1A, the Woolnough Member overlies reddish brown mudstone, and is overlain by siltstone interbedded with sandstone. Both contacts are sharp but interpreted as conformable. Interbedded halite and siltstone are present below and above the Woolnough Member.

Age and correlation: The age controls are as for the Browne Formation. For biostratigraphic and secular isotope curve correlations see the discussion of the Browne Formation above and in Hill and Walter (2000), Hill et al. (2000a,b), and Walter et al. (2000). Based on stromatolites, the Woolnough Member can be correlated with part of the Skates Hills Formation of the northwestern Officer Basin. It can also be correlated with the Loves Creek Member of the Bitter Springs Formation of the Amadeus Basin, the Yackah beds of the Georgina Basin, and the Coominaree Dolomite of central Australia (Grey, 1995a). The Coominaree Dolomite is only a thin unit, which may correlate exactly with the Woolnough Member rather than with the Browne Formation as a whole. No material suitable for radiometric dating has been recognized in the Woolnough Member.

Depositional setting: The Woolnough Member was deposited in a saline peritidal environment, possibly in part

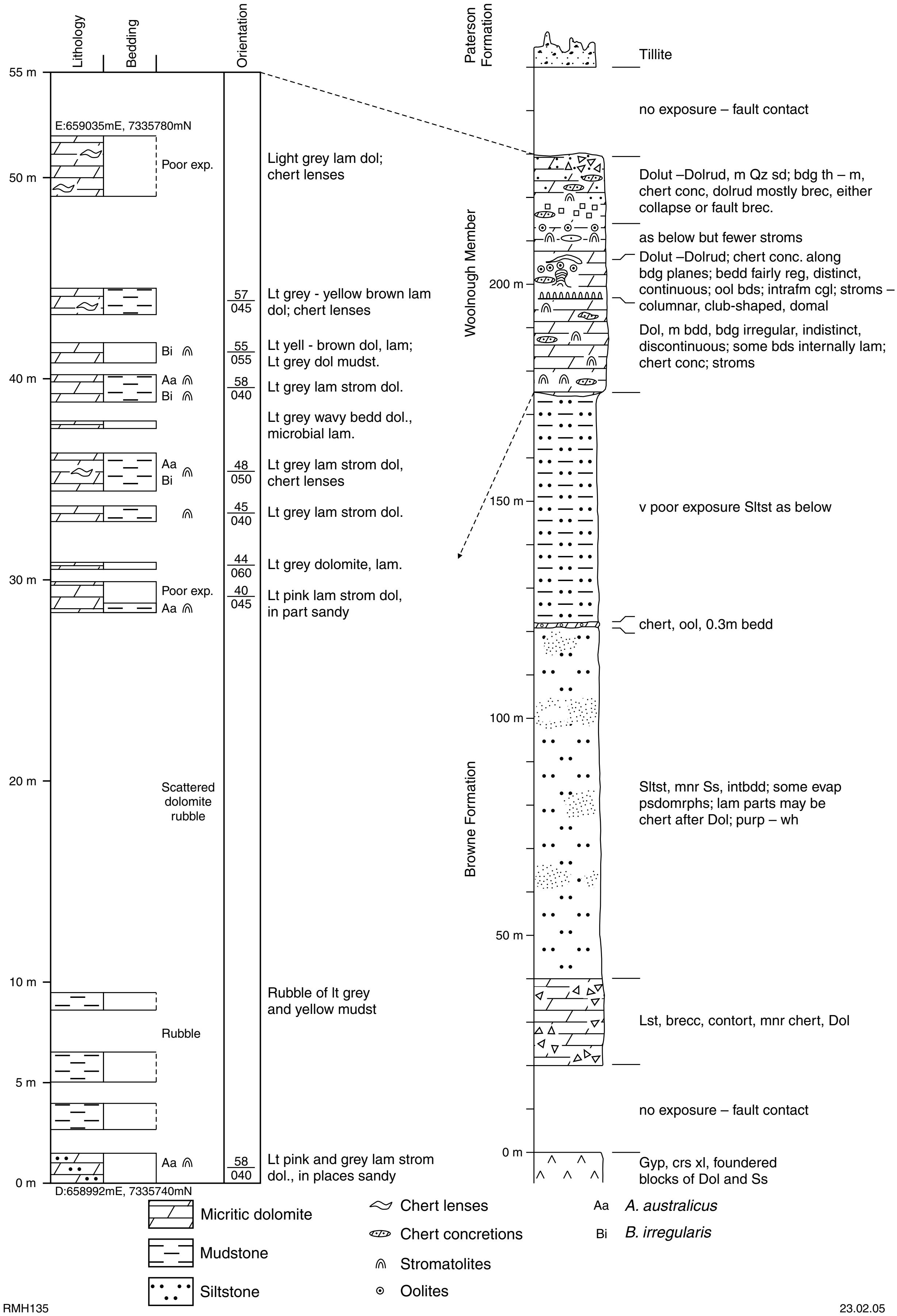

Figure 14. Measured sections of Woolnough Member at Woolnough Diapir. Section on right after Jackson and van de Graaff (1981, fig. 20). Section on left, D–E, measured by MKS; coordinates MGA Zone 51

a sabkha. Some stromatolites are indicative of a subtidal setting, but some bioherms have eroded tops, which could be the result of either wave action or subaerial erosion.

References: Veevers and Wells (1959a,b), Leslie (1961), Wells (1963, 1980), Wilson (1964, 1967), Mack and Herrmann (1965), Wells and Kennewell (1974), Lowry et al. (1972), Jackson and van de Graaff (1981), Cockbain and Hocking (1989), Walter et al. (1995), Grey (1995a), Stevens and Apak (1999, 2000), Hill and Walter (2000), Hill et al. (2000a,b), Walter et al. (2000).

Lancer Member

Definition: The Lancer Member is a section of very well sorted, medium-grained sandstone, showing very large scale cross-bedding, in the upper Browne Formation. The member has been recognized only in GSWA Lancer 1, after which it is named, but is sufficiently important to warrant recognition as a named member. The unit is named and defined in the Lancer 1 basic well completion report (Haines et al., 2004); the definition is repeated and extended here.

Distribution and type section: The Lancer Member is present in Lancer 1, between 1201.9 and 1297.7 m drilled depth (95.8 m thickness). This is the type section (Fig. 10). The member may correlate with sandy facies of the Mundadjini Formation in the northwest Officer Basin, or with the silty and sandy upper part of the Skates Hills Formation (as described by Williams, 1992). The section identified as Hussar Formation in WMC NJD 1 (330–376.85 m) by Hocking (2003) could instead be Lancer Member, beneath silty lower Hussar Formation, based on firstly the presence of the Lancer Member rather than evaporites in Lancer 1, and secondly, the similar position of Lancer 1 and NJD 1 relative to the inferred western basin margin.

Lithology: The Lancer Member consists of fine- to medium-grained, very porous, well-sorted orange-brown quartz sandstone, and minor silty beds up to 0.6 m thick. It shows very large scale cross-bedding with foresets dipping up to 30° and up to 11 m thick, and reverse graded centimetre-scale beds (translatent strata).

Relationships and boundary criteria: The Lancer Member rests on orange-brown siltstone and fine-grained sandstone here considered as undifferentiated Browne Formation. The contact is sharp, but this may simply reflect dunes migrating over playas or supratidal mudflats. The upper contact is steep (implying the sandstone was at least partly lithified) and clearly erosional beneath basal Hussar Formation. Above the contact, there is 10 cm of reworked sandstone with mud clasts, then evaporitic mudstone of probable supratidal mudflat origin, with some reworked sand in the lower 5 m. Steep dune foresets are truncated at the boundary. This juxtaposition of facies requires some sort of hiatus, so the boundary is probably disconformable. Sandstone laminae are present in the mudstone but decrease upward over about 5 m.

Age and correlation: At the time of writing, no detailed palaeontological work had been done on material from Lancer 1. The *Acaciella australica* Stromatolite Assemblage is present below the Lancer Member, in the Woolnough Member, and the *Baicalia burra* Stromatolite Assemblage is present above the Lancer Member upward from the middle Hussar Formation. Comparison with the section intersected by Empress 1A indicates the member correlates with the halite interval in the upper Browne Formation in Empress 1A.

Depositional setting: The sorting, lithology, very large cross-bedding and translatent strata indicate the Lancer Member is an eolian dune deposit. The siltstones intercalated with the sandstone are presumably interdune deposits, possibly reflecting shallow ephemeral lakes.

References: Haines et al. (2004).

Hussar Formation

Definition and nomenclature: The name 'Hussar Beds' was proposed as an informal name by Townson (1985) and was used informally by Phillips et al. (1985) for a predominantly sandstone interval recognized in Yowalga 3, Kanpa 1A, Hussar 1, and Lungkarta 1. Only brief descriptions were given, with no type section or other definitive data. Cockbain and Hocking (1989) amended the name to Hussar Formation, but did not add defining data. Iasky (1990) designated Yowalga 3 as the type section based on the sections given in Townson (1985).

The description given here constitutes a substantial revision and redefinition of the name Hussar Formation. Since the original definition, the unit has been recognized in other drillholes and some possible outcrops.

Synonymy: 'Hussar Beds', ?'Robert beds', possibly 'Woolnough Formation' (in part).

Distribution and thickness: The Hussar Formation was intersected in Yowalga 3, Kanpa 1A, Hussar 1, and Lungkarta 1, and was cored in Empress 1A and Lancer 1 (Fig. 4). The type section of the Hussar Formation in Yowalga 3 is 897 m thick (991–1888 m). The formation is 494.4 m thick (707.5 – 1201.9 m) in Lancer 1; 671 m thick in Hussar 1 (1294–1965 m); nearly 700 m thick in Kanpa 1A (1817–2515 m); and at least 526 m thick in Lungkarta 1 (1196–1770 m TD), which bottomed within the Hussar Formation (Perincek, 1998). The section in Empress 1A is complete but only 386.3 m thick (860.8 – 1247.1 m, Stevens and Apak, 1999), perhaps due to proximity to the basin margin. The greater thickness and sandier nature of the Hussar Formation in Lancer 1, compared with that in Empress 1A, may reflect influx from the Paterson Orogen.

Hocking (2003) reinterpreted the interval from 330 to 376.85 m in WMC NJD 1 mineral exploration corehole as uppermost Hussar Formation, based on lithology and similarities to the section in Empress 1A. Based on the section in Lancer 1, an alternative interpretation is Kanpa Formation above 203.5 m, Hussar Formation between 330 and 203.5 m, and Browne Formation between 376.85 and 330 m.

Doubtful occurrences: No outcrops can be assigned unequivocally to the Hussar Formation. Scattered quartz sandstone exposures overlying evaporite and carbonate in the Madley Diapirs, were originally assigned to the 'Woolnough Formation' by Jackson and van de Graaff (1981) prior to recognition of the Hussar Formation. They could be undifferentiated Browne Formation, Lancer Member, or Hussar Formation. Outcrops on COOPER of sandstone overlain by dolomite containing *Baicalia burra* could be Hussar or Kanpa Formation.

Sandstone outcrops to the east of the Eagle Highway and David Carnegie Road on ROBERT and THROSSELL (Jackson, 1978b; Bunting et al., 1978), previously referred to as 'Robert Beds' by Lowry et al. (1972) and Jackson and van de Graaff (1981), are probably Hussar Formation, but could instead be Kanpa or Steptoe Formation. Regional trends show stratigraphic younging into the basin at outcrop level, and they are slightly basinwards of nearby carbonate outcrops mapped as Kanpa Formation based on stromatolite assemblages. This implies that they overlie the Kanpa Formation outcrops, but dips are subhorizontal and a minor fault could change the inferred relationships. They are here left as undifferentiated Buldya Group sandstone.

Type section: Neither Townson (1985) nor Phillips et al. (1985) designated a type section for the Hussar Formation. Iasky (1990) selected Yowalga 3, from 991 to 1888 m (Fig. 15), as the most appropriate type section because it provided the thickest section through the formation and was listed first in Townson's list of intersections. Only short sections of Yowalga 3, Hussar 1, Kanpa 1A, and Lungkarta 1 were cored, so stratigraphic interpretation was based mainly on cuttings and drill logs.

The interval between 860.8 and 1247.1 m (862.7 and 1249.1 m log depth) in Empress 1A provides a fully cored, though thin, reference section (Fig. 16). The sections in Lancer 1 and Hussar 1 (Fig. 16) are additional reference sections for the northern Officer Basin.

Lithology: Few direct details are available about rock types in the type section in Yowalga 3 because of the lack of core. In Empress 1A, the base of the Hussar Formation is a reddish brown to dark-grey mudstone 92.8 m thick. This unit can be traced on seismic lines and well logs, corresponds to 'Unit D' of Townson (1985), and is a significant regional marker horizon. The remainder of the Hussar Formation in Empress 1A is predominantly sandstone interbedded with dolomite, mudstone, and minor intercalations of conglomerate (Stevens and Apak, 1999).

Phillips et al. (1985) described the Hussar Formation in Hussar 1 as interbedded sandstone, dolomite, limestone, siltstone, and shale. The lower part of the succession contains fine-grained sandstones with ripple marks, contorted and slumped beds, and compaction structures. In the upper part of the succession, the sandstone is coarse to fine grained, subrounded, friable to firm, and usually well sorted. Grains are often frosted. Limestone and dolomite are generally grey-white to cream and cryptocrystalline to microcrystalline.

The formation is similar elsewhere in the basin and consists of sandstone, mudstone, dolomite, and minor evaporite. Combining information from Yowalga 3, Kanpa 1A, Hussar 1, and Lungkarta 1, Townson (1985) recognized four units. The basal unit (D) is red-grey silty shale with thin dolomite beds, and is overlain in turn by mixed dolomite, sandstone, and shale (C), grey to red-brown siltstone and shale with microcrystalline dolomite beds (B), and at the top, medium- to coarse-grained, friable massive sandstone, with minor interbeds of grey-brown-red shale, siltstone, and argillaceous dolomite (A). These units can be recognized broadly in Lancer 1, although the section as a whole is sandier.

Apak and Moors (2000a) recognized five parasequence sets in the Hussar Formation (Figs 17, 18). Parasequence set H1 is predominantly argillaceous siltstone with minor dolomite and sandstone marking a major transgression — the regional seismic marker noted above. Parasequence set H2 is a mudstone and dolomite unit containing a single stromatolite, *Tungussia*? form indet., and the first appearance of the acritarch *Cerebrosphaera buickii* — a key marker species (Cotter, 1999; Hill et al., 2000b). Parasequence set H3 consists of a basal siltstone and mudstone interval, and grades upwards into interbedded mudstone, sandstone, and dolomite with minor anhydrite. Parasequence set H4 is a sandstone-dominated succession with thin mudstone interbeds, and Parasequence set H5 is a sandstone–carbonate–sandstone unit. Set H5 marks the first appearance of *Baicalia burra*, a key species of the *Baicalia burra* Stromatolite Assemblage (Stevens and Grey, 1997; Hill et al., 2000b), rather than set B2 as stated, incorrectly, by Apak and Moors (2000a,b).

A thin but pronounced pebble conglomerate is present at 1060.7 m in Empress 1A and a correlative erosional contact is present in Lancer 1 at 1069.75 m, where lithified carbonate is overlain by siltstone with scattered jigsaw-fit carbonate intraclasts suggestive of at least a slight hiatus. The contact is essentially at the top of the lower, predominantly fine-grained portion of the Hussar Formation. The significance of this contact has yet to be assessed.

Relationships and boundary criteria: The lower boundary of the Hussar Formation is taken at the base of a thick mudstone that overlies interbedded halite, reddish mudstone, sandstone, and dolomite of the Browne Formation, or the eolian Lancer Member in Lancer 1. In general, the Browne Formation contains halite and the lowermost Hussar Formation does not. In Empress 1A, the contact is interpreted as a conformable contact that shows a local scour surface of no regional significance (Stevens and Apak, 1999). There is some inconsistency in the literature about the nature of the contact (Townson, 1985; Phillips et al., 1985; Perincek, 1998; Carlsen et al., 1999; Stevens and Apak, 1999; Apak and Moors, 2000a,b), but recent seismic and well-log interpretations show no compelling evidence for an unconformity, although the contact could locally be a disconformity. In areas where halite dominates the uppermost Browne Formation, it is difficult to envision how there could be a major disconformity without visible evidence of significant halite dissolution. In Lancer 1, there has been a hiatus, as sands of the uppermost Lancer Member are reworked through the lower 5 m of the Hussar Formation (see ***Lancer Member***, above), but its magnitude is unknown.

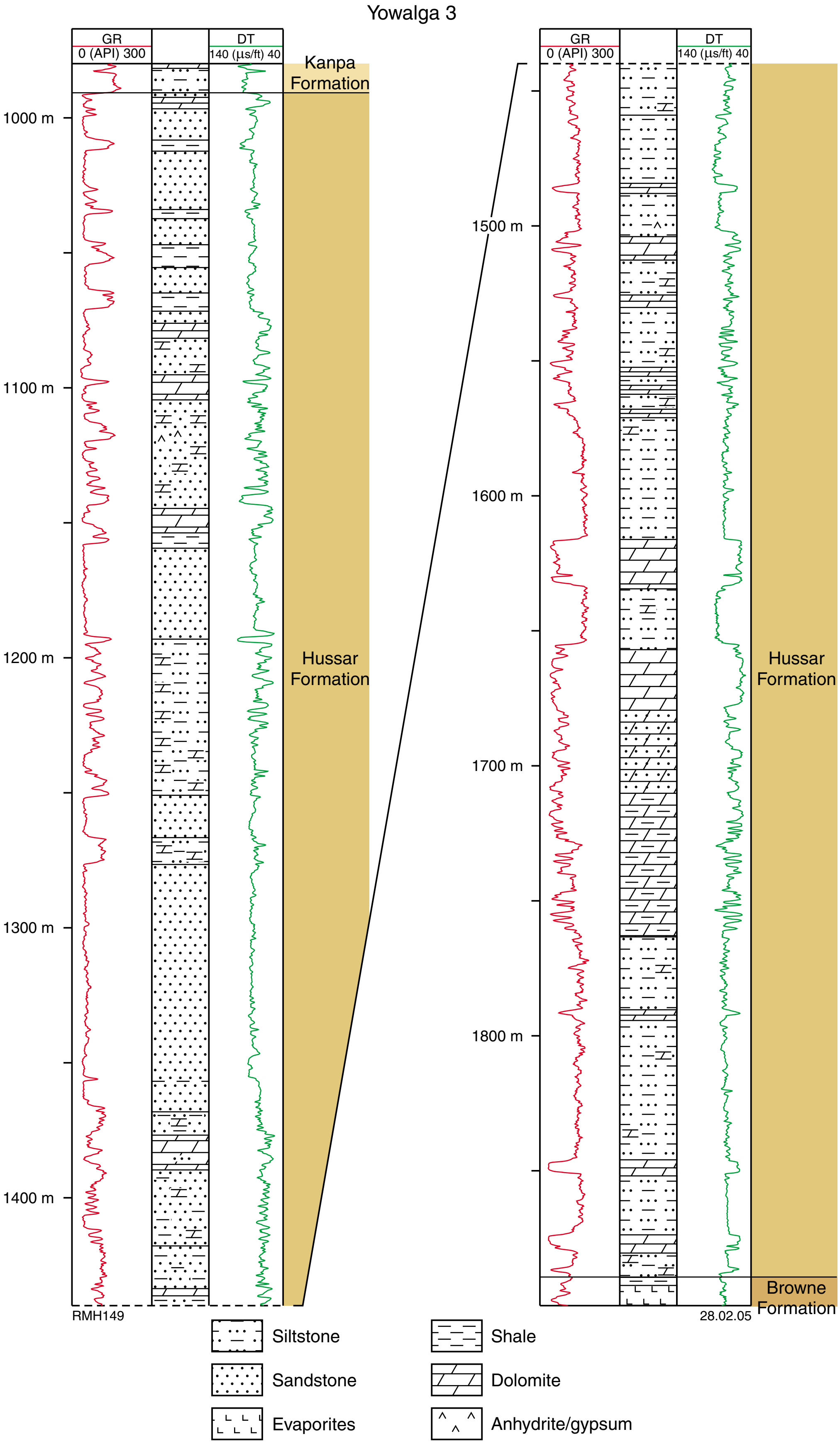

Figure 15. Type section, Hussar Formation, Yowalga 3

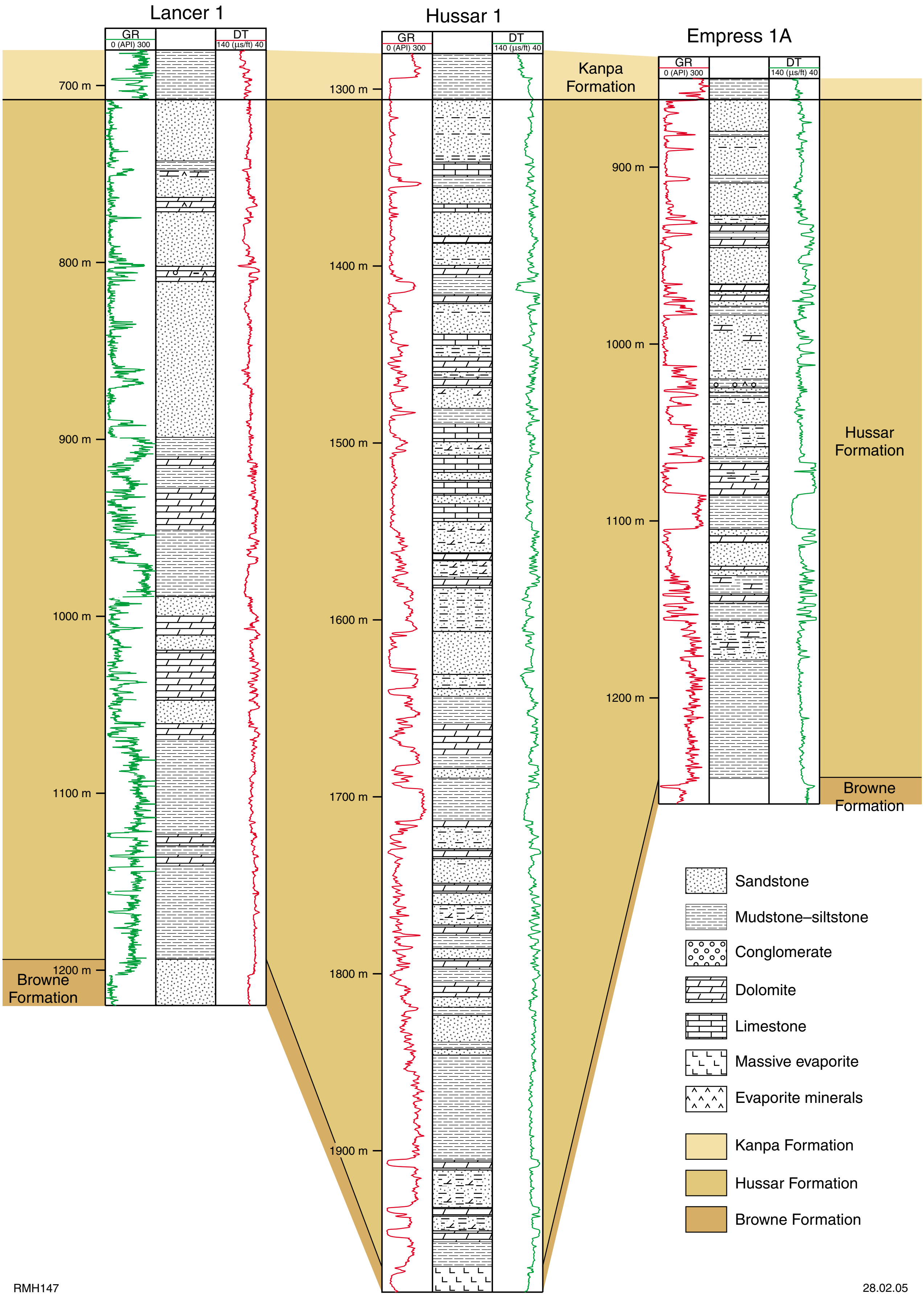

Figure 16. Reference sections, Hussar Formation, Empress 1A, Hussar 1, and Lancer 1

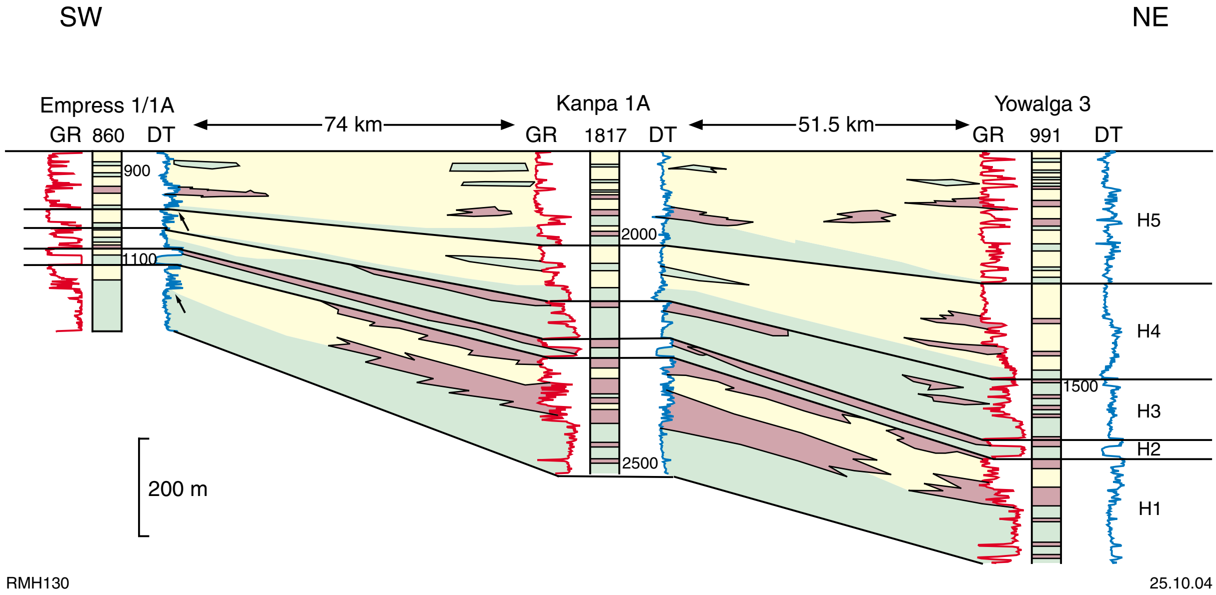

Figure 17. Cross section of Hussar Formation Empress 1A – Kanpa 1A – Yowalga 3, showing parasequence sets of Apak and Moors (2000a), after Apak and Moors (2000a, fig. 8b). See Figure 11 for legend

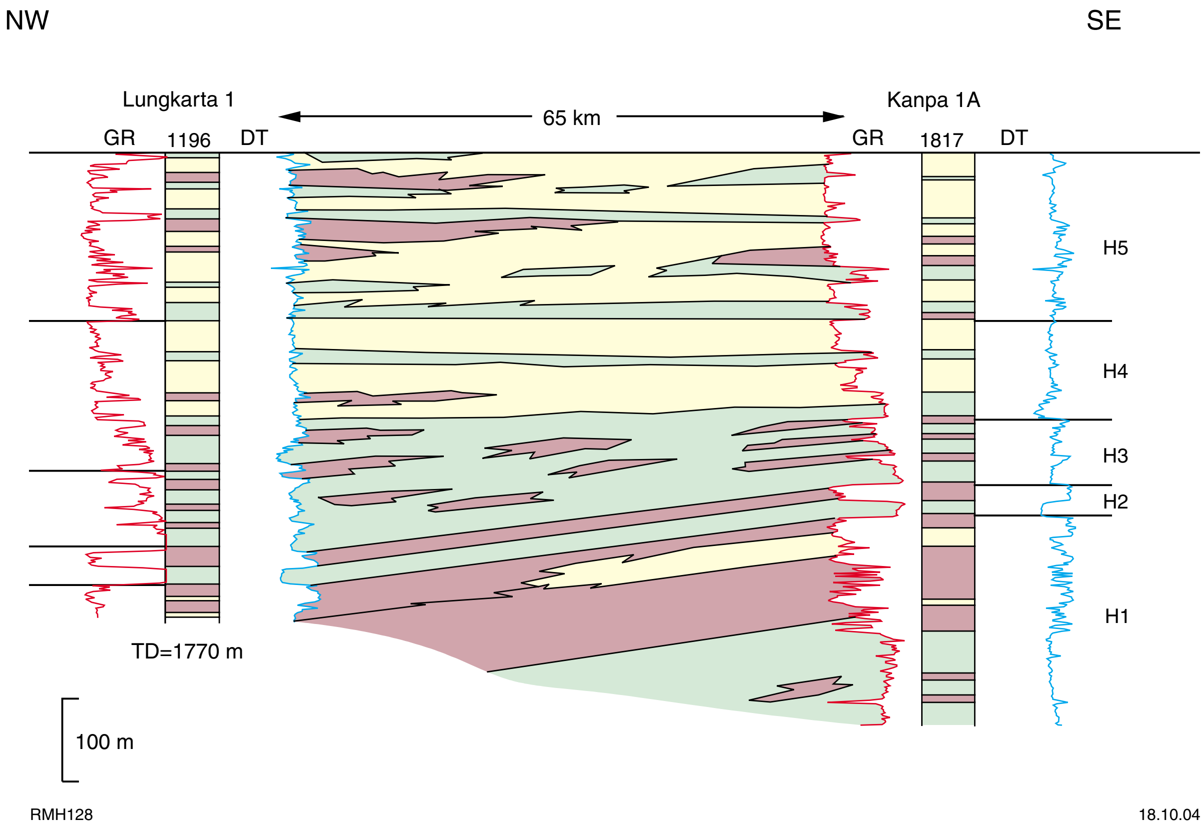

Figure 18. Correlation between Hussar Formation in Lungkarta 1 and Kanpa 1A, after Apak and Moors (2000a, fig. 8c). See Figure 11 for legend

The contact with the overlying Kanpa Formation is conformable, and is taken at the base of a thick mudstone unit that marks a substantial transgression. In Empress 1A, the top of the Hussar Formation is characterized by a thick white to reddish brown sandstone-dominated unit of which the upper part is heavily oxidized and leached (Stevens and Apak, 1999).

Age and correlation: Lithostratigraphic and biostratigraphic correlations, together with isotope chemostratigraphy, suggest correlation with the lower part of the Burra Group of the Adelaide Rift Complex (Hill and Walter, 2000; Hill et al., 2000b; Walter et al., 2000). Rhyolite from the Boucaut Volcanics at the base of the Burra Group has U–Pb SHRIMP zircon ages of 777 ± 7 Ma (Preiss, 2000), so the Hussar Formation is probably of a similar age. A SHRIMP U–Pb detrital zircon age of 926 ± 25 Ma provides a maximum depositional age for a sandstone in the middle Hussar Formation in Empress 1A (Nelson, D. R., 2002, written comm.).

Cotter (1999) reported several palynomorph species from Hussar 1, Lungkarta 1, and Yowalga 2. A similar assemblage is found in Empress 1A (Grey, 1999c). The middle Hussar Formation is characterized by the first appearance of the genus *Cerebrosphaera*. Cotter (1999) identified two species: *C. buickii*, previously recorded from the Svanbergfjellet Formation of Spitsbergen (Butterfield et al., 1994); and a new species, *C. ananguae*. Both appear to be key species for the younger Cryogenian (Hill et al., 2000b). The following species have been recorded from the Hussar Formation (Cotter, 1999; Grey, 1999c): *C. ananguae*, *C. buickii*, *Chuaria* sp. cf. *circularis*, *Eoentophysalis croxfordii*, *Eomicrocystis* sp. cf. *elegans*, *Leiosphaeridia crassa*, *L.* sp. cf. *exsculpta*, *L. jacutica*, *L. minutissima*, *L. tenuissima*, *Simia annulare*, *Stictosphaeridium sinapticuliferum*, *Synsphaeridium* spp., *Siphonophycus robustum*, *S. septatum*, *S. solidum*, and *S. typicum*.

Palynomorphs were reported from Yowalga 3 shortly after drilling (Grey, 1981; Townson, 1985), but no species could be identified at the time. Additional samples were prepared using techniques that increase the yield of acid-insoluble microfossils (Grey, 1999d), and were found to contain a well-preserved assemblage containing *Cerebrosphaera*, indicating this section is no older than the middle Hussar Formation (Grey, 1998, and unpublished data; Cotter, 1999). *Cerebrosphaera* spp. is present in the Skillogalee Dolomite in the middle of the Burra Group in the Adelaide Rift Complex (Hill et al., 2000b), above the dated (777 ± 7 Ma) Boucaut Volcanics (Preiss, 2000).

There are at least 24, and possibly 28 stromatolitic horizons in the Hussar Formation in Lancer 1, but elsewhere they are typically uncommon and restricted to a few carbonate horizons. A previously unknown form, tentatively identified as *Tungussia*? form indet., is present at 1077.4 m in Empress 1A and between 943 and 956.5 m in Lancer 1. *Baicalia burra* (marking the first appearance of the *Baicalia burra* Stromatolite Assemblage) is present above 974.5 m in Empress 1A.

Depositional setting: Apak and Moors (2000a,b, 2001) considered that the Hussar Formation showed repeated progradational sedimentary cycles from shelf through shoreline, and tidal flat to fluvial environments, with upward-coarsening shoreface sandstone deposits. The shoreline and tidal-flat environments were in part evaporitic. There is no indication of deposition in any environment deeper than nearshore marine shelf in Empress 1A.

References: Apak and Moors (2000a,b), Carlsen et al. (1999), Cotter (1999), Hill and Walter (2000), Hill et al. (2000b), Iasky (1990), Jackson and Muir (1981), Jackson and van de Graaff (1981), Perincek (1998), Phillips et al. (1985), Stevens and Apak (1999), Stevens and Grey (1997), Townson (1985), Walter et al. (1995), Walter et al. (2000).

Kanpa Formation

Definition and nomenclature: The name 'Kanpa Beds', after Kanpa 1A, was introduced by Townson (1985) and used informally by Phillips et al. (1985) for an interbedded dolomitic siltstone and sandstone interval in Kanpa 1A, Hussar 1, and Lungkarta 1. Only brief descriptions were given. Cockbain and Hocking (1989) upgraded the name to Kanpa Formation, but did not provide further information. Iasky (1990) selected the interval from 1301 to 1817 m in Kanpa 1A as the type section. The description given here constitutes a substantial revision and redefinition of the name Kanpa Formation, because since the original description, the unit has been recognized in other drillholes and some possible outcrops.

The Kanpa Formation, as redefined here, incorporates the 'type section' of the 'Babbagoola Formation', the former 'Neale Formation', and several outcrops not previously assigned to this unit.

Synonymy: 'Kanpa Beds', '?Kanpa Beds', 'Kanpa beds', 'Neale Beds', 'Neale Formation', 'Babbagoola Beds', 'Babbagoola Formation'.

'Neale Formation': Jackson and van de Graaff (1981) proposed the 'Neale Beds' (Neale Formation of Cockbain and Hocking, 1989) for a gently dipping succession of dolomite and minor limestone in central NEALE. No type section was designated, but the type area was given as central NEALE (in the area around 28°15'S, 125°15'E; MGA Zone 51, 721000E 6873000N). The *Baicalia burra* Stromatolite Assemblage is present in outcrops in this area, so these outcrops are now assigned to the Kanpa Formation. The name 'Neale Formation' has priority, but because the outcrop is very rubbly, and only part of the unit is exposed, the name Kanpa Formation, which relates to the full thickness of the unit as seen in several drillholes, is preferred.

'Babbagoola Formation': The name 'Babbagoola Formation' is ambiguous in that its type section is incomplete, and it can be demonstrated that rocks previously assigned to the 'Babbagoola Formation' actually belong to different units of quite different ages, so that correct usage is difficult to establish. The name is therefore abandoned, even though it has priority over the name Kanpa Formation, which is largely synonymous but does not suffer from similar problems.

The 'Babbagoola Formation' was first used by Jackson (1966b) for sections in Hunt Oil Yowalga 2 and BMR Throssell 1, and published without description by Peers and Trendall (1968) and Peers (1969). The name was amended to 'Babbagoola Beds' by Lowry et al. (1972), and described by Jackson and van de Graaff (1981). Subsequently, the unit was recognized in Hussar 1, Lungkarta 1, Kanpa 1A, and Yowalga 3 (Townson, 1985), and raised to formation status by Cockbain and Hocking (1989).

Jackson and Muir (1981) recorded the presence of 'microfossils' in drillcore samples from the 'Babbagoola Formation' in Yowalga 2 (the type section of the 'Babbagoola Formation') and Throssell 1. Most were described as sphaeromorph acritarchs, but some small acanthomorphs were noted, which at that time was taken to indicate a largely Cambrian age. Acanthomorph acritarchs have since been found to be common in upper Proterozoic rocks, so the 'Babbagoola Formation' assemblages were reassessed. The original prepared slides are not available, but scrutiny of the illustrations in Jackson and Muir (1981) suggests many of the illustrations are of organic debris, and those that are of fossils are of long-ranging forms that provide little biostratigraphic data. Accordingly, Yowalga 2 and Throssell 1 were resampled (Grey, 1998, and unpublished data; Cotter, 1999; Hill et al., 2000b), and samples prepared using techniques that increase the yield of acid-insoluble microfossils (Grey, 1999d). Samples from Throssell 1 were barren, but a well-preserved assemblage dominated by *Cerebrosphaera* was found in samples from Yowalga 2 and Yowalga 3, which indicates that the relevant intervals in Yowalga 2 and 3 are part of the Buldya Group and younger than the middle Hussar Formation, rather than being Cambrian.

From palynological evidence, the sections in Hussar 1 above 892 m, Lungkarta 1 above 809 m, Kanpa 1A above 880 m, and Throssell 1 from 101 to 198.12 m (all initially placed in the 'Babbagoola Formation') are much younger, and do not belong in the Buldya Group. They are probably latest Neoproterozoic or earliest Cambrian in age, and were referred to as 'McFadden Formation equivalent' in recent GSWA publications. The section in Hussar 1 is probably Wahlgu Formation, and the other sections are now referred to the Lungkarta Formation.

In summary, the name 'Babbagoola Formation' has been applied to two separate lithostratigraphic units. Secondly, the 'type section' in Yowalga 2 contains only the upper 143 m of a unit that may reach over 500 m in thickness. By contrast, the name Kanpa Formation relates to the full thickness of the same unit in several drillholes. Consequently, the 'Babbagoola Formation' is abandoned in favour of the Kanpa Formation for the older portion belonging to the Buldya Group. As detailed above, younger parts are reassigned to the Wahlgu and Lungkarta Formations.

Keene Basalt: The Keene Basalt is a sequence of at least five basalt flows that is present within the Kanpa Formation in Lancer 1 between 527 and 576 m. There are minimal sediments interbedded within the basalt, and it is regarded as a separate unit rather than a part of the Kanpa Formation. The basalt is defined and described below, under **Igneous rocks associated with the Officer Basin**.

Distribution and thickness: The Kanpa Formation was initially recognized in Kanpa 1A (from 1301 to 1817 m, later revised to 1341–1817 m, 476 m thickness), Hussar 1 (892–1294 m, 402 m thickness), and Lungkarta 1 (809–1196 m, 387 m thickness but with an eroded top). Sections in Yowalga 2 (846 to TD at 989 m) and in Yowalga 3 (880–991 m) were previously assigned to the 'Babbagoola Formation' (Perincek, 1998; revised Apak and Moors, 2000b). Empress 1A provides a cored section, originally recorded as 483 to 860.8 m (484.1 – 862.7 m log depth) by Stevens and Apak (1999), but recently revised to 616.9 to 860.8 m (243 m thickness), after the recognition of the Steptoe Formation (Apak and Moors, 2000b). Lancer 1 provides a second cored section, between 466.5 and 707.5 m (241 m thickness), with an interval of five basalt flows (Keene Basalt) between 527 and 576 m (Haines et al., 2004). Drillhole NJD 1 probably also intersected a relatively complete section of Kanpa Formation, similar to that in Empress 1A (Hocking, 2003). The lesser thickness of these sections may be due to thinning towards the western basin margin.

Outcrops to the west of the Eagle Highway on ROBERT and northeast THROSSELL, and near Neale Junction (NEALE) are here assigned to the Kanpa Formation, as they contain *Baicalia burra* and other stromatolites typical of the Kanpa Formation. They were previously mapped either as undifferentiated Proterozoic units or as 'Neale Formation', and span only a few metres stratigraphic thickness.

A small outcrop at the top of the succession at Constance Headland on the MADLEY 1:250 000 sheet contains *Baicalia burra* and *Conophyton* new form, providing a confident correlation with the Kanpa Formation. The Constance Headland succession was shown as part of the Nabberu Basin by Jackson and van de Graaff (1981, plate 1), and as undifferentiated Proterozoic by other workers.

Several outcrops on BIRKSGATE (SA) and COOPER previously mapped as Townsend Quartzite may be better assigned to the Kanpa Formation, based on stromatolite biostratigraphy. The upper part of an outcrop 8 km south of Skirmish Hill (central COOPER) overlies rocks containing *Basisphaera irregularis* (which is characteristic of the Browne Formation). The upper part of the outcrop is therefore part of the upper Buldya Group, possibly Kanpa Formation, rather than Townsend Quartzite. *Baicalia burra* is present 4 km west of Pirrilyungka, indicating that this area, mapped as ?Townsend Quartzite, is also part of the Kanpa Formation. *Baicalia burra* was also identified from the core of an anticline in the Patricia Johnson Hills on BIRKSGATE, indicating that these strata are Kanpa Formation rather than 'Pindyin beds' as mapped. Outcrops in the Livesay Range on southwest COOPER shown as Townsend Quartzite were described as 'well bedded sandstones with occasional thin bands of grey to black silicified oolite' by Daniels (1971b), a description more consistent with the Kanpa Formation. The exposures were assigned to the Punkerri Formation by Jackson and van de Graaff (1981), and this interpretation is accepted here, although the possibility remains that they are Kanpa Formation.

From descriptions, the 'Wright Hill beds' and some outcrops mapped as Pindyin Sandstone in the eastern

Officer Basin in South Australia (Major, 1973a,b; Drexel et al., 1993) are probable correlatives of parts of the Buldya Group. Several outcrops contain oolitic carbonate and may be correlatives of the Kanpa Formation, although biostratigraphic evidence is needed to confirm this. This correlation is consistent with biostratigraphic and stable isotope correlation between the Kanpa Formation and part of the Burra Group of the Adelaide Rift Complex (Hill et al., 2000b).

Type section or area: No type section was designated when the unit was named (Townson, 1985; Phillips et al., 1985). Iasky (1990) assumed that the preferred section for the unit was the interval in Kanpa 1A from 1301 to 1817 m (Fig. 19). The upper 40 m were later assigned to the Steptoe Formation (Apak and Moors, 2000a,b). The cored intervals in Empress 1A between 616.7 and 860.8 m (618.0 to 862.7 m log depth) and Lancer 1 between 466.5 and 707.5 m (Fig. 20) are the most continuous and best-represented sections known through the formation, and are here designated as reference sections.

Outcrop of the Kanpa Formation is typically poor. A locality 18 km north of Throssell 1 and 1.5 km west of the Eagle Highway (MGA Zone 51, 637100E 7000300N) provides a field reference section.

Lithology: The Kanpa Formation is a mixed carbonate–siliciclastic sequence of interbedded dolomite (predominantly stromatolitic), mudstone, shale, siltstone, and sandstone, with some evaporites and chert. Townson (1985) recognized four units from the combined data available from Kanpa 1A, Hussar 1, and Lungkarta 1: a basal shale, overlain by siltstone with interbedded shale, sandstone and dolomite, overlain in turn by shale with interbedded dolomite and siltstone; and an uppermost dolomite and shale unit, grading upward into siltstone and shale. Apak and Moors (2000a,b) recognized two conformable parasequence sets: K1, a basal, predominantly mudstone parasequence set overlain by mixed rock types; and K2, comprising a basal mudstone overlain by a mixed but dolomite-dominated sequence.

Relationships and boundary criteria: The Kanpa Formation conformably overlies the Hussar Formation (Townson, 1985; Phillips et al., 1985; Apak and Moors, 2000a,b). The contact is taken at the base of a thick mudstone ('Unit D' of Townson, 1985) that can be correlated regionally on drill logs. In Empress 1A, the basal Kanpa Formation is a grey to green mudstone, conformable on leached and oxidized sandstone of the Hussar Formation at 860.8 m.

The upper contact between the Kanpa and Steptoe Formations is recorded in Empress 1A and Kanpa 1, at 617 m and 1341 m respectively (Apak and Moors, 2000b), where a dolomite unit is conformably overlain by a thick mudstone that is regionally extensive on seismic profiles. This relationship cannot be seen in Lancer 1, where the Steptoe Formation appears to have been eroded or not deposited (Haines et al., 2004).

The Kanpa Formation is intercalated with the Keene Basalt in Lancer 1. The top of the uppermost basalt flow of the Keene Basalt appears to be eroded, rather than a chilled flow top, suggesting an erosional hiatus. Petrographic examination of core indicates significant weathering at the top of the unit, gradually decreasing downwards, in an arid alkaline climatic setting (Pirajno, F., 2004, written comm.). There are no intraclasts of basalt within the overlying fine-grained Kanpa Formation. The significance of this contact is yet to be assessed, but the weathering suggests a disconformity after extrusion of the flows. There is no other indication from electric logs, core examination, or comparison with the section in Empress 1A that the hiatus is major.

Age and correlation: Stromatolite biostratigraphy, palynology, and isotope chemostratigraphy permit correlation of the Kanpa Formation with the Skillogalee Dolomite and overlying formations in the Burra Group of the Adelaide Rift Complex (Hill and Walter, 2000; Hill et al., 2000b). The Boucaut Volcanics at the base of the Burra Group have U–Pb SHRIMP zircon ages of 777 ± 7 Ma (Preiss, 2000), giving a probable maximum age for the Kanpa Formation. The Sturtian glaciation, which marks the base of the overlying Umberatana Group in the Adelaide Rift Succession, is estimated to be about 700 Ma in age (Preiss, 2000; Walter et al., 2000). So far, no rocks of unequivocal Sturtian age have been recognized in Western Australia, but, if present, they would lie stratigraphically above both the Steptoe and Kanpa Formations. A sandstone interval in the Kanpa Formation between 692.4 and 694.3 m in Empress 1A contains detrital zircons that provide a maximum age constraint of 725 ± 11 Ma from SHRIMP U–Pb dating (Nelson, D. R., 2002, written comm.) for the top of the Kanpa Formation.

The *Baicalia burra* Stromatolite Assemblage ranges from the underlying Hussar Formation into the overlying Steptoe Formation, and is present in carbonate horizons throughout the Kanpa Formation. The assemblage is dominated by *B. burra*, which is geographically widely distributed. *Baicalia burra* is often accompanied by *Conophyton* new form, which at present has been found only in the Kanpa Formation, and *Tungussia wilkatanna*. The assemblage is present in Kanpa 1A at 891.34, 892.81, and 895.26 m, and is abundant in Empress 1A. It has been found at many field localities, particularly near the Eagle Highway on THROSSELL, in outcrops on central NEALE previously referred to as 'Neale Formation', and on COOPER and BIRKSGATE.

Baicalia burra and *Conophyton* form indet. have also been collected from the Tarcunyah Group near Constance Headland in the northwestern Officer Basin. Both *B. burra* and *T. wilkatanna* are present in the Burra Group of the Adelaide Rift Complex (Preiss, 1972, 1974, 1987), supporting correlation between the upper Buldya Group and at least part of the Burra Group. *Baicalia burra* has also been recorded in Tasmania (Griffin and Preiss, 1976), as an erratic in Sturtian glacial deposits of the Black River Dolomite (Calver, 1998; K. Grey, unpublished data).

Palynomorphs were extracted from the Kanpa Formation in Hussar 1 (Hos, 1982; Townson, 1985), and Lungkarta 1 (van Neil, 1984), but at the time none was identified. A moderately diverse assemblage of

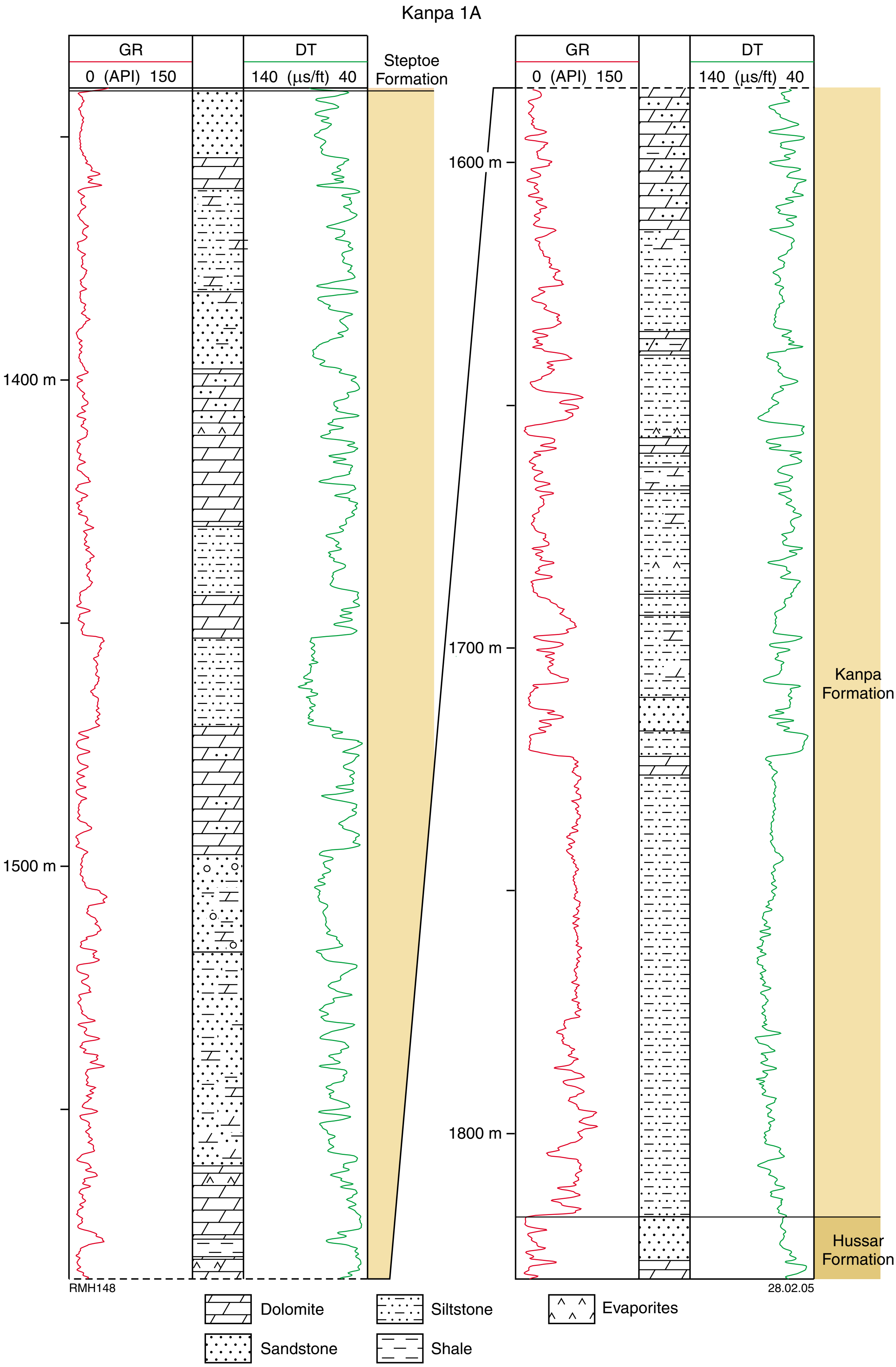

Figure 19. Type section, Kanpa Formation, Kanpa 1A

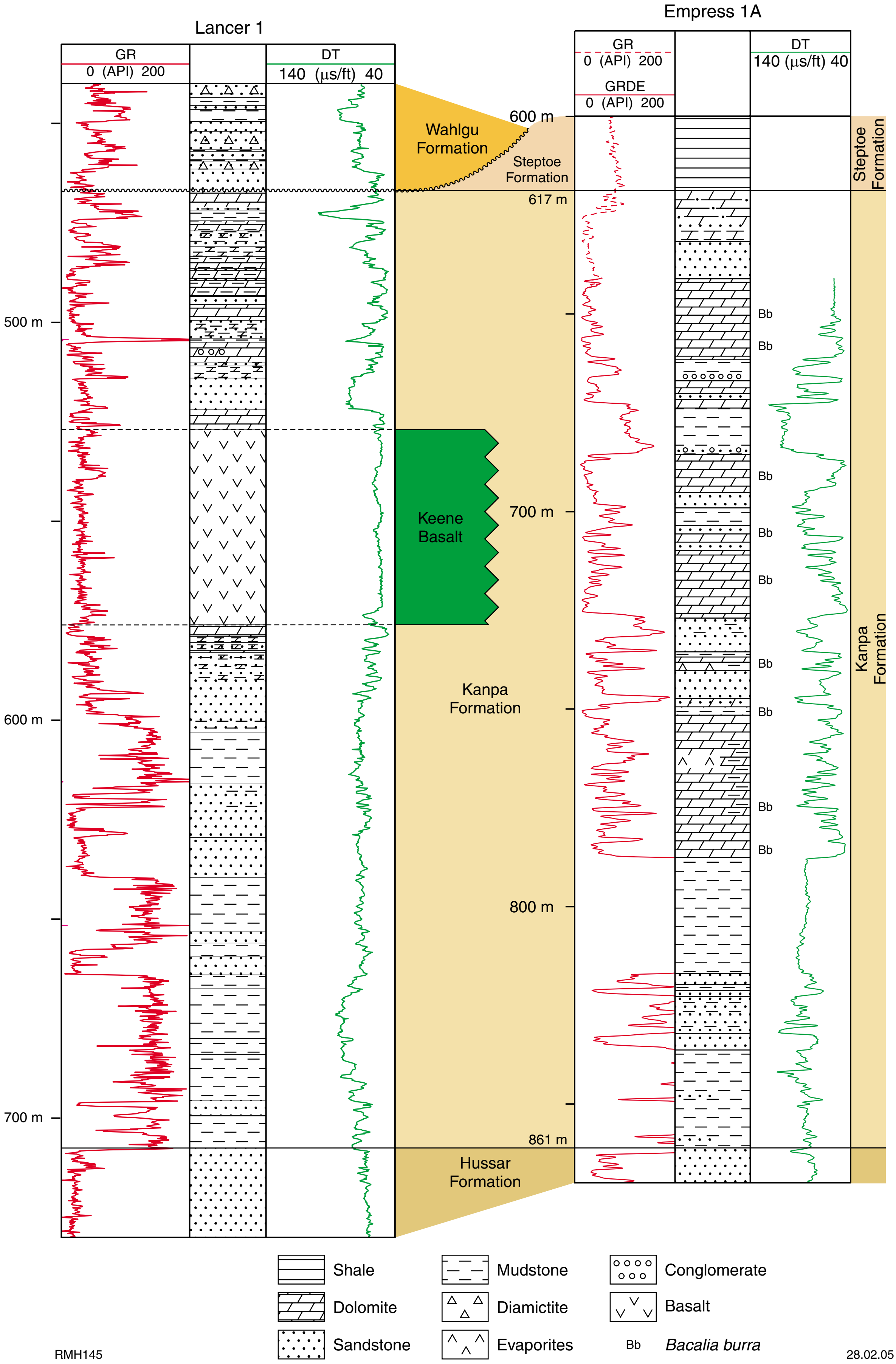

Figure 20. Reference sections, Kanpa Formation, Empress 1A and Lancer 1, and type section, Keene Basalt, Lancer 1

palynomorphs (Grey and Cotter, 1996; Cotter, 1999; Hill et al., 2000b) has since been identified from these samples and additional samples from Yowalga 2, Hussar 1, and Lungkarta 1. A similar assemblage is present in Empress 1A (Grey, 1999c). The following taxa of sphaeroidal acritarchs and microfossils were identified: *Cerebrosphaera ananguae*, *C. buickii*, *Chuaria* sp. cf. *circularis*, *Coneosphaera* sp. cf. *arctica*, *Eoentophysalis croxfordii*, *Leiosphaeridia crassa*, *L.* sp. cf. *exsculpta*, *L. jacutica*, *L. minutissima*, *L. tenuissima*, *L. ternata*, *Simia* sp., *Myxococcoides cantabrigiensis*, *Ostiana microcystis, Pterospermopsimorpha insolita, Satka colonialica, Simia annulare*, *Stictosphaeridium sinapticuliferum*, ?*Symplassosphaeridium* sp., *Synsphaeridium* spp., *Tasmanites* sp. The following filamentous microfossils have also been recorded from the Kanpa Formation: *Calyptothrix* sp. cf. *alternata, Clavitrichoides rugosus, Oscillatoriopsis amadeus, Oscillatoriopsis* sp., *Siphonophycus kestron, S. robustum, S. septatum*, *S. solidum*, *S. typicum*, Tubular sheath A, Tubular sheath B.

The distinctive acritarch *Cerebrosphaera buickii* first appears about the middle of the Hussar Formation in the western Officer Basin (Cotter, 1999; Hill et al., 2000b). In the Adelaide Rift Complex it has been recorded from the Emeroo Subgroup and the Skillogalee Dolomite (Hill et al., 2000b), offering further support for correlation between the Kanpa Formation and part of the Burra Group.

Isotope chemostratigraphy, in particular the $\delta^{13}C$ isotope curve, supports correlation of the Kanpa Formation and Burra Group (Hill and Walter, 2000; Hill et al., 2000b; Walter et al., 2000). The Kanpa Formation in Empress 1A is characterized by $\delta^{13}C$-enriched values of between 6.8% and 8.1%, followed by a decrease to 0%, then an increase to 4%. This pattern allows interbasinal correlation between the upper Kanpa Formation and the upper Burra Group at about 760 Ma. Hill and Walter (2000) further suggested that these isotope values, together with the presence of *Cerebrosphaera buickii* in Spitsbergen (Butterfield et al., 1994) can be used to tie the Burra Group to successions in Canada, Spitsbergen, and Namibia. Tie line IV of Hill and Walter (2000), which represents the heaviest known mid-Neoproterozoic $\delta^{13}C$ values, links the Kanpa Formation to the middle Ombombo Subgroup of Namibia, from which a volcanic-ash layer has provided a U–Pb zircon date of 758 ± 3.5 Ma (Hoffman et al., 1996).

Depositional setting: The Kanpa Formation was deposited in a carbonate-dominated shallow-marine to tidal-flat setting in which there were frequent minor sea-level fluctuations (Apak and Moors, 2000b).

References: Apak and Moors (2000a,b), Bagas et al. (1999), Cotter (1999), Grey and Cotter (1996), Grey (1999c), Hill and Walter (2000), Hill et al. (2000a,b), Hocking (2003), Iasky (1990), Jackson (1966b), Jackson and Muir (1981), Jackson and van de Graaff (1981), Lowry et al. (1972), Peers (1969), Peers and Trendall (1968), Perincek (1996a,b, 1998), Phillips et al. (1985), Stevens and Apak (1999), Townson (1985), Tyler et al. (1998), Walter et al. (2000).

Steptoe Formation

Definition and nomenclature: The name 'Steptoe Beds' was proposed informally by Townson (1985), after Steptoe airstrip, 15 km northwest of Yowalga 3, and used informally by Phillips et al. (1985) for a section of interbedded sandstone, dolomite, and siltstone in Kanpa 1A. Only brief descriptions were given. Cockbain and Hocking (1989) upgraded the name to Steptoe Formation, but did not define it, and Iasky (1990) set the interval from 829 to 1301 m in Kanpa 1A as the type section by default.

The description given here constitutes the first full definition of the Steptoe Formation. Since the original description, the unit has been recognized in Empress 1A, where it was originally included as part of the Kanpa Formation (Stevens and Apak, 1999), but later identified as a separate formation (Apak and Moors, 2000b). No outcrops of Steptoe Formation have yet been recognized.

The Steptoe Formation appears very similar to the Kanpa Formation lithologically, and its differentiation in the subsurface is largely based on a prominent seismic reflector at the base of the Steptoe Formation (Apak and Moors, 2000a,b). Townson (1985) clearly saw the Steptoe Formation as a sandier unit above the siltstone- and dolomite-dominated Kanpa Formation.

Distribution and thickness: The Steptoe Formation has been recognized in Kanpa 1A (829–1341 m, 512 m thickness) and Empress 1A (483–617 m, 134 m thickness; Apak and Moors, 2000b; Fig. 4), and the lowermost part of the unit may be present in WMC NJD 1 (Hocking, 2003). It can be traced on some seismic sections, such as line T82-43 (Townson, 1985; Apak and Moors, 2000a,b). In Lancer 1, the Steptoe Formation, if deposited, was either eroded before deposition of the Wahlgu Formation, or is indistinguishable in the sandier section (Haines et al., 2004).

Type section: Iasky (1990) placed the type section of the Steptoe Formation in Kanpa 1A, between 829 and 1301 m (Fig. 21). This was extended by Apak and Moors (2000b) to 1341 m depth. The section in Empress 1A between 483 and 617 m (484.1 – 618.3 m log depths) provides a reference section (Fig. 22).

Lithology: Townson (1985) recognized four units in the Steptoe Formation. In ascending order, these are sandstone with minor dolomite, massive dolomite with minor siltstone, sandstone passing upward into siltstone, and sandstone passing upward into siltstone and dolomite. Apak and Moors (2000a,b) identified two parasequence sets: S1, consisting of a basal claystone, sandstone, mudstone, loose sand and stromatolitic dolomite (containing the *Bacalia burra* Stromatolite Assemblage); and S2, consisting of a basal massive shale, overlain by sandstone, interbedded with shale and anhydritic dolomite. The S2 parasequence set is known only from Kanpa 1A. In Empress 1A, the younger unit (S2) has been eroded and the S1 parasequence set shows signs of karstification and erosion near its top.

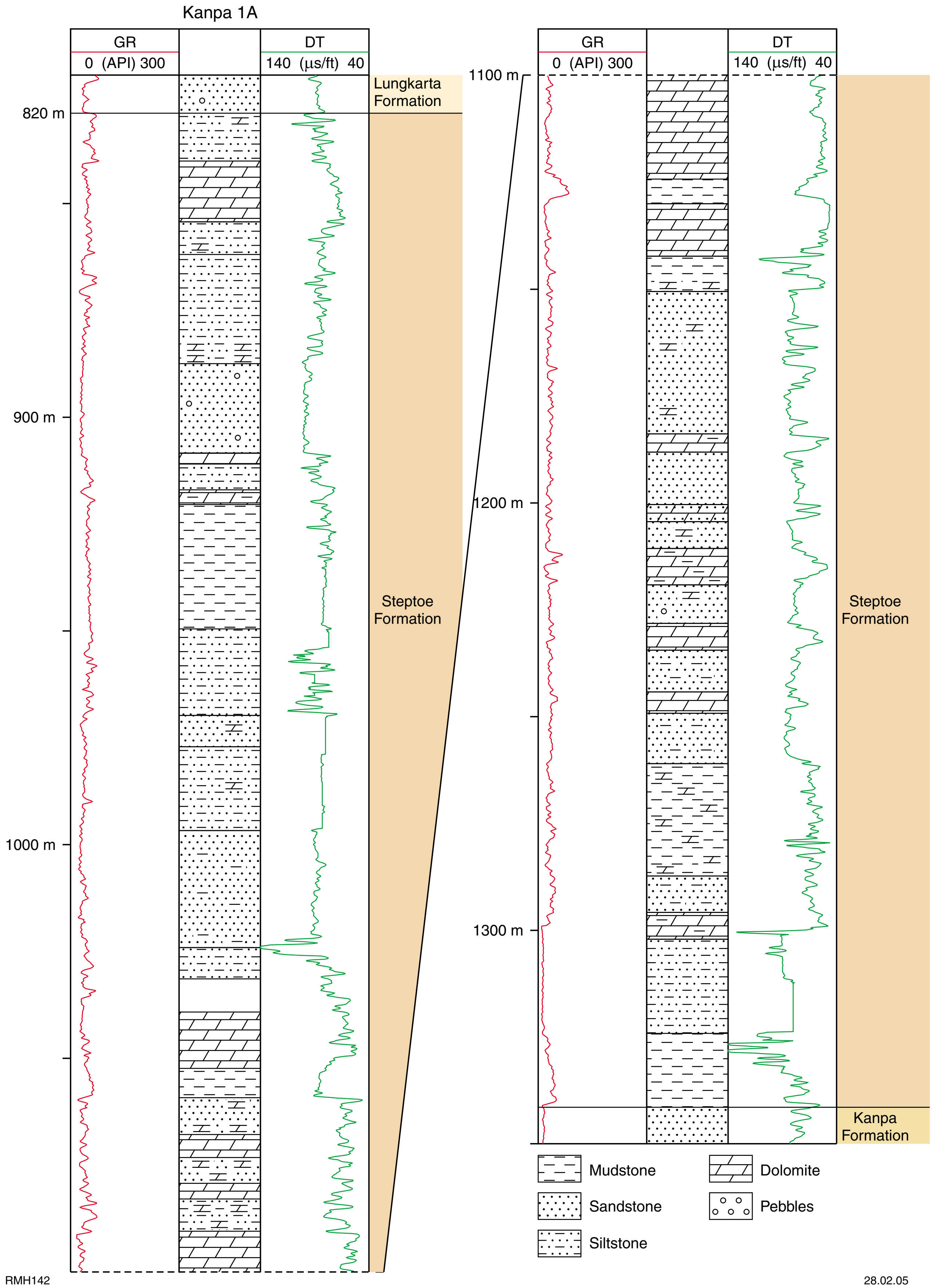

Figure 21. Type section, Steptoe Formation, Kanpa 1A

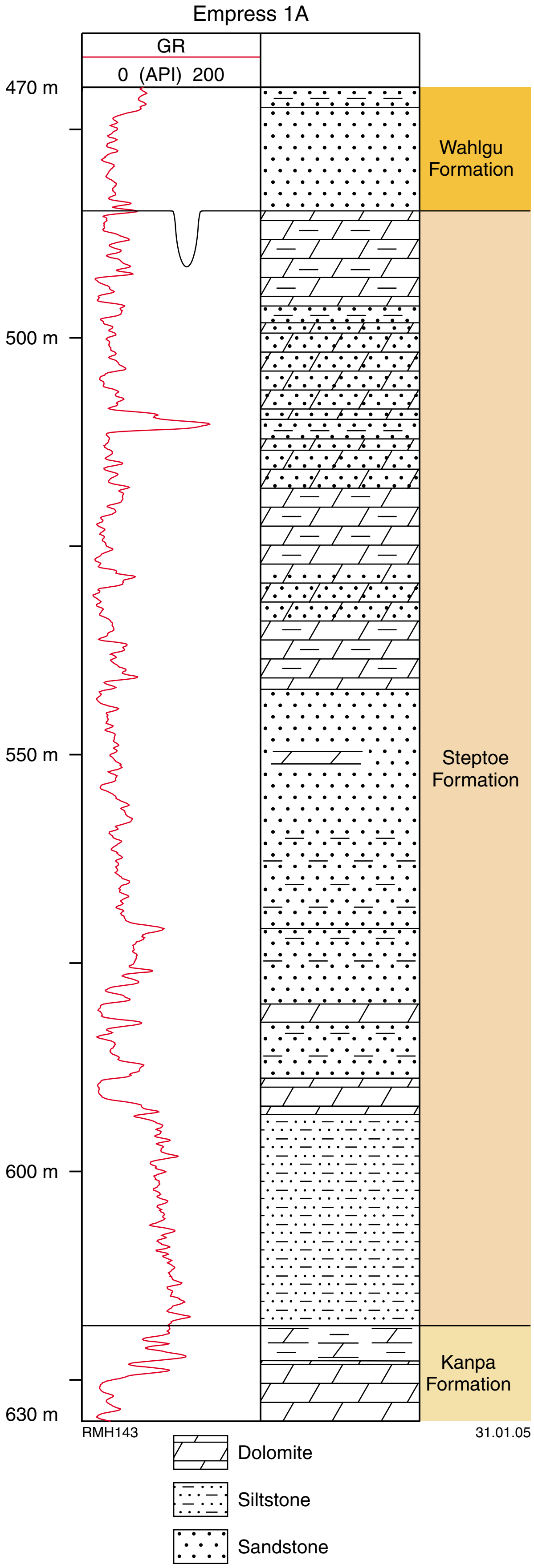

Figure 22. Reference section, Steptoe Formation, Empress 1A

Relationships and boundary criteria: In the type section in Kanpa 1A, the Steptoe Formation appears to be conformable on the Kanpa Formation (Townson, 1985, fig. 8). In Empress 1A, the lower boundary is taken at the base of a massive claystone, and is conformable.

The top of the formation is an erosional unconformity with the Lungkarta Formation in Kanpa 1A, and an eroded and karstified surface overlain by glacigenic Wahlgu Formation in Empress 1A.

Age and correlation: There is no direct evidence for the age of the Steptoe Formation. It must be younger than about 720 Ma, based on a detrital zircon age of 725 ± 11 Ma from SHRIMP U–Pb dating (Nelson, D. R., 2002, written comm.) of a sandstone in the upper Kanpa Formation in Empress 1A. Isotope chemostratigraphy, palynology, and stromatolite biostratigraphy that support correlation with the Burra Group of the Adelaide Rift Complex (Grey, 1999b,c; Hill et al., 2000b; Hill and Walter, 2000) were published before the Steptoe Formation was differentiated from the Kanpa Formation in Empress 1A.

The formation contains components of the *Baicalia burra* Stromatolite Assemblage (Stevens and Grey, 1997; Hill et al., 2000b). These are *Baicalia burra*, *Tungussia wilkatanna,* and a pseudocolumnar form. *Baicalia burra* and *T. wilkatanna* are found in the Burra Group of the Adelaide Rift Complex. Palynomorphs are sparser than in the underlying Kanpa Formation, but are similar to those found in the Kanpa Formation, including the presence of *Cerebrosphaera buickii*, at least in Parasequence set S1.

Depositional setting: Townson (1985) interpreted the depositional environment as an inland playa with eolian dune sands. Apak and Moors (2000a,b) considered deposition to have been in a range of shallow-marine to coastal environments, in large part restricted and generally more inshore than the Kanpa Formation. Based on the similarity of the Kanpa and Steptoe Formations in Empress 1A, the depositional environments were little different. Both were dominantly coastal with evaporitic conditions and intermittent emergence.

References: Apak and Moors (2000a,b), Hill and Walter (2000), Hill et al. (2000b), Hocking (2003), Iasky (1990), Phillips et al. (1985), Stevens and Apak (1999), Townson (1985), Tyler et al. (1998).

Ilma Formation

Definition and nomenclature: The 'Ilma beds' were named by Lowry (1970), after Lake Ilma, redescribed by Jackson and van de Graaff (1981), and upgraded to formation status by Cockbain and Hocking (1989). Lowry designated a type locality, but did not measure a type section because of poor outcrop. Exposures of the Ilma Formation were re-examined during the present study. Little can be added to the earlier descriptions.

Distribution and thickness: The Ilma Formation is exposed on northwest MASON, around the type locality on the northern margin of the Eucla Basin. Exposure is very poor, but the succession appears to be moderately to steeply dipping and folded. Lowry (1970) suggested that the Ilma Formation thickens northward, underlies or extends through a large part of the Officer Basin, and may have a thickness of several hundred metres. Four drillholes intersected, and reached total depth in, rocks interpreted as Ilma Formation: Jubilee 1 (151.5 – 167 m, core available below 154.5 m), 2 (125.3 – 140.3 m), and 3 (229.5 – 231.3) on JUBILEE, and Mason 1 (240–246 m), 10 km west of the type area on MASON (Ellis, 1981). The holes were electrically logged, and GSWA holds core from each hole.

Type section or area: Lowry (1970) specified the only outcrop (around MGA Zone 52, 364800E 6760700N on northwestern MASON) as the type locality. This is an area of scattered rubble, subcrop, and poor discontinuous exposure (Fig. 23). The section in Mason 1 is designated a reference section, as it is cored and shows the relationship with the overlying Mason Conglomerate.

Lithology: The Ilma Formation consists of stromatolitic and sandy oolitic dolomite with minor limestone, chert, and sandstone. The dolomite is medium grained, sandy, and has a matrix of fine sparry calcite. Ooliths have formed around rounded or subrounded quartz grains, and have only thin carbonate rims. The stromatolites are silicified and columnar. Pink fine-grained dolomite and carbonate with black ooliths in a milky matrix are present as float in the Quaternary cover. In drillholes, the Ilma Formation consists of silicified carbonate, siltstone, and quartzitic sandstone (Ellis, 1981). Evaporite pseudomorphs and textures are common. Silicified marl and oolitic carbonate, siltstone, minor conglomerate, quartzite, and sandstone were recorded in Jubilee 1, with stromatolitic structures noted at about 150 m by Ellis (1981). Pink, well-sorted, fine-grained, large-scale cross-bedded sandstone, mudstone, and siltstone are present in Jubilee 2. Jubilee 3 bottomed in a few metres of pink siltstone and carbonate with distinct nodules and growths suggestive of evaporites, and Mason 1 in dark-grey siltstone, chocolate shale, and fine-grained sandstone. The drillhole intersections are similar to the Buldya Group in other drillholes.

Relationships and boundary criteria: It is inferred that the Ilma Formation rests unconformably on crystalline basement, as drillholes farther south on the Transcontinental Railway intersected crystalline basement beneath the Eucla Basin succession (Lowry, 1970). From airphoto interpretation, the Tertiary Colville Sandstone is angularly unconformable on the Ilma Formation. In Jubilee 1 and 2, the Permian Paterson Formation overlies it with a sharp contact. In Jubilee 3 and Mason 1, the Mason Conglomerate overlies the Ilma Formation with an apparently transitional contact (see **Mason Conglomerate**, below).

Age and correlation: Stromatolites were reported from the Ilma Formation (Lowry, 1972; Jackson and van de Graaff, 1981), of which Preiss (1976) identified one as *Baicalia* cf. *burra.* On this basis, the Ilma Formation was correlated with the Neale Formation. Further investigation (Grey and Jackson, 1983) demonstrated that this stromatolite and another specimen (*Acaciella australica*) were Paterson Formation erratics from an outcrop on JUBILEE, rather than specimens in situ from the Ilma Formation. Lowry (1970) mentioned that the fossils occurred as clasts in younger conglomerates that were probably derived from the Ilma Formation. A single specimen collected from the Ilma Formation was poorly preserved, not identifiable, and not retained in the GSWA collection.

Stromatolites collected more recently from the Ilma Formation are very poorly preserved, and do not resemble the JUBILEE clasts. They have not yet been identified. Stromatolitic limestone was noted in Jubilee 1, but GSWA does not hold core from this interval.

The Ilma Formation in core is very similar lithologically to the Buldya Group in NJD 1, Empress 1A, and Lancer 1. On this basis, the formation is tentatively included within the group.

Depositional setting: The Ilma Formation was deposited in near-shore, coastal, and possibly sabkha to hypersaline lagoon environments, based on evaporitic structures including tepees, apparent nodules and possible enterolithic bedding, evaporitic pseudomorphs, oolitic carbonate, and fine-grained carbonate. An interval of cross-bedded, fine-grained, well-sorted sandstone between 125.3 and 127.6 m in Jubilee 2 may be an eolian deposit.

References: Lowry (1970), Preiss (1976), Ellis (1981), Jackson and van de Graaff (1981), Grey and Jackson (1983), Cockbain and Hocking (1989), Iasky (1990), Perincek (1998).

Mason Conglomerate

Definition and nomenclature: The Mason Conglomerate is a conglomeratic unit dominated by a polymictic breccia that has been recognized in Mason 1 and 2, and Jubilee 3, mineral exploration drillholes on MASON and JUBILEE respectively. The name was used informally in a company report (Ellis, 1981), and is here formalized and defined, because it is a distinctive rock type that should be readily identifiable on seismic sections. No outcrops are known, and the interval in Mason 1 is here designated as the type section. The Mason Conglomerate overlies the Ilma Formation in Mason 1 and Jubilee 3, and Mason 2 bottomed in the formation; it is overlain in Mason 1 and 2 by a unit that Ellis (1981) assigned to the upper 'Babbagoola Beds' (now Lungkarta Formation). There is no known synonymy.

Distribution and thickness: The Mason Conglomerate was recorded in Mason 1 from 230.6 to 240 m, Mason 2 from 143 to 143.6 m (TD), and Jubilee 3 from 229.5 to 230 m (Perincek, 1998). Perincek presented graphic logs of the drillholes, but did not note that they had been partly cored. From the drillhole data it is evident that deposition extended laterally for at least 60 km (Ellis, 1981), although it may not have been continuous, given the three intersections are all thin.

Type section: Mason 1, from 230.6 to 240 m. Core for this interval is held by GSWA.

Lithology: The conglomerate is typified by angular to subrounded, dominantly pebble-sized clasts, ranging from 2 to 100 mm in diameter with a large proportion between 10 and 20 mm, in a silty to sandy matrix. They are

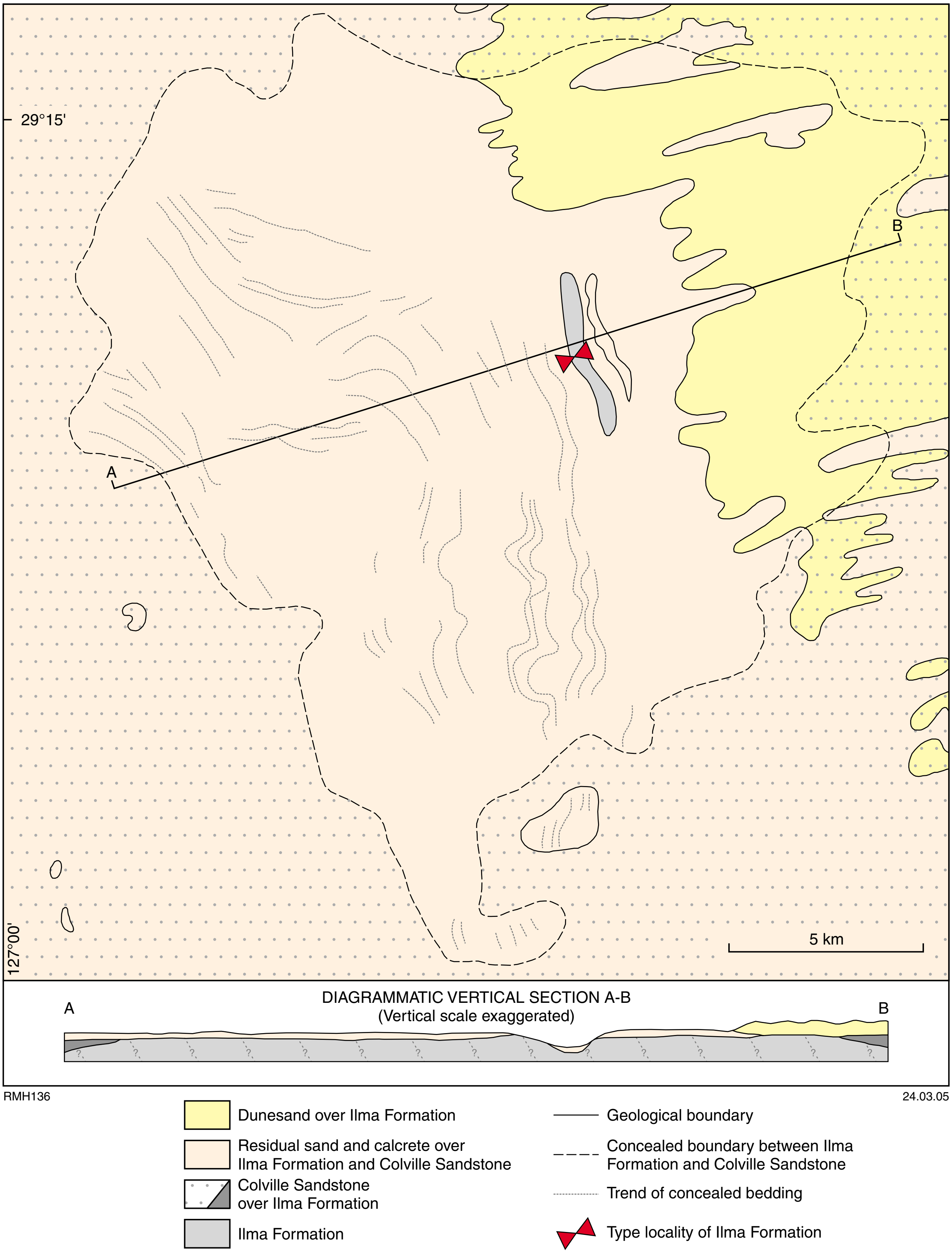

Figure 23. Type locality of Ilma Formation, after Lowry (1970, fig. 11)

composed predominantly of pink siltstone and limestone, with some silicified oolitic limestone. Many clasts are lithologically similar to the underlying Ilma Formation. In Mason 1, the conglomerate is interbedded with sandstone and siltstone, in fining-upward cycles ranging in thickness from about 30 cm to a metre. The cycles gradually coarsen upward from sandstone–siltstone cycles of the Ilma Formation, forming an overall coarsening-upward sequence. Above 231 m in Mason 1 the abundance of conglomerate decreases, with thin fining-upward cycles that fine over a metre into sandstone of the overlying unit. Both contacts appear, on this basis, to be transitional and conformable. Evaporite pseudomorphs and nodules are evident in places.

Relationships and boundary criteria: In Mason 1 and Jubilee 3, the conglomerate overlies the Ilma Formation. Ellis (1981) showed the Mason Conglomerate as conformable on the Ilma Formation (unlike Perincek, 1988), and the section in Mason 1 indicates a conformable, transitional relationship. Ellis showed the contact with the 'Babbagoola Beds' (Lungkarta Formation) as unconformable (again, unlike Perincek, 1988), but the contact in Mason 1 appears to be transitional and thus conformable. In Jubilee 3, the conglomerate is overlain by a sandstone, which Ellis (1981) assigned to the Lennis Sandstone — a Palaeozoic unit of the Gunbarrel Basin.

Age and correlation: There are no indications within the conglomerate as to its age. Ellis (1981) suggested similarities to the 'Davies Bore Conglomerate', which is an informal Cambrian unit in the eastern Officer Basin later included in the Wallatinna Member of the Observatory Hill Formation (Benbow, 1982; Morton, 1997). It is unlikely that the Mason Conglomerate is this young.

The underlying Ilma Formation is also unconstrained with respect to age, but is lithologically similar to the Buldya Group. If so, the Mason Conglomerate is also a part of the group, based on the contact in Mason 1, although similar conglomerates have not been found elsewhere in the western Officer Basin. By extension, the units identified as Lungkarta Formation in Mason 1 and 2 are also Buldya Group.

Depositional setting: Ellis (1981) suggested that the angularity and sorting of the clasts indicated that they were not of glacial origin. The fining-upward cycles, moderate imbrication, and associated sandstone, siltstone, evaporitic indicators, and carbonate suggest either a brief fluvial period during arid coastal to nearshore deposition, or coastal wave to storm deposition. In either case, there was limited reworking of underlying material.

References: Ellis (1981), Perincek (1998).

Ungrouped units

Wahlgu Formation

Definition and nomenclature: The Wahlgu Formation is a diamictite-dominated unit, named after Wahlgu Rockhole on WESTWOOD, east of Empress 1 and 1A, which contains the type section. Rocks now referred to the Wahlgu Formation were previously assigned to the Lupton Formation. Apak and Moors (2001) introduced the name 'Wahlgu Formation', briefly described the unit, and explained why the name was introduced, but did not fully define the unit. They continued to use Wahlgu Formation in preference to Lupton Formation in a report on the Gibson area (Moors and Apak, 2002). The new formation name is preferred because correlation between the succession in Empress 1 and 1A and unequivocal Lupton Formation cannot be clearly demonstrated, and the relationships and age of the Lupton Formation are very poorly known, whereas rocks referred to the Wahlgu Formation are reasonably constrained.

Distribution and thickness: The Wahlgu Formation is recognized in Empress 1 and 1A, from 317.1 to 483 m drilled depth (165.9 m thickness) and in Lancer 1 from 344.3 to 466.5 m (122.2 m thickness). These rocks in Empress 1 and 1A were previously considered as probable Lupton Formation (Stevens and Apak, 1999). The top of the Wahlgu Formation is defined as the top of the cap dolomite where this can be recognized. Other intersections of glacigene rocks of probable Supersequence 3 age, and correlative sections on seismic lines, in the main part of the western Officer Basin are also now referred to the Wahlgu Formation rather than the Lupton Formation. At this stage, the cap dolomite is included as the top of the Wahlgu Formation; further study may lead to it being assigned to a separate unit.

The section between 747 and 897 m in Hussar 1 is probably Wahlgu Formation (Haines et al., 2004), and the section in Lungkarta 1 from 704 to 809 m may be Wahlgu Formation, based on sidewall core descriptions. In Lungkarta 1, significant shale is present beneath sandstone, between Table Hill Volcanics above and Kanpa Formation below. This is more suggestive of Wahlgu Formation than of Lungkarta Formation (see Perincek, 1998; Moors and Apak, 2002) although the upper sandy unit could be Lungkarta Formation. The boundary between the Wahlgu and Lungkarta Formations is also placed much lower in Hussar 1, at 704 rather than 560 m, after comparison with the cored section in Lancer 1 (see **Lungkarta Formation**, below).

The Wahlgu Formation is missing from the succession in many drillholes, because of later erosion or discontinuous deposition, or both. Some intersections may also have been misidentified as other units. Much of the section between the Wahlgu and Lungkarta Formations in the eastern Officer Basin is absent in Western Australia, implying differences in tectonic activity across the basin, with greater erosion in the western Officer Basin. In at least some places where the Wahlgu Formation is absent, the formation was probably deposited and then removed prior to deposition of younger formations (Moors and Apak, 2002). Younger parts of the section appear to be present in the correlative Boondawari Formation in the northwest Officer Basin.

In the Yowalga area, the 'Base McFadden Formation equivalent' and 'Top Kanpa Formation' seismic horizons approximately mark the top and base respectively of the combined Wahlgu Formation ('Lupton Formation' of Apak and Moors, 2000b) and overlying unnamed sandstone unit as intersected in Empress 1A.

Type section: Empress 1 and 1A, between 317.1 and 483 m (Fig. 24). This section was referred to as ?Lupton Formation in Stevens and Apak (1999), and Lupton Formation in Grey et al. (1999) and later publications. The section in Lancer 1 (Fig. 24) is a reference section.

Lithology: The Wahlgu Formation in Empress 1 and 1A consists of a wide variety of clastic rock types, ranging from unsorted diamictite, pebbly and sandy mudstone, moderately sorted sandstone, mudstone, and conglomerate, and well-sorted and normally graded sandstone to mudstone. An interval at the top of the Wahlgu Formation, from 317.1 to 318.7 m, consists of interlaminated and interbedded, fine- to coarse-grained, light-grey and moderate-brown sandstone, moderate-brown mudstone and thin dolomite bands. This interval contains patches of rounded, jaspilitic grains that resemble the reddish chert units recorded from the Marinoan 'upper marker cap dolomite' in Ellery Creek in the Amadeus Basin. The top contact of the Wahlgu Formation appears to be erosional in Lancer 1, so the cap dolomite, if ever present, has been eroded.

Relationships and boundary criteria: The Wahlgu Formation disconformably overlies the Steptoe Formation, with an eroded, heavily karstified boundary in Empress 1A. The uppermost Steptoe Formation comprises stromatolitic dolomite. Eroded, but in situ, specimens of *Baicalia burra* at about 496 m are surrounded by sediment similar in character to that of the overlying Wahlgu Formation. This, in turn, is overlain by vuggy and brecciated dolomite, and then by relatively unaltered dolomite containing more columns in situ of *B. burra*, indicating that the overlying dolomite is still part of the Steptoe Formation. The interval probably represents a palaeocave system, in which the cave floor silted up with sediment from the overlying Wahlgu Formation (Preiss, W. V., 1998, written comm.).

In Lancer 1, the Wahlgu Formation is overlain, possibly disconformably, by a sandstone unit assigned to the Lungkarta Formation that is characterized by very large scale cross-bedding. The Wahlgu Formation is overlain by a 30 m-thick unnamed sandstone interval in Empress 1 and 1A, discussed under **Unnamed sandstone**, below. This sandstone is unconformably overlain by the Table Hill Volcanics.

Age and correlation: In Empress 1A, the minimum age of the Wahlgu Formation is constrained by an Ordovician K–Ar age of 484 ± 4 Ma for the overlying Table Hill Volcanics (Amdel, 1999; Stevens and Apak, 1999). This age should be taken as an alteration age rather than a crystallization age, as other dates for the Table Hill Volcanics and correlative units cluster around 500 to 510 Ma (Antrim Plateau Volcanics, 513 ± 12 Ma SHRIMP U–Pb of zircon, Hanley and Wingate, 2000; Table Hill Volcanics, Rb–Sr 563 ± 40 Ma to K–Ar 500 ± 7 Ma; Walter et al, 1995; Veevers, 2000; unnamed gabbro in Boondawari 1, 508 ± 5 Ma SHRIMP U–Pb of baddeleyite and zircon, Wingate, M. T. D., 2002, written comm.). A detrital zircon from 457.5 m in Empress 1A indicates a maximum age of sedimentation of 791 ± 18 Ma (Nelson, 1999; Stevens and Apak, 1999) by U–Pb SHRIMP dating.

Limited sampling indicates that $\delta^{13}C_{carbonate}$ isotope values compare with those for the Marinoan 'upper marker cap dolomite' found elsewhere in the Centralian Superbasin and Adelaide Rift Complex. The thin bands of micritic, light-grey dolomite contain incipient stromatolite columns of ?*Elleria minuta*, a taxon that grew in erosional hollows on the upper surface of the cap dolomite in the Amadeus Basin (Walter et al., 1979). The recognition of a 'cap dolomite', isotope chemostratigraphy (Walter, M. R., and Hill, A. C., 1998, written comm.), and limited stromatolite biostratigraphy combine to support a correlation with the Marinoan glacial succession elsewhere in Australia.

The Wahlgu Formation can be correlated with the Marinoan glacial succession throughout the Centralian Superbasin and the Adelaide Rift Complex (although they vary in lithology and chronological extent), and in Lancer 1 is very similar to the diamictite and sandstone in the Boondawari Formation in the northwestern Officer Basin.

Depositional setting: Some pebbles in the diamictite have typical glacial striations, but the deposits are more probably glaciomarine, rather than continental moraine (Eyles and Eyles, 1998). The well-laminated and graded fine-grained clastic beds may be distal, glacially related, turbidite deposits rather than lacustrine varves. A predominantly shallow-marine depositional environment is indicated, in which large volumes of glacially derived clastic sediments were deposited rapidly by debris flow and turbidity currents. Channelling and reworking of some of these deposits resulted in well-sorted and stratified deposits (Eyles and Eyles, 1998). Well-sorted and well-rounded sand between 334.8 and 336.6 m in Empress 1A may be eolian, indicating that at least part of the section could be of non-marine origin.

References: Stevens and Apak (1999), Apak and Moors (2000b).

Unnamed sandstone

In Empress 1 and 1A, an unnamed sandstone unit lies immediately above the cap dolomite of the Wahlgu Formation, between 317.1 and 286 m (Fig. 24). It is fine to medium grained with minor coarse- to very coarse grained bands, and is predominantly moderate brown, quartzitic, and subfriable. The tops of stromatolites in the Wahlgu Formation immediately below the lower contact are eroded, suggesting at least a slight erosional unconformity. The sandstone is unconformably overlain by the Table Hill Volcanics, and the top of the unit has been weakly metamorphosed to a depth of about 80 cm and more-strongly contact metamorphosed in the uppermost 10 cm. There are minor mudstone interbeds from 1 mm to 2 cm thick, and both the sandstone and the mudstone are slightly dolomitic. The sandstone has two major units, a lower fining-upward interval overlain by an upper coarsening-upward sequence. Stevens and Apak (1999) interpreted these as the products of a post-glacial transgression followed by regression as accommodation space created by the transgression was filled.

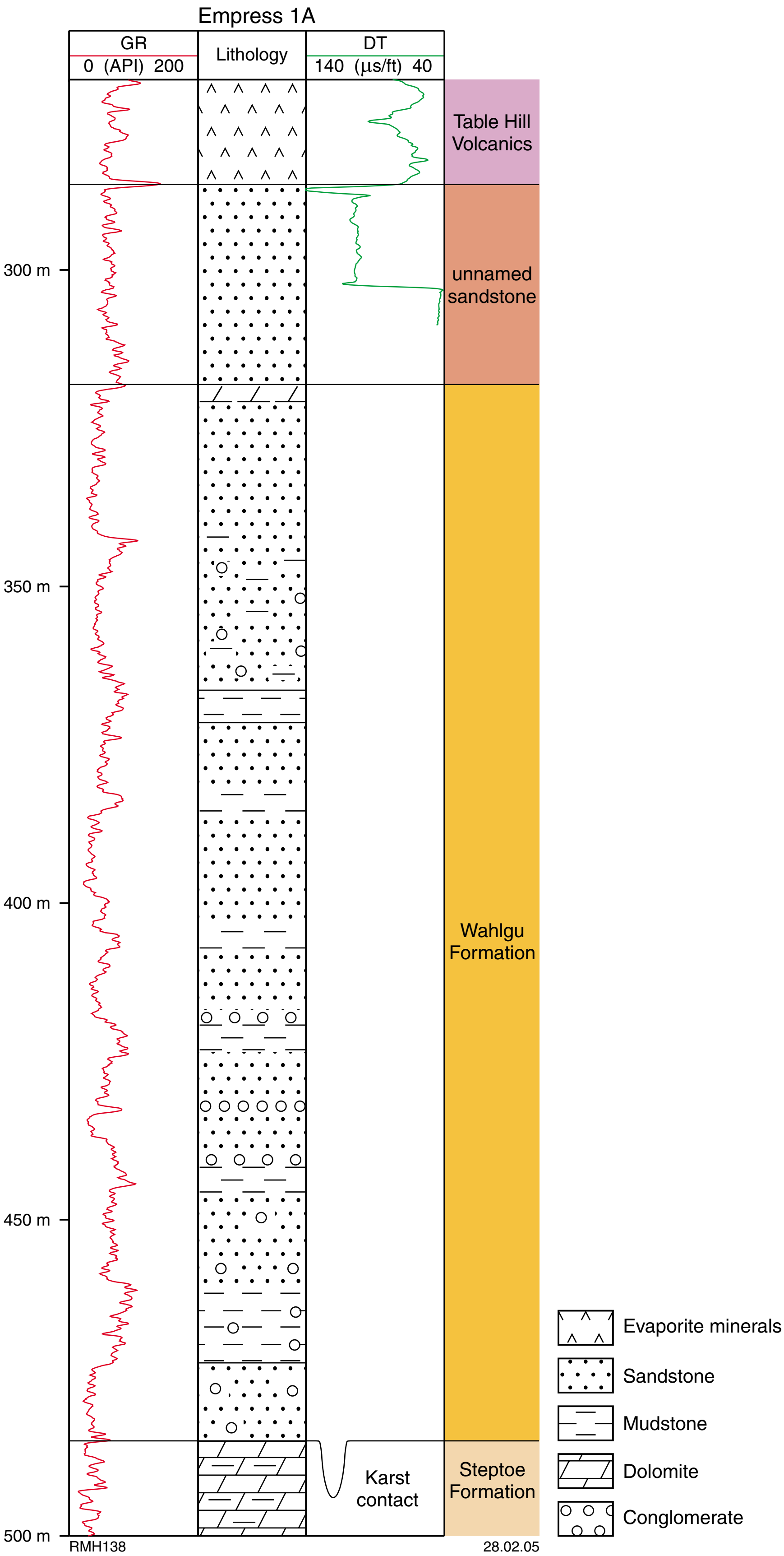

Figure 24. Type section, Wahlgu Formation, and section of overlying unnamed sandstone, Empress 1A

For several reasons the sandstone is left as an unnamed unit rather than being included in the Wahlgu Formation. In outcrop, it would represent a distinct change in rock type that could be used as a formation boundary, and the dolomite at the top of the Wahlgu Formation is probably the top Marinoan 'cap dolomite'. The top of the cap dolomite marks a significant stratigraphic boundary that has been selected as the probable base of a new 'Ediacaran system' with a type section in the Flinders Ranges of South Australia. Because of this, and the appearance of erosion associated with the stromatolite horizons at the top of the Wahlgu Formation, the sandstone is not included in the Wahlgu Formation. It is probably the lower Lungkarta Formation, based on the section in Lancer 1, but could equally correlate with sandstone intervals present above the cap dolomite in the Boondawari Formation in outcrop (see **Boondawari Formation**, below). Because of this uncertainty, the interval is left unassigned. The Seacliff Sandstone in the Adelaide Rift Complex and Tarlina Sandstone of the eastern Officer Basin are possible correlatives in South Australia (Preiss, W. V., 2004, written comm.).

The age of the sandstone is constrained by the age of the Table Hill Volcanics above and the Wahlgu Formation below.

Lupton Formation

Definition and nomenclature: The 'Lupton Beds' were named by Lowry et al. (1972), after the Lupton Hills, and defined by Jackson and van de Graaff (1981). Cockbain and Hocking (1989) amended the name to Lupton Formation.

Since then, a re-examination of the type section at the Lupton Hills, a reassessment of outcrops accepted as Lupton Formation, and a review of glacigene successions of the Officer Basin by Grey et al. (1999) have changed the understanding of the Lupton Formation. In initial mapping of the Officer Basin (Jackson and van de Graaff, 1981), both the Lupton and Turkey Hill Formations were assumed to be glacigene, and deposited during a single Neoproterozoic glacial episode. The presence of glacigene deposits in the Carboniferous–Permian Paterson Formation of the overlying Gunbarrel Basin complicates interpretation of diamictites where there is poor outcrop or age control was poor.

The Neoproterozoic diamictite succession in Empress 1A was tentatively assigned to the Lupton Formation by Stevens and Apak (1999), but is here assigned to the newly defined Wahlgu Formation (see above) because of uncertainties of correlation between the Empress 1A section and the outcropping Lupton Formation. The section in Empress 1A is reasonably well constrained to the Marinoan glacial episode (c. 600 Ma; Grey et al., 1999; Walter and Hill, 1999), whereas the age of the Lupton Formation in outcrop is constrained only by the underlying Townsend Quartzite and Lefroy Formation, and the regionally overlying Phanerozoic Table Hill Volcanics.

In 1999, GSWA Vines 1, 24 km south of the Musgrave Complex, intersected 2 km of a ?Lower Cambrian siliciclastic succession defined as the Vines Formation by Stevens et al. (2002a,b). This includes about 1.4 km of matrix-supported conglomerate to clast-bearing mudstone (diamictite). The Lupton Formation could correlate with either the Marinoan diamictite (Wahlgu and Boondawari Formations) if a glacial origin is assumed, or with the Vines Formation on lithology and proximity.

Distribution and thickness: The Lupton Formation is part of a southwesterly dipping succession exposed along the southern margin of the Musgrave Complex on TALBOT and COOPER. The succession is very poorly exposed, and was originally measured at only two field sections. Re-examination of the type locality suggests the type section is 69 m thick (not 240 m as originally indicated by Jackson and van de Graaff, 1981), but neither the stratigraphic base nor top is exposed. At Ainslie Gorge, 140 km to the west, the formation is 250 m thick and quite different lithologically. The diamictite is about 15 m thick at outcrops in the Lupton Hills (Grey et al., 1999), whereas all 250 m exposed at Ainslie Gorge is diamictite (Jackson and van de Graaff, 1981, fig. 13). This raises the possibility that the only true Lupton Formation is in the type area, and that the Ainslie Gorge succession is a different unit of unknown relationships.

The interval in Empress 1 and 1A was recorded as '?Lupton Formation' by Carlsen et al. (1999), Stevens and Apak (1999), Grey et al. (1999), and Apak and Moors (2000a,b), but is here assigned to the Wahlgu Formation. Similarly, intersections of probable Marinoan glacigene rocks (Supersequence 3) elsewhere in the basin are also here assigned to the Wahlgu Formation rather than the Lupton Formation, because of the greater age control associated with the section in Empress 1A. Perincek (1998) assigned the interval from 59 to 95.1 m (TD) in BMR Talbot 5 to the Lupton Formation, noting conglomeratic mudstone in a core at the base of the hole. This section has no age constraints, and could be Lupton Formation.

In summary, the Lupton Formation is now recognized only in widely spaced outcrops south of the Musgrave Complex on TALBOT and COOPER and in BMR Talbot 5.

Type section or area: The type section of the Lupton Formation (Fig. 25) is at Lupton Hills on central COOPER (MGA Zone 52, 404800E 7063970N). Jackson and van de Graaff (1981) described the type section as being 240 m thick, but failed to note a synclinal axis in the outcrop. This reduces the exposed thickness to 69 m (Grey et al., 1999; see also Fig. 25). The section through the Lupton Formation south of Ainslie Gorge (immediately south of the type section of the Lefroy Formation) illustrated by Jackson and van de Graaff (1981, fig. 13) is here designated as a reference section, with the modification that the contact between the Lefroy Formation and the Lupton Formation is revised downward from 610 to 600 m, and the contact is inferred to be unconformable (Fig. 9).

Lithology: The Lupton Formation contains diamictite, cross-bedded sandstone, and minor siltstone (Jackson

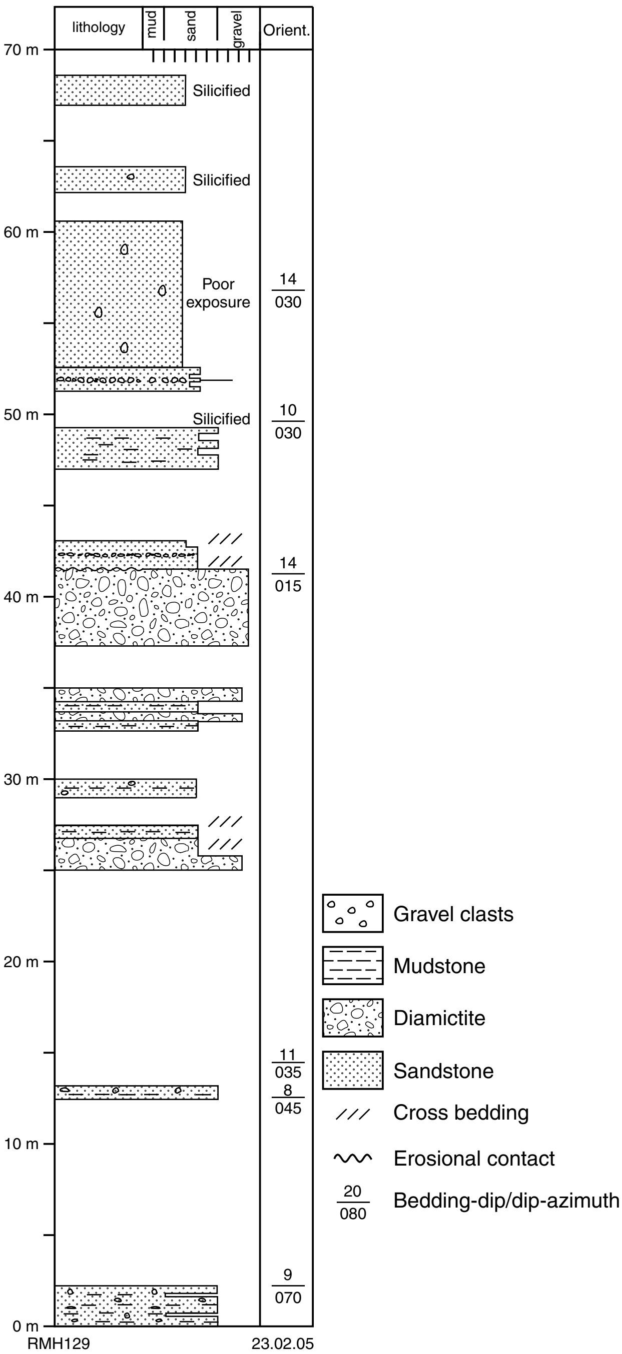

Figure 25. Type section of Lupton Formation, Lupton Hills, after Grey et al. (1999, fig. 3). Interpreted environments follow Stevens et al. (2002a,b)

and van de Graaff, 1981). Earlier authors referred to the formation as a ‘tillite’, but there is only limited evidence of glacial influence, and the rock type is better described as a diamictite (Grey et al., 1999).

The type locality at Lupton Hills consists of a lower unit of massive, very poorly sorted pebble to boulder conglomerate, overlain by an upper unit of interbedded conglomerate, sandstone, and siltstone. Outcrops elsewhere are mostly fine-grained diamictite with scattered large boulders, and interbedded fine-grained, well-bedded sandstone and coarse-grained, cross-bedded sandstone (Jackson and van de Graaff, 1981). There are rare faceted and striated clasts.

The basal part of the Lupton Formation in the Ainslie Gorge area is very different from the succession at Lupton Hills. It consists of an apparent gradation from the laminated siltstone of the Lefroy Formation to indistinctly bedded siltstone with isolated cobbles and boulders up to 0.4 m in diameter. The siltstone is overlain by a thick succession of mostly fine grained diamictite with scattered larger boulders. As discussed under **Lefroy Formation** (above), an unconformity is inferred at about 600 m in Jackson and van de Graaff’s (1981) section at Ainslie Gorge.

Southeast of Ainslie Gorge there is a folded succession of diamictite, fine-grained, well-bedded sandstone, and coarse-grained, cross-bedded sandstone that contains isolated boulders of granite and quartzite up to 0.9 m in diameter. Clasts of oolitic chert were reported from near the Hocking Range (Daniels, 1974).

Relationships and boundary criteria: The lower contact is not generally exposed. Although it appears conformable in the Ainslie Gorge area, the juxtaposition of the Lefroy Formation with a glacigene unit, when glacigene rocks are not recorded elsewhere in the Officer or Amadeus Basins in the lower Buldya Group, indicates an unconformable relationship with a significant age difference. Elsewhere clasts of Townsend Quartzite, oolitic chert, and other rocks suggest that the contact is unconformable. The upper contact is not seen.

Age and correlation: There is no internal evidence for the age of the Lupton Formation. It is unclear whether the Lupton Formation in the type area and at Ainslie Gorge is related to Sturtian or Marinoan glaciation, or to parts of the Vines Formation.

A large canyon incised through the Lefroy Formation and Townsend Quartzite into the uppermost unit of the Mesoproterozoic Mission Group of the Musgrave Complex can be inferred on Landsat imagery in the region of Ainslie Gorge on TALBOT. The interpreted strike-length of this feature is about 15 km, with Ainslie Gorge located at its northwestern edge. The canyon may correlate with the canyon-cutting event in the eastern Officer Basin (Morton and Drexel, 1997). If the infill is Lupton Formation, then the Lupton Formation may correlate with the Narana Formation (Supersequence 4) in the eastern Officer Basin. Alternatively, the cutting and infill could be related to the Permian Paterson Formation.

Depositional environment: The depositional setting of the Lupton Formation is equivocal. It is probably glacigene, but could be simply an alluvial fan to fluvial deposit related to uplift of the Musgrave Complex.

References: Apak and Moors (2000a,b), Cockbain and Hocking (1989), Grey et al. (1999), Iasky (1990), Phillips et al. (1985), Stevens and Apak (1999), Stevens et al. (2002a,b).

Turkey Hill Formation

Definition and nomenclature: The 'Turkey Hill Beds', first described by Gower and Boegli (1977), were later named (after Turkey Hill on northeast RASON) and described by Jackson and van de Graaff (1981). The name was amended by Cockbain and Hocking (1989). The Turkey Hill Formation is here revised to incorporate changes to the type locality, distribution, and possible age of the formation.

Distribution and thickness: The Turkey Hill Formation is exposed at the type locality at Miller Soak on northeast RASON, and was previously mapped near Munjil Soak on north-central RASON, near the southwestern margin of the Gunbarrel Basin. It has only been recognized in this region. Locally, the succession is steeply dipping (up to 65°, more commonly 10 to 30°). An isolated outcrop 2 km north of Munjil Soak, previously assigned to the Turkey Hill Formation, was examined in 1998 by MKS, who interpreted it as extremely weathered, foliated granite. The Turkey Hill Formation has not been penetrated by any drillholes. From the known dips and extent of outcrop, the Turkey Hill Formation is at least several hundred metres thick, particularly in the region of Miller Soak (Jackson and van de Graaff, 1981).

Type locality: Miller Soak on RASON (MGA Zone 51, 625320E 6884870N). No section has been measured here; it is a type locality only.

Lithology: The Turkey Hill Formation comprises sandstone, siltstone, and mudstone, and possibly diamictite (see below). Gower and Boegli (1977) first described glacial deposits at Miller Soak on northeast RASON, but were uncertain whether they were Permian or Proterozoic, as relationships of glacial material with either flat-lying Permian rocks or dipping ?Proterozoic rocks could not be established. Jackson and van de Graaff (1981) described the same succession as moderately to steeply dipping sandstone faulted against diamictite containing lenses of dipping sandstone and siltstone beneath subhorizontal glacigene Paterson Formation. As the diamictite appeared to be structurally related to the sandstone, they included it in the Turkey Hill Formation. Van de Graaff's original field notes are equivocal as to whether the diamictite is Permian or Proterozoic, but preferred a Proterozoic age. Re-examination of the type locality by MKS, GMC, and SNA during the present study found a sequence of steeply dipping and faulted mudstone, coarsening upward to typically fine-grained, cross-bedded quartz sandstone. They did not recognize diamictite that was unequivocally within the dipping succession. Instead, the diamictite at Miller Soak was interpreted as part of the overlying Permian Paterson Formation.

Northwest of Miller Soak, the Turkey Hill Formation consists of medium-bedded sandstone, siltstone, and mudstone.

Relationships and boundary criteria: The basal contact is not exposed. The Permian Paterson Formation unconformably overlies the Turkey Hill Formation at the type locality.

The GA/GSWA/pmdCRC deep crustal seismic line 01AGS-NY1 passes about 8 km north of the Turkey Hill Formation at the type locality. In this area, near-horizontal reflectors are present down to a major reflector at 0.2 seconds TWT, which is interpreted to be crystalline basement at a depth of about 300 m (if a near-surface velocity of 3000 m/s is assumed). The near-horizontal reflectors above 0.2 seconds could be entirely from the Gunbarrel Basin, or also include Officer Basin strata. Farther to the east along the seismic line a group of reflectors unconformably underlies this seismic package as basement deepens. It cannot be established whether these deeper and more-deformed strata are of Neoproterozoic or Mesoproterozoic age.

Age and correlation: There is no internal evidence for the age of the Turkey Hill Formation, and its stratigraphic position is problematical. It was originally regarded as equivalent to the Lupton Formation (Jackson and van de Graaff, 1981), but if the diamictites are not part of the Turkey Hill Formation, this correlation is less probable. The steep dips and extent of the structuring suggest a Proterozoic age, but given the location of the outcrops, they could be the same sequence (probably Mesoproterozoic) as at the base of NJD 1 (Hocking, 2003) rather than Neoproterozoic. If Jackson and van de Graaff's (1981) preferred interpretation of the outcrops is correct, the glacial influence invites correlation with other, probably Marinoan, glacial units of the Officer Basin.

The overall coarsening-upward clastic succession is interpreted as a shallowing-upward shallow-marine shelf depositional environment. There is a similarity in both gross lithology and depositional environment between the Turkey Hill Formation and the unnamed sandstone that overlies the Wahlgu Formation in Empress 1A. Thus, a tentative post-Marinoan glaciation age (i.e. basal Ediacaran) is possible for this formation.

Depositional setting: The coarsening-upward succession noted by MKS and others may be a deltaic progradation, in a shallowing-upward marine to coastal setting. If diamictite is present within the formation, this could reflect either floating ice shelves, or mass-flow deposits unrelated to glaciation.

References: Gower and Boegli (1977), Jackson and van de Graaff (1981), Cockbain and Hocking (1989), Iasky (1990).

Lungkarta Formation

Definition and nomenclature: The Lungkarta Formation is a sandstone-dominated, mixed siliciclastic unit that rests on Wahlgu Formation and possibly Mason Conglomerate, and is locally overlain by Table Hill Volcanics. The formation is named after drillhole Lungkarta 1, although the identification of Lungkarta Formation in this drillhole is now questionable after the drilling of Lancer 1 (see *Distribution and thickness*). The formation was referred to in earlier reports of the current phase of study as 'McFadden Formation equivalent' (Apak and Moors, 2000a,b, 2001; Moors and Apak, 2002; Apak and Carlsen, 2002), but as Lungkarta Formation by Haines et al. (2004).

The Lungkarta Formation is widely recognized on seismic sections and in some drillholes, but has not so far been identified in outcrop. In Hussar 1, Lungkarta 1, and Kanpa 1A, the formation was initially referred to as the 'Babbagoola beds' (Townson, 1985; Phillips et al., 1985) or 'Babbagoola Formation' (Cockbain and Hocking, 1989). Part of the 'Babbagoola Formation', including the type section, is now known to be part of the Buldya Group (Grey and Cotter, 1996; Perincek, 1998), but the remainder of the unit originally referred to the Babbagoola Formation is apparently younger than this. Based mainly on its relative stratigraphic position, Perincek (1998) correlated this younger interval with outcrop of the McFadden Formation in the northwestern Officer Basin. Apak and Moors (2000b, 2001) supported this correlation with some modification and referred to the unit as the 'McFadden Formation equivalent' because continuity with unequivocal outcrops of McFadden Formation could not be demonstrated. This argument is accepted here, and the name Lungkarta Formation proposed and defined.

Distribution and thickness: The Lungkarta Formation has been penetrated in Hussar 1 (159–?707 m), Kanpa 1A (658–829 m), Lancer 1 (205–344.3 m), and 90 RCHE 003 (134–150 m, TD). Moors and Apak (2002) placed the top of the Lungkarta Formation at 101 m in Hussar 1, but this is revised to 159 m here after comparison with the section in Lancer 1. The interval from 101 to 159 m in Hussar 1 is tentatively assigned to the Durba Sandstone.

The lower boundary in Hussar 1 is tentatively placed at 707 m, rather than 560 m as suggested by Moors and Apak (2002), although it could also be placed at 647.5 m. The interval between 560 and 707 m bears greater similarity in described lithology and correlated thickness to the Lungkarta Formation in Lancer 1 (Haines et al., 2004) than to the Wahlgu Formation, to which it was previously assigned by Moors and Apak (2002). Note that Perincek (1998) earlier assigned the 647.5–892 m interval to the 'McFadden Formation', and the interval from 101 to 647.5 m (now mostly Lungkarta Formation) to an 'unnamed unit'.

Perincek (1998) assigned the interval in Lungkarta 1 between the Table Hill Volcanics (base 704 m) and the Kanpa Formation (top 809 m) to the 'McFadden Formation'. Moors and Apak (2002, fig. 22) followed this interpretation but failed to distinguish the Table Hill Volcanics between 540 and 704 m. Lithological descriptions of the interval between 704 and 809 m are more suggestive of the Wahlgu Formation than the Lungkarta Formation. The interval consists of brown and grey shale below a sandstone unit, as is seen in the Wahlgu Formation and the Boondawari Formation in outcrop. The 704–809 m interval is therefore assigned to the Wahlgu Formation, although the identification is by no means unequivocal, especially for the upper, sandy unit below the Table Hill Volcanics.

The interval from 169 to 205 m in Lancer 1, although initially placed in the Lungkarta Formation by Haines et al. (2004), is here placed in the Durba Sandstone after examination of the Durba and Diebil Hills.

Seismic data indicate that the Lungkarta Formation is widespread in the western Officer Basin. Apak and Moors (2001) recognized a lower and an upper member in the Lungkarta Formation (referred to by them as 'McFadden Formation equivalent') in the Lennis area, with a composite thickness of up to 1200 m, separated by a relatively prominent seismic reflector ('intra-McFadden Formation equivalent' reflector). They noted the lower member varied considerably in thickness, as a result of contemporaneous salt movement and salt walls, whereas the upper member showed more uniform depositional conditions, with some post-depositional erosion adjacent to salt walls. There are no wells intersecting the unit in this area, so it is difficult to confidently indentify and extend seismic reflectors. There is reasonable seismic control for extending the upper member to areas with well control, but the lower member remains recognized only on seismic lines, with no close ties to well intersections or outcrop. The 'intra-McFadden Formation equivalent' reflector of Apak and Moors (2001) may instead mark an unconformity at the base of the Lungkarta Formation, and the lower member may correlate with sandstone intervals that overlie the cap dolomite in the upper Boondawari Formation in outcrop in the northwest Officer Basin (i.e. the lower interval is a high part of Supersequence 3, rather than the earliest phase of Supersequence 4). The unnamed sandstone in Empress 1A above the cap dolomite of the uppermost Wahlgu Formation could correlate either with Apak and Moors' (2001) lower member, or with unequivocal Lungkarta Formation (the upper member).

Sections in BMR Westwood 1 (sandstone, 74–85.34 m, TD) and BMR Westwood 2 (dominantly claystone, 87–101.5 m, TD) are problematical. They were assigned initially to the 'Babbagoola Beds', a name that Perincek (1998) dropped in favour of the McFadden Formation. They could be Lungkarta Formation, or belong to older lithostratigraphic units. We tentatively accept the interpretation of Perincek (1998) for BMR Westwood 1, but not for BMR Westwood 2 because of the dissimilar lithology.

Sections in Mason 1 (171–230.6 m) and 2 (91–143 m) and NRH 3 (176–224.0 m, TD) were initially assigned to the 'Babbagoola Beds' by Ellis (1981). The section in Mason 1 appears conformable on the Mason Conglomerate, which in turn appears conformable on the Ilma Formation. If the Ilma Formation is part of the Buldya Group (as is likely, based solely on lithology, see **Ilma Formation** above), then the intersections in Mason 1 and 2 and probably NRH 3 are also Buldya Group. Ellis (1981) described the lithology as reddish brown, fine-grained sandstone overlying grey calcareous sandstone with evaporitic indications and thin siltstone interbeds. This description fits much of the Buldya Group, so these intersections are here tentatively considered as undivided Buldya Group.

In Weedy 1, Perincek (1998) assigned a basalt unit to the Table Hill Volcanics, and an underlying sandstone and mudstone unit to the 'McFadden Formation'. However, if the K–Ar ages of 657 ± 8 and 640 ± 10 Ma (Nelson, 2002) on the basalt are correct, the basalt is not the Table Hill Volcanics, and the sandstone and mudstone section is an older Neoproterozoic unit.

Type section or area: The section in Hussar 1 (159–560 m) is the thickest known section but is not cored. For that reason, the section in Lancer 1 from 205 to 344.3 m (139.3 m) is designated as the type section (Fig. 26), although it is thinner and possibly less complete than the section in Hussar 1. None of these sections penetrates the ‘lower Lungkarta Formation’ in the Lennis area, discussed above.

Lithology: The Lungkarta Formation contains sandstone, with lesser amounts of siltstone, mudstone, evaporite pseudomorphs, and minor gypsum. The type section consists of 139.3 m of sandstone, with minor interbedded conglomerate and mudstone. Several conglomerate beds are present near the base, and the interval between 214 and 344.3 m is dominated by sandstone with cross-bed sets at least 30, and possibly 40 m thick, inviting comparison with the giant cross-bedding seen at Durba and Diebil Hills in exposures of the McFadden Formation. The interval above 214 m is horizontally bedded and cross-bedded, but at far smaller scale (Haines et al., 2004). The reference section in Hussar 1 appears to be similar, in that it is described as sandstone with minor interbedded conglomerate and mudstone, but the sedimentary structures are unknown. Kanpa 1A contains sandstone with minor dolomite, and 90RCHE 003 and BMR Westwood 1 intersected only sandstone.

Relationships and boundary criteria: The Lungkarta Formation unconformably overlies the Wahlgu Formation in Hussar 1 and Lancer 1, and the Steptoe Formation in Kanpa 1A. In Lancer 1, the only cored intersection, the break is erosional and disconformable rather than angularly unconformable (Haines et al., 2004).

The Lungkarta Formation is overlain by probable Durba Sandstone in Lancer 1 and Hussar 1, with a hiatus of unknown duration. Elsewhere, Palaeozoic or younger rocks unconformably overlie the Lungkarta Formation. In BMR Westwood 1, the Lungkarta Formation is unconformably overlain by 74 m of basalt assigned to the Table Hill Volcanics.

Age and correlation: There is no conclusive evidence for the age of the Lungkarta Formation other than its relative stratigraphic position. Correlations and interpretations of a Cambrian age made by Jackson and Muir (1981) based on material from Throssell 1 and Yowalga 2 are not valid (see ‘*Babbagoola Formation*’ under **Kanpa Formation**). As the Lungkarta Formation overlies the Wahlgu Formation in Hussar 1, it must be younger than the Marinoan glaciation, and therefore younger than c. 600 Ma.

An upper age constraint is provided in Westwood 1, where basalts of the Table Hill Volcanics overlie the Lungkarta Formation. The Table Hill Volcanics in Empress 1 and 1A (which may rest on Lungkarta Formation; see **Unnamed sandstone**, above) were dated as Early Ordovician from a K–Ar age of 484 ± 4 Ma (Amdel, 1999; Stevens and Apak, 1999), although this is probably an alteration age as more robust dates of c. 510 Ma are recorded elsewhere for correlative igneous rocks (Hanley and Wingate, 2000; Wingate, M. T. D., 2002, written comm.).

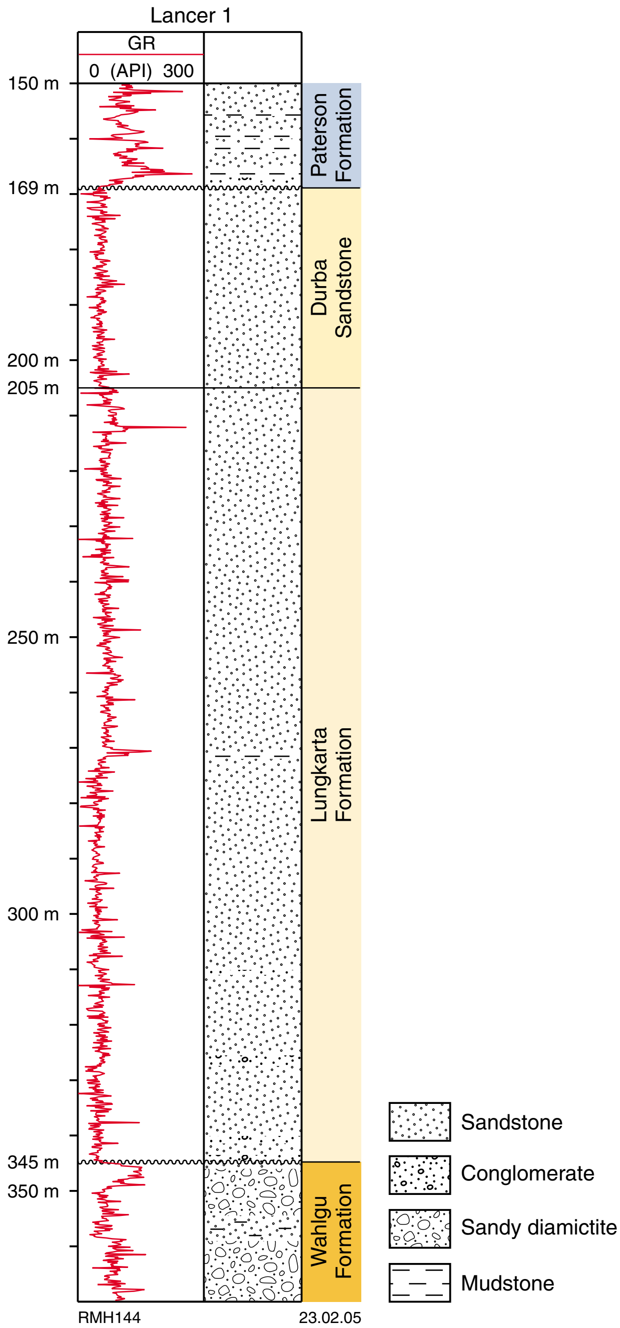

Figure 26. Type section, Lungkarta Formation, Lancer 1

The very similar lithology and stratigraphic position of the Lungkarta and McFadden Formations strongly imply they are correlatives, although continuity from exposed McFadden Formation to subcropping Lungkarta Formation in drillholes cannot be demonstrated.

Depositional setting: In Lancer 1, the Lungkarta Formation is clearly an eolian dune deposit, with minor interdune deposits, preserved as thin conglomerate layers, and some playa-lake deposits (Haines et al., 2004). Thin fluvial intercalations are present in the lower Lungkarta Formation in Lancer 1 (Haines et al., 2004). Other intersections here accepted as Lungkarta Formation are compatible with this interpretation.

References: Jackson and van de Graaff (1981), Jackson and Muir (1981), Townson (1985), Phillips et al. (1985), Perincek (1998), Carlsen et al. (1999), Apak and Moors (2000b, 2001).

Punkerri Sandstone

Definition and nomenclature: The name 'Punkerri Beds' was proposed by Major (1974) after Punkerri Hills in South Australia, and amended to Punkerri Formation by Cockbain and Hocking (1989). A description of the 'Punkerri Beds' in Western Australia was published by Jackson and van de Graaff (1981). The unit was referred to as the Punkerri Sandstone by Zang (1995b), and formally defined in Morton and Drexel (1997).

Distribution: The main outcrop belt of the Punkerri Sandstone is in the Birksgate Sub-basin, on BIRKSGATE and LINDSAY in South Australia, but the unit extends to the northeast corner of WAIGEN, COOPER, and possibly central TALBOT in Western Australia. The formation is more than 1200 m thick in South Australia (Jackson and van de Graaff, 1981; Morton, 1997), and Jackson and van de Graaff (1981) measured a section in the Patricia Johnson Hills (WAIGEN) about 600 m thick. A section was measured in the same area during the present study.

Type section or area: Major (1974) defined the type section as being across the southern flank of the Punkerri Hills (MGA Zone 52, 639700E 6939000N) on eastern BIRKSGATE.

Lithology: The Punkerri Sandstone consists of pink quartzite and feldspathic sandstone, siltstone, and minor conglomerate and oolitic carbonate. The formation consists of two units at Punkerri Hills: a lower purple or red-brown, medium-grained, micaceous, flaggy quartzose sandstone, at least 265 m thick, and an upper unit of white, pink, and red feldspathic and quartzose sandstone with minor interbedded red siltstone, which is at least 935 m thick (Major, 1974). The upper unit contains Ediacara fauna fossils (Daily, 1964; Jenkins and Gehling, 1978).

Two units are also present on northeast WAIGEN (Jackson and van de Graaff, 1981): a lower, parallel-bedded to (near the top) cross-bedded, reddish brown sandstone unit about 200 m thick; and an upper, mostly parallel-bedded quartz arenite unit about 400 m thick with some fine-grained sandstone and siltstone intercalations.

Relationships and boundary criteria: Neither the lower nor upper contact is exposed. They are inferred to be regional disconformities. Major (1974) inferred that the Punkerri Sandstone was disconformable on the Wright Hill Formation in South Australia, based on the presence of oolitic chert pebbles probably derived from the Wright Hill Formation in the base of the Punkerri Sandstone. The 'Wirrildar beds' (middle Marla Group) in South Australia overlies the Punkerri Sandstone. No outcrops of this unit are known in Western Australia, but it may underlie low calcrete mounds on the state border (Jackson and van de Graaff, 1981).

Age and correlation: No radiometric dating or palynology has been carried out on the Punkerri Sandstone.

In South Australia, the Punkerri Sandstone contains poorly preserved Ediacara assemblage fossils that are considered to be latest Neoproterozoic (c. 565 Ma) in age. In 1964, J. E. Johnson discovered several fossils (identified as *Rangea arborea*, *Charnia*, *Tribrachidium heraldicum*, *?Charniodiscus* and a 'double spiral'; Daily, 1964) at the northern end of the Punkerri Hills (Major, 1974). Jenkins and Gehling (1978) re-examined some of the specimens, and Glaessner (1984) subsequently noted the locality. They dismissed one specimen as inorganic. However, a second appears similar to *Charniodiscus,* although it is too poorly preserved to be properly identified. The specimens are from scree, but were apparently derived from the upper Punkerri Sandstone. The presence of Ediacara fauna indicates correlation with the Rawnsley Quartzite (Adelaide Rift Complex) and the lower Arumbera Sandstone (Amadeus Basin).

Depositional setting: The Punkerri Sandstone was deposited mostly in a tidally influenced, shallow-marine setting, based on lithology, fauna and sedimentary structures. The presence of conglomeratic sandstone (Jackson and van de Graaff, 1981) may indicate some fluvial deposition. Morton (1977) suggested that the depositional setting for the Punkerri Sandstone in South Australia was similar to that of the Pound Subgroup.

References: Thomson (1969), Major (1974), Jackson and van de Graaff (1981), Jenkins and Gehling (1978), Pitt et al. (1980), Zang (1995b), Morton (1997).

Vines Formation

Definition and nomenclature: The Vines Formation (Stevens et al., 2002a,b) consists of matrix-supported conglomerate and poorly sorted to unsorted siliciclastic rocks (diamictite), with subordinate finer grained siliciclastic rock types (Apak et al., 2002b). The formation was named after GSWA Vines 1 drillhole on the VINES 1:100 000 map sheet, and fully defined by Stevens et al. (2002b). The unit is known only from Vines 1, from 4 to 2017.5 m total depth, and is the only dominantly conglomeratic unit of latest Neoproterozoic – early Cambrian age in the western Officer Basin. There is no known synonymy.

Distribution, thickness, and relationships: The Vines Formation has been recognized only in Vines 1 from 4 to 2017.5 m, where the well reached total depth (2013.5 m drilled thickness). It is greater than 2003 m stratigraphic thickness assuming an average structural dip of 5° (Apak et al., 2002b; Stevens et al., 2002).

Within the Officer Basin, the Vines Formation could correlate with the Lupton Formation (based on lithological similarity alone), or perhaps the upper parts of the Lungkarta or McFadden Formations (based on all three units being generated by the Petermann or Paterson Orogenies), or with one of several formations in South Australia that formed during or immediately after the Petermann Orogeny (e.g. Wallatinna Member, Observatory Hill Formation). The most likely correlative in both age and rock type from the Amadeus Basin is the Mount Currie Conglomerate (Yulara area).

Type section: The type section and only known intersection is in Vines 1 (Fig. 27) from 4 to 2017.5 m total depth (cuttings from 4 to 44.5 m; fully cored from 44.5 to 2017.5 m; core and cuttings are stored by GSWA). There is no outcrop at the drillsite.

Lithology: The Vines Formation consists of sandstone, diamictite, siltstone, shale, mudstone, conglomerate, and rare thin interbeds of carbonate and evaporitic rocks. Six informal units were recognized in Vines 1 within a single conformable succession (Apak et al., 2002b; Stevens et al., 2002a,b). All six units, numbered upward from unit 1, are a mixture of sandstone, conglomerate (in part diamictite), and siltstone, with units 1 and 5 containing less conglomerate than other units. The differentiation of these units is based primarily on changes in lithology observed in the core and to a lesser extent on wireline-log character. All units are conformable. The upper contacts of units 1, 3, and 5 are sharp, whereas the upper contacts of units 2 and 4 are gradational. Clast composition indicates gradual changes in provenance upwards through the formation, from sedimentary to igneous and metamorphic, perhaps reflecting unroofing of the Musgrave Complex.

Age and correlation: The Vines Formation contains only reworked palynomorphs and some recent contaminants, such as pollen grains and woody fragments (K. Grey *in* Apak et al., 2002b; Grey, 2002). Two significant palynological components are recognized, both of which span the entire drillhole and both of which are mechanically abraded.

The older component includes palynomorphs diagnostic of a mid-Neoproterozoic age (mid- to late Cryogenian, c. 750 to 700 Ma). It is present in several wells in the Officer Basin in rocks in the upper Buldya Group (from the middle Hussar Formation upward into the Kanpa and Steptoe Formations; Hill et al., 2000b) and is characterized by fragments of *Cerebrosphaera buickii*. Specimens are present throughout Vines 1, and nearly all specimens are severely fragmented and degraded, indicating extensive reworking.

The younger component consists of unnamed acritarchs that are lighter in colour than those unequivocally assigned to the older component (see above), and have more highly developed excystment structures, indicating that they are probably no older than earliest Cambrian. From their taphonomy and preservation, most specimens are badly corroded, which suggests that they too have been subjected to reworking and therefore indicates that sedimentation was later than earliest Cambrian. Some elements of this assemblage have been recorded (but not described) from the western and eastern Officer Basin and the Georgina Basin (Cotter, 1997, 1999; Gravestock et al., 1997; Grey, 1998; Grey and Cotter, 1996). They are present in the Narana Formation, probably in younger formations of the eastern Officer Basin, and in the Elkera and Central Mount Stuart Formations of the Georgina Basin, and probably range upward into the earliest Cambrian.

The younger component indicates a maximum age of earliest Cambrian for the reworked assemblage and, consequently, the Vines Formation. Other limitations suggest an age not much younger than earliest Cambrian.

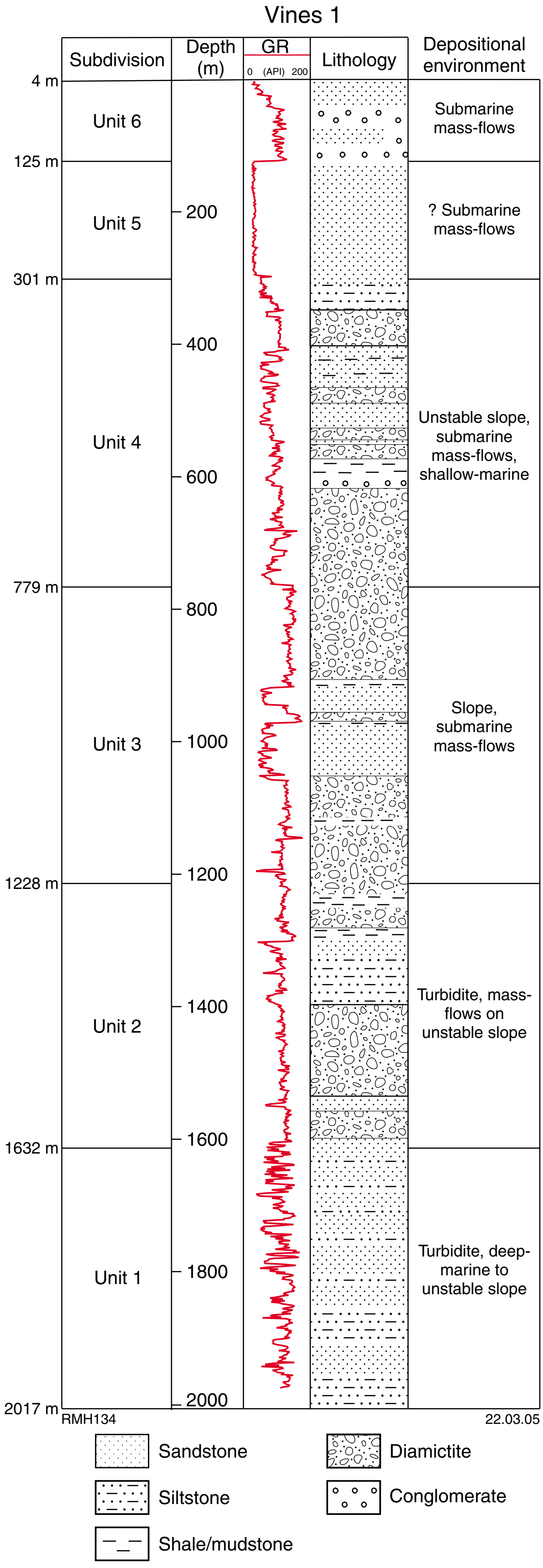

Figure 27. Type section, Vines Formation, Vines 1

Cambrian and younger successions in drillholes in the eastern Officer Basin commonly contain fossils such as trilobite fragments, sponge spicules, archaeocyathids, and distinctive acritarch species (Gravestock et al., 1997). None of these have been observed in Vines 1.

Sedimentary zircon grains from 307.84 to 309.29 m have a youngest weighted mean Pb–U SHRIMP date of 658 ± 8 Ma (Nelson, 2002), providing a maximum age for deposition of the Vines Formation. No sediments of this age are known in the western Officer Basin, but the age is very similar to K–Ar ages of 657 ± 8 and 640 ± 10 Ma (Nelson, 2002) for basalt in Weedy 1 on eastern JUBILEE.

A mean palaeomagnetic pole for rocks above 1900 m is consistent with Australian palaeomagnetic poles from the late Neoproterozoic to Cambrian, approximately 610–540 Ma (S. Pisarevsky, *in* Apak et al., 2002b).

Depositional setting: Stevens et al. (2002) considered that the succession in Vines 1 represented a single major regressive cycle from turbiditic deep-marine to unstable slope deposits at the base, grading up through diamictite-dominated submarine mass-flows on an unstable slope at 1632 m, to sandstone-dominated submarine mass-flows above about 301 m. No significant sedimentary breaks are recognized within the 2 km-thick succession intersected in Vines 1. The succession indicates significant tectonic instability along the southern margin of the Musgrave Complex throughout deposition.

References: Stevens et al. (2002a,b), Apak et al. (2002b).

Northwestern Officer Basin

The sedimentary succession now assigned to the northwestern Officer Basin (north of the Earaheedy, Scorpion, and Salvation Basins and east of the Pilbara Craton and Collier Basin) was originally included in the Bangemall Basin by Bunting et al. (1982) and Muhling and Brakel (1985). These rocks were later recognized as a distinct younger succession, probably of Neoproterozoic age, and the Savory Group and Savory Basin (named after Savory Creek) were defined to embrace them (I. R. Williams, 1989, 1990a, 1992, 1995a,b; Williams and Tyler, 1991). Bagas et al. (1995) pointed out that the Tarcunyah and Savory Groups were probably correlatives of the Officer Basin succession and probably should be included in a single tectonic unit. Perincek (1996a,b) and Stevens and Carlsen (1998) included the Savory Group and Basin in the Officer Basin. Bagas et al. (1999) noted that the Savory Group contained an unconformity of about 150–200 m.y. duration, abandoned both the group and the basin, and proposed the Sunbeam Group for the lower 'Savory Group' and the Disappointment Group for the upper 'Savory Group', with the Boondawari Formation and Durba Sandstone as ungrouped units. Hocking et al. (2000a) extended the Sunbeam Group to include the Coonabildie Formation, formerly of the Kahrban Subgroup (Muhling and Brakel, 1985), but subsequent dating of dolerite sills intruding the unit (Wingate, 2002; Nelson, 2002) established it to be an older succession, which Hocking and Jones (2002) assigned to the Salvation Group.

The outcome of these revised correlations is the excision of all of the oldest sequence recognized by Williams (1992) from the Officer Basin succession. The Coonabildie, Brassey Range, Glass Spring, and Jilyili Formations are part of the Salvation Group, with a minimum age of 1080 Ma (Wingate, 2002; Nelson, 2002), rather than Neoproterozoic. They probably correlate with the Collier Group. The northwestern Officer Basin contains the amended Sunbeam Group, the Boondawari Formation, the Disappointment Group, and the Durba Sandstone. The Ward and Oldham Inliers are older Mesoproterozoic inliers (Hocking et al., 2000b) near, or at the southern edge of, the northwestern Officer Basin.

Neoproterozoic palynomorphs have been recorded from sandstone mapped as Brassey Range Formation in a syncline near Trainor water bore 6 (Grey and Stevens, 1997). This syncline lies to the north of the main zone of outcrop of the Brassey Range Formation, and is here tentatively assigned to the Spearhole Formation.

Sunbeam Group

Definition and nomenclature: The Sunbeam Group (Bagas et al., 1999) includes the Watch Point, Coondra, Spearhole, Mundadjini, and Skates Hills Formations, and was named after Sunbeam Creek on TRAINOR. Descriptions below are derived mainly from Williams (1992). The Sunbeam Group is equivalent to Williams' (1992) Depositional Sequence B. Most formations now placed in the Salvation Group were originally included in the Sunbeam Group, but were excised after radiometric dating indicated they were part of an older succession (Hocking and Jones, 2002).

The Sunbeam Group incorporates most of the older part of the former 'Savory Group' (Williams, 1992, 1994), and is found in the northwestern Officer Basin — formerly the 'Savory Basin'. The cumulative thickness of the group is about 4000–5000 m. Although parts of some formations can be correlated with parts of the Buldya Group, direct correlation between other parts of the two groups has not been established, and for this reason separate terminology is retained for the two areas.

Williams (1992, p. 18, 22, 27) reported a regional disconformity to unconformity between the Spearhole Formation and the Jilyili, Glass Spring, and Brassey Range Formations. Although this was originally interpreted as being mainly a disconformity or localized unconformity, it is now apparent that this is the unconformity between the Salvation and Sunbeam Groups.

Age: The age of the Sunbeam Group is based on stratigraphic position and the recognition of the *Acaciella australica* Stromatolite Assemblage in the Skates Hills Formation, near the base of the group. *Acaciella australica* and *Basisphaera irregularis* are common in the Skates Hills Formation, and indicate correlation with the Browne Formation of the southwestern Officer Basin, the Bitter Springs Formation of the Amadeus Basin, the Yackah beds of the Georgina Basin, and the Coominaree Dolomite of the Adelaide Rift Complex (Grey, 1995a; Hill et al., 2000b). Palynological studies also support these correlations (Grey and Cotter, 1996; Stevens and Grey, 1997; Hill et al., 2000b). The Coominaree Dolomite is older than the Rook Tuff and the Wooltana Volcanics of the Adelaide Rift Complex, so the Skates Hills Formation is inferred to be older than about 800 Ma and possibly older than 827 Ma — the age of the Gairdner Dyke Swarm. The Sunbeam Group is overlain by the Boondawari Formation, which has an inferred age of about 600 Ma by correlation with Marinoan glaciations elsewhere in Australia.

Correlation: With the exception of the Skates Hills Formation, correlation between the Sunbeam Group and the Buldya Group is based on lithological comparison. The lower Skates Hills Formation is a correlative of the Woolnough Member of the Browne Formation, based on stromatolite biostratigraphy. Sandstone in the upper part of the Skates Hills Formation may be a lateral equivalent of the Hussar Formation. The Mundadjini Formation is partly evaporitic, apparently laterally equivalent to the Skates Hills Formation, and probably corresponds at least in part to the Browne Formation of the southwestern Officer Basin. Correlation between basal sandstone units of the two groups remains problematic. The different formations may represent a series of alluvial to coastal systems around the margin of the basin, but their relative ages are not known, so it is difficult to be certain whether the Watch Point, Coondra, and Spearhole Formations correlate with the Townsend Quartzite and Lefroy Formation of the southwestern Officer Basin.

References: Williams (1990a, 1992, 1994), Grey (1995), Bagas et al. (1995, 1999), Hocking and Jones (2002).

Watch Point Formation

Definition and nomenclature: The Watch Point Formation is one of several sandy formations recognized at the base of the Sunbeam Group, and consists of fine- to medium-grained sandstone, siltstone, and shale. Williams and Tyler (1991) named the formation, after Watch Point on ROBERTSON, and rocks assigned to the formation were previously described by Muhling and Brakel (1985) as either Backdoor Formation or Balfour Shale. Williams (1992) considered the Watch Point Formation to be transitional between his Depositional Sequences 1 and 2, and there are significant westward palaeocurrents, so it is possible that the Watch Point Formation is part of the older Salvation Group rather than the Sunbeam Group.

Distribution and thickness: The formation extends along the northwestern margin of the Officer Basin, north of the Spearhole Formation and south of the Coondra Formation, and is up to 400 m thick (Williams, 1992).

Type section: Williams (1992) defined a type area 6.5 km east-southeast of Robertson Range homestead (MGA Zone 51, 282500E 7402300N). A section at Watch Point that underlies the Coondra Formation is here designated a reference section.

Lithology: The Watch Point Formation consists of brown to grey, fine- to medium-grained sandstone interbedded with grey to olive-green siltstone and silty sandstone, and brown to blue-grey shale. Some fine-grained sandstone is glauconitic.

Relationships and boundary criteria: The Watch Point Formation rests unconformably on more deformed rocks of the Manganese Group of the Collier Basin. It is overlain, apparently conformably but sharply, by the Coondra Formation at Watch Point. Contacts elsewhere are faulted (Williams, 1992). If the contact is unconformable (a paraconformity with no angular relationship), then it may well be a part of the Salvation Group.

Age and correlation: The age of the Watch Point Formation can be assessed only from its stratigraphic relationships. The key contact, with the Coondra Formation at Watch Point, was regarded by Williams (1992) as conformable but could be a paraconformity. If the former, then the Watch Point Formation is a fine-grained facies at the base of the Officer Basin succession, perhaps a correlative of the Lefroy Formation.

Depositional setting: Sedimentary structures listed by Williams (1992) include intraclasts, mud-cracked shale, climbing ripples and cross-bedding. In conjunction with the lithology, these suggest a tidal setting with intermittent emergence.

References: Muhling and Brakel (1985), Williams and Tyler (1991), Williams (1992), Bagas et al. (1999).

Coondra Formation

Definition and nomenclature: The Coondra Formation was defined by Williams and Tyler (1991) and fully described by Williams (1992). The formation is named after Coondra Coondra Springs on ROBERTSON. Muhling and Brakel (1985) previously mapped rocks included in the Coondra Formation as Calyie Sandstone.

Distribution and thickness: The Coondra Formation is exposed in the far northwest of the northwestern Officer Basin, adjacent to, and locally faulted against, the upper Mesoproterozoic Manganese Group. Williams estimated the unit is up to about 1000 m thick, based on air photos.

Type area: Williams and Tyler (1991) and Williams (1992) listed two type areas for the Coondra Formation, for different facies. Boulder conglomerate and coarse-grained sandstone is exposed between Coondra Coondra Springs and Boolginya Rockhole, and coarse-grained sandstone and pebble to cobble conglomerate are exposed around Yooldoowindi Spring. The first of these (approximately centred on MGA Zone 51, 301000E 7443000N) is accepted here as the type area, and the second as a principal reference locality.

Lithology: The Coondra Formation consists of coarse-grained sandstone interbedded with pebble to boulder conglomerate, in part matrix supported (Williams, 1992).

Relationships and boundary criteria: The Coondra Formation conformably overlies the Watch Point Formation and is disconformably overlain by the Mundadjini Formation (Williams, 1992). Stratigraphic relationships are commonly disturbed or masked by later faulting. Clast types in the Coondra Formation indicate that it was derived in part by reworking of the adjacent Manganese Group, although palaeocurrent data shown by Williams (1992) indicate flow was dominantly parallel to the basin margin.

Age and correlation: The age of the Coondra Formation, like that of the Watch Point Formation, is inferred solely from stratigraphic relationships. If the underlying Watch Point Formation is part of the Officer Basin (see above), then the Coondra Formation is of lower Supersequence 1 age. If the Watch Point Formation is older and the Coondra Formation is conformable on it, then it may be the same age as the Salvation Group. Given the similarity in palaeocurrent pattern and lithology to the Spearhole Formation (see Williams, 1992), the two units are at present best considered as correlatives, indicating that the Coondra Formation is a basal unit in the Officer Basin.

Depositional setting: From descriptions by Williams (1992), the Coondra Formation appears to be an alluvial fan to proximal braided fluvial deposit.

References: Muhling and Brakel (1985), Williams and Tyler (1991), Williams (1992), Bagas et al. (1999).

Spearhole Formation

Definition and nomenclature: The Spearhole Formation (Williams, 1992) is a sandstone and conglomerate unit at the base of the Officer Basin succession along the southwest margin of the northwestern Officer Basin. 'Spearhole' is an alternative local name for Hann Rockhole on BULLEN (Williams, 1992).

Distribution and thickness: The Spearhole Formation extends from the western end of the Oldham Inlier to the western boundary of the northwestern Officer Basin, south of the Kimberley Well Fault of Williams (1992). Williams estimated the formation to be up to 1000 m thick from airphotos. Boondawari 1 intersected a complete section of Spearhole Formation, resting disconformably on Brassey Range Formation, between 313 and 769 m (456 m thick).

Type area: Williams (1992) listed three localities with typical exposures, after noting the difficulty of access to the Spearhole Formation. He later (Williams, 1995a,b) referred to these as type areas. The localities are 20 km east of Moffetah Well (MGA Zone 51, 262300E 7317400N), the Dean Hills, and 21 km west of CSR Well 14 on the western side of the Ward Hills (MGA Zone 51, 357500E 7314400N). The first is among the westernmost exposures of the Spearhole Formation, the second in the middle part of the Spearhole Formation, and the last near the base of the Spearhole Formation among the easternmost exposures. The last, adjoining the Ward Hills, is accepted here as the type area, as it is the only one of the three that shows stratigraphic relationships, namely the basal contact with the Oldham Sandstone. The other two localities are considered as reference localities.

Boondawari 1 and Mundadjini 1 provide fully cored reference sections of the Spearhole Formation, from 313 to 769 m in Boondawari 1, and 359 to 600 m (TD) in Mundadjini 1 (Fig. 28).

Lithology: The Spearhole Formation is dominated by coarse- to fine-grained sandstone. Granule to boulder conglomerate is present in the lower parts of the unit, and fine-grained sandstone and siltstone near the top. Sandstone intervals are commonly cross-bedded, with foresets up to 6 m thick indicating unimodal northward flow. Williams (1992) described the lithology in detail.

Relationships and boundary criteria: Williams (1992) considered the Spearhole Formation to be disconformable on older units, disconformably overlain by Mundadjini Formation, and faulted against the Coondra Formation. Owing to the isolated, discontinuous nature of exposures in the Little Sandy Desert, these relationships are largely inferred.

Age and correlation: There is no direct evidence for the age of the Spearhole Formation. The formation is regarded as a correlative of the Townsend Quartzite and Lefroy Formation solely because of its position apparently at the base of a major basin succession, and the similar trend from high-energy deposition at the base to lower energy deposition at the top. The Spearhole Formation has not been recognized around the Oldham Inlier, so there was probably no depositional continuity with the Townsend Quartzite. It is possible that the unit is older, and a similar age to the 'Bloods Range beds' of the basal Amadeus Basin 'rift sequence' (Scrimgeour et al., 1999; Close et al., 2003), although considerably less deformed.

Depositional setting: Williams (1992) interpreted the Spearhole Formation as a braided fluvial deposit with a provenance west to southwest of the northwestern Officer Basin.

References: Williams (1992, 1995a,b), Bagas et al. (1999).

Mundadjini Formation

Definition and nomenclature: The Mundadjini Formation (Williams and Tyler, 1991) is a sandstone-dominated unit with lesser interbedded siltstone, shale, and dolomite. The formation was named after Mundadjini Spring on ROBERTSON (note that Mundadjini Spring is actually located within Coondra Formation, not Mundadjini Formation; see Williams and Tyler, 1991).

Distribution and thickness: The Mundadjini Formation extends through the central part of the northwestern Officer Basin, north of the Ward and Oldham Inliers. Partially cored sections of the Mundadjini Formation are present from Boondawari 1 (surface to 313 m, cored below 300 m and with a limited suite of electric logs from surface) and Mundadjini 1 (surface to 359 m, cored and logged below 170 m). Some sandy and conglomeratic outcrops immediately overlying the Oldham Inlier in the Phenoclast Hill – Quadrio Lake area would be better mapped as Mundadjini Formation than as Skates Hills Formation as was done by Williams (1995a). Williams (1992) estimated a maximum thickness of 1800 m from airphotos.

Type locality: When defining the Mundadjini Formation, Williams and Tyler (1991) listed two type areas: 16 km east-northeast of the junction of Savory and Bobbymia Creeks (MGA Zone 51, 299500E 7372000N), and 20 km south-southwest of the junction of Savory and Bobbymia Creeks (MGA Zone 51, 280100E 7345600N). Of these, the first is reasonably accessible, as it lies immediately south of the access track along Savory Creek to Durba

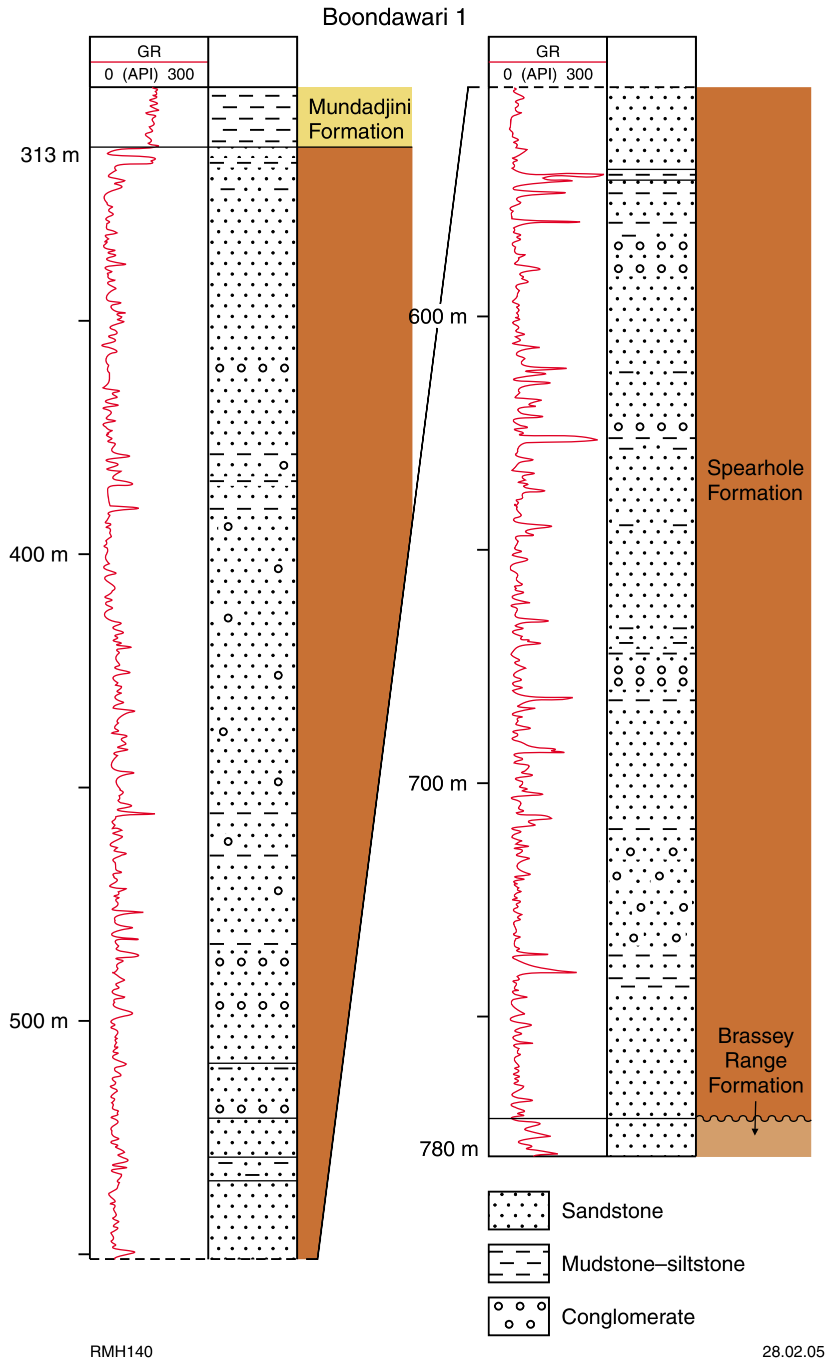

Figure 28. Reference section, Spearhole Formation, Boondawari 1

Hills. Williams (1992) added Ripple Hill on northwest TRAINOR as a third type area. Because of accessibility and precedence, the first locality, near Savory Creek, is taken as the type area, and the other two localities are regarded as reference localities. The sections in Mundadjini 1 and Boondawari 1 provide reference sections with vertical control (Fig. 29).

Lithology: The Mundadjini Formation in outcrop is dominated by fine- to medium-grained, texturally mature quartz sandstone, with lesser interbedded siltstone and dolomite, in part stromatolitic. Williams (1992) noted minor amounts of coarse-grained sandstone, conglomerate, and shale. Bedding ranges from rippled, with flat-topped and ladderback forms present, through parallel bedded to cross-bedded. Mud cracks, eolian adhesion surfaces, and various ripple forms were figured by Williams (1992). Gypsum and halite pseudomorphs are locally common, but no evaporite minerals are known in outcrop. Some dolomite beds are stromatolitic. The lithology was documented in detail by Williams (1992).

The sections in Mundadjini 1 and Boondawari 1 both have a siltstone to mudstone lower member, a distinct middle sandstone member, and an upper siltstone member, which is in turn divisible into a lower sandy siltstone and

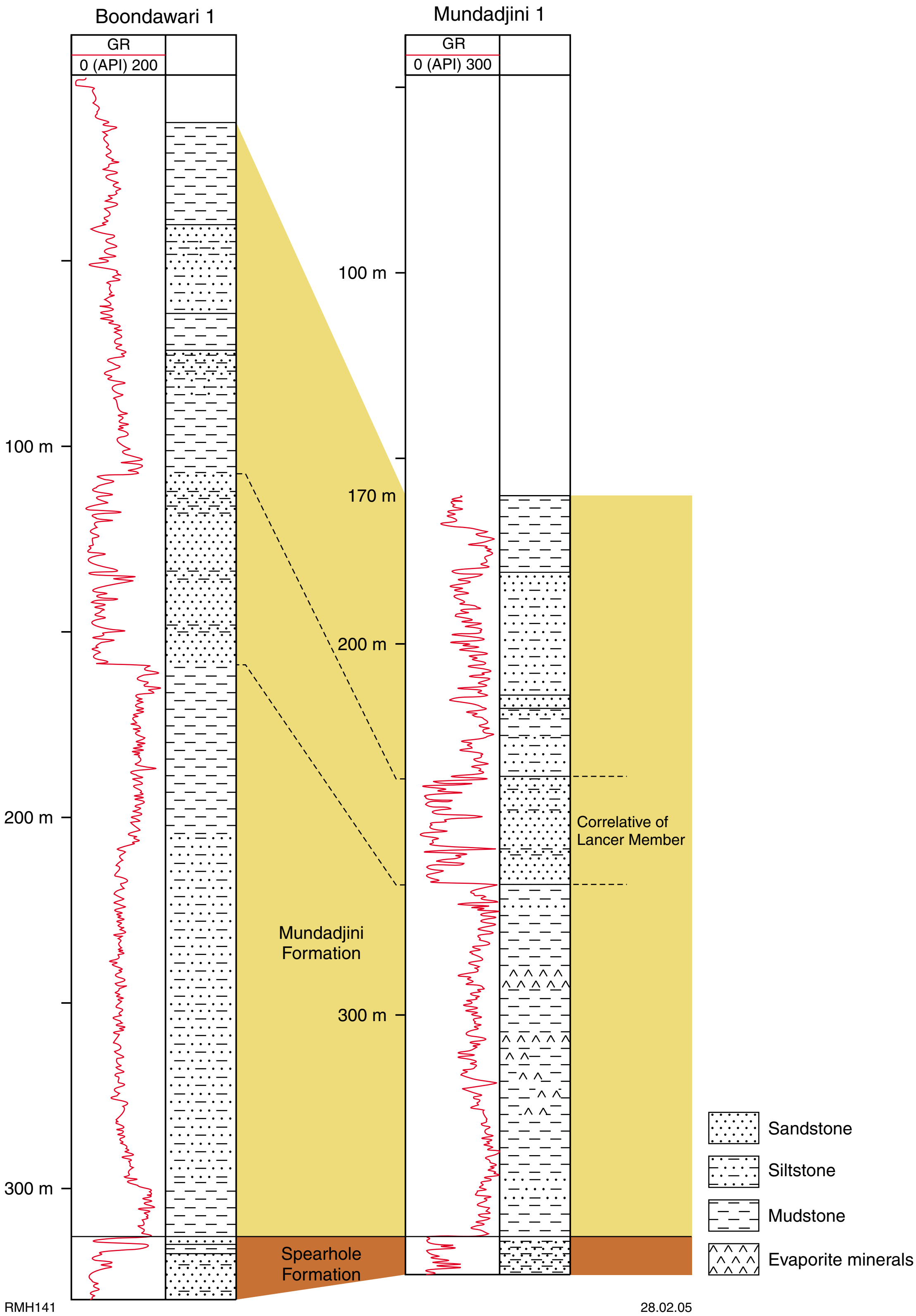

Figure 29. Reference sections, Mundadjini Formation, Mundadjini 1 and Boondawari 1

an upper siltstone (Fig. 29). The formation is dominated by siltstone overall, and scattered anhydrite is present below the central sandstone in Mundadjini 1. The sandstone interval may be equivalent to the thicker sandstone exposures in areas such as Ripple Hill, which are tidal sandflat deposits.

Relationships and boundary criteria: The stratigraphic relationships of the Mundadjini Formation are usually inferred from regional geology. The formation is angularly unconformable on the Ward and Oldham Inliers, and disconformable on the Coondra and Spearhole Formations (Williams, 1992). Younger units are unconformable on the Mundadjini Formation. The Mundadjini Formation appears, in outcrop, to be a sandier lateral equivalent of the Skates Hills Formation.

On lithology alone, the section in Boondawari 1 correlates very well with the Browne Formation and lower Hussar Formation in Lancer 1 (Fig. 12). The lower siltstone member has a basal mudstone as in the Lancer 1 section, overlain by about 150 m of siltstone and mudstone (but no dolomite). The lower Browne Formation has a similar thickness in Lancer 1. The central sandstone and overlying sandy siltstone in Boondawari 1 are similar in broad lithology and thickness to the Lancer Member. The siltstone to mudstone interval near the top of Boondawari 1 and the cored interval in Mundadjini 1 may thus be a correlative of the fine-grained interval at the base of the Hussar Formation. Given that the section in Lancer 1 correlates closely with that in Empress 1A, this implies a remarkable lateral continuity of deposition, with limited lateral facies and thickness changes (from evaporites in Empress 1A, to eolian sandstone in Lancer 1, to probable sandy coastal deposition in Boondawari 1).

Age and correlation: The age of the Mundadjini Formation is inferred largely from its apparent stratigraphic position relative to the Skates Hills Formation, which contains a well-preserved *Acaciella australica* Stromatolite Assemblage and appears to be approximately laterally equivalent to the Mundadajini Formation. By contrast, the Mundadjini Formation contains a poorly preserved stromatolite of uncertain affinity. From lithology, the Mundadjini Formation could be equivalent to the Hussar Formation or to the eolian Lancer Member in Lancer 1 in the upper Browne Formation. This sandstone is equivalent to evaporites elsewhere in the Browne Formation.

Depositional setting: The lithology, textural maturity of constituent sandstones, sedimentary structures, and abundant evaporite pseudomorphs indicate that the Mundadjini Formation was deposited in shallow-water nearshore, coastal, and tidal sandflat conditions, in places evaporitic. The lateral persistence of these facies implies a very low palaeoslope. Coarse-grained sandstone intervals noted by Williams (1992) are probably fluvial.

References: Muhling and Brakel (1985), Williams and Tyler (1991), Williams (1992, 1995a,b), Bagas et al. (1999).

Skates Hills Formation

Definition and nomenclature: The Skates Hills Formation is a mixed carbonate and siliciclastic unit at the base of the Officer Basin succession immediately north of the Oldham Inlier. It was named by Williams et al. (1976), described by Brakel and Leech (1980), fully defined by Muhling and Brakel (1985), and described at length by Williams (1992). The formation is named after Skates Hills, which is a group of hills near the northeast extent of the formation on easternmost TRAINOR and westernmost MADLEY.

Distribution and thickness: The formation is found along the northern margin of the Oldham and Ward Inliers, and was previously considered to be a part of the Savory Group that overstepped onto the inliers. Williams (1992) indicated that the type section is about 50 m thick, but a traverse over the type section shown by Stevens and Adamides (1998, fig. 4) implies a thickness of 200 to 300 m. Williams estimated the maximum thickness of the formation to be about 200 m, from airphotos. The basal conglomerate at Phenoclast Hill may be thicker, but this facies and the sandstone immediately above may be better placed in the Mundadjini Formation, which is a characteristically sandy, rather than dolomitic, correlative of the Skates Hills Formation.

Type area: The type section for the Skates Hills Formation lies on the northeast side of Quadrio Lake, about 6 km north-northeast of Phenoclast Hill (MGA Zone 51, 470200E 7284500N). Stevens and Adamides (1998, fig. 4) showed a traverse through this section. Williams added type areas (here regarded as reference localities) for the stromatolite-rich part of the succession in the Skates Hills Formation on the northern margin of Skates Hills (MGA Zone 51, 507600E 7285100N) and 36 km southeast of Phenoclast Hill (MGA Zone 51, 496500E 7256300N).

Lithology: The Skates Hills Formation as defined contains dolomite, commonly stromatolitic, medium- to fine-grained sandstone, siltstone, and thick but discontinuous basal conglomerate intervals at, and northwest of, Phenoclast Hill. The dolomite is the defining feature of the Skates Hills Formation, was described in detail by Williams (1992), and grades into an upper unit of pink to red shale, siltstone, and flaggy, fine- to medium-grained sandstone. The conglomerate, and basal sandstone immediately north of Quadrio Lake and below the dolomite beds that are characteristic of the Skates Hills Formation, may be better placed in the Mundadjini Formation.

The basal conglomerate at Phenoclast Hill is at least 30 m thick, contains clasts of sandstone, quartzite, vein quartz, silicified shale, and chert, together with some subrounded boulders up to 0.5 m in diameter. Many clasts are derived from the underlying Cornelia Sandstone, which is the core unit of the Oldham Inlier. Elsewhere, the basal unit consists of red-brown, coarse-grained sandstone, granule sandstone, and some pebbly units. The basal unit is overlain by maroon, purple, cream, and grey, fine-grained sandstone, and micaceous siltstone and shale, with some quartz wacke lenses and chert (Williams, 1992).

The middle unit that characterizes the Skates Hills Formation is dominated by laminated to thick-bedded (up to 10 m), grey, blue, buff, cream, and pink, and finely crystalline dolomite. Seven kilometres northeast of Phenoclast Hill, the unit is 21 m thick, and the carbonate is interbedded with sandstone, siltstone, shale, and chert. A thick white-weathering, black chert lies near the base of the dolomite unit 12 km southeast of the Cornelia Range. The chert is faintly laminated and podded, and has desiccation cracks. The dolomite contains chert pods and lenses, and there are also interbeds of shale, siltstone, and fine-grained sandstone. Evaporitic conditions are indicated by the presence of cauliflower chert, anhydrite nodules replaced by silica, and crystal voids after gypsum. Stromatolites are widespread, and exist as domed or tabular bioherms up to 2 m in diameter. Some stromatolites (commonly of *Basisphaera irregularis*) have been differentially silificied at most localities (Grey, 1995a).

The upper unit is a thin succession of pink to red shale, siltstone, and flaggy, fine- to medium-grained ferruginous sandstone. Sandstone and siltstone units contain small planar cross-beds, symmetrical ripples, and flute casts. Rare sandy dolomite horizons contain stromatolites.

Relationships and boundary criteria: The Skates Hills Formation is recognized only in outcrop in the southeast part of the northwestern Officer Basin, where it rests unconconformably on Mesoproterozoic or Palaeoproterozoic rocks of the Oldham Inlier (Quadrio Formation, possibly Cornelia Sandstone). The formation is a lateral correlative of the Mundadjini Formation, and the two appear to be distinguished by the greater abundance of dolomite in the Skates Hills Formation, at the expense of sandstone. The Skates Hills Formation is disconformably overlain by McFadden Formation or, to the southeast, Phanerozoic rocks.

Based on the presence of the *Acaciella australica* Stromatolite Assemblage in the Skates Hills Formation, it is at least in part a lateral equivalent of the Woolnough Member, and possibly part the upper Browne Formation, and can be confidently correlated with the Loves Creek Member of the Bitter Springs Formation (Amadeus Basin). Stratigraphic levels equivalent to the lower Browne Formation may be absent in the Skates Hills Formation, as *A. australica* is first encountered near the base of the succession in the northwestern Officer Basin, unlike in the central Officer Basin where a thick evaporitic interval (not yet found in the Skates Hills Formation) is present below the stromatolites in the Browne Formation. The relationships for the Skates Hills Formation thus appear similar to the sections in Empress 1A and Lancer 1, in which the lower Browne Formation is absent. A lower unit, the Spearhole Formation, is present farther northwest below the correlative Mundadjini Formation, but only south and east of the Ward Inlier.

Age and correlation: The Skates Hills Formation contains the stromatolites *Acaciella australica* and *Basisphaera irregularis*, which allows confident correlation with the Woolnough Member, and perhaps part of the upper Browne Formation of the southwestern Officer Basin, and with unit 2 of the Loves Creek Member of the Bitter Springs Formation (Walter, 1972; Grey, 1995a). Correlation with the Coominaree Formation of the Callanna Group of the Adelaide Rift Complex gives a minimum age for the Skates Hills Formation of about 800 Ma and a probable (though not proven) maximum age of about 820 Ma (see discussion under **Browne Formation**).

Depositional setting: The Skates Hills Formation was deposited mostly in a nearshore marine to coastal setting, with areally restricted, fault-related, alluvial-fan deposition of conglomerate at the base. Braided fluvial deposition is recorded locally by unimodally trough cross-bedded sandstone. Cauliflower cherts and casts of evaporite crystals (Williams, 1992) indicate coastal evaporitic conditions, as in the Mundadjini Formation, but significant evaporite intervals, not surprisingly, have not been found in outcrop. Stromatolitic bioherms show upward-shallowing cycles similar to those described by Southgate (1989, 1991) from the Loves Creek Member of the Bitter Springs Formation (Grey, 1995a).

References: Williams et al. (1976), Brakel and Leech (1980), Muhling and Brakel (1985), Williams (1990a, 1992, 1994), Grey (1995), Walter et al. (1995), Bagas et al. (1999).

Boondawari Formation

Definition and nomenclature: The Boondawari Formation is a unit of diamictite, sandstone and siltstone that rests disconformably to angularly unconformably between older and younger units in the northwestern Officer Basin. Williams (1987) first recognized the diamictite, and Williams and Tyler (1991) named the formation, after Boondawari Soak on ROBERTSON. There is no synonymy.

Distribution and thickness: The formation outcrops poorly and discontinuously throughout the northwestern Officer Basin, but is best exposed in the Boondawari Creek drainage area, where it is up to 800 m thick, estimated from airphotos (Williams, 1992). Extensive outcrops are also present between the Ward and Oldham Inliers.

Type area: Williams and Tyler (1991) listed two type areas: the Boondawari Creek area east from Boondawari Soak (around MGA Zone 51, 344500E 7391500N), and 7.5 km north-northeast of Boondawari Soak for the basal glacigenic diamictite. Williams (1992) added a locality 29 km east-southeast of CSR Well 13 for a diamictite and coarse-grained sandstone succession. The first listed is designated here the type locality, and the latter two are regarded as reference localities showing different facies and levels in the Boondawari Formation.

Lithology: Williams (1992, 1994) and Walter et al. (1994) gave detailed descriptions of the Boondawari Formation. The formation consists of diamictite, fine- to coarse-grained sandstone, conglomerate, siltstone, mudstone, dolomitic siltstone, and dolomite, in part stromatolitic. Three main lithological units are recognized, and would be better divided into separate formations, but this is not possible because of the lack of stratigraphic control between exposures (Williams, 1992). The lower unit is dominated by diamictite. Polished, striated, and faceted clasts in the diamictite (Williams, 1987) indicate a glacial origin, and comprise over 20 lithological types, including metamorphic, igneous, and a wide variety of sedimentary rock types (Williams, 1987, 1992, 1994). There is some sedimentary rhythmite above diamictite that appears similar to Elatina Formation rhythmites in South Australia (G. E. Williams, 1989). A thin-bedded, pink dolomite probably overlies the diamictite, although precise relationships are difficult to determine because of poor outcrop. This may be equivalent to the cap dolomite recorded elsewhere above early Marinoan glacigene sediments.

The middle Boondawari Formation, overlying the diamictite, consists mainly of coarse- to fine-grained, cross-bedded sandstone containing scattered pebbles, cobbles, and local boulders, some of which may be dropstones. Nodular sandstone, feldspathic sandstone, quartz wacke, siltstone, and polymictic conglomerate are present as interbeds in the sandstone.

The upper Boondawari Formation has been recognized primarily in the Boondawari Creek area, where it is an argillaceous carbonate rich unit, consisting of a series of upward-coarsening units, ranging from shale to fine- and coarse-grained, rippled to cross-bedded sandstone. Shale and carbonate increase upward as the sandstone content decreases. Some sandstone and siltstone horizons have graded bedding, local mud-cracks, and load and flute casts. Carbonate includes thin- to thick-bedded dolomite, oolitic dolomite, and thin-bedded limestone. Finely laminated dolomite and limestone near the top of the formation contain stromatolites (Walter et al., 1994), including *Eleanora boondawarrensis* and *Acaciella savoryensis*.

Relationships and boundary criteria: The Boondawari Formation is disconformable on the Mundadjini Formation, and angularly unconformable on rocks of the Ward and Oldham Inliers. The McFadden Formation unconformably overlies (or may be faulted against) the Boondawari Formation near Well 15 on the Canning Stock Route. North of the Emu Fault, the Boondawari Formation is faulted against the younger Tchukardine Formation.

The lower Boondawari Formation is a probable correlative of the Wahlgu Formation in the southwestern Officer Basin, based on the presence of a possible cap dolomite and the lithological similarity of the Wahlgu Formation in Lancer 1 to the Boondawari Formation. It is probably equivalent to the Olympic Formation and Pioneer Sandstone (diamictite, glacial outwash sandstone, and cap dolomite), the Pertatataka Formation (siltstone and minor sandstone), the Julie Formation (stromatolitic carbonate), and the lower Arumbera Sandstone of the Amadeus Basin succession. The lithological succession in the Boondawari Formation is also remarkably similar to Marinoan glacial units of the Adelaide Rift Complex.

Age and correlation: The stromatolite form-species, *Eleanora boondawarrensis* and *Acaciella savoryensis*, have so far been recorded only from the Boondawari Formation, and provide little biostratigraphic information (Walter et al., 1994). Preliminary carbon isotope chemostratigraphy supports the probable correlation between the thin cap dolomite in the Boondawari Formation, the cap dolomite in the Wahlgu Formation, and the cap dolomite in the Pioneer Formation of the Amadeus Basin and Nuccaleena Formation of the Adelaide Rift Complex (Walter et al., 1994). Similarly, the very high positive $\delta^{13}C_{carbonate}$ values obtained from the stromatolitic carbonate near the top of the Boondawari Formation correspond to high positive values in the Julie Formation of the Amadeus Basin, the top of the Wonoka Formation of the Adelaide Rift Complex, and the Wilari Dolomite of the eastern Officer Basin (Calver, 1995, 2000; Calver and Lindsay, 1998; Walter et al., 1994).

The formation is intruded by a dolerite, which was given a preliminary Rb–Sr isotopic age of approximately 640 Ma (J. de Laeter *in* Williams, 1992). A crystallization age of 508 ± 5 Ma for intrusive dolerite in Boondawari 1 has since been obtained (Wingate, M. T. D., 2002, written comm.). This age agrees with other radiometric ages for the Table Hill and Antrim Plateau Volcanics (Veevers, 2000; Hanley and Wingate, 2000).

Depositional setting: The Boondawari Formation is part of 'Depositional Sequence C' (Williams, 1992), and was derived from widespread sources lying mainly to the west and south of the basin margins. Williams (1987, 1992) interpreted the diamictites as glacigenic, deposited in a shallow-marine environment, distant from the ice-source. Palaeocurrent directions for sandstones interbedded with, and overlying, the diamictite are from the northwest to east, with a minor southwest component indicating supply from the Paterson Orogen. Williams (1992) suggested that the middle Boondawari Formation was deposited in a high-energy, sandy shelf environment with a continuing glacial influence. The upper carbonate succession represents an upward-shallowing, quiet, near-shore environment with local build-up of carbonate. The basin appears to have shallowed further during the deposition of carbonates containing stromatolitic bioherms, oolites and pisolites, and halite pseudomorphs.

References: Williams (1987, 1990a, 1992, 1994, 1995a,b), Williams and Tyler (1991), Williams and Williams (1980), Walter et al. (1994, 1995), Bagas et al. (1999).

Disappointment Group

The Disappointment Group (Bagas et al., 1999) includes the McFadden, Tchukardine, and Woora Woora Formations and was named after Lake Disappointment. The Durba Sandstone is not included in the group because its age and relationship to the McFadden Formation remain equivocal. The Durba Sandstone is probably part of the same sedimentary package, but could be significantly younger (see **Durba Sandstone**, below). The group extends mostly around the northeast margin of the basin, and is found mainly east of the Marloo Fault on RUDALL, TRAINOR, and western MADLEY. The group includes those formations that have predominantly southwesterly palaeocurrents as shown by Williams (1992) for his Depositional Sequence D. Lithologically it consists of sandstone, siltstone, and conglomerate. The group overlies or is in faulted contact with older rocks. The Disappointment Group overlies the Sunbeam Group and Boondawari Formation, and is overlain by Carboniferous–Permain Paterson Formation, but is otherwise poorly constrained. Its extent and possible correlatives are uncertain. Williams (1992) described the group as being associated with the onset of tectonism during the c. 550 Ma Paterson Orogeny (Table 1). The group probably corresponds to the Lungkarta Formation to the east and southeast (see above).

Table 1. Summary of geological history of the Tarcunyah, Throssell Range, and Lamil Groups

Age (Ma)	*Geological event*
c. 900	Maximum age of deposition in the Yeneena Basin (Throssell Range and Lamil Groups), and Miles Orogeny (Bagas, 2004a,b)
720	Likely age of the southwesterly directed compression associated with the Miles Orogeny, which was locally accompanied by lower greenschist-facies metamorphism. The orogeny affected the Palaeoproterozoic Rudall Complex, and the Neoproterozoic Yeneena Basin and Tarcunyah Group. Structures attributed to the orogeny include northwesterly trending folds with a locally developed axial-planar cleavage, and normal and reverse faults with a component of either dextral or sinistral strike-slip transport
800–610	Poorly constrained age for the Blake Movement. Structures attributed to the Blake Movement are open folds with axial planes trending about 030°, and indicate a regional compression towards the northwest. This event is probably part of the Paterson Orogeny (Bagas, 2004a)
630–680	Emplacement of monzogranites and syenogranites in the Lamil Group as laccolithic sheets in broad domal and synformal structures after the Miles Orogeny and prior to the Paterson Orogeny. These Neoproterozoic granites appear to be unique to the Telfer region in the Paterson Orogen, and may be partly related to the genesis of gold and base metal mineralization around Telfer
c. 550	Approximate age of the Paterson Orogeny
Post-Paterson Orogeny	Deposition of Phanerozoic sedimentary rocks in the Canning Basin north of the northern Officer Basin

McFadden Formation

Definition and nomenclature: The McFadden Formation (‘McFadden Sandstone’ of Williams and Willliams, 1980; defined by Muhling and Brakel, 1985; and amended and fully described by Williams, 1992) is a sandstone-dominated unit that extends over much of the Paterson Orogen adjacent to the Paterson Orogen. The formation is disconformable to angularly unconformable on older units, and is overlain with apparent disconformity but no pronounced angularity by the Durba Sandstone. The unit was named after the McFadden Range on GUNANYA.

Distribution and thickness: The McFadden Formation extends from the Oldham Inlier (from which it is separated by the Skates Hills Formation) northwestward to the northern tip of the Officer Basin against the Paterson Orogen. Williams (1992) considered that the maximum thickness could be as much as 1500 m, and noted that the top is everwhere eroded, indicating the deposited thickness may have been even greater.

Trainor 1, 5.5 km northwest of the Oldham Inlier and separated from it by outcropping stromatolite-bearing Skates Hills Formation, intersected 83 m of subhorizontal sandstone above a steeply dipping shaly section later assigned to the Quadrio Formation by Hocking et al. (2000b). Stevens and Adamides (1997) interpreted the sandstone as McFadden Formation, but it could equally be a basal sandstone facies of the Skates Hills Formation, distal to the conglomerates exposed at Phenoclast Hill.

Type section or area: Williams (1992) designated the type area of the McFadden Formation as a series of mesas, up to 100 m high, in the McFadden Range (MGA Zone 51, 429000E 7527000N). Durba Hills, where sandstone shows spectacular giant cross-bedding beneath a thin cover of Durba Sandstone, is here designated a reference area, with a specific section at a giant broad trough exposed as the northwest tip of Durba Hills.

Lithology: The McFadden Formation is dominated by fine- to coarse-grained, well-sorted sandstone, with local siltstone pockets and conglomeratic interbeds, and was described at length by Williams (1992). The sandstone is a lithic arenite, texturally mature but compositionally immature, and is generally trough cross-bedded with unimodal southward to southwestward palaeocurrents. Grain size coarsens towards the north and east. Granule and pebble sandstone and beds of polymictic pebble to cobble conglomerate are present in the McFadden Range. The cross-bedding is commonly giant scale, notably in Durba and Diebil Hills, where single trough sets are more than 50 m thick, 150 m wide, and extend down-dip for at least 1 km.

Relationships and boundary criteria: Stratigraphic contacts between the McFadden Formation and other units are rarely exposed, except where it is overlain by Durba Sandstone. This contact is sharp and erosional, but the magnitude of the hiatus cannot be determined. The formation disconformably overlies Skates Hills Formation in the south, Boondawari Formation in the west and northwest, and the Mundadjini Formation in the north. Williams (1992) noted several faulted contacts with other units, including the possibly coeval Tchuckardine Formation. The Lungkarta Formation in Lancer 1 contains giant cross-bedding, possibly of eolian origin (Haines et al., 2004), that is comparable in size to that exposed in Durba Hills and nearby areas.

Age and correlation: There is no direct evidence of the age of the McFadden Formation. Its palaeocurrent pattern and lithology suggest deposition must have been during a period of rapid uplift of the Paterson Orogen when there was abundant supply of unwinnowed lithic detritus. The Paterson Orogeny, at c. 550 Ma (Bagas and Smithies, 1998; Bagas et al., 2000), satisfies these conditions and is compatible with the known stratigraphic relationships of the sandstone.

Depositional setting: Williams (1992) interpreted the McFadden Formation as a sand-dominated delta prograding onto a sandy marine shelf. The size of the cross-bedding is indicative of eolian deposition as large prograding, slightly lunate dunes, although the grain size is coarser and the sorting poorer than would normally be associated with dune foresets. Interdune deposits and lags have not been recognized. Fluvial deposits are present in the McFadden Hills, based on Williams (1992) descriptions, and in outcrops mapped as McFadden Formation on the Canning Stock Route between Wells 14 and 15. These are presumably stratigraphically lower than the Durba and Diebil Hills.

References: Williams et al. (1976), Williams and Williams (1980), Muhling and Brakel (1985), Williams (1992), Bagas et al. (1999).

Tchukardine Formation

Definition and nomenclature: The Tchukardine Formation is a sandstone-dominated unit that is exposed in several separate fault blocks at the northern tip of the northwestern Officer Basin. The formation was named and defined by Williams (1992), after Tchukardine Pool on RUDALL.

Distribution: The Tchukardine Formation is recognized only in several areally restricted fault blocks at the northern end of the northwestern Officer Basin adjacent to more-deformed rocks of the Paterson Orogen (Williams, 1992). The thickness is estimated from airphotos at more than 700 m (Williams, 1992).

Type section or area: Williams proposed two type areas: one near Tchukardine Pool (MGA Zone 51, 357800E 7506500N) in dissected tablelands 60 to 70 m high extending about 10 km south from Hanging Rock, and another in the Wells Range about 50 km to the southeast. The first of these is here regarded as the type area because of proximity to Tchukardine Pool, and the second as a reference area.

Lithology: The Tchukardine Formation is dominated by medium-grained sandstone, with rare intercalations of silty shale, siltstone, and conglomerate (Bagas et al., 2000; Williams, 1992). Glauconite is present but rare. Cross-bedding is in places very large to giant scale, and indicative of westward to southwestward flow.

Relationships and boundary criteria: The Tchukardine Formation is unconformable on the Wongarlong and Mundadjini Formations (Bagas et al., 2000). The unit is otherwise seen only in faulted contact with other rocks of known stratigraphic relationships. It is lithologically similar to, and adjacent to, the lower McFadden Formation, but unequivocal correlation cannot be demonstrated. Williams (1992) noted that the Woora Woora Formation disconformably overlies the Tchukardine Formation in the Woora Woora Hills.

Conglomerate, sandstone, siltstone, and diamictite at the base of the Tchukardine Formation between Boorabee Hill (previously Bocrabee Hill) and Hanging Rock, which Williams (1992, p. 49) was uncertain of including in the Tchukardine Formation, is here taken as Boondawari Formation and, possibly, undifferentiated Sunbeam Group.

Age and correlation: There is no direct evidence of the age of the Tchukardine Formation. It has stratigraphic relationships and appearance similar to those of the McFadden Formation, and is inferred to be a lateral equivalent, deposited during the onset of the Paterson Orogeny at c. 550 Ma.

Depositional setting: Williams (1992) and Bagas et al. (2000) interpreted the Tchukardine Formation as a sandy marine-shelf deposit, based on the presence of glauconite and giant cross-beds, thought to represent migrating sandwaves. As with the McFadden Formation, the scale of the cross-bedding is more suggestive of eolian deposition, although the glauconite is difficult to explain in a non-marine setting. From descriptions and figures in Williams (1992), the cross-bedding appears to be smaller than the 50 m sets in the McFadden Formation. Taking this and the unimodal palaeocurrent pattern into consideration, deposition could have been in a coastally situated, major fluvial-dominated distributary system.

References: Williams (1992), Bagas et al. (1999).

Woora Woora Formation

Definition and nomenclature: The Woora Woora Formation is a sandstone-dominated unit that is present around the Woora Woora Hills (after which it was named, by Williams, 1992) at the northern tip of the northwestern Officer Basin, west of the Marloo Fault.

Distribution: The Woora Woora Formation is recognized only in the area around the Woora Woora Hills (Williams, 1992), where it may be up to 400 m thick. Deposited thickness is greater as the upper surface is always eroded.

Type section or area: The type area is the Woora Woora Hills (MGA Zone 51, 344000E 7491000N).

Lithology: The Woora Woora Formation consists of quartzose medium-grained sandstone with a characteristic clay matrix, with locally common interbeds of siltstone and silty claystone (Williams, 1992). Bedding ranges from massive through flaggy to cross-bedded. Cross-sets are commonly as much as 6 m thick.

Relationships and boundary criteria: The Woora Woora Formation is disconformable on the Tchukardine and Mundadjini Formations (Williams, 1992), and is very similar lithologically to the upper McFadden Formation, which lies on the eastern side of the Marloo Fault.

Age and correlation: The age of the Woora Woora Formation is inferred solely from its stratigraphic position and regional tectonic setting, as synorogenic with the c. 550 Ma Paterson Orogeny.

Depositional setting: The Woora Woora Formation is interpreted as the product of high-energy deltaic progradation into shallow-marine conditions off the rapidly rising Paterson Orogen.

References: Williams (1992), Bagas et al. (1999).

Durba Sandstone

Definition and nomenclature: The Durba Sandstone was named by Williams et al. (1976) after Durba Hills on GUNANYA, described by Williams and Williams (1980), and fully defined by Muhling and Brakel (1985). The Durba Hills constitute the largest area of outcrop, where the unit forms a sandstone buttress at the top of the plateau. The Durba Sandstone may be part of, or significantly younger than, the Officer Basin succession (as defined by Hocking, 1994), but there is no firm evidence as to its age (see below).

Distribution: The Durba Sandstone outcrops in widely separated areas parallel to the northeast margin of the northwestern Officer Basin. Its main exposure is in the spectacular inselberg of Durba Hills. The upper surface of the formation is everywhere eroded, and the maximum preserved thickness is less than 100 m, based on airphotos and reconnaissance examination of the Durba and Diebil Hills.

The section between 169 and 205 m in Lancer 1 is similar to the Durba Sandstone in outcrop, and could be the same unit rather than Lungkarta Formation as shown by Haines et al. (2004). The section between 101 and 159 m in Hussar 1 also appears similar.

A sandy section is present from 364 to 540 m in Lungkarta 1, above Table Hill Volcanics. This could also be Durba Sandstone, if a considerable hiatus separates the Lungkarta and McFadden Formations from the Durba Sandstone. If the Durba Sandstone is synorogenic with the Paterson Orogeny, reworking McFadden Sandstone with little difference in age, then the sandy section in Lungkarta 1 is a different unit, probably coeval with the Lennis or Wanna Sandstones. The interval from 93 to 169 m in Lancer 1 may be a correlative, rather than Paterson Formation. Without further data, the correlations remain equivocal.

Type section or area: Williams (1992) lists three type areas: the northern end of the Durba Hills (Williams and Williams, 1980), the gorge upstream from Durba Springs, and Mudjon Gorge at the western end of the Calvert Range. Of these, the gorge upstream of Durba Springs (MGA Zone 51, 451030E 7372470N) is here taken as the type section, and the others are regarded as reference sections. There is no known synonymy or revision of the name.

Lithology: The Durba Sandstone is an overall upward-fining succession that consists of a basal pebble and cobble, sandy conglomerate up to 3 m thick and discontinuous, overlain by medium- to coarse-grained conglomeratic sandstone and medium- to fine-grained, well-sorted sandstone (Williams, 1992). Conglomerate commonly infills channels cut in underlying rocks. The sandstone is thick bedded and in places medium to coarse grained near the base of the formation, becoming medium to fine grained and flaggy upwards, and locally has a clay matrix. It is commonly cross-bedded to rippled, with scattered indicators of emergence and desiccation (Williams, 1992). Palaeocurrent directions are northward, suggesting that the probable provenance was the Ward and Oldham Inliers (Hocking et al., 2000b).

Relationships and boundary criteria: The formation overlies gently folded Boondawari Formation near Budgie Springs. In the Diebil and Durba Hills it is apparently disconformable on subhorizontal McFadden Formation, with an essentially planar contact that truncates giant (up to 50 m high at the northwest tip of Durba Hills) trough foresets in the McFadden Formation. The Durba Sandstone is also disconformable on McFadden Formation in the Calvert Range. The magnitude of the disconformity is unknown.

Age and correlation: There is no constraint on the minimum age of the Durba Sandstone. It presumably pre-dates the Permian Paterson Formation. It post-dates the McFadden Formation, which is probably a synorogenic product of the Paterson Orogeny in the northwestern Officer Basin. It is possible that the Durba Sandstone correlates with the Wanna or Lennis Sandstones of the Gunbarrel Basin south of the Musgrave Complex, both of which are similarly unconstrained with respect to age except that they clearly post-date the Middle–Late Cambrian Table Hill Volcanics. There are significant phases of siliciclastic deposition in the Ordovician and Devonian in the Amadeus and Canning Basins, one of which may have extended to the Officer Basin.

Alternatively, the Durba Sandstone could be closely related to the McFadden Formation and the Paterson Orogeny. In the Durba and Diebil Hills, the Durba Sandstone is a clean quartz arenite such as could be reworked from the lithic arenite of the McFadden Formation, and palaeocurrent directions within it (Williams, 1992) indicate a southward provenance. Further, there is no indication of a substantial hiatus in Lancer 1 between probable fluvial sandstone assigned here to the Durba Sandstone (169–205 m), and eolian sandstone assigned to the Lungkarta Formation (205–344.3 m). The Durba Sandstone may thus be a synorogenic deposit related to the emergence of, and shedding from, the Ward and Oldham Inliers. These inliers may have been the axis of foreland bulges if the northwest Officer Basin is considered as a south-facing foreland basin during the Paterson Orogeny (but not necessarily at earlier times). This line of reasoning supports a late Neoproterozoic, to possibly early Cambrian, age for the Durba Sandstone, and probable correlation with other synorogenic or late orogenic units with an age near the Neoproterozoic–Phanerozoic cusp through central Australia.

Depositional setting: The Durba Sandstone is a fluvial deposit. The lack of siltstone and consistency of palaeocurrents (see Williams, 1992, figs 94 and 95) indicates a braided fluvial setting, with northwards flow perhaps related to uplift of the Ward and Oldham Inliers (Hocking et al., 2000b). This is an almost exact reversal of palaeocurrent directions from the McFadden Formation, assuming that some of the directions shown by Williams (1992) are fluvial rather than eolian.

References: Williams et al. (1976), Williams and Williams (1980), Muhling and Brakel (1985), Williams (1992), Bagas et al. (1999).

Northern Officer Basin and correlatives within the Paterson Orogen

Much of the northern Officer Basin succession is included in the Paterson Orogen, which is a southeasterly trending belt of Proterozoic rocks that extends about 1200 km across the central part of Western Australia (Williams and Myers, 1990). Rocks of the orogen are exposed east of the Pilbara Craton to the northwest, and in the Musgrave Complex to the southeast. The exposed northwest part of the orogen was originally referred to as the Paterson Province (Daniels and Horwitz, 1969; Blockley and de la Hunty, 1975).

The northwest Paterson Orogen contains the Palaeoproterozoic Rudall Complex, the Neoproterozoic Tarcunyah Group (which is assigned to the Officer Basin), and the Yeneena Basin (Williams et al., 1976; Bagas et al., 1995; Williams and Bagas, 1999; Bagas, 2001, 2004b). The Yeneena Basin contains the Lamil Group (Williams and Bagas, 1999) and the Throssell Range Group (amended herein from Throssell Group). On PATERSON 1:100 000 (Bagas, 2000), the orogen is intruded by Neoproterozoic granites that have an age between c. 654 and c. 630 Ma (Nelson, 1999; Dunphy and McNaughton, 1998.). The geological history of the Paterson Orogen is summarized in Table 1.

Tarcunyah Group

The Tarcunyah Group is named after Tarcunyah Creek on RUDALL, and forms the northeastern Neoproterozoic part of the northwestern Officer Basin. The group was first named by Bagas et al. (1995), and described by Bagas and Smithies (1998) and Bagas et al. (1999), and defined by Williams and Bagas (1999). Because the degree of deformation is greater than in the main part of the basin, it is also part of the Paterson Orogen, together with the Neoproterozoic Yeneena Basin succession (Fig. 30). Based on stromatolite assemblages and regional geological similarities, the Tarcunyah Group correlates with the Sunbeam Group and Buldya Group (Fig. 3; Bagas et al., 1999).

The Tarcunyah Group (Williams and Bagas, 1999) unconformably overlies the Rudall Complex (Bagas, 2004a). The Vines–Southwest–McKay fault system separates the group from the Yeneena Basin to the east (Bagas et al., 2000). The Tarcunyah Group is unconformably overlain by, or is in faulted contact with, outliers of the Neoproterozoic Tchukardine Formation of the Disappointment Group on THROSSELL 1:100 000 (Williams and Bagas, 1999).

In approximate stratigraphic order from oldest to youngest, the Tarcunyah Group consists of the Googhenama Formation, Gunanya Sandstone, Karara Formation, Waroongunyah Formation, Waters Formation, Choorun Formation, Brownrigg Sandstone, Yandanunyah Formation, Wongarlong Formation, and Nooloo Formation (Fig. 30). This order takes into account the uncertainty of the stratigraphic relationship of the Choorun Formation in the succession.

The Googhenama, lower Choorun and Karara Formations, and the Gunanya Sandstone appear to correlate with the Spearhole Formation, and the stratigraphically higher Waroongunyah and Waters Formations may correlate with the Mundadjini Formation (Bagas et al., 1999). The remainder are stratigraphically higher than rocks preserved in the Sunbeam Group, but may correlate with the Hussar, Kanpa, and Steptoe Formations (upper Buldya Group). Certainly, the pattern of alternating sandy (Brownrigg Sandstone, Wongarlong Formation) and dolomitic units (Yandanunyah and Nooloo Formations) is similar to that of the Buldya Group.

Some areas are still mapped as undifferentiated Tarcunyah Group. These include the Constance Headland area, and a group of synclines separated by faulted-out anticlines east of Lake Disappointment on BLANCHE–CRONIN 1:100 000. Stromatolite assemblages in carbonate units in both areas indicate they correlate in part with the succession between the Browne and Kanpa Formations. *Baicalia burra* is present near the top of the Constance Headland succession, and possible *Acaciella australica* is present near the base of the same succession (Stevens and Grey, 1997; K. Grey, unpublished data). The *Acaciella australica* Stromatolite Assemblage is present in the synclines on BLANCHE–CRONIN 1:100 000 (K. Grey, unpublished data). Sandstone units are also present, and the complete stratigraphic range of these successions remains uncertain.

Googhenama Formation

The Googhenama Formation ('Googhenama Conglomerate' of de la Hunty, 1964) was amended and extended by I. R. Williams (1989) to include the poorly defined Bocrabee Sandstone. The type section is south of Googhenama Rockhole (also known as Fig Tree Soak; MGA Zone 52, 326500E 7562600N), in the upper reaches of Googhenama Creek, and presumably includes only the lower conglomeratic facies. The unit is an approximately 500 m-thick succession of interbedded fine- to coarse-grained, light-pink to purple sandstone, and granular to pebbly conglomerate that unconformably overlies Archaean basement rocks along the western margin of the Tarcunyah Group (Williams and Trendall, 1998a,b). The formation is probably a correlative of the Gunanya Sandstone, Karara Formation, and the lower part of the Choorun Formation (Fig. 30; Bagas et al., 1999).

Conglomerate in the Googhenama Formation is lenticular, commonly matrix supported, and quartz-pebble rich or polymictic. Conglomerate beds in the lower part of the succession are polymictic and contain granitoid, vein quartz, chert, quartzite, sandstone, and rare jasper clasts that are probably derived from nearby basement rocks, whereas conglomerate higher up the succession is oligomictic, containing only quartz pebbles (Williams and Trendall, 1998a,b). The sandstone units are quartzose, with trough cross-laminations and ripple marks suggesting a western provenance. The formation was deposited in a fluvial setting.

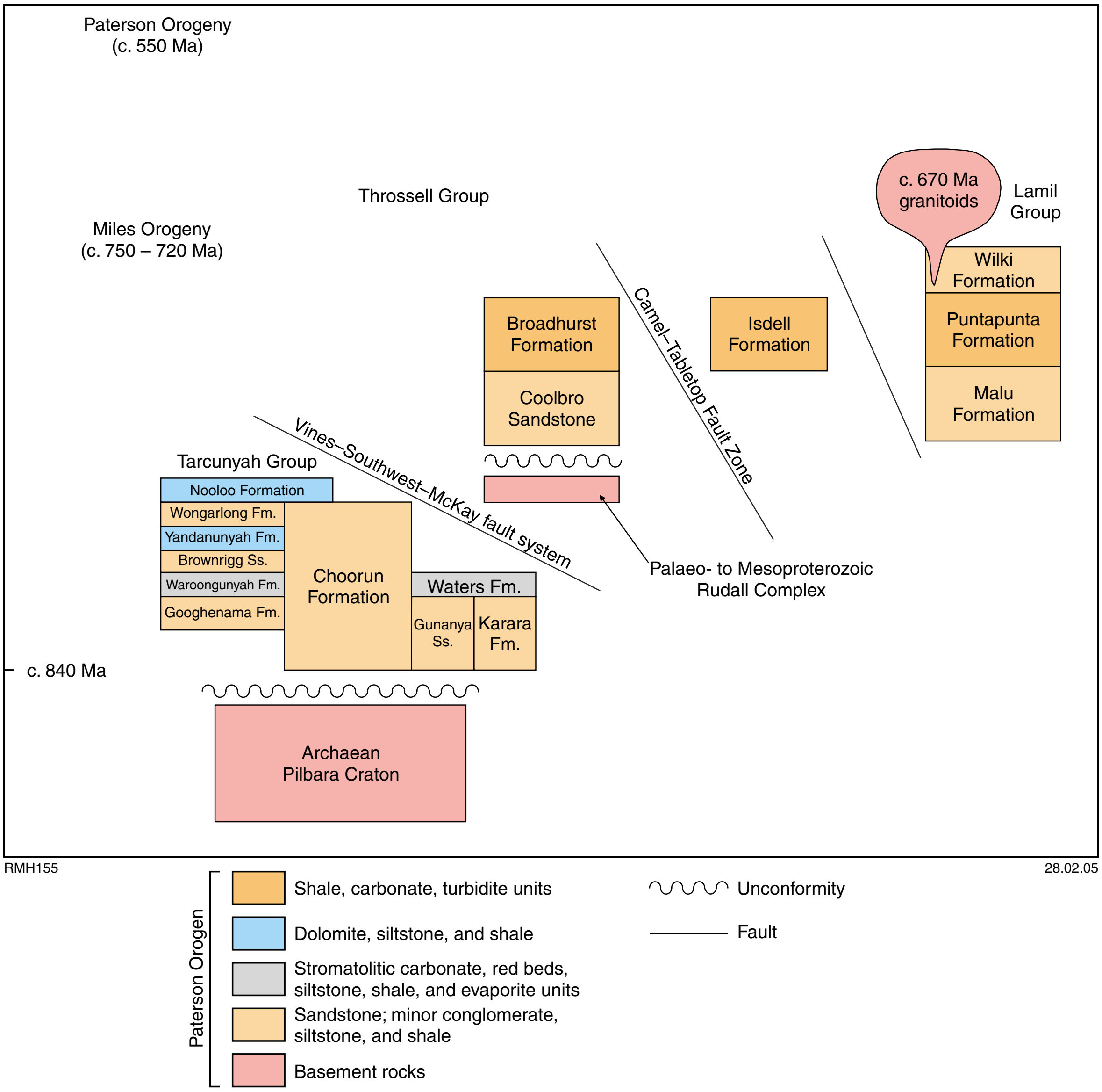

Figure 30. Inferred stratigraphic relationships, Tarcunyah, Lamil, and Throssell Range Groups

Gunanya Sandstone

The Gunanya Sandstone was named and described by Hickman and Bagas (1998) but no type section was specified. A type section is here specified, so the description here constitutes the first full definition of the Gunanya Sandstone. The formation was named after Gunanya Spring, on northeast GUNANYA. The Gunanya Sandstone outcrops in the southeastern part of the outcrop extent of the Tarcunyah Group (Bagas et al., 2000), primarily in the McKay Range, and unconformably overlies the Rudall Complex (Fig. 30). The type section is here specified as the section of Gunanya Sandstone along McKay Creek on northern GUNANYA 1:100 000 and southern CONNAUGHTON 1:100 000. It shows the lower part of the sandstone. The upper part of the Gunanya Sandstone is shown in a reference section at the headwaters of Waters Creek on RUDALL 1:100 000, from MGA Zone 51, 439000E 7457300N to about 441700E 7457300N. The formation is about 500 m thick, and consists of conglomerate and arkosic sandstone with thin lenticular interbeds of pebbly sandstone. The conglomerate at the base of the formation is about 10 m thick, fines upward, and contains well-sorted and rounded matrix-supported quartz pebbles. The sandstone is medium to coarse grained, and like the Googhenama Formation and Karara Formation is characteristically light pink to purple. Abundant trough cross-laminations and asymmetrical ripple marks indicate northwestward palaeocurrents.

Karara Formation

The Karara Formation was named as 'Karara Beds' by Williams et al. (1976) after Karara Well on RUNTON, and defined by Crowe and Chin (1979), who specified a type section in hills between Canning Stock Route Well 23 and Karara Well, at MGA Zone 51, 531000E 7447000N. The formation is recognized in a small area on BLANCHE–CRONIN 1:100 000 (Bagas, 1999), about 50 km southeast of outcrops of Gunanya Sandstone, where it unconformably overlies the Rudall Complex (Bagas et al., 2000). The formation consists of conglomerate, cross-bedded and ripple-marked sandstone, and minor amounts of quartz–feldspar wacke and shale. The conglomerate is thin and lensoidal at the base of the formation, and contains subrounded clasts, up to 1 m in diameter, which are derived from the Rudall Complex. The conglomerate fines upward into a well-bedded, fine-grained and distinctive pink sandstone. The formation closely resembles the Gunanya Sandstone, with which it is correlated (Fig. 30; Bagas and Smithies, 1998).

Waroongunyah Formation

The Waroongunyah Formation (named and defined by I. R. Williams, 1989) conformably overlies the Googhenama Formation on THROSSELL 1:100 000 (Williams and Bagas, 1999) and correlates with the Waters Formation (Fig. 30). The formation is named after Waroongunyah Rockhole, and has its type section 8.5 km northeast of Canning Well on Balfour Downs, at MGA Zone 51, 333500E 7529400N. The Waroongunyah Formation is up to about 600 m thick and contains dolomite interbedded with pink to grey-white siltstone and shale, and thin beds of brown, fine-grained sandstone containing scattered halite pseudomorphs. The dolomite outcrops as brown, grey, blue, and pink, massive to laminated dolomite, stromatolitic dolomite, commonly silicified oolitic dolomite, and sandy dolomite. The stromatolitic dolomite has been identified at several localities along the eastern margin of THROSSELL (Williams and Bagas, 1999; Bagas et al., 2000). The formation is a transgressive shallow-marine sequence probably deposited shorewards of carbonate build-ups. These may have been barrier islands or carbonate platforms marginal to the Pilbara Craton (Williams and Bagas, 1999).

Waltha Woora Formation

The Waltha Woora Formation (named and defined as 'Waltha Woora Beds' by Noldart and Wyatt, 1962; redefined by Hickman, 1978) is exposed in a fault-controlled basin west of the Gregory Range in the southwestern part of BRAESIDE 1:100 000 (Williams and Trendall, 1998a) and the central-northern part of PEARANA 1:100 000 (Williams and Trendall, 1998b). The formation unconformably overlies the Archaean–Palaeoproterozoic Mount Bruce Supergroup and is unconformably overlain by the Permian Paterson Formation.

Noldart and Wyatt (1962) nominated a type locality on Waltha Woora Creek (MGA Zone 51, 312000E 7616000N) north of the Woodie Woodie manganese mine on PEARANA 1:100 000. Hickman (1978) redefined the succession as a formation and included it in the Bangemall Basin. Studies of stromatolite taxa by Grey (1978, 1984b, unpublished data) indicate that the formation can be correlated with the Waroongunyah Formation of the Tarcunyah Group (Williams and Trendall, 1998a,b), and with the undifferentiated Tarcunyah Group on southern BLANCHE–CRONIN 1:100 000 (Bagas, 1999).

The Waltha Woora Formation consists of a lenticular, basal, medium- to coarse-grained sandstone, and conglomerate, conformably overlain by locally stromatolitic dolomite, siltstone, shale and minor sandstone interbeds (Williams and Trendall, 1998b). The basal clastic unit is restricted to local palaeodepressions and channels in the basement. The stromatolites in the overlying predominantly carbonate unit range from small digitate forms to bioherms up to 10 m thick (Williams and Trendall, 1998a).

The Waltha Woora Formation was probably deposited in an isolated sub-basin contemporaneously with rocks of the Tarcunyah Group (Williams and Trendall, 1998b).

Waters Formation

The Waters Formation was named and described by Hickman and Bagas (1998), but no type section was specified. A type section is here specified, so the description here constitutes the first full definition of the Waters Formation. Waters Creek flows through a major belt of exposure of the Waters Formation on the west side of the McKay Range, and the type area is here designated as along the creek, in a faulted syncline (from about MGA Zone 51, 439000E 7456500N to about 436800E 7457500N). The stratigraphic top of the Waters Formation is not exposed in this section. The Waters Formation is up to 100 m thick in outcrop, correlates with the Waroongunyah Formation (Fig. 30), and conformably overlies the Gunanya Sandstone on RUDALL in the southeastern exposure of the Tarcunyah Group. Drillhole LDDH 1 intersected approximately 600 m of Waters Formation (Grey and Cotter, 1996; Stevens and Carlsen, 1998).

The Waters Formation consists of reddish-brown to grey, carbonaceous shale containing gossanous (oxidized sulfidic shale) and nodular limonite horizons. The shale contains thin interbeds of planar and trough cross-bedded, fine- to coarse-grained, upward-fining sandstone and minor carbonate. The cross-beds indicate northward to northeastward palaeocurrents. The carbonate units are commonly concealed by calcrete or silcrete but, where exposed, are dark grey and include thin gossanous layers. Boulders of stromatolitic carbonate have been found, although no stromatolites were found in the bedrock (Hickman and Bagas, 1998). Palynomorphs from LDDH 1 indicate that this section correlates with the Browne Formation (Grey, 1995b; Grey and Cotter, 1996; Grey and Stevens, 1997).

Choorun Formation

The Choorun Formation (defined by Chin et al., 1980; redefined by Williams and Bagas, 1999; definition modified herein) is recognized to the west of the Southwest Thrust, which separates the Choorun Formation from the Yeneena Basin to the east. The formation is named after Choorun Waterhole on RUDALL. Chin et al. (1980) specified multiple type areas, for different facies in the unit. Not all of these are now regarded as Choorun Formation. The formation was redefined by Williams and Bagas (1999), and is now restricted to coarse- and medium-grained siliciclastic rocks along the eastern margin of the exposed Tarcunyah Group. The type section is here specified as a composite section (as yet unmeasured) in the Curran Curran Rockhole area (from a base at about MGA Zone 51, 392300E 7506000N to a top at 390000E 7509500N). The Choorun Formation unconformably overlies the Rudall Complex, and is conformably overlain by the Nooloo Formation (Williams and Bagas, 2000; Fig. 30). The relationship between these two formations and the other formations included in the Tarcunyah Group is not clear; however, the Choorun Formation is a possible correlative of the Waroongunyah and Googhenama Formations.

The Choorun Formation is an upward-fining, fluviatile succession, at least 1800 m thick, of matrix-supported, pebble to cobble conglomerate and pebbly sandstone containing vein quartz and sandstone clasts, overlain by a pinkish medium- to coarse-grained sandstone containing siliceous nodules (Williams and Bagas, 1999, 2000). The sandstone is commonly cross-laminated with sets over 1 m thick. Palaeocurrent directions are generally to the north and northeast (Williams, 1992).

Brownrigg Sandstone

The Brownrigg Sandstone (I. R. Williams, 1989) is at least 600 m thick (Williams and Bagas, 2000) and exposed on the eastern side of the Marloo Fault along the northern boundary of POISONBUSH 1:100 000. The formation is faulted against the younger Wongarlong Formation to the east, and the Tchukardine and Woora Woora Formations of the Disappointment Group to the west. It is named after Brownrigg Hill on NULLAGINE, and has its type section 9 km northeast of Canning Well on BALFOUR DOWNS (at MGA Zone 51, 334400E 7528500N).

The Brownrigg Sandstone consists of white, cream to light-brown, fine- to coarse-grained quartz sandstone with scattered, small pebbles of vein quartz. The formation is well bedded with flaggy and massive units. Cross-laminations with sets up to 3 m thick, ripple marks, and current striae are common. The palaeocurrent direction is commonly towards the northeast and east. Ripple marks are symmetrical wave-based forms. The formation is probably a shallow-marine shelf deposit (Williams and Bagas, 2000).

Yandanunyah Formation

The Yandanunyah Formation (I. R. Williams, 1989) outcrops in the eastern part of THROSSELL 1:100 000 and BALFOUR DOWNS, where it conformably overlies the Brownrigg Sandstone and is conformably overlain by the Wongarlong Formation (Williams and Bagas, 1999). The formation is named after Yandanunyah Rockhole on BALFOUR DOWNS, and has its type section 10 km east-northeast of Canning Well (at MGA Zone 51, 335000E 7528500N).

The Yandanunyah Formation is about 300 m thick and, in outcrop, consists of varicoloured interbedded siltstone and shale, calcareous shale that is commonly capped by a siliceous breccia, and minor silicified, blue-white oolitic and laminated carbonate that is stromatolitic in places. A similar oolitic lithofacies is present in the Waroongunyah Formation, suggesting a similar depositional environment.

Wongarlong Formation

The Wongarlong Formation (Williams and Bagas, 1999) is at least 1200 m thick and conformably overlies the Yandanunyah Formation on THROSSELL (Williams and Bagas, 1999) and POISONBUSH 1:100 000 (Williams and Bagas, 2000). The formation is named after Wongarlong Rockhole. Williams and Bagas (1999) nominated type areas west of Tarcunyah Creek (in a section from MGA Zone 51, 354900E 7513200N to 359500E 7513100N), and around Wongarlong Rockhole. The second of these is not shown as Wongarlong Formation on the relevant geological map (BALFOUR DOWNS, I. R. Williams, 1989), which pre-dates the definition of the formation, so it is here considered as a reference area rather than a type area. The section west of Tarcunyah Creek is designated as the type section.

The Wongarlong Formation consists of medium- to fine-grained sandstone interbedded with laminated and micaceous siltstone, shale, and silty shale. Bladed or needle-like pseudomorphs after gypsum, and intraformational clasts of siltstone and shale are found in places in the sandstone. Some alternating sandstone and siltstone–shale units form upward-coarsening successions. Cross-lamination is common in the lower parts of sandstone beds and ripple marks are common in the upper parts. The formation has been interpreted to be a shallow-marine shelf deposit characterized by repetitive thickening and coarsening-upward cycles that are up to 30 m thick (Williams and Bagas, 1999), although the gypsum pseudomorphs and intraclasts are suggestive of emergence.

Nooloo Formation

The Nooloo Formation (Williams and Bagas, 1999) is a poorly exposed unit on THROSSELL and POISONBUSH 1:100 000, named after Nooloo Soak. The formation appears to conformably overlie the Wongarlong and Choorun Formations on POISONBUSH 1:100 000 (Williams and Bagas, 2000). Two type areas were specified, in southeast and northwest THROSSELL 1:100 000 (MGA Zone 51, 388000E 7512000N, and 352000 7557000N), for different facies within the formation. The first of these is here taken as the type area because it shows more of the facies variability within the Nooloo Formation.

The Nooloo Formation consists of thinly bedded carbonate (dolomite and limestone) with rare blue chert nodules, calcareous shale and siltstone, thinly bedded, fine- to coarse-grained sandstone, siltstone, shale, and rare carbonate-cemented sandstone. Where the dolomite is absent, interbedded sandstone, commonly silicified siltstone and shale, pebbly conglomerate, and wacke sandstone prevail. Cross-laminations and symmetrical ripple marks are prominent in some of the sandstone interbeds, and indicate a palaeocurrent direction to the northeast. Williams and Bagas (1999) interpreted the Nooloo Formation as a deep-water shelf deposit.

Yeneena Basin

The Yeneena Basin was introduced by Williams and Myers (1990) as a subdivision of the Paterson Orogen. The basin is adjacent to the Phanerozoic Canning Basin and lies to the northeast of the northwestern Officer Basin, from which it is separated by the Vines–Southwest–McKay fault system. The Yeneena Basin includes the Lamil and Throssell Range Groups (Bagas, 2004b). The Yeneena Basin may be related to the Amadeus or Murraba Basins, which are separated from the Officer Basin by the Warri Ridge. This ridge is a major, long-lived structure that was significantly reactivated during the c. 550 Ma Paterson–Petermann Orogenies of central Australia (Grey, 1990; Camacho and Fanning, 1995; Walter et al., 1995).

Bagas et al. (2002) suggested that the Throssell Range and Lamil Groups are of Supersequence 2 age, based on the similarity of detrital zircon age profiles to those from the Lower Inindia Beds of the Amadeus Basin in the Northern Territory, and a maximum age from SHRIMP U–Pb dating of c. 900 Ma (Nelson, 2000; Bagas et al., 2002). No sedimentary rocks of Supersequence 2 age have yet been conclusively recognized in Western Australia.

Throssell Range Group

The Throssell Range Group was originally proposed as the Throssell Group (Bagas and Williams, 1999), which is invalid because Throssell is pre-empted by the Throssell Shale of the Mount House Group in the Kimberley region. The name is here amended to Throssell Range Group. The group is a mixed sandstone, shale, and carbonate (limestone and dolomite) succession that unconformably overlies, and is locally faulted against, the Rudall Complex (Willams and Bagas, 1999; Bagas et al., 2000). The group consists of the siliciclastic Coolbro Sandstone and the carbonaceous Broadhurst Formation, and is named after the Throssell Range on RUDALL. The siliciclastic Taliwanya Formation and the carbonaceous Pungkuli Formation were originally placed in the 'Throssell' Group, but some parts as originally mapped may belong to an older unnamed Mesoproterozoic succession, based on detrital zircon ages from the overlying Gunanya Sandstone (Bagas et al., 2002).

From sedimentary structures, the Throssell Range Group was probably deposited in fluvial to shallow-water marine-shelf environments (Bagas and Smithies, 1998; Hickman and Bagas, 1999) during the onset of the Miles Orogeny (Table 1; Bagas et al., 2002).

Coolbro Sandstone

The Coolbro Sandstone was named and described by Williams et al. (1976) and defined by Chin et al. (1980) for a fine- to coarse-grained sandstone that forms extensive prominent outcrops in central RUDALL. The type section is in the headwaters of Coolbro Creek (around MGA Zone 51, 392000E 7546500N), after which the formation is named. Regionally, the sandstone thins over a short distance to the southwest (Chin et al., 1980), from as much as 4000 m on BROADHURST 1:100 000 (Hickman and Clarke, 1994) to less than 30 m on THROSSELL 1:100 000 (Williams and Bagas, 1999) and POISONBUSH 1:100 000 (Williams and Bagas, 2000).

The Coolbro Sandstone consists predominantly of massive to well-bedded sandstone, with individual beds ranging from 0.5 to 3 m thick. The sandstone becomes finer grained in the upper part of the formation, and is commonly interbedded with siltstone lenses in a transitional zone into the overlying the Broadhurst Formation. Trough and planar cross-beds are common throughout the formation. North- to northeast-directed palaeocurrents in the formation suggest a provenance to the southwest (Hickman and Bagas, 1998). The basal part of the formation commonly contains lenticular polymictic conglomerate with rounded boulders and pebbles of gneiss, granitoid rocks, quartzite, chert, schist, and vein quartz, interpreted as channel-fill or braided stream deposits (Bagas et al., 2000). Well-sorted, matrix-supported, vein quartz conglomerate beds locally display crude vertical grading and are commonly ferruginous, indicating a pyrite component in the fresh rock. The rock commonly grades into a fine- to medium-grained quartz sandstone, which forms the bulk of the formation.

The Coolbro Sandstone has been dynamically metamorphosed under low-grade, greenschist facies conditions during early deformation assigned to the Miles Orogeny (Bagas and Smithies, 1998). It contains flattened or recrystallized quartz grains, and a variably sericitic matrix. Tourmaline is a common accessory.

Broadhurst Formation

The Broadhurst Formation was named and briefly described by Williams et al. (1976) and defined by Chin et al. (1980), who gave a type locality in the Broadhurst Range on RUDALL (at MGA Zone 51, 421000E 7537500N). The formation conformably overlies the Coolbro Sandstone, and is separated from the Tarcunyah Group to the west by the Vines–Southwest Thrust. The Broadhurst Formation is around 2000 m thick (Hickman and Clarke, 1994; Williams and Bagas, 1999). The formation is characterized by poorly outcropping, metamorphosed, grey, carbonaceous (graphitic) shale and siltstone, sandstone, lithic wacke, carbonate, and lenses of well-exposed, fine- to coarse-grained sandstone. Much of the sandstone is cross-bedded with a palaeocurrent direction indicating a southwesterly provenance (Hickman and Bagas, 1998; Williams and Bagas, 1999). Sandstone interbedded with siltstone and shale also outcrops in the lower part of the formation between Coolbro Creek and the Cottesloe prospect, on BROADHURST 1:100 000. The sandstone is separated from the Coolbro Sandstone by 50–100 m of shale and carbonate rock. Carbonate rock is composed of dolomite and limestone, and is grey, thinly bedded to laminated, carbonaceous, and sulfidic. Basalt outcrops at one locality 12 km west of Mount Isdell (BROADHURST 1:100 000; Hickman and Clarke, 1994).

Taliwanya Formation

The Taliwanya Formation (Bagas and Smithies, 1998) was originally mapped as the basal formation of the 'Throssell' Group on CONNAUGHTON 1:100 000. Comparison of age populations of detrital zircons later implied that the only area where this may be true is north of the McKay Range, and all other outcrops are an older unit (Bagas et al., 2002). Stratigraphic relationships between the Taliwanya and overlying Pungkuli Formations of the McKay Range and the Coolbro Sandstone and Broadhurst Formation of the Throssell and Broadhurst Ranges are problematical because of the lack of outcrop in intervening areas, but the four units were tentatively grouped lithostratigraphically by Bagas et al. (2000). The Taliwanya Formation is interpreted as a correlative of the Coolbro Sandstone on lithological grounds, although it is much thinner than the Coolbro Sandstone on BROADHURST 1:100 000 (Hickman and Clarke, 1994) and RUDALL 1:100 000 (Hickman and Bagas, 1998). The formation is named after the local name for the Talawana Track, which links the Canning Stock Route and Newman and passes just south of the outcrop belt of the Taliwanya Formation. The type locality is here specified midway between the McKay and Harbutt Ranges, where both the upper and lower contacts are present (around MGA Zone 51, 467500E 7465200N), so the description here is the first full definition of the Taliwanya Formation.

The Taliwanya Formation is up to 170 m thick and is predominantly arkosic sandstone containing local thick beds of polymictic conglomerate, and rare, thin interbeds of fine-grained lithic wacke, siltstone, and shale. The shale becomes more abundant towards the conformable contact with the overlying Pungkuli Formation. The conglomerate contains pebbles, cobbles, and boulders of quartzite, vein quartz, orthogneiss, and rare angular clasts of ironstone. The clasts are commonly rounded or subrounded, supported by an arkosic matrix, and locally display an upward decrease in clast size into the overlying arkosic sandstone. The conglomerate is interpreted as a channel-fill deposit. Cross-bedding and asymmetrical ripple marks are locally preserved in the sandstone (Bagas and Smithies, 1998).

Pungkuli Formation

The Pungkuli Formation (Bagas and Smithies, 1998) is exposed in, and north of, the McKay Range on CONNAUGHTON 1:100 000. Bagas and Smithies thought that the Pungkuli Formation was overlain by the Tarcunyah Group north of the McKay Fault, but the outcrops in question have since been reassessed and may belong to an older, unnamed Mesoproterozoic succession (Bagas et al., 2002). The formation is about 900 m thick and probably correlates with the Broadhurst Formation (Bagas and Smithies, 1998). Pungkuli is the local name for the eastern McKay Range. A type section is here specified, so the description here constitutes the first full definition of the Pungkuli Formation. The type section is here specified as being along a broad syncline midway between the McKay and Harbutt Ranges, from the top of the Taliwanya Formation type section (MGA Zone 51, 467500E 7465000N) to the contact with the Gunanya Sandstone (at about 471000E 7461500N).

The Pungkuli Formation consists of interbedded, laminated, slightly micaceous, grey to dark brown-black shale, locally carbonaceous shale and siltstone, thin units of sulfidic shale and sandstone, and minor carbonate and chert. Lenticular bedding and rare wave-ripple marks suggest deposition in a quiet, shallow-water environment. Thinly bedded, light-pink, grey to cream-coloured recrystallized dolomite interbedded with light-grey chert, calcareous shale, siltstone, and minor black sulfidic and carbonaceous shale and sandstone is well exposed at the base of the Pungkuli Formation in McKay Range (Bagas and Smithies, 1998). Fine-scale cross-bedding, flute marks in thin sandstone interbeds, and stromatolites in carbonate are indicative of sedimentation in shallow-water conditions.

Lamil Group

The Lamil Group (named by Williams and Bagas, 1999; introduced formally by Bagas, 2000) is a mixed sandstone, shale, and carbonate (limestone and dolomite) succession that is in faulted contact with the Throssell Range Group, and consists of the Malu, Puntapunta, Isdell, and Wilki Formations (Bagas, 2000, 2004b; Fig. 30). The Lamil Group is younger than c. 900 Ma, which is the age of detrital zircons extracted from sandstone beds in the Malu Formation (Bagas et al., 2002), and older than c. 654 Ma, which is the SHRIMP U–Pb titanite age of post-orogenic monzogranites and syenogranites that intrude the group (Dunphy and McNaughton, 1998). The group is named after the Lamil Hills on PATERSON RANGE, which are composed of Malu Formation.

The deformation history of the Lamil Group includes northeast–southwesterly directed compression and upright folding associated with the c. 750 Miles Orogeny (Bagas et al., 1995, 2000; Bagas, 2000; Table 1).

Malu Formation

Bagas (2000) redefined the Malu Quartzite of Chin et al. (1982) as Malu Formation, and included within this unit the Telfer Formation of Chin et al. (1982) as the Telfer Member. The Malu Formation consists of fine- to medium-grained sandstone with minor shale and dolomite. The unit is in faulted contact with an unnamed carbonate sequence (previously correlated with the Isdell Formation) to the south of Karakutikati Range on PATERSON RANGE, and is conformably overlain by the Puntapunta Formation. The Telfer Member is differentiated from the rest of the Malu Formation by a higher proportion of interbedded siltstone, and rare carbonate beds. Both units contain quartz-rich sandstone, siltstone, and shale. The formation is at least 2 km thick in the Malu Hills, after which it is named, and drillholes associated with the Telfer mine have intersected similar thicknesses. The type area is the Malu Hills (MGA Zone 51, 417200E 7611200N) in central PATERSON RANGE.

Although bedding is poorly preserved in outcrop, the Malu Formation has a distinctive banded pattern on aerial photographs. Sandstone beds are commonly less than 5 m thick and coarsening-upward sequences can locally be discerned (Bagas, 2000). Owing to widespread diagenetic silicification in the region, sedimentary structures are rarely preserved. Flute marks, parallel laminations, and cross-bedding with a palaeocurrent direction to the northeast are locally preserved (Bagas, 2000).

Turner (1982) interpreted the Malu Formation as deep-water turbidite deposits in northeasterly prograding submarine fans, and also suggested that the Telfer Member marked a transition from deep water to an outer carbonate-shelf environment, in which the overlying Puntapunta Formation was deposited.

It was previously thought that the Isdell Formation underlies the Malu Formation. However, drillcore that was thought to commence in the Malu Formation and reach total depth in the Isdell Formation comprises a continuous, alternating sequence of sandstone, siltstone, and shale (Hewson, 1996; Bagas, 2000), with no thick carbonate interbeds typical of the Isdell Formation. The entire section is here regarded as Malu Formation.

Organic carbon in samples from drillholes near the Telfer mine site is thermally mature, and no identifiable palynomorphs are present (Grey, 1995c).

Puntapunta Formation

The Puntapunta Formation (named and defined by Chin et al., 1982) is an outer carbonate-shelf deposit that is conformable on the Malu Formation, and is conformably overlain by the Wilki Formation (Bagas, 2000). The lower contact is the top of the highest sandstone bed in the Malu Formation (Bagas, 2000). The upper contact is the top of the highest carbonate unit in the Puntapunta Formation, which corresponds to the base of the lowermost sandstone in the Wilki Formation. The Puntapunta Formation is about 1.5 km thick and is well exposed as low-lying outcrops. The type area is on the northern side of the Karakutikati Range (MGA Zone 51, 413900E 7587200N), 5 km west of Puntapunta Hill, in south-central PATERSON RANGE.

The formation consists of a laminated to thinly bedded sequence of dolomitic sandstone, grey dolomitic siltstone, chert, shale, rare limestone, and very rare beds of dolorudite, which form lensoid channels that are around 2 m wide and 0.5 m thick (Bagas, 2000). The cross-bedding includes 20–50 mm-thick planar cross-sets and approximately 100 mm-thick trough cross-sets. Cross-bedding indicates palaeocurrents flowed towards the northeast.

Isdell Formation

The Isdell Formation was named and briefly described by Williams et al. (1976), and defined by Chin et al. (1980), who listed the type locality as southwest of Mount Isdell on northern RUDALL (MGA Zone 51, 414000E 7559500N). The formation is exposed around Mount Isdell near the northern boundary of BROADHURST 1:100 000 (Hickman and Clarke, 1994), and is composed of carbonate rocks intercalated with relatively thin units of calcareous siltstone and shale. The carbonate consists of dark-grey dolomitic limestone and dolomite containing minor sulfidic shale and calcarenite interbeds, and rare intraformational carbonate conglomerate. Both graded bedding and fine-scale cross-lamination are locally preserved. The total thickness of the formation exceeds 1000 m (Hickman and Clarke, 1994). The similar lithology of the Isdell and Puntapunta Formations suggests they may be correlatives, given that the stratigraphic relationship of the Isdell Formation to the Malu Formation is unknown.

Similar rocks types are present 10 km farther north on southern PATERSON 1:100 000, and were correlated by Chin et al. (1982) with the Isdell Formation. This carbonate succession is tectonically overlain by the Malu Formation in the Karakutikati Range. The contact is a northeast-dipping thrust with movement towards the southwest, so stratigraphic relationships cannot be established. Bagas (2000) regarded the 'Isdell Formation' in this area as an unnamed unit for this reason.

Wilki Formation

The Wilki Formation is the youngest exposed stratigraphic unit of the Lamil Group. The formation was originally named and defined as the Wilki Quartzite (Chin et al., 1982) and was redefined as Wilki Formation by Bagas (2000), who also included the informally named 'Kaliranu beds' of Williams (1990b) as the Kaliranu Member. The type section is in the Wilki Range (MGA Zone 51, 429500E 7596700N) on PATERSON RANGE.

The Wilki Formation is about 1.4 km thick and is thought to overlie the Puntapunta Formation conformably, although the contact between the two formations is not exposed (Bagas, 2004b). The basal part of the Wilki Formation is poorly exposed and dominated by graphitic shale and siltstone, interbedded with fine-grained silty sandstone. This unit is about 250 m thick and seems to be transitional with the underlying Puntapunta Formation (Bagas, 2000).

Much of the Wilki Formation is a monotonous sequence of silicified sandstone, and sedimentary structures are not preserved. Bedding comprises laterally extensive, fine- to medium-grained sandstone and recessive silty sandstone (Bagas, 2000). The Kaliranu Member is a poorly exposed sequence towards the top of the Wilki Formation that includes interbedded shale, siltstone, fine-grained sandstone, and silty dolomite. The member is at least 200 m thick. Turner (1982) suggested a shallow-marine depositional environment for the Wilki Formation.

Igneous rocks associated with the Officer Basin

Large volumes of mafic sills and dykes are present in an area of central Australia that extends for about 1300 km along an east-southeast trend and includes within its bounds the Officer Basin. These mafic rocks have ages of approximately 1465, 1070, 825 and 500 Ma, indicating four major thermal events in the region. These thermal events resulted in the emplacement of large igneous provinces (LIPs) along what was probably a major zone of crustal weakness. Two of these LIPs probably bracket the Officer Basin, and were intersected in Empress 1 and 1A. The province resulting from the 1070 Ma event was named the Warakurna Large Igneous Province by Wingate et al. (2004). In addition, extrusive basaltic rocks were intersected in Weedy 1 (K–Ar, c. 650 Ma) and Lancer 1.

Drillhole intersections

Empress 1A intersected mafic rocks of two ages, 484 ± 8 Ma (K–Ar; Table Hill Volcanics) at 216 m, and 1058 ± 13 Ma (K–Ar) at 1602 m, immediately above and slightly below the Officer Basin succession (Nelson, 1999; Amdel, 1999; Stevens and Apak, 1999). The younger rocks are interpreted as part of the Table Hill Volcanics, which extends from 203 to 286 m drilled depth. The later age from Empress 1A is about 20 m.y. younger than other radiometric dates of the Table Hill Volcanics, and this is taken to reflect the age of alteration rather than crystallization. The older age is comparable with ages from the Musgrave Complex (see Glikson et al., 1996; Close et al., 2003) and those of widespread intrusions in the Capricorn Orogen (Cawood and Tyler, 2004) grouped into the Warakurna LIP, provided the age in Empress 1A reflects alteration rather than the time of crystallization. The older volcano-sedimentary succession extends from 1521.8 to 1624.6 m drilled depth (TD).

In the northwest Officer Basin, Akubra 1 and Boondawari 1 intersected gabbroic rocks at two levels: 64–181 m (TD) and at 1280–1366 m (TD) respectively. SHRIMP U–Pb geochronology of baddeleyite and zircon from gabbro in Boondawari 1 yielded a crystallization age of 508 ± 5 Ma (Wingate, M. T. D., 2002, written comm.). This age is close (within error) to that of a dolerite dyke (513 ± 12 Ma; SHRIMP U–Pb, zircon) that is geochemically correlated with the Antrim Plateau Volcanics (Hanley and Wingate, 2000) and Table Hill Volcanics. The Table Hill Volcanics has a minimum age of 484 ± 8 Ma (Empress 1A, Carlsen and Grey, 1998).

Weedy 1 intersected channelized basalt flows with a K–Ar age of c. 650 Ma (Nelson, 2002) in the southern Officer Basin, and Lancer 1 in the northern Officer Basin intersected multiple mafic flows, here named the Keene Basalt, within the Kanpa Formation. The Keene Basalt is as yet undated, but probable *Baicalia burra* are present less than a metre both above and below the flows.

Keene Basalt

Lancer 1 intersected mafic extrusive igneous rocks between 527 and 576 m. Kanpa Formation overlies and underlies the igneous rocks, which are here named the Keene Basalt after Lake Keene, 10 km west of Lancer 1. The type section is the drillhole section, and a formal definition is in Haines et al. (2004).

From preliminary examination of the core, there appear to be five flows, with textures ranging from basaltic to gabbroic in the central, slower cooling parts of each flow (Haines et al., in prep.). The rocks beneath the flows have been baked and show some indications of dewatering; those above the flows are not contact metamorphosed but show dewatering structures, perhaps indicative of earthquakes associated with volcanism. The top of the uppermost flow has been eroded down into the gabbroic core of the flow, prior to deposition of overlying fine-grained sediments. Weathering of the flows is apparent in thin section, and decreases downward. The mineralogy indicates an arid alkaline environment during weathering. Further details of petrography, age, or chemistry are not yet available, though work is in progress.

Based on broad regional correlations, the Keene Basalt could correlate with the Mundine Well Dyke Swarm, which has an age of 755 ± 3 Ma (Wingate and Giddings, 2000). The Keene Basalt must be younger than the Boucaut Volcanics of the Adelaide Rift Complex, which has an age of 777 ± 7 Ma (Preiss, 2000), as this unit is found at the base of the Burra Group, which in turn correlates with the base of the Hussar Formation, based on palynology and stromatolite and isotope correlation (Hill et al., 2000). The stratigraphic position of the Keene Basalt, well above the base of the Hussar Formation, and a detrital zircon SHRIMP U–Pb age of 725 ± 11 Ma for top Kanpa Formation in Empress 1A, are both compatible with correlation between the Keene Basalt and the Mundine Well Dyke Swarm.

Northwestern Officer Basin

Amygdaloidal basaltic rocks, and dolerite and gabbro sills and dykes outcrop extensively but poorly in, or adjacent to, the northwestern Officer Basin region (de la Hunty, 1969; Williams and Tyler, 1991; Williams, 1992, 1995a,b). In addition to north-northeasterly and northeasterly trending dykes, mafic rocks outcrop in the Akubra–Boondawari, Robertson Range, and Trainor Hills areas (Figs 31, 32). Some of these rocks are part of the igneous event that formed the 1070 Ma Glenayle Dolerite (Nelson, 2002; Hocking et al., 2000a, 2003; Pirajno and Hocking, 2001, 2002), but some dykes intrude the Glenayle Dolerite, Salvation Group, and Officer Basin succession. The age of these younger dykes is not known. Some dykes may belong to the 826 Ma Gairdner Swarm, and others may be associated with extrusion of the Table Hill Volcanics and emplacement of the ‘Boondawari dolerite’ (see below, ‘Boondawari Dolerite’ of Williams, 1992; invalid name as ‘Boondawari’ is pre-empted by the Boondawari Formation) at about 500 Ma, or with the same magmatic event that led to the flows encountered in Weedy 1 (c. 650 Ma, Nelson, 2002; see below) or in Lancer 1 in the Kanpa Formation.

Individual dykes range up to 30 km long and 10 m wide. They commonly cluster near the northwestern margin of the northwestern Officer Basin, and are similar to dykes in the Capricorn and Paterson Orogens. Most are strongly kaolinized, but dolerite textures are locally preserved, indicating an original fine to medium grain size. Some can be seen to pre-date the Boondawari Formation, and so may be coeval with the flows in either Weedy 1 or Lancer 1.

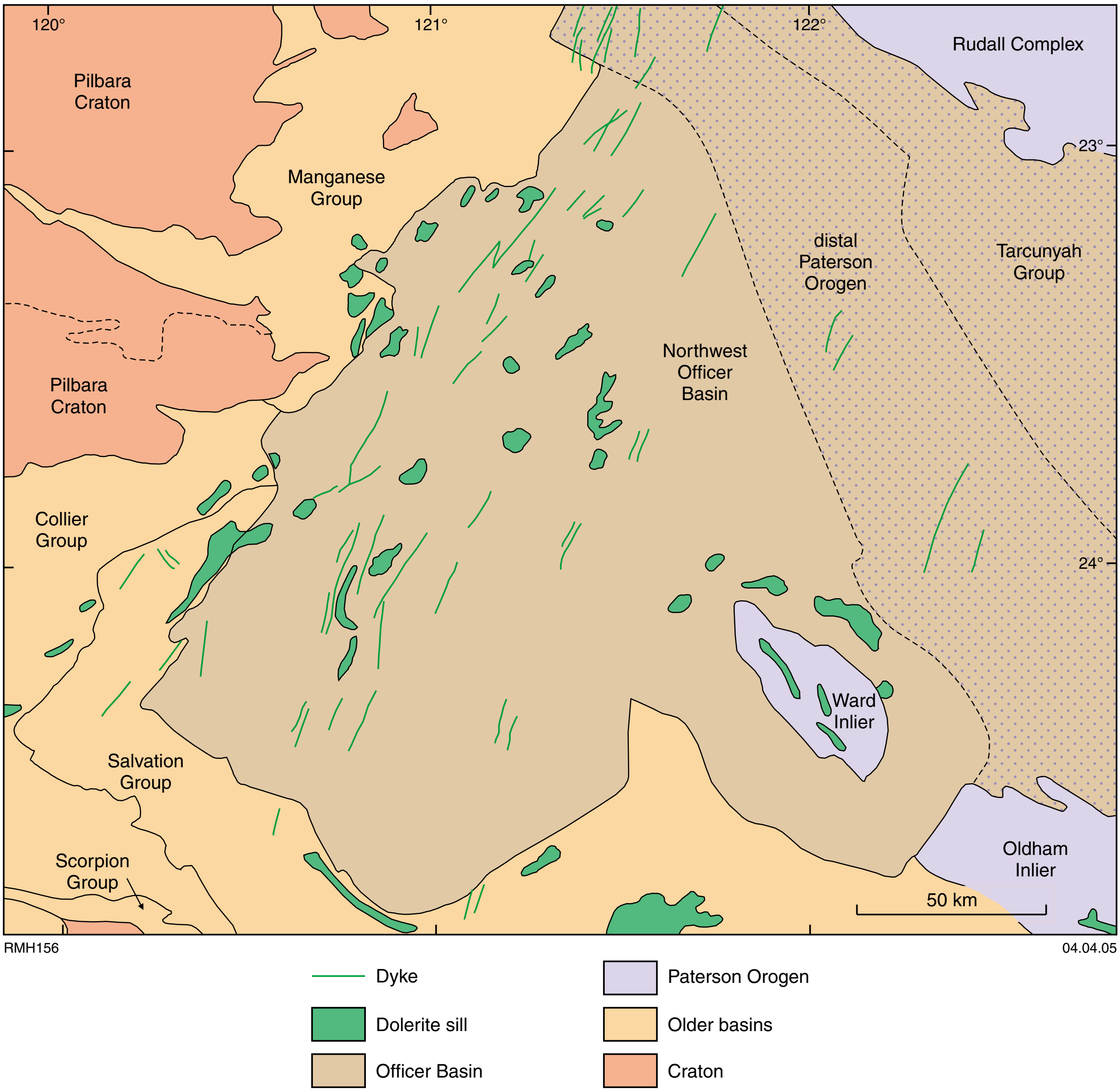

Figure 31. Extent of mafic igneous rocks in the northwestern Officer Basin

Trainor Hills and west of Well 15

Gabbro, dolerite, and plagioclase-phyric basaltic rocks with a general west-northwest trend outcrop around Trainor Hills and west of CSR Well 15 (Figs 31, 32). Most rocks are commonly weathered and overlain by residual ferruginous duricrust, but fresh exposures can be seen locally in creek beds and low-lying areas. These scattered outcrops may be part of a single mafic body or series of multiple cogenetic sills, intrusive into the Mundadjini Formation, extending for at least 60 km. Total or aggregate thickness is not known, but Williams (1992) estimated a maximum of 800 m.

These rocks are holocrystalline, two-pyroxene gabbroic rocks, containing augite, enstatite, and labradorite (An_{52} to An_{66}) as the main phases, with accessory kaersutite, brown hornblende, apatite, sericite, red-brown biotite, epidote, chlorite, quartz, Fe–Ti oxides, and lesser sulfide blebs (pyrite and chalcopyrite). Most accessories are alteration phases that replace the main assemblage (e.g. kaersutite tends to replace the clinopyroxene). Biotite contains inclusions of a radioactive phase (pleochroic haloes), possibly baddeleyite. Interstitial granophyre (quartz–feldspar) is commonly present. Fine-grained rocks appear basaltic in hand specimens, but are probably chilled margins of the sill(s). They consist of skeletal plagioclase microlites, locally with swallowtail terminations (indicative of rapid cooling), and clinopyroxene granules and microphenocrysts, in places altered to chlorite and carbonate. In chilled-margin samples, there are abundant disseminations of ilmenite and sulfides (mostly pyrite);

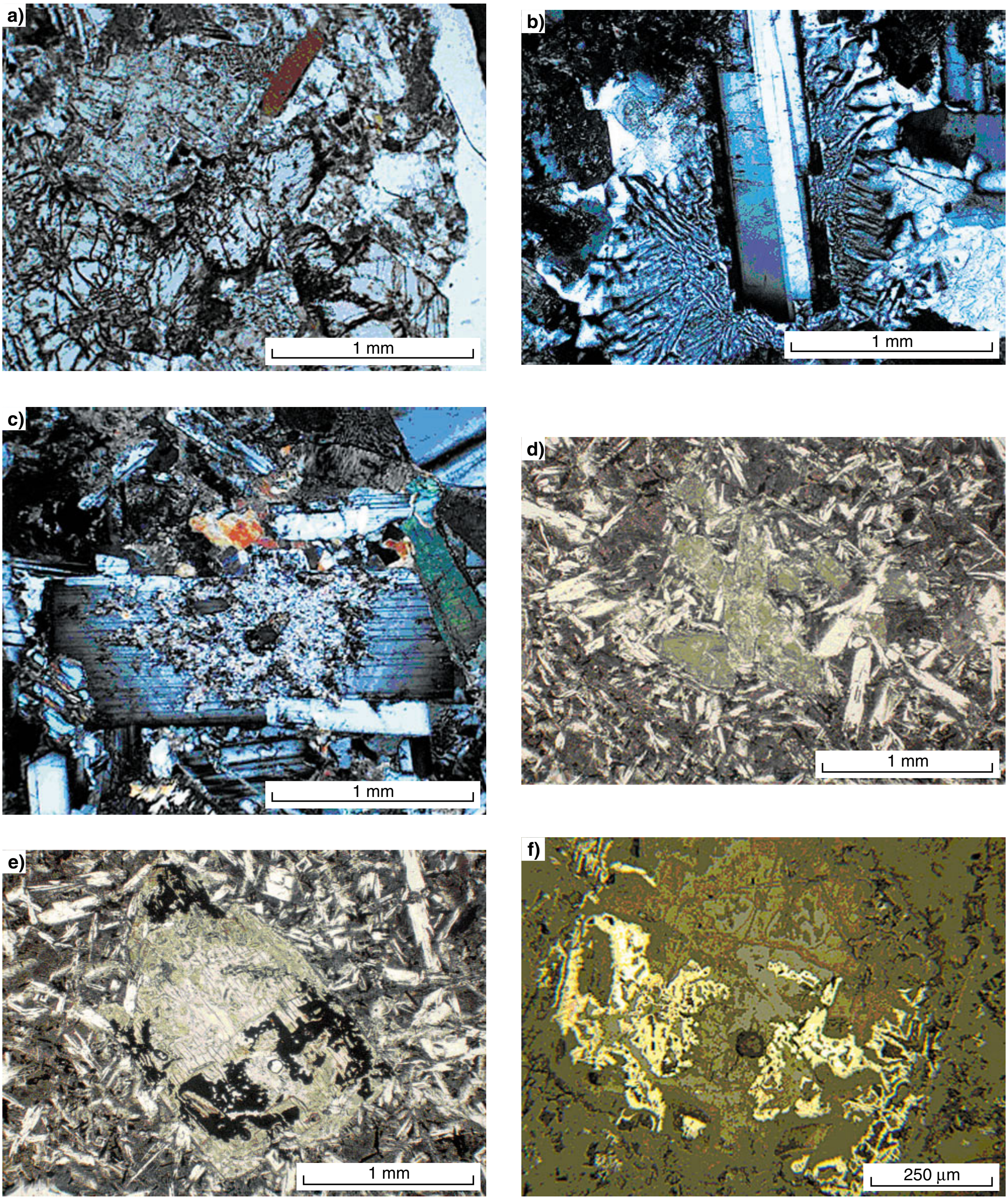

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Figure 32. Exposed intrusive rocks, northwest Officer Basin: a) GSWA sample 171728 (plane-polarized light) two-pyroxene dolerite with secondary hornblende and biotite; intruding Boondawari Formation, Trainor Hills (421360E, 7316750N); b) GSWA sample 171731C (cross-polarized light) labradorite associated with granophyre intruding Mundadjini Formation, west of CSR Well 15 (411720E, 7327780N); c) GSWA sample 171731D (cross-polarized light) sericitic alteration of labradorite, west of CSR Well 15 (411720E, 7327780N);d) GSWA 171787 (plane-polarized light) chlorite and carbonate-altered clinopyroxene in a chilled margin of dolerite, note swallowtail terminations of plagioclase microlites indicative of rapid cooling, Ripple Hill (383810E, 7342370N); e) GSWA sample 171787 (plane-polarized light) augite phenocryst showing alteration to chlorite, carbonate, and pyrite (black), Ripple Hill (383810E, 7342370N); f) GSWA sample 171787 (reflected light) pyrite replacing augite phenocryst, Ripple Hill (383810E, 7342370N). All localities are MGA Zone 51

in one case the sulfides replace augite phenocrysts, suggesting introduction of sulfur. Bunches of plagioclase crystals impart a glomeroporphyritic texture, and have a composition of An_{66} (labradorite; determined on albite–Carlsbad twins). The country rocks show hornfels spotting, indicating thermal metamorphism.

Akubra–Boondawari area

A northerly trending, 11 km-long and 1.5 km-wide gabbroic sill is present near Boondawari Soak in the north-central portion of the northwest Officer Basin (Williams, 1992). Another dolerite intrusion is present north-northwest from this area, at Akubra Hills. Boondawari 1 and Akubra 1 intersected gabbroic rocks between 1290 and 1367 m (TD) and from 63 to 181 m (TD), respectively (Figs 33–35). The age of these rocks is comparable with that of the Table Hill Volcanics (see above).

The sill near Boondawari Soak is about 80 m thick, with a subophitic texture, and contains augite and plagioclase (An_{46} to An_{56} compositions, andesine–labradorite) as main minerals, with varying amounts of brown hornblende, chlorite, sericite, chlorite, titanite, ilmenite, actinolite, and scattered small sulfide blebs. The footwall sandstone is hornfelsed to an assemblage of quartz, cordierite, fibrolite, and chlorite. Sandstone in the hangingwall is recrystallized and partially resorbed (?melted) with chlorite and K-feldspar as alteration phases. In the field, the gabbro and dolerite are medium to coarse grained, subophitic, with augite, labradorite, minor amounts of orthopyroxene, brown hornblende, and, locally, olivine (Williams, 1992). Granophyric patches are also present. The Boondawari gabbro–dolerite is intruded by leucocratic dykes containing albite, amphibole, magnetite, and titanite (Williams, 1992).

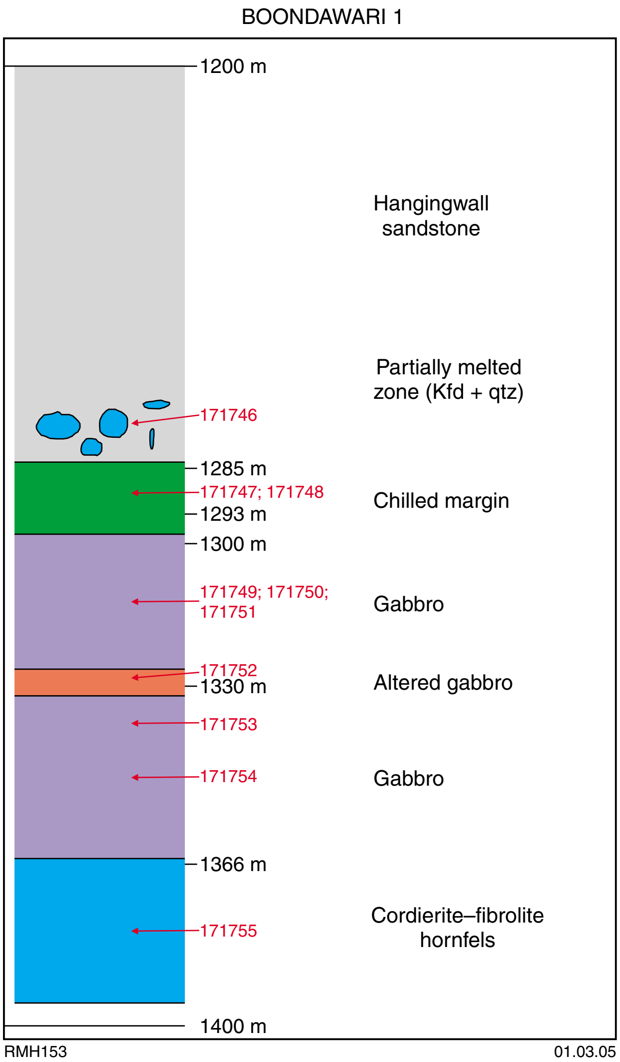

Figure 33. GSWA sample locations (red numbers) and sill characteristics, Boondawari 1

Akubra 1 (Figs 34b–d, 35) intersected medium- to coarse-grained altered gabbroic rock from 63 to 181 m (TD), gradational into a central zone (88–104 m) of granophyre-rich, pink-brown, finer grained gabbro. The main gabbro consists of labradorite (An_{54} to An_{66}) laths up to 4–5 mm long, and augite; accessories include ilmenite, acicular apatite, leucoxene, brown-green hornblende, dark-brown kaersutite, sericite, and chlorite. These are alteration minerals that replace, to varying degrees, labradorite, augite, and ilmenite. The granophyric section exhibits abundant quartz–feldspar intergrowths (granophyre sensu stricto), cloudy plagioclase, brown-green hornblende, blue-green chlorite sheafs, and apatite needles (up to 5 mm long). Minor sulfides are present throughout and include pyrite and chalcopyrite.

Robertson Range

At the western margin of the Officer Basin on ROBERTSON, mafic sills and dykes are present near, and along, the northeast-trending fault boundaries (Robertson Fault System) between the Officer and Collier Basins. They mostly intrude Coondra Formation or, farther south, the Jilyili and Glass Spring Formations of the Salvation Group. Very little is known about these rocks. Williams (1992) and Williams and Tyler (1991) described fine- to coarse-grained dolerite sills and small intrusions. At least 14 mafic bodies are present in this area, within the lower part of the Officer Basin succession. These rocks contain clinopyroxene, altered labradorite, accessory magnetite, and minor sulfides. Locally, orthopyroxene may be present. Amphibole replaces the pyroxenes in some areas (Williams and Tyler, 1991). Fine-grained mafic units (basaltic in appearance) are characterized by bands of amygdales, which are filled with chalcedonic silica and chlorite (Williams, 1992). The amygdaloidal bands tend to occupy the top of sills and the margins of dykes, suggesting that these basaltic rocks are chilled phases of intrusions. Sedimentary rocks at the contact with the sills are recrystallized and indurated, and locally exhibit columnar jointing (Williams, 1992).

Ward and Oldham Inliers

The Ward and Oldham Inliers are northwest-trending windows of basement in the northwest Officer Basin, and contain sandstone, shale, and minor chert of the Oldham Sandstone, Quadrio Formation, and Cornelia Sandstone.

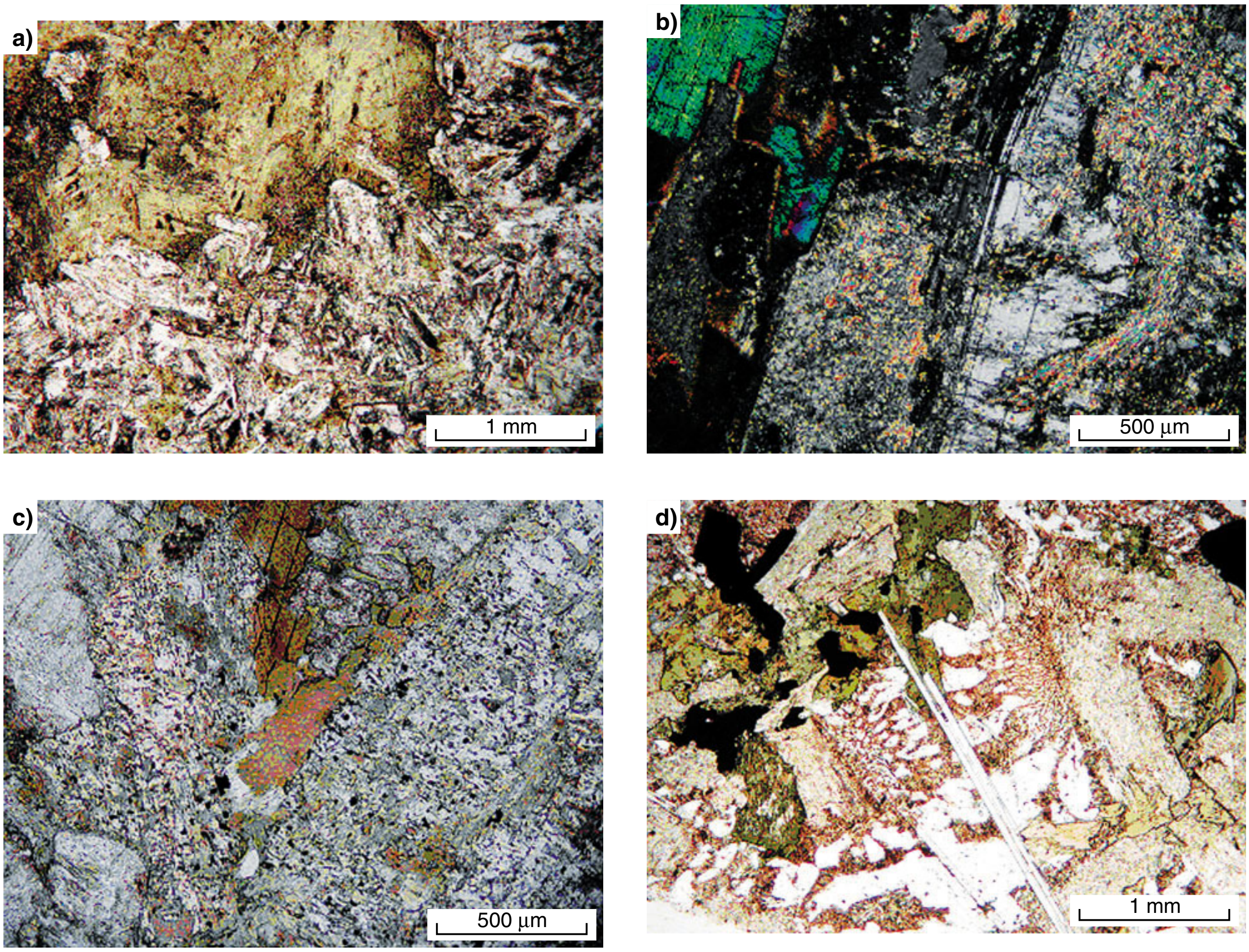

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Figure 34. Mafic intrusive rocks in Boondawari and Akubra 1: a) GSWA sample 171752 (plane-polarized light) actinolite and clinopyroxene (top left) and fine-grained sericitized plagioclase (lower half), Boondawari 1 (1328.5 m); b) GSWA sample 171761 (cross-polarized light) labradorite lath with sericite alteration, Akubra 1 (66 m); c) GSWA sample 171762 (plane-polarized light) brown hornblende replacing clinopyroxene, Akubra 1 (73 m); d) GSWA sample 171779 (plane-polarized light) acicular apatite cutting through granophyre, Akubra 1 (89 m). Sample locations shown in Figures 33 and 35

From regional considerations, these rocks could correlate with the Collier, Edmund, or Earaheedy Groups (Hocking et al., 2000b; R. M. Hocking, unpublished data). Mafic sills intrude rocks of both inliers, trend northwest, and appear to be bedding parallel. They are commonly deeply weathered to kaolinitic clays, but with the igneous texture still recognizable in places. One sill in the Ward Inlier is about 35 m thick. Where exposed, sedimentary rocks bounding the sills and dykes are visibly baked. Dykes are also present, but their relationship to the sills is unknown. The sills are interpreted as part of the 1070 Ma intrusive event, but some dykes may be younger, as similar dykes cut sills farther south on Glen-Ayle Station on STANLEY.

Igneous rocks in the Paterson Orogen

Monzogranite and syenogranite

Granites intrude the Lamil Group on the PATERSON, LAMIL and COOLYU 1:100 000 sheets, range in composition from monzogranite to syenogranite, and are commonly massive and not deformed (Bagas, 2000). They are highly fractionated (with average SiO_2 contents >71 wt% and Rb/Sr ratios of up to 20.5), metaluminous, and I-type in nature (Goellnicht et al., 1991). Contact metamorphic aureoles are up to 2 km wide (Goellnicht, 1992), and reach the pyroxene-hornfels facies grade (Chin et al., 1982). The granites can be divided into an oxidized suite, which contains magnetite and has a positive aeromagnetic signature, and a reduced suite that is ilmenite-stable and has a negative magnetic signature (Budd et al., 2002). The oxidized suite trends northeast and the reduced suite trends northwest and east-southeast (Bagas, 2000).

The granites are predominantly equigranular, medium- to coarse-grained biotite monzogranite, with areas of fine-grained leucocratic syenogranite. The monzogranite locally grades into porphyritic phases, which are considered local variants (Bagas, 2000). The monzogranite consists of perthitic K-feldspar (orthoclase and minor microcline), which is megacrystic in places, quartz, minor biotite, plagioclase with myrmekitic rimming, apatite, titanite, zircon, allanite, opaque minerals, and rare hornblende.

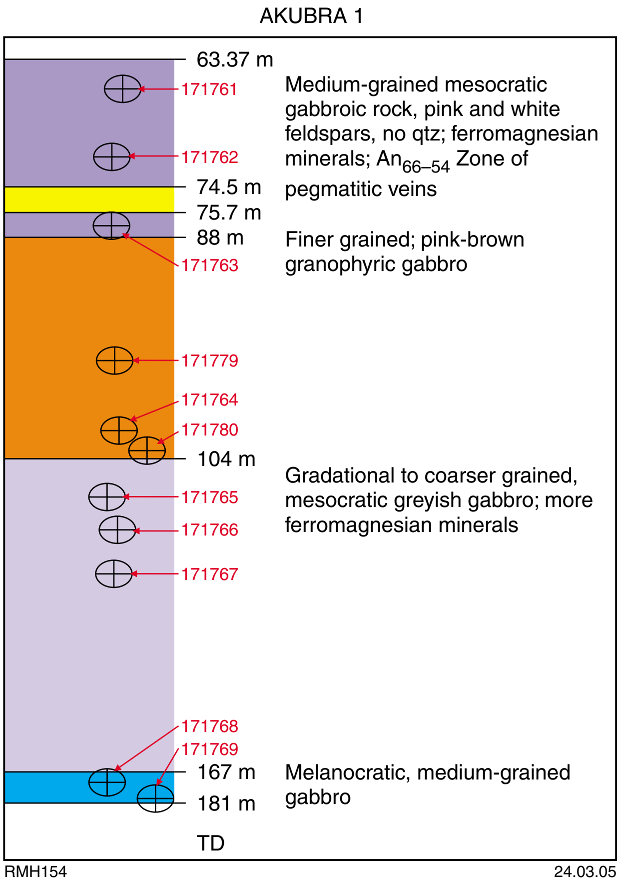

Figure 35. GSWA sample locations (red numbers) and sill characteristics, Akubra 1

The syenogranite is an equigranular and medium-grained rock that consists of perthitic K-feldspar, lesser zoned plagioclase, minor biotite, titanite, zircon, apatite, and opaque minerals.

Three monzogranite samples from northwestern PATERSON 1:100 000 and northeastern LAMIL 1:100 000 have titanite SHRIMP U–Pb ages of c. 654 Ma (Dunphy and McNaughton, 1998). These ages are regarded as the most valid for constraining the true crystallization age of the samples, given the high to extremely high concentration of uranium in the zircons that has essentially destroyed their structure and resulted in significant lead loss (Dunphy and McNaughton, 1998). The ages are also comaparable with the ages of basalts in Weedy 1 and 2 in the southern Officer Basin (see below). The zircon ages for the monzogranite samples range from c. 600 to 630 Ma (Nelson, 1995, 1999), and are taken as minimum ages for the granitic rocks and not their crystallization ages (Dunphy and McNaughton, 1998).

Pegmatite and aplite

Minor dykes of aplite and pegmatite (with chilled aplitic margins) intrude the monzogranite and syenogranite on the PATERSON, LAMIL, and COOLYU 1:100 000 sheets, or are found within contact metamorphic aureoles in the Lamil Group, and are hosted in cleavage planes and faults. Pegmatite dykes contain coarse-grained quartz, biotite, and muscovite, and aplite dykes consist of fine-grained quartz, potassium feldspar, and plagioclase with minor biotite (Bagas, 2000). Based solely on the fact that they intrude 640–680 Ma granite, the dykes may be coeval with the Table Hill Volcanics.

Mafic and ultramafic rocks

At least three generations of mafic and ultramafic intrusive rocks have been recognized in the Neoproterozoic successions of the Paterson Orogen. These are dolerite dykes, thin sills and stockworks of gabbro, dolerite, and silicified ultramafic rocks, and hornfelsed dolerite. Hornfelsed dolerite, observed in diamond drillcore from hornfels zones around granites to the northwest of the Telfer mine, suggests that the dolerite was intruded before, or synchronously with, the granites (Bagas, 2000). Hornfelsed dolerite is fine to medium grained and consists of microphenocrysts of plagioclase altered to sericite and anhedral epidote, and clinopyroxene (augite) altered to chlorite (Bagas, 2000). The matrix comprises fine- to medium-grained interlocking lath-like plagioclase, and ragged to bladed actinolite that probably replaced the original clinopyroxene. Fine-grained leucoxene and minor magnetite also constitutes the matrix (Bagas, 2000). Dolerite dykes occupy late, extensional, northerly trending fractures in the Rudall Complex and northern Officer Basin (Bagas et al., 2000). Williams (1992) implied a post-600 Ma age for these dykes, although no direct geochronology has been undertaken. Thin sills and stockworks of gabbro, dolerite, and silicified ultramafic rocks intrude the Throssell Range and Lamil Groups in northern BROADHURST (Hickman and Clarke, 1994). These rocks are poorly exposed, highly altered, and their ages are uncertain.

Southern Officer Basin

Weedy drillholes

Two holes, Weedy 1 and Weedy 2, were drilled near the southern margin of the western Officer Basin, as a joint CRA/GSWA project to investigate a sinuous linear magnetic anomaly between Carlisle Lakes and Shell Lakes. Both holes intersected a similar section: Paterson Formation, a mixed siliciclastic unit that Perincek (1998) assigned to the ?Devonian Lennis Sandstone, basaltic igneous rocks, and a sandstone and mudstone unit at the bases of the holes, which Perincek (1998) assigned to the McFadden Formation (now Lungkarta Formation). The basalt was intersected between 133.1 and 224 m in Weedy 1, and between 145.1 and 185 m in Weedy 2.

Two samples from Weedy 1 were dated using K–Ar techniques, and returned ages of 657 ± 4 and 640 ± 5 Ma (Amdel Ltd, 1993, written comm.) from the intervals 196–198 m and 206–208 m respectively (Nelson, 2002 recorded the ages as 657 ± 8 and 640 ± 10 Ma, with 2σ error). The samples show some alteration, explaining the spread in age, and the dates should be taken as indicating a minimum age of about 650 Ma (Amdel Ltd, 1993, written comm.). As the dates are minimum ages, they may be related to the 691 Ma age recorded from detrital zircons in the Wahlgu Formation in Empress 1 and 1A (Nelson, 2002).

Reconnaissance petrography (from textures in Weedy 1 at 166 m) indicates that the rocks are olivine basalts, in part rapidly cooled. The shape of the magnetic anomaly and the nature of the rocks suggest multiple flows in a sinuous channel. The unit overlying the basalt could be Lennis Sandstone, or equally Lungkarta Formation if deposition took place shortly after extrusion of the basalt. The unit below is interbedded red-brown and grey-green sandstone and mudstone, with conglomerate increasing in abundance down the holes, and could be Lungkarta Formation, as interpreted by Perincek (1998), but could equally be Ilma Formation.

Large igneous provinces

Mafic igneous rocks of two ages — the c. 1070 Glenayle and Prenti Dolerites and the c. 500 Ma Table Hill Volcanics — bracket the Officer Basin sedimentary succession. The mafic sills and dykes that intrude the sedimentary rocks of the Officer Basin are presumably mostly the feeders of the overlying Table Hill Volcanics, although those that intrude the oldest part of the succession (Coondra and Watch Point Formations) may belong to the 827 Ma Gairdner Dyke Swarm (Zhao et al., 1994; Wingate et al., 1998), and some may be associated with the volcanic rocks in Lancer 1 and Weedy 1.

The 1070–1000 Ma interval appears to be associated with a global thermal event also recorded in North America (Mid-Continent Rift System flood basalts, Allen et al., 1995) and southern Africa (Umkondo mafic igneous province, Hanson et al., 1998). The mafic sills that intrude the Edmund, Collier, and Earaheedy Basins and the mafic lavas intersected in Empress 1A are coeval with the 1050–1080 Ma volcanic rocks and dykes of the Musgrave Complex (Glikson et al., 1996). This led Wingate et al. (2004) to suggest that in central Western Australia these igneous mafic rocks constitute a large igneous province (the Warakurna LIP) trending east-southeast for at least 1300 km (Morris and Pirajno, 2002; Pirajno et al., 2002).

The 827 Ma Gairdner Dyke Swarm extends northwest for some 1200 km from the eastern margin of the Gawler Craton (South Australia), through to the Musgrave Block (South Australian usage) and perhaps beyond to the Officer Basin. The swarm may have been the feeder to overlying flood basalts (Mason et al., 1978; Preiss, 1987; Cowley and Flint, 1993; Barovich and Foden, 2000).

The c. 500 Ma Table Hill Volcanics is approximately coeval with the Antrim Plateau Volcanics, and it is possible that this unit may be part of the same thermal event, forming another LIP. The mafic rocks of the Table Hill and Antrim Plateau Volcanics share similar geochemical characteristics (Gole, M., 2001, written comm., and unpublished data), including Ta–Nb negative anomalies (MORB normalized) suggestive of strong crustal contamination. If the Table Hill and Antrim Plateau Volcanics igneous rocks belong to the same LIP, they extend for some 1700 km in a north–south direction and at least 1300 km in an east–west direction, with a possible aggregate areal extent of about 2.2×10^6 km^2.

Contributions to geological knowledge

This re-assessment of the Officer Basin in Western Australia has rationalized and clarified the lithostratigraphic framework for the basin. Uncertainties remain in places, but overall the knowledge of the stratigraphic relationships has improved significantly. Greater knowledge of the stratigraphic levels and relationships of specific areas in the basin will ensure that future exploration for minerals and petroleum in the Officer Basin carries reduced risks. New exploration models may arise for the same reason. Other contributions to our knowledge of the basin that have arisen from the current review are discussed briefly below.

The apparent distribution of the Townsend Quartzite does not support the concept of a single sand sheet, deposited synchronously across the Centralian Superbasin. The sandstone is absent in all drillholes that penetrate the base of the Officer Basin succession. The formation is present in the areas adjoining the Musgrave Complex, and probable correlatives (Spearhole, Watch Point, and Coondra Formations) are present along the northeastern margin of the basin, in the Savory area. This suggests that the sandstone was deposited in tectonically active areas where there was some hinterland relief, but not in passive margins such as that adjoining the Yilgarn Craton. Very similar sequences are present in basal sandstone units south and north of the complex (in the Amadeus Basin) and in the northwestern Officer Basin, reflecting common climatic and tectonic controls, but deposition was not continuous between these areas.

The succession shows pronounced lateral continuity through the Officer Basin, with very similar facies and thicknesses in locations hundreds of kilometres apart. Lateral facies changes are few, except in the upper Browne Formation where an evaporitic upper part is replaced landwards by eolian deposits, as could be expected. Other than this transition, the degree of similarity in thickness and facies from Boondawari 1 through Lancer 1 to Empress 1A and NJD 1 is remarkable.

At the level of the Browne Formation, facies thicken into the basin from Empress 1A and Lancer 1 to Yowalga 3. This indicates greater subsidence towards the Musgrave Complex and Paterson Orogen, presumably due to thrusting of basement along this margin. Higher in the Buldya Group, thicknesses are more uniform, implying tectonic quiescence.

With the drilling of Lancer 1, the succession exposed in the northwest Officer Basin can be correlated reasonably well with the succession encountered in the main part of the western Officer Basin. Although the succession in the northwest Officer Basin is sandier, correlation is possible formation by formation, and at a finer scale for part of the succession. The greater abundance of sandy lithologies in the northwest Officer Basin is attributed to continued greater tectonic activity in the basin hinterland than for areas adjoining the Yilgarn Craton.

Correlation of the McFadden Formation with the Lungkarta Formation, based on bedding and lithology, and the lack of indication of a significant hiatus between the Lungkarta Formation and probable Durba Sandstone in Lancer 1, strongly suggest the Durba Sandstone is related to the McFadden Formation and the Paterson Orogeny, rather than being a significantly younger unit. In this scenario, the McFadden Formation and Lungkarta Formation are first-generation, eolian-dominated units derived from erosion of the rising Paterson Orogen, and the Durba Sandstone is derived from uplift of the Ward and Oldham Inliers during the late Neoproterozoic Paterson Orogeny. The sandstone incorporated reworked Lungkarta Formation and McFadden Formation prior to final deposition in a trough along the northeast margin of the northwestern Officer Basin.

This geometry suggests the northwestern Officer Basin (and probably the remainder of the western Officer Basin) was a foreland basin during the Paterson Orogeny (but not necessarily at earlier times), bounded by the Vines–McKay fault system. A matching basin was present north of the orogen, preserved as the Yeneena Basin (Lamil and Throssell Range Groups) in the northwest, and the Amadeus Basin in the northeast. The Clutterbuck Formation records shedding immediately north of the orogen at this time. The Ward and Oldham Inliers and their southeastward subsurface extension towards the Musgrave Complex developed as a distinct foreland bulge south of the rising Paterson Orogen.

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Appendix 1

Terminology

This report follows guidelines set by Staines (1985) and Salvador (1994) for lithostratigraphic nomenclature. Superseded and informal stratigraphic names are placed in inverted commas. Subdivisions of the Proterozoic follow the Precambrian timescale approved by the International Union of Geological Sciences (IUGS). Unless otherwise stated, the terminology applied to tectonic subdivisions and nomenclature follows that of Trendall (1990, p. 3–9). Other terms used in this document are defined below.

- A **basin** is an 'area underlain by a substantial thickness of sedimentary rocks which possess unifying characteristics of stratigraphy and structure, due to their deposition during a regionally restricted episode of crustal depression or a related sequence of such episodes. As well as being applied to the deposited rocks, or to their outcrop area after erosion, the term is used also for the actual crustal depression in which they accumulated' (Trendall, 1990, p. 4).

- **Diamictite** is a 'nongenetic term…for a nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes, such as a rock with sand and/or larger particles in a muddy matrix; e.g. a tillite or a pebbly mudstone' (Jackson, 1997, p. 175). Many of the units previously referred to as tillites should really be described as diamictites because their direct association with glaciation cannot be demonstrated. Definitions of terminology relating to glacigene units as currently applied are given below.

- A **sub-basin** is a 'first-order subdivision of a basin, and … contains no implications as to form or age. It is a distinctive area within a basin. It may well be, but does not have to be, a specific depocentre which was active at a specific time' (Hocking, 1994, p. 8). Specific subdivisions of basins are listed and defined by Hocking (1994).

- A **succession** is: '(a) A number of rock units or a mass of rock strata that succeed one another in chronologic order; e.g. an inclusive stratigraphic sequence involving any number of stages, series, systems, or parts thereof, as shown graphically in a geological column or seen in an exposed section. (b) The chronologic order of rock units' (Jackson, 1997, p. 637). The term 'succession' is used in preference to the term 'sequence', which in recent years has acquired a more restricted meaning through its use in sequence stratigraphy.

- A **till** is 'dominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier without subsequent reworking by meltwater, and consisting of a heterogeneous mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape' (Jackson, 1997, p. 666).

- A **tillite** is a 'consolidated or indurated sedimentary rock formed by lithification of glacial till' (Jackson, 1997, p. 666).

- **Tilloid** is used as 'a nongenetic term for a rock resembling tillite in appearance but whose origin is in doubt or unknown' (Jackson, 1997, p. 666).

Appendix 2

Gazetteer of localities

The precision of the information varies widely for the localities below, according to the data source. Localities have not generally been visited and fixed by GPS. The degree of rounding provides a guide as to the precision. All readings are GDA94

Feature	*Zone*	*Easting*	*Northing*	*1:250 000 sheet*
Ainslie Gorge	52	265720	7095770	COOPER
Akubra Hill	51	336700	7405700	ROBERTSON
Bartlett Bluff	51	657130	6781180	NEALE
BMR Talbot 21 locality	52	258500	7099900	TALBOT
Bobbymia Creek	51	275000	7356000	ROBERTSON
Boolginya Rockhole	51	303870	7443260	ROBERTSON
Boondawari Soak	51	342970	7390750	ROBERTSON
Breaden Bluff	51	654880	7024780	ROBERT
Brown Range	52	260120	7100190	TALBOT
Broadhurst Range	51	417500	7528000	RUDALL
Brownrigg Hill	51	318600	7566600	NULLAGINE
Budgie Spring	51	368000	7407000	GUNANYA
Buldya Soak	51	635130	6981780	THROSSELL
Calvert Range	51	478320	7347784	GUNANYA
Canning Well, Balfour Downs	51	325800	7525700	BALFOUR DOWNS
CSR Well 14	51	403500	7314200	TRAINOR
CSR Well 15	51	419200	7330200	TRAINOR
CSR Well 23	51	522600	7447700	RUNTON
Choorun Waterhole	51	390400	7500400	RUDALL
Constance Headland	51	507300	7343300	MADLEY
Coolbro Creek	51	414100	7550300	RUDALL
Coondra Coondra Springs	51	297700	7442900	ROBERTSON
Curran Curran Rockhole	51	390900	7508400	RUDALL
David Carnegie Road	51	624900	7187800	HERBERT
Dean Hills	51	273000	7316900	BULLEN
Denison Range, S.A.	53	589000	6887000	WARRINA
Diebil Hills	51	436120	7388160	GUNANYA
Durba Hills	51	445730	7367160	GUNANYA
Durba Springs	51	451030	7372470	GUNANYA
Eagle Highway	51	627000	7196200	HERBERT
Ellery Creek, N.T.	53	293000	7362700	HERMANNSBURG
Empress Spring	51	635520	7038860	NEALE
Googhenama Rockhole (Fig Tree WH)	51	326500	7562600	BALFOUR DOWNS
Gunanya Spring	51	471000	7447200	GUNANYA
Hanging Rock	51	364020	7510520	RUDALL
Hann Rockhole	51	336860	7301950	BULLEN
Harbutt Range	51	480000	7467000	RUDALL
Hocking Range	52	345130	7082690	TALBOT
Ida Range	51	597120	7074170	ROBERT
Karakutikati Range	51	413900	7587200	PATERSON RANGE
Karara Well (CSR Well 24)	51	535000	7443600	RUNTON
Lake Disappointment	51	484130	7412190	GUNANYA
Lake Ilma	52	375120	6770190	MASON
Lake Throssell	51	610120	6944170	THROSSELL
Lake Wells	51	510100	7050170	KINGSTON/ROBERT
Lamil Hills	51	389500	7616600	PATERSON RANGE
Lilian Creek gorge	52	295400	7087700	TALBOT
Lindsay Hill	51	646920	6782670	PLUMRIDGE
Livesey Range	52	354720	7051470	COOPER
Lupton Hills	52	404800	7063970	COOPER
Madley Diapirs	51	640000	7320000	MADLEY
Malu Hills	51	417200	7611200	PATERSON RANGE
Marloo Hills	51	342870	7491430	BALFOUR DOWNS
McFadden Range	51	429000	7527000	GUNANYA
McKay Range	51	445000	7460000	RUDALL/GUNANYA
Michael Hills	52	489420	7099090	COOPER

Appendix 2 (continued)

Feature	*Zone*	*Easting*	*Northing*	*1:250 000 sheet*
Miller Soak	51	625320	6884870	RASON
Moffetah Well (abandoned)	51	217500	7317500	BULLEN
Mount Agnes	52	496710	7029600	COOPER
Mount Isdell	51	417400	7563300	RUDALL
Mount Lancelot	51	517534	7099570	ROBERT
Mount Madley	51	596520	5289065	MADLEY
Mudjon Gorge	51	471620	7351190	GUNANYA
Mundadjini Spring	51	313800	7412800	ROBERTSON
Munjil Soak	51	565400	6878600	RASON
Mystery Hill	51	301500	7343000	BULLEN
Neale Junction	51	720700	6873000	NEALE
Nooloo Soak	51	387000	7498700	RUDALL
Patricia Johnson Hills	52	497000	6975000	WAIGEN/BIRKSGATE
Pindyin Hills (SA)	52	655800	6955300	LINDSAY
Pirrilyungka outstation	52	442930	7065340	COOPER
Point Lefroy	52	276120	7093280	TALBOT
Punkerri Hills, SA	52	639700	6939000	BIRKSGATE
Puntapunta Hill	51	417000	7589000	PATERSON RANGE
Ripple Hill	51	383750	7341800	TRAINOR
Robertson Range	51	285000	7400000	ROBERTSON
Robertson Range Homestead	51	282500	7402300	ROBERTSON
Savory Creek	51	270000	7352000	ROBERTSON
Skates Hills	51	505300	7293900	MADLEY
Skirmish Hill	52	442510	7080380	COOPER
South Hill	52	467130	7072070	COOPER
Steptoe airstrip	52	781000	7112500	YOWALGA
Sunbeam Creek	51	430130	7236780	TRAINOR
Tarcunyah Creek	51	336000	7528000	RUDALL
Tchukardine Pool	51	357800	7506500	RUDALL
Throssell Range	51	370000	7564000	RUDALL
Townsend Ridges	52	297000	7087000	TALBOT
Trainor Hills	51	421000	7317500	TRAINOR
Turkey Hill	51	626030	6889570	RASON
Wahlgu Rockhole	51	717200	7004300	WESTWOOD
Waltha Woora Creek	51	312000	7616000	NULLAGINE
Ward Hills	51	403000	7300000	TRAINOR
Waroongunyah Rockhole	51	344600	7510200	BALFOUR DOWNS
Watch Point	51	279500	7423300	ROBERTSON
Wilki Range	51	429500	7596700	PATERSON RANGE
Wongarling Rockhole	51	338900	7537200	BALFOUR DOWNS
Woodie Woodie mine	51	317500	7607000	NULLAGINE
Woolnough Diapir	51	655960	7334000	MORRIS/WARRI
Woolnough Hill	51	658600	7345200	WARRI
Woora Woora Hills	51	344000	7491000	BALFOUR DOWNS
Yandanunyah Rockhole	51	337900	7525400	BALFOUR DOWNS
Yooldoowindi Spring	51	281000	7399200	ROBERTSON

Appendix 3

List of taxa recorded

The names of authors of scientific names have been omitted in the text and text figues and instead are presented here. The names are the names of authors of taxa, not references, and therefore they are not necessarily cited in the reference list.

Spheroidal microfossils and acritarchs

Cerebrosphaera ananguae Cotter 1999

Cerebrosphaera buickii Butterfield 1994 in Butterfield et al. 1994

Chuaria sp. cf. *Ch. circularis* Walcott 1899; emend. Vidal and Ford 1985

Coneosphaera sp. cf. *Co. arctica* Hofmann 1994 in Hofmann and Jackson 1994

Eoentophysalis croxfordii (Muir 1976) Butterfield 1994

Eomicrocystis malgica Golovenok and Belova 1984

Eomicrocystis sp. cf. *E. elegans* Golovenok and Belova 1984

Leiosphaeridia crassa (Naumova 1949) Jankauskas 1989

Leiosphaeridia sp. cf. *L. exsculpta* (Timofeev 1969) emend. Mikhailova in Jankauskas et al. 1989

Leiosphaeridia jacutica (Timofeev 1966) emend. Mikhailova and Jankauskas in Jankauskas et al. 1989

Leiosphaeridia minutissima (Naumova 1949) emend. Jankauskas in Jankauskas et al. 1989

Leiosphaeridia tenuissima Eisenack 1958

Leiosphaeridia ternata (Timofeev 1966) emend. Mikhailova in Jankauskas et al. 1989

Myxococcoides cantabrigiensis Knoll 1982

Myxococcoides inornata Schopf 1968

Ostiana microcystis Hermann 1976

Pterospermopsimorpha granulata Mikhailova in Jankauskas et al. 1989

Pterospermopsimorpha insolita Timofeev 1969

?Pterospermopsimorpha sp.

Satka colonialica Jankauskas 1979

Simia annulare Timofeev 1969 emend. Mikhailova in Jankauskas et al. 1989

Simia sp.

Skiagia cf. *Sk. pusilla* Zang in Zang and Walter 1992

Stictosphaeridium sinapticuliferum

?*Symplassosphaeridium* sp.

Synsphaeridium sp.

Synsphaeridium spp.

Tasmanites sp.

?*Trachyhystrichosphaera* spp.

Filamentous microfossils

Calyptothrix sp. cf. *Ca. alternata* Jankauskas 1980

Clavitrichoides rugosus Mikhailova in Jankauskas et al. 1989

Eoentophysalis croxfordii (Muir 1976) Butterfield 1994

Heliconema sp.

Obruchevella sp.

Oscillatoriopsis amadeus (Schopf and Blacic 1971) Butterfield 1994

Oscillatoriopsis sp.

Siphonophycus kestron Schopf 1968

Siphonophycus robustum (Schopf 1968) Knoll et al. 1991

Siphonophycus septatum (Schopf 1968) Knoll et al. 1991

Siphonophycus solidum (Golub 1979) emend. Butterfield 1994

Siphonophycus typicum (Hermann 1974) Butterfield et al. 1994

Stromatolites

Acaciella australica (Howchin 1914) Walter 1972

Baicalia burra Preiss 1972

Basisphaera irregularis Walter 1972

Boxonia pertaknurra Walter 1972

Elleria minuta Walter and Krylov *in* Walter et al. 1979

Inzeria intia Walter 1992

Jurusania nisvensis Raaben 1964

Kulparia alicia (Cloud and Semikhatov 1969) Walter 1972

Tungussia form nov.

This Report provides a comprehensive integration of the lithostratigraphy of the Neoproterozoic – earliest Cambrian, western Officer Basin and correlative areas of the Paterson Orogen, based on scattered, discontinuous exposures, sparse drillhole data, and a regional seismic grid. Separate stratigraphic frameworks for the main part of the basin, the northwest Officer Basin, and the more-deformed Paterson Orogen are linked and fully described. The oldest part of the succession is a mixed carbonate–clastic–evaporite succession that ranges in age from c. 830 to c. 700 Ma, and equates to Supersequence 1 of the Centralian Superbasin. This is overlain by glacigene rocks of Supersequence 3 age (c. 600 Ma). An uppermost Neoproterozoic – Lower Cambrian sandstone-dominated sequence (Supersequence 4) caps the succession, and is assumed to be related to the Paterson and Petermann Orogenies, although age control is minimal. This interval may be related to a thick, conglomeratic ?Lower Cambrian unit intersected just south of the Musgrave Complex, in GSWA Vines 1.

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