A NEW LOWER CAMBRIAN SHELLY FOSSIL BIOSTRATIGRAPHY FOR SOUTH AUSTRALIA

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ABSTRACT

Definition of early Cambrian chronostratigraphic boundaries is problematic with many subdivisions still awaiting ratification. Integrated multi-proxy data from well-resolved regional-scale schemes are ultimately the key to resolving broader issues of global correlation within the Cambrian. In Australia, early Cambrian biostratigraphy has been based predominantly on trilobites. Phosphatic shelly fauna have great potential as biostratigraphic
tools, especially in pre-trilobitic strata because they are widespread and readily preserved, but they have remained underutilised. Here we demonstrate their value in a new biostratigraphic scheme for the early Cambrian of South Australia using a diverse shelly fauna including tommotiids, brachiopods, molluscs and bradoriids.

Biostratigraphic data are derived from ten measured stratigraphic sections across the Arrowie Basin, targeting Hawker Group carbonates including the Wilkawillina, Wirrapowie and Ajax limestones and the Mernmerna Formation. The stratigraphic ranges of shelly fossils are predictable and repeatable across the Arrowie Basin, allowing three discrete shelly biozones to be identified, spanning Terreneuvian, Stage 2 to Series 2, Stages 3–4. The *Kulparina rostrata* Zone (new) and much of the overlying *Micrina etheridgei* Zone (new) are pre-trilobitic (predominantly Terreneuvian). The Cambrian Series 2, Stage 3 *Dailyatia odyssei* Zone (new) features a very diverse shelly fauna and will be described in detail in a separate publication. These zones provide robust means to correlate early Cambrian successions in neighbouring coeval basins in Australia, particularly the Stansbury Basin. Wider correlation is possible throughout East Gondwana, especially with South China.

Key words:

Small shelly fossils; tommotiids; Cambrian; biostratigraphy; correlation.

1. INTRODUCTION

The Arrowie Basin is a large (55,000 km²) depositional basin situated in east-central South Australia (Fig. 1) that has one of the best exposed successions of lower Cambrian sedimentary packages anywhere in the world (Gravestock and Cowley, 1995; Zang et al., 2004; Jago et al., 2012). Calcareous and organophosphatic shelly fossils (often called “Small
Shelly Fossils” [SSF]) are ubiquitous across carbonate-dominated parts of the basin and have
been described in a series of papers (Bengtson et al., 1990; Brock and Cooper, 1993; Brock
and Paterson, 2004; Paterson and Brock 2007; Skovsted et al., 2006, 2008, 2009a, 2009b,
2013a; Betts et al., 2014; 2015, in press; Larsson et al., 2014; Jacquet et al., 2014; Jacquet
and Brock, 2015). This study integrates results derived from systematic sampling along 10
stratigraphic sections measured through the broadly coeval Wilkawillina, Wirrapowie and
Ajax limestones that crop out as distinctive folded tracts in the Flinders Ranges (Fig. 1): In
the north-west; the AJX-M and AJX-N (Figs. 2-3) sections. In the north-east; the MORO and
MOG sections (Figs. 4-5). In the central Flinders Ranges; WAR, BALT, MMT, the
Wilkawillina type section (WILK), and 10MS-W (Figs 6-10), and in the south; CR1 (Fig.
11). These stratigraphic sections intersect the lower part of the Hawker Group, from the
Parachilna Formation to the Second Plain Creek Member (upper Wilkawillina Limestone)
and Wirrapowie Limestones, and into the lower Memmerna Formation (equivalent to
depositional sequence sets C1.1A, C1.1B, C1.2 of Gravestock and Cowley, 1995) (Fig.12).

The biozones defined herein are derived from a total of 694 stratigraphic horizons
sampled systematically at regular intervals (approximately 5–10 m) for shelly fossils. The
data from these 10 stratigraphic sections have been used to define new shelly fossil biozones,
reassess previously suggested schemes and discuss intrabasinal, regional and international
correlation of the lower Cambrian package in the Arrowie Basin, South Australia.

Some authors have raised doubts about the utility of early Cambrian fossils for
reliable biostratigraphic subdivision (Landing, 1994; Maloof et al., 2010; Landing and Geyer,
2012; Landing et al., 2013). The most often cited reasons for this include the strongly
endemic nature of many early Cambrian fauna and the diachronous appearances of key taxa
(Geyer, 2001; Peng et al., 2012). In response to this, chemostratigraphy has been suggested as
the method of choice for global correlation (Landing et al., 2013). However, there remains some doubt regarding the application of chemostratigraphic data (Swart and Eberli 2005; Swart 2008; Parkhaev, 2014). Biostratigraphic ranges of key early Cambrian shelly fossils have been shown to be invaluable tools for relative dating and correlation (Devaere et al., 2013; Guo et al., 2014; Rozanov, 1995; Steiner et al., 2004; Steiner et al., 2007; Yang et al., 2014). Integration of regional biostratigraphic schemes, chemostratigraphic data are crucial to solving broader issues of global correlation within the Cambrian system.

2. PREVIOUS BIOSTRATIGRAPHIC WORK

Early contributions to provide stratigraphic context to the succession of Cambrian strata in the Flinders Ranges were made by Robert Etheridge (Etheridge, 1890), Griffith Taylor (Taylor, 1910), Walter Howchin (Howchin, 1922, 1925), Robert Bedford (Bedford and Bedford, 1939 and references therein), Douglas Mawson (Mawson, 1937, 1938, 1939) and R.W. Segnit (Segnit, 1939). Daily (1956) produced the first biostratigraphy of the lower Cambrian succession of South Australia by establishing 12 informal "faunal assemblages" that were (until relatively recently) widely used for broad regional correlation in South Australia (see also Daily, 1972). Unfortunately, Daily’s (1956) faunal assemblages were not accompanied by formal taxonomic descriptions or definition of precise boundaries. In addition, only general locality data and vague stratigraphic ranges of the most important diagnostic taxa were provided, preventing accurate correlation across and between adjacent basins (Jago et al., 2006; Paterson and Brock, 2007). Cooper and Jago (2007) outlined the history of investigations into South Australian Cambrian biostratigraphy.

Subsequent biostratigraphic schemes have been based on a variety of fossil groups (see reviews by Zang, 2002; Jago et al., 2006, 2012; Paterson and Brock, 2007; Kruse et al.,
2009), with separate zonations based on archaeocyaths (Walter, 1967; Gravestock 1984; Zhuravlev and Gravestock, 1994), trilobites (Jell in Bengtson et al., 1990) and acritarchs (Zang et al., 2007). In the absence of a local stage subdivision specifically for the Australian lower Cambrian, previous workers such as Gravestock and Cowley (1995), Brock and Cooper (1993), Shergold (1996), Young and Laurie (1996), Brock et al., (2000), Gravestock et al., (2001), Jago et al., (2006; 2012) and Kruse et al., (2009) have correlated the Australian lower Cambrian successions (not always very successfully) with the widely used Siberian stage subdivision (Nemakit-Daldynian, Tommotian, Atdabanian, Botoman and Toyonian) in the sense of Rozanov and Sokolov (1984).

3. AIMS and METHODS

In an attempt to fill this knowledge lacuna, a comprehensive fieldwork campaign over the last decade has resulted in systematic collection of fossiliferous, sedimentologic and geochemical samples from more than 20 separate stratigraphic sections and over 100 supplementary spot localities that, in composite, intersect the entire lower Cambrian succession in the Arrowie and Stansbury Basins. This comprehensive sampling has produced in excess of 1000 separate, stratigraphically constrained microfossil data points. Standard acetic acid leaching techniques were used to extract shelly material from the carbonates (see methods in Skovsted et al., 2012, Guo et al., 2014), that have yielded a great diversity and abundance of phosphatic, secondarily phosphatised and silicified shelly fossil groups. Microfossils were picked from dried residues using a binocular stereo microscope, and imaged with the JEOL JSM-6480LA and JEOL 7100FE Analytical Scanning Electron Microscopes in the Microscopy Unit, Department of Biological Sciences at Macquarie University.
The collected faunal data are presented in two parts – the biostratigraphic scheme herein is derived from 10 stratigraphic sections intersecting a broad suite of carbonate facies in the lower Hawker Group of the Arrowie Basin (Fig. 1). This part of the succession includes the broadly coeval Wilkawillina, Wirrapowie and Ajax limestones occurring below the regionally significant hiatus called the “Flinders Unconformity” (Gravestock and Cowley, 1995; Gravestock and Shergold, 2001) in the Arrowie Basin. Biostratigraphic analysis of the overlying succession (Mernmerna Formation and equivalents) is currently in preparation and will be published separately.

This work provides detailed fossil range data facilitating construction of a new biostratigraphic zonation of the lower Cambrian succession of South Australia (Terreneuvian, Stage 2 to Series 2, Stages 3–4). As a first step in establishing this new regional biostratigraphic framework, the aim of this paper is to formally name and define three new shelly fossil biozones (in ascending order) – the *Kulparina rostrata* Zone, the *Micrina etheridgei* Zone and the *Dailyatia odyssei* Zone. These zones can be correlated intra-basinally across a broad suite of synchronous carbonate-dominated facies represented by the Wilkawillina, Wirrapowie and Ajax limestones as well as inter-basinally with the broadly synchronous fossiliferous packages in the Stansbury and Officer Basins in South Australia, and the Amadeus Basin in the Northern Territory. They also have faunal ties with early Cambrian strata in China, Avalonia, Laurentia and Siberia.

The biozones established here are based on the most abundant, widespread (at least within the basin), readily identifiable and best preserved taxa, including tommotiids, brachiopods, molluscs, and bradoriid arthropods. The *Kulparina rostrata* Zone and part of the *Micrina etheridgei* Zone are pre-trilobitic, at least in terms of East Gondwanan trilobite occurrences (see discussion below on the correlation of Australian lower Cambrian trilobite zones with the global assemblages).
Though many SSF and associated taxa are now understood to have had a truly global distribution, strong provincialism of many taxa (Larsson et al., 2014; Skovsted et al., 2015a, 2015b) and time lags between origination, dispersal and first appearance has hindered application of SSF as tools for global biostratigraphic correlation (Landing et al., 2013). Resolution of regional or basin-scale sequences is fundamentally important for global chronostratigraphy, especially when using complementary methods such as isotope chemostratigraphy. The International Commission on Stratigraphy (ICS) encourages the integration of a variety of methods to independently correlate proposed chronostratigraphic schemes (Remane et al., 1996). This is echoed by authors such as Geyer (2001), Landing et al. (2013), Babcock et al. (2015), and Smith et al. (2014, 2015), who strongly advocate the integration of independent chronostratigraphic data such as isotopic chemostratigraphy (and magnetostratigraphy, where possible) with biostratigraphic schemes. Hence, samples for chemostratigraphic analyses were collected alongside biostratigraphic samples with the aim of integrating the biostratigraphy and lithostratigraphy with isotopic curves (for example, see Zhu et al., 2006; Betts et al., 2015). This will facilitate high resolution intra-basin correlation in addition to correlation between neighbouring basins (e.g. Stansbury Basin), and should also contribute to efforts in global correlation of the lower Cambrian. Integration of chemostratigraphic data with the biostratigraphic scheme presented here is currently in progress and will be published separately.

4. HAWKER GROUP - STRATIGRAPHIC REVIEW

The Hawker Group (Dalgarno, 1964) represents approximately 4200 m of carbonate-dominated formations cropping out in broad synclinal tracts in the central part of the Arrowie Basin (Fig. 1). The Hawker Group succession is represented by sequence set €1.0 of
Gravestock (1995) that now includes five disconformity-bounded sedimentary sequences (Zang et al., 2004; Jago et al., 2012). The lowest Cambrian sequence, ∈1.0, consists of prodeltaic and deltaic siltstones and sandstones of the Uratanna Formation, which disconformably underlie Hawker Group rocks, deposited in valleys cut into the Ediacaran Rawnsley Quartzite. The Uratanna Formation has limited distribution in the Arrowie Basin and where it is absent, the Parachilna Formation (lowermost unit of the Hawker Group) disconformably overlies the Rawnsley Quartzite (Gravestock, 1995; Zang et al., 2004; Jago et al., 2012). For detailed reviews of the stratigraphy and lithology of the Hawker Group succession see Dalgarno (1964), Haslett (1975), Clarke (1986a, 1986b, 1986c, 1990a, 1990b), Gravestock (1988), Gravestock and Cowley (1995), Zang et al. (2004), Paterson and Brock (2007), and Jago et al. (2006; 2012).

4.1 Parachilna Formation and Woodendinna Dolostone (Sub-sequence ∈1.1A)

Sub-sequence ∈1.1A contains the lowstand to transgressive Parachilna Formation and conformably overlying highstand Woodendinna Dolostone. This sequence package is terminated by a disconformable surface in the Bunkers Graben and overlain by the lower Wilkawillina Limestone (Mt. Mantell Member) which incises into the Woodendinna Dolostone at some localities (Zang et al., 2004). Six stratigraphic sections (AJX-M, AJX-N, WAR, BALT, MMT, MORO; see Fig. 12) intersect or are measured from the Parachilna Formation, an iron-rich, fine- to coarse-grained, cross-bedded, quartz-rich sandstone with thinly bedded siltstone or shale. The upper part of the formation is heavily bioturbated with abundant Diplocraterion parallelum Torell, 1870; such vertical “pipercrock” is used by Mángano and Buatois (2014) to define Cambrian Stage 2 on a global scale.
The Woodendinna Dolostone is a highstand systems tract with microbialites, oncolites and low stromatolite bioherms deposited in shallow marine carbonate shelf to supratidal settings (Haslett 1975). The unit crops out in both the WILK and 10MS-W sections in the Bunkers Graben (Figs 9 and 10, respectively) and the MORO section on the eastern limb of the Arrowie Syncline (see Fig. 12). The unit is pervasively dolomitised and as a result is often strongly weathered and poorly outcropping and shelly fossils have not been recovered.

4.2 Lower Wilkawillina Limestone (Sub-sequence $\varepsilon$1.1B)

Sub-sequence $\varepsilon$1.1B commences with the Mt. Mantell Member of the lower Wilkawillina Limestone (Clarke, 1986a), representing a shallow shelf carbonate with apparent lateral facies changes that passes basinwards (eastwards) into the Wirrapowie Limestone that contains the oldest known archaeocyaths in Australia (Jago et al., 2012). The disconformity between the Woodendinna Dolostone ($\varepsilon$1.1A) and the lower Wilkawillina Limestone ($\varepsilon$1.1B) is only manifest on shallow carbonate shelf areas and there does not appear to be a corresponding break within the Wirrapowie Limestone (for instance, in section CR1; Fig. 11).

The Mt. Mantell Member was originally defined on shallow platform successions in the Bunkers Graben and Range (Clarke, 1986a) and is intersected by stratigraphic sections Balc (61.56 m), MMT (20.25 m), WILK (25.0 m), and 10MS-W (33.53 m) (Fig. 12). A relatively thick, equivalent package of lower Wilkawillina Limestone occurs in the eastern Arrowie Syncline in the MORO section (Fig. 4). The Mt. Mantell Member is a high energy, shallow platform carbonate interpreted to have been deposited above wave base (Clarke, 1986a, 1990a; Betts et al., 2014). In all sections, deposition of the Mt. Mantell Member is strongly microbially mediated (Renalcis and Epiphyton), with limestones fabrics often
exhibiting a clotted appearance and massive outcrop style. Although transported archaeocyath fragments, laminate microbialites and stromatolites occur, no shelly fossils have been recorded from the Mt. Mantell Member.

The Hideaway Well Member conformably overlies the Mt. Mantell Member and crops out in the BALC (42.07 m), MMT (47.87 m), WILK (30.0 m), and 10MS-W (54.38 m) sections in the central Flinders Ranges, and at the MORO (59.0 m) section in the Arrowie Syncline in the north-east Flinders Ranges (Fig. 12). The Hideaway Well Member is characterised by increased abundance of archaeocyaths, both fragmentary and in situ, and relatively large bioherms are commonly developed in this member, with some measuring up to 100 m in lateral extent in the MORO section (Betts et al., 2014). The Hideaway Well Member represents a high-energy, shallow water carbonate environment and also preserves the oldest shelly fauna known from the Arrowie Basin.

The Winnitinny Creek Member (Clarke 1986a) of the Wilkawillina Limestone conformably overlies the Hideaway Well Member and is intersected in the BALC (94.74 m), MMT (169.29 m), WILK (145.0 m), and 10MS-W (108.76 m) sections in the Bunkers Graben and Range, and the MORO (135.0 m) and MOG (62.65 m) sections in the Arrowie Syncline (Figs 1, 12). Archaeocyaths occur throughout the Winnitinny Creek Member, though it is chiefly characterised by a very abundant and diverse shelly fauna. This assemblage includes a wide variety of brachiopods, tommotiids, helcionellid and bivalved molluscs, bradoriid arthropods, sponge spicules and rare echinoderm plates. Trilobites are also known to occur in the upper parts of the member with *Elicicola calva* Jell in Bengtson et al., 1990 described by Paterson and Brock (2007, p. 138-139, fig. 13) from the base of the MMF section in the Bunkers Range. The palaeoenvironment is interpreted to have been of lower energy compared to the preceding Hideaway Well Member, though deposition was still on the carbonate shelf (Betts et al., 2014). The Winnitinny Creek Member interfingers with
coeval ribbon carbonates of the Wirrapowie Limestone in the MORO and MOG sections north of the Wirrealpa Hinge Zone (Fig. 1).

In sections on the shallow carbonate shelf in the central Flinders Ranges (Wirrealpa Hinge Zone of Gravestock and Cowley, 1995), the Winnitinny Creek Member is truncated by a distinctive red, karstic surface. This represents a regionally significant hiatus called the “Flinders Unconformity” (FU) (James and Gravestock, 1990) that defines the top of sequence package ∈1.1B in shallow shelf facies (Gravestock and Shergold 2001; Zang et al., 2004; Jago et al., 2012) and separates the lower and upper Wilkawillina Limestones in the Bunkers Graben (Clarke, 1986b). The FU represents a period of diachronous sub-aerial exposure and erosion of the Wilkawillina Limestone in shallow shelf settings succeeded by deposition of iron-rich micro-stromatolitic microbialites during a transgression event. The disconformable surface does not occur (or is not apparent) in all sections, particularly those to the south (10MS-W) and the north (MORO and MOG) (Fig. 12) of the Wirrealpa Hinge Zone, indicating that pronounced breaks in sedimentation did not occur in all localities across the Arrowie Basin (see also James and Gravestock 1990, p. 458-459).

4.3 Wirrapowie Limestone (Sequence ∈1.1)

The Wirrapowie and Wilkawillina Limestones are coeval carbonate facies representing adjacent, interfingering platform and restricted lagoonal palaeoenvironments, respectively (Haslett, 1975) (Fig.12). Lack of cross-bedding, quartz grains and other coarse detrital material indicate a predominantly low energy regime, and lack of mud-cracks, halite casts and other evidence of subaerial exposure indicates that the environment remained consistently submerged (Haslett, 1975). There is no evidence of the disconformity separating sub-sequence sets ∈1.1A and B in the Wirrapowie Limestone. Higher energy facies are
represented by occasional oolitic beds and sporadic, high energy events resulting in the
deposition of intraformational conglomerates and breccias (as in the WAR section; Fig. 6).
Coeval deposition of the Wirrapowie and Wilkawillina limestones is confirmed by the
synchronous ranges of brachiopods, tommotiids and bradoriids in both facies.

4.4 Ajax Limestone (Sub-Sequence ∈1.1B and Sequence ∈1.2)

The Ajax Limestone (Fig. 1–3) crops out in the Mt. Scott Range in the northeast of
the Arrowie Basin. The lower 110–120 m was deposited as part of systems tract ∈1.1B,
broadly equivalent to the lower Wilkawillina and Wirrapowie limestones. The reddened
horizon of the Flinders Unconformity is not apparent in AJX-M or AJX-N sections, and there
is a transition to sequence package ∈1.2 which is truncated by a disconformity surface near
the top of the AJX-M section (Fig. 2). Shallow water facies including stromatolitic
boundstones dominate the lower 120 m of the AJX-M section. This is overlain by shelly
fossil and archaeocyath rich nodular limestones and bioclastic limestones (Fig. 2; see also
Brock et al., 2006; Skovsted et al., 2009a).

4.5 Second Plain Creek Member (Wilkawillina Limestone) and lower Memmerna Formation
(Sequence ∈1.2)

The Second Plain Creek Member of the Wilkawillina Limestone (“middle
Wilkawillina Limestone” of Gravestock and Hibburt (1991) only outcrops in the Bunkers
Graben (WILK, Figs. 9, 12). The Second Plain Creek Member is interpreted to have been
deposited on a starved carbonate platform during rapid transgression and is transitional
between the relatively shallow facies of the Winnitinny Creek Member and the deeper outer shelf facies of the overlying Mernmerna Formation (Clarke, 1986b).

The Mernmerna Formation is subdivided into three members, from lowest to highest; the Six Mile Bore Member, the Linns Springs Member and the Third Plain Creek Member (Clarke, 1986c). The Mernmerna Formation crops out in the MMT (7.5 m) and MOG (369.8 m) sections and Bunkers Graben where WILK and 10MS-W were measured (the WILK and 10MS-W sections terminate at the boundary between the Wilkawillina Limestone and the Mernmerna Formation) (Fig. 12). The duration of the hiatus represented by the disconformity between the top of the Winnitinny Creek Member of the lower Wilkawillina limestone (Sequence ∈ 1.1B) and the outer shelf deposits of Mernmerna Formation (Sequence ∈ 1.2) is variable. Most sections on the shallow platform are missing all or large parts of the lower Mernmerna Formation due to lack of deposition (e.g. BALC, Fig. 7 and MMT, Fig. 8 sections).

The nodular limestones of the Mernmerna Formation (Sequence ∈ 1.2) are interpreted to have been deposited in low energy, outer shelf, ramp and slope settings (Haslett, 1975; Daily, 1976), with input of allochthonous carbonates containing slumps or slide structures (Clarke, 1990c; Gravestock, 1995) representing active shelf collapse and slope processes.

5. NEW BIOSTRATIGRAPHIC ZONES

Distinctive shelly fossil assemblages recur consistently throughout all measured sections within carbonate packages of subsequence ∈ 1.1B in the lower Hawker Group, and permit the establishment of three successive biozones. The *Kulparina rostrata* Zone has relatively low diversity shelly fauna, but is characterised by overlapping or partially
overlapping ranges of tommotiids and a paterinid brachiopod. The overlying *Micrina etheridgei* Zone is represented by a high diversity assemblage containing a mix of tommotiids, brachiopods, molluscs and arthropods. The base of the *Dailyatia odyssei* Zone is broadly equivalent with the base of sequence package $\epsilon_{1.2}$, and is formally defined, but full description of the taxa associated with this zone and its regional and global correlation is currently in preparation and will be published separately.

5.1 *Kulparina rostrata* Zone

The *K. rostrata* Zone occurs in the Hideaway Well Member and lower half of the Winnitinny Creek Member of the Wilkawillina Limestone (e.g. MORO, Fig. 4; BALC, Fig. 7; MMT, Fig. 8; WILK, Fig. 9) and the lower 430 m of the Wirrapowie Limestone in the WAR (Fig. 6) and CR1 sections (Figs. 11-12). The designated reference section is 10MS-W (Fig. 10, Appendix 9). Diversity within the zone is relatively low, typically containing five or six taxa including eccentrothecimorph and camenellan tommotiids and a paterinid brachiopod.

5.1.1 Lower Boundary

The lower boundary of the *K. rostrata* Zone is defined by the first occurrence of either the eccentrothecimorph tommotiid *Kulparina rostrata* Conway Morris and Bengtson in Bengtson, Morris, Cooper, Jell and Runnegar, 1990 (Fig. 13H-N, Q) or the paterinid brachiopod *Askepasma saproconcha* Topper, Holmer, Skovsted, Brock, Balthasar, Larsson, Petterson Stolk and Harper, 2013 (Fig. 13A-G).
5.1.2 Upper Boundary

The upper boundary of the *Krostrata* Zone is coincident with the base of the overlying *M. etheridgei* Zone based on the first occurrence of either *M. etheridgei* or *A. toddense*. In 10MS-W (Fig. 10) and CR1 (Fig. 11) the last occurrence of *K. rostrata* and the first occurrences of either *M. etheridgei* or *A. toddense* are in the same horizon. In all other sections, ranges of both *K. rostrata* and *A. saproconcha* are completely restricted to within the zone. The upper boundary of the *K. rostrata* Zone in all sections is located below the incoming of trilobites in East Gondwana.

5.1.3 Accessory Taxa

Accessory taxa in the *K. rostrata* Zone include the camenellan tommotiids *Dailyatia ajax* Bischoff, 1976 (Fig. 14A-G), *Dailyatia macroptera* (Tate, 1892) (Fig. 14H-K), *Dailyatia bacata* Skovsted, Betts, Topper and Brock, 2015 (Fig. 14P-S) and *Dailyatia helica* Skovsted, Betts, Topper and Brock, 2015 (Fig. 14L-O) (see also Skovsted et al. 2015).

*Dailyatia ajax* and *D. macroptera* have stratigraphic ranges that extend below (e.g. BALT, Fig. 7; CR1; Fig. 11) and above the defined boundaries of the *K. rostrata* Zone. *Dailyatia bacata* and *D. helica* have first occurrences in the *K. rostrata* Zone but range into the overlying *M. etheridgei* Zone. The eccentrothecimorph tommotiid *Paterimitra pyramidalis* Laurie, 1986 also has a first occurrence in this zone and ranges into the overlying *M. etheridgei* and *D. odyssei* zones (Fig. 13, O-P, R-V).

Shields attributed to *Sinskolutella cuspidata* Betts, Topper, Valentine, Skovsted, Paterson, and Brock, 2014 based on distinctive dactiloscopic microornament (Fig. 19, E-H, see Betts et al. 2014, fig. 6) occur in the *K. rostrata* Zone in the MMT section; the lowest
known occurrence of bradoriids in the Arrowie Basin (Fig. 8, Appendix 7). However,
occurrence *S. cuspidata* in the *M. etheridgei* Zone (MORO and MOG sections), and
potentially also the *D. odyssei* Zone (unpublished data), suggests a long stratigraphic range
for this taxon, spanning pre-trilobitic to *P. janeae* Zone strata.

5.2 Micrina etheridgei Zone

The *Micrina etheridgei* Zone is restricted to the upper half of the Winnitinny Creek
Member of the Wilkawillina Limestone and temporal equivalents in the Wirrapowie and Ajax
limestones. Diversity within the zone is relatively high (~28 species in the AJX-M section),
including eccentrothecimorph and camenellan tommotiids, organophosphatic brachiopods,
helcionellid molluscs, bradoriid arthropods and lobopods.

5.2.1 Lower Boundary

The *Micrina etheridgei* Zone is often highly fossiliferous (e.g. MMT section, Appendix 7). The lower boundary is defined by the first occurrence of the tannuolinid
tommotiid *Micrina etheridgei* (Tate, 1892) (Fig. 15J-P) or the paterinid brachiopod
*Askepasma toddense* (Fig. 16A-H). *Askepasma toddense* Laurie, 1986 (Fig. 16A-H) has a
mutually exclusive stratigraphic range with the older (possibly ancestral) *Askepasma
saproconcha*. *Askepasma toddense* ranges from the Winnitinny Creek Member of the
Wilkawillina Limestone into the Second Plain Creek Member (WILK, Fig. 9) above the FU.
A taxon similar to *A. toddense* occurs in the *D. odyssei* Zone in the Mernmerna Formation,
though these are typically poorly preserved and may be reworked (MOG section, Fig. 5; Fig.
16C).
5.2.2 Upper Boundary

The upper boundary of the M. etheridgei Zone is coincident with the base of the overlying D. odyssei Zone based on the first occurrence of Dailyatia odyssei Evans and Rowell, 1990 or Stoibostrombus crenulatus Conway Morris and Bengtson in Bengtson et al., 1990. In sections measured through platformal carbonates in the central Flinders Ranges (Fig. 1) such as BALC (Fig. 7), MMT (Fig. 8), WILK (Fig. 9), 10MS-W (Fig. 10) the M. etheridgei Zone is capped by the regionally significant Flinders Unconformity (FU). This surface is manifest as a distinctive karstic microstromatolitic “reddened horizon” (Gravestock and Cowley 1995). The duration of this hiatus is variable across the Arrowie Basin (see also James and Gravestock 1990, p. 458-459). The duration of the unconformity in the WILK section for example, represents an unknown period of subaerial exposure and non-deposition (Fig. 9). Here, the upper boundary of the M. etheridgei is delineated by the karstic surface. Micrina etheridgei (as well as accessory taxa Dailyatia ajax, D. macroptera, D. helica and D. bacata) does not occur stratigraphically above the “reddened horizon”.

5.2.3 Accessory Taxa

Shelly taxa that have first occurrences within the M. etheridgei Zone include a number of organophosphatic brachiopods, helcionelloid molluscs, bradoriids and lobopods, some of which have correlative potential (see below). Accessory taxa include D. ajax, D. macroptera, D. helica and D. bacata which range from the underlying K. rostrata Zone and terminate within the M. etheridgei zone.
Organophosphatic brachiopods such as *Eoobolus* spp. (which includes *Sukaharilingula* Ushatinskaya 2012), *Karatele yorkensis* Holmer and Ushatinskaya in Gravestock et al., 2001 (Popov et al., 2015, p. 32, have recently synonymized *Karatele* with *Schizopholis*), *Eodicellomus elkaniformis* Holmer and Ushatinskaya in Gravestock et al., 2001, and *Kyrshabaktella davidi* Holmer and Ushatinskaya in Gravestock et al., 2001 (Fig. 16 I-U and Fig. 17 A-T) all have first occurrences in the *M. etheridgei* Zone, but range into the overlying *D. odyssei* Zone.

The tommotiid *Eccentrotheca helenia* Skovsted, Brock, Topper, Paterson and Holmer, 2011 (Fig. 15, A-I) first occurs in the *M. etheridgei* Zone. First appearance of *E. helenia* has been taken as a proxy for the lower boundary of the *A. huoi* Zone. This level consistently occurs above the defined lower boundary of the *M. etheridgei* Zone (Fig. 4; see also Betts et al., 2014, fig. 2), demonstrating that the lower part of the zone is pre-trilobitic.

The *M. etheridgei* Zone records the first occurrences of a number of helcionelloid molluscan taxa that range into the overlying *D. odyssei* Zone (Fig. 18). Taxa include *Pelagiella subangulata* (Tate, 1892), *Anabarella australis* Runnegar in Bengtson et al., 1990 and *Mackinnonia rostrata* (Zhou and Xiao, 1984), often preserved as steinkerns (Fig. 18).

The difficulty in accurately identifying steinkern material to species level makes utilisation of these taxa problematic in biostratigraphic schemes (see also discussion by Jacquet and Brock 2015). *Pelagiella subangulata* has been suggested as a possible proxy to define the base of Series 2, Stage 3 on a global scale (see Peng et al., 2012). Whilst some steinkerns probably represent *P. subangulata* (Fig. 18A, D; AJX-M, Fig. 2, AJX-N, Fig. 3, MORO, Fig. 4, MOG, Fig. 5), we take a cautious taxonomic approach and acknowledge the difficulties of confidently identifying steinkern material to species level.
The *M. etheridgei* Zone hosts a unique assemblage of bradoriids that are restricted to the zone (~10 species) (Figs. 19, 20), key amongst these are *Liangshanella circumbolina* Topper, Skovsted, Brock & Paterson, 2011, *Quadricona madonae* Topper, Skovsted, Brock & Paterson, 2011 (Fig. 20, E, F) and *Zepaera jagoi* Topper, Skovsted, Brock & Paterson, 2011 (Topper et al., 2011). The range of the Chinese taxon *Parahoulongdongella bashanensis* (Shu, 1990) is also restricted to the *M. etheridgei* Zone (Fig. 20, A-D). Endemic taxa include *Jiucunella phaseloa* Betts, Topper, Valentine, Skovsted, Paterson, Brock, 2014 (Fig. 19, A-D) is restricted to the *M. etheridgei* Zone. Similarly, the haoiid *Jixinlingella daimonikoa* Betts, Topper, Valentine, Skovsted, Paterson, Brock, 2014 (Fig. 19, S-U), *Mongolitubulus anthelios* Betts, Topper, Valentine, Skovsted, Paterson, Brock, 2014 (Fig. 19, M-R) and *Neokunmingella moroensis* Betts, Topper, Valentine, Skovsted, Paterson, Brock, 2014 (Fig. 19, I-L) occur only in the *M. etheridgei* Zone (MORO and MOG, Figs. 4-5). A distinctive new species of *Mongolitubulus* (Fig. 20 J-K) occurs in the *M. etheridgei* Zone in CR1/589.7 (Appendix 10) and MOG 114.1 (63.7 m true thickness from base). *Mongolitubulus* spines are abundant throughout these sections though abraded specimens are difficult to assign to species.

Other shelly fossils in the *M. etheridgei* Zone include sclerites of the lobopodian *Microdictyon* Bengtson, Matthews and Missarzhevsky in Missarzhevsky and Mambetov, 1981 (Fig. 21, T-V). The FAD of *M. effusum* may be utilised to define the base of Cambrian Series 2, Stage 3 where trilobites might be absent (Peng et al., 2012). Steiner et al., (2007) noted *Microdictyon effusum* Bengtson, Matthews and Missarzhevsky in Missarzhevsky and Mambetov, 1981 as an accessory taxon in a number of biozones subdividing lower Cambrian strata on the Yangtze Platform in South China. However, Topper et al., (2011a) suggested that the morphology of *Microdictyon* sclerites can vary intraspecifically and also along the trunk of a single animal. In the studied sections, *Microdictyon* sclerites have only been
recovered from AJX-M (Fig. 2), MORO (Fig. 4) and MOG (Fig. 5) and show a sporadic stratigraphic distribution throughout the *M. etheridgei* Zone and into the overlying *D. odyssei* Zone. This, coupled with taxonomic difficulties outlined by Topper et al., (2011a), precludes the biostratigraphic application of *Microdictyon* at the specific level in the Arrowie Basin and potentially elsewhere.

5.3 *Dailyatia odyssei* Zone

5.3.1. Lower Boundary

The lower boundary of the *Dailyatia odyssei* Zone is defined by the first appearance of the camenellan tommotiid *Dailyatia odyssei* (Fig. 21. M-O), or the problematic ecdysozan *Stoibostrombus crenulatus* (Fig. 21. H-L). *Dailyatia odyssei* has a stratigraphic range that is younger and, importantly, does not overlap the range of any other *Dailyatia* species in South Australia (AJX-M, Figs 2, MOG, Fig. 5, WILK, Fig. 9). In the AJX-M section, *D. odyssei* occurs in the uppermost 3.4 m of the *A. huoi* trilobite Zone (Fig. 2; Appendix 1). However, *D. odyssei* has a long stratigraphic range encompassing the *Pararaia tatei*, *P. bunyerooensis* and lowermost part of the *P. janeae* trilobite zones (Skovsted et al., 2015a).

In MMT (Fig. 8), the Flinders Unconformity represents an unknown period of subaerial exposure and non-deposition. The presence of the *D. odyssei* Zone is indicated by the occurrence of *Stoibostrombus crenulatus* but does not represent the true base of the zone due to the FU. In MMT, the Third Plain Creek Member of the Mernmerna Formation (*P. bunyerooensis* trilobite Zone) rests directly on the Winnitinny Creek Member of the Wilkawillina Limestone. Hence, the Six Mile Bore and Linns Springs members of the
Mernmerna Formation are missing in the MMT (Fig. 8) section and the true lower boundary
of the $D. \text{odyssei}$ Zone cannot be accurately ascertained.

The FU also obscures the relationship between the $M. \text{etheridgei}$ and $D. \text{odyssei}$ zones
in WILK (Fig. 9). Here, the incoming of both $D. \text{odyssei}$ and $S. \text{crenulatus}$ is in the same
horizon in the Second Plain Creek Member (RS337/A), the first sample taken
stratigraphically above the FU. However, increased sampling between the samples directly
above and below the disconformity surface, would more clearly define the boundaries.

Additionally, in the BALC section (Fig. 7) the entire Mernmerna Formation (and therefore
the $D. \text{odyssei}$ Zone) is completely absent due to lengthy hiatus at the FU (Fig. 22).

5.3.2. Accessory Taxa

Common taxa in the lower part of the $D. \text{odyssei}$ Zone include tommotiids,
stoibostrombids, brachiopods and bradoriids (Figs. 19-21). The tommotiid $Lapworthella$
$fasciculata$ Conway Morris and Bengtson in Bengtson et al., 1990 (Fig. 21A-G, K) has a first
occurrence in the underlying $M. \text{etheridgei}$ Zone, but ranges up into the $D. \text{odyssei}$ Zone
where it can be very abundant (e.g. WILK section, Appendix 8). $Paterimitra\ pyramidalis$ also
ranges into the $D. \text{odyssei}$ Zone from the $K. \text{rostrata}$ Zone. Other problematic microfossils
associated with the $D. \text{odyssei}$ Zone include $Protohertzina$ sp. and $Mongolodus$ sp. spines
(Fig. 21W, X).

Brachiopods in the $D. \text{odyssei}$ Zone include $Eoobolus$ spp., $Karatele\ yorkensis$,
$Kyrshabaktella\ davidii$, $Eodicellomus\ elkaniiformis$, $Minlatonia\ tuckeri$ Holmér and
Ushatinskaya in Gravestock et al., 2001 (Figs 16-I and 17-A-T) which range up from the $M.\ \text{etheridgei}$ Zone. Other shelly taxa in the $D. \text{odyssei}$ Zone include $Mickwitzia$ sp. an
undescribed new genus of organophosphatic brachiopod (Fig. 21P-R). Helcionelloid molluscs such as *Mackinnonia* Runnegar in Bengtson et al., 1990 (Fig 18N-U), *Anabarella* Vostokova, 1962 (Fig. 18I-M) and *Pelagiella* Matthew, 1895 (Fig. 18A-H) and bradoriids are also abundant in the *D. odyssei* Zone, with many ranging up from the underlying *M. etheridgei* Zone.

6. CORRELATION IN EAST GONDWANA

The new shelly fossil biozones defined here can be correlated across the Arrowie Basin and with neighbouring depocentres such as the Stansbury, Officer, Amadeus and Georgina basins.

6.1 Arrowie Basin

The oldest faunal assemblage (FA1) reported by Daily (1956) was based on shelly material from the Flinders Ranges (Mt. Scott Range, Lake Frome and Wilson-Quorn areas). This archaeocyath-rich assemblage also contains a single unidentified organophosphatic (“atrematous”) brachiopod (Daily 1956, p. 129). Daily’s FA1 appears to largely overlap with the *K. rostrata* Zone based on a rich archaeocyath fauna and low diversity shelly fauna (see Fig. 22).

Daily (1956) noted that *Micromitra (Paterina) etheridgei* (= *Micrina etheridgei* Laurie, 1986) was abundant in his faunal assemblage 2 (FA2). In the new biostratigraphic scheme, we recognise the importance of *M. etheridgei* as a key faunal indicator and use it to define the *M. etheridgei* Zone. In addition, Daily (1956) also noted the presence of
Ambonychia macroptera in FA2, now identified as the tommotiid species Dailyatia macroptera (see Skovsted et al., 2015a), which first appears in the K. rostrata Zone and ranges into the overlying M. etheridgei Zone. The brachiopod Kutorgina peculiaris (Tate, 1892) was also noted by Daily (1956) in FA2. Askepasma saproconcha may have been misidentified as K. peculiaris by Daily (1956), which also has a relatively large sulcate shell (see Walcott, 1912, pl. V, fig. 2), suggesting Daily’s FA2 may partially overlap the K. rostrata Zone and the M. etheridgei Zone.

Daily’s (1956) FA3 and FA4 are trilobite-rich, and include helcionellids and hyoliths. Jell in Bengtson et al., (1990, p.15) correlated Daily’s FA3 with the A. huoi Zone based on the occurrence of Yorkella australis Woodward, 1884 and Abadiella huoi Chang, 1966 (see also Paterson and Brock, 2007). Daily’s FA4 correlates with the P. tatei Zone based on the occurrence of the eponym (Daily 1956, p. 130; Jell in Bengtson et al., 1990, p.15). Daily’s (1956) FA3 and FA4 are therefore likely to correlate with the upper M. etheridgei Zone and the D. odyssei Zone, respectively. Correlation of Daily’s (1956) faunal assemblages 1–4 with the new biozones is shown in Figures 22 and 23.

Trilobites are currently the most readily utilised biostratigraphic tool for defining a lower Cambrian biozonation in Australia. Jell in Bengtson et al., (1990) initially erected four trilobite biozones – (from oldest to youngest): Abadiella huoi, Pararaia tatei, P. bunyerooensis, and P. janeae. Paterson and Brock (2007) described a new faunal assemblage within the P. bunyerooensis Zone in the Bunkers Range and recognised a close faunal connection between the trilobites of South Australia and South China for this time interval. They also noted that the first appearance of trilobites in the Arrowie Basin, including the eponym of the oldest trilobite zone, Abadiella huoi, occurs in the upper half of the Winnitinny Creek Member of the Wilkawillina Limestone and equivalent strata in the Ajax.
The first appearance of *A. huoi* always occurs above the base of the *M. etheridgei* Zone as defined here, though the zones overlap. The upper boundary of the *A. huoi* Zone, best expressed in the AJX-M section, occurs 12 m stratigraphically above the top of the *M. etheridgei* Zone where it overlaps with the lower boundary of the *D. odyssei* Zone (Fig. 2).

6.2 Stansbury Basin

The early Cambrian shelly fauna of the Stansbury Basin have been relatively well studied. However, much of the taxonomic syntheses that underpin these early biostratigraphic investigations (Bengtson et al., 1990; Gravestock et al., 2001) predate extensive modern systematic treatments of key shelly fossil taxa from South Australia (see references herein). The result is that it can be difficult to tease out the true biostratigraphic signals from these monographs. Ultimately, only recollection of fossil material along measured stratigraphic sections will resolve uncertainties in correlation with the Arrowie Basin.

6.2.1 Small Shelly Fossils

Gravestock et al., (2001) established three shelly fossil zones (from oldest to youngest): *Hippopharangites dailyi, Halkieria parva* and *Kaimenella reticulata*. However, the *Hippopharangites dailyi* and *Halkieria parva* biozones are based on taxa with poorly understood multi-element scleritomes. Meagre illustrations of these species do not show all sclerite types for each taxon, hindering meaningful taxonomic comparisons and their biostratigraphic utility. Additionally, inconsistencies in the definitions of these zones have prevented their widespread application.
*Kulparina rostrata* as originally described by Bengtson et al., (1990) is entirely restricted to the upper part of the Kulpara Limestone at Horse Gully (= type locality).

Skovsted et al., (2011b, p. 281; see also Skovsted et al., 2015b) noted that the specimens originally described as *Eccentrotheca guano* Bengtson in Bengtson et al., (1990, p. 119-120, fig 71-73) from the Kulpara Limestone are actually sclerite morphotypes of *K. rostrata*. All figured specimens of *K. rostrata* (Bengtson et al., 1990, Figs 71-73, 86-90) are derived from two samples (6429RS103 and UNEL1858) located 8.0 m and 7.5 m, respectively, below the disconformity between the Kulpara and Parara limestones. Re-examination of sample 6429RS104, 3.0 m below the disconformity in the upper Kulpara Limestone at Horse Gully contains abundant *K. rostrata* along with *Dailyatia ajax*, *D. macroptera*, *D. bacata* and many fragments of a paterinid brachiopod, attributable to *Askepasma saproconcha*. The occurrence of *K. rostrata* cannot be confirmed above sample 6429RS104 (see Bengtson et al., 1990, fig. 4). Hence, the *K. rostrata* Zone occurs in a ~5.0 m interval between samples 6429RS103 and 6429RS104 in the Kulpara Limestone. The low diversity fauna in this interval also accords with typical assemblages of the *K. rostrata* Zone in the Arrowie Basin.

Gravestock et al., (2001, fig.11) also reported the presence of *Kulparina cf. rostrata* in the lower Parara Limestone in the SYC-101 drillcore, located 25 km south of Horse Gully. None of this material was figured, however the fact that the taxon co-occurs with a moderately high diversity shelly assemblage in the lower Parara Limestone, strongly suggests that the specimens are not *K. rostrata*. Thus, there is no definitive evidence that *K. rostrata* has a range that extends above the Kulpara Limestone on Yorke Peninsula.

Sample 6429RS105, located 1.0 m below the disconformity horizon at Horse Gully (see Bengtson et al., 1990, fig. 4), contains a high diversity shelly assemblage (15+ taxa) including *Micrina etheridgei*, *Dailyatia ajax*, *D. macroptera*, numerous hyoliths, spicules, hyolithelmint tubes, *Sinosachites delicatus* (Jell, 1981), *Hippopharangites dailyi* Bengtson...
in Bengtson et al., 1990 and *Eremactis* spp. Indeterminate paterinid fragments are also present. This suggests the *M. etheridgei* Zone is restricted to a ~1.0 m interval directly beneath the disconformity surface. Importantly, whilst *M. etheridgei* is reported in samples immediately above the disconformity at Horse Gully by both Bengtson et al., (1990; sample 6429RS106) and Gravestock et al., (2001; samples HG0 and HG1) there is no record of *D. ajax*, *D. macroptera*, *D. bacata* or *D. helica* above the disconformity. This suggests that the disconformity surface in the western Stansbury Basin (at least at Horse Gully) may record a significantly longer hiatus than the Flinders Unconformity on platform successions in the Arrowie Basin. Both the *K. rostrata* Zone and the *M. etheridgei* Zone are represented by a very narrow (possibly condensed) interval at Horse Gully.

The Parara Limestone succession overlying the disconformity surface at the Horse Gully section contains a very diverse shelly fauna including halkieriids, hyoliths, *Microdictyon*, bradoriids and the micromolluscs *Mackinnonia*, *Pelagiella* and *Anabarella*. This level also contains *Stoibostrombus crenulatus* (in sample 6429RS106) and the trilobite *Yorkella australis* (Jell in Bengtson et al., 1990), confirming that the lower part of the Parara Limestone at Horse Gully correlates with the *D. odyssei* Zone in the Arrowie Basin (Fig. 22).

*Stoibostrombus crenulatus* is also reported in the Parara Limestone in SYC-101, CD-2, and Port Julia-1A sections where it occurs with typical *D. odyssei* Zone taxa, such as the helcionellloid molluscs *Mackinnonia rostrata* and *Pelagiella subangulata* and a wide variety of brachiopods such as *Eoobolus* sp., *Minlatonia tuckeri* and *Eodicellomus elkaniiformis*. The tannuoliniid *Micrina etheridgei* is also present in HG1 (Parara Limestone) in Horse Gully. Gravestock et al., (2001, Fig. 4) reported occurrences of *Dailyatia ajax* in the Parara Limestone above the disconformity surface (HG1 and HG9), but none of the specimens are illustrated and re-collection and detailed examination of samples through this interval of the Parara Limestone reveal that *Dailyatia* is completely absent.
In the eastern Stansbury Basin, a measured section through the Sellick Hill Formation and Fork Tree Limestone on Fleurieu Peninsula was measured by T. Brougham (2009, unpublished Honours thesis) and by MJB, JBJ, SMJ and GAB (2013, unpublished data). The tommotiid taxon *Sunnaginia imbricata* Missarzhevsky, 1969 was recovered from horizons within Facies E (*sensu* Alexander and Gravestock 1990) in the upper Sellick Hill Formation (Fig. 22). *Sunnaginia* Missarzhevsky, 1969 was widely dispersed during the early Cambrian, with occurrences recorded in Siberia, Mongolia, Avalonian North America, and the United Kingdom (Murdock et al., 2012), but this taxon has not been recovered from the Arrowie Basin. In the upper Sellick Hill Formation, *S. imbricata* co-occurs with *Dailyatia ajax*, *Kulparsina rostrata* and a probable new species of *Askepasma*. Typical elements of the *K. rostrata* Zone including *D. ajax*, *D. macroptera* and *K. rostrata* occur throughout the overlying Fork Tree Limestone. The presence of taxa indicative of the *K. rostrata* Zone at the top of the Fork Tree Limestone suggests that this unit is older than previously thought and likely correlates with the Hideaway Well and Winnitinny Creek members of the Wilkawillina Limestone in the Arrowie Basin. The lack of trilobites from outcrop in the Fork Tree Limestone supports this correlation. The typically diverse *M. etheridgei* Zone shelly fauna, including the eponym, is absent in the overlying Heatherdale Shale (apart from one specimen collected in a loose nodule; Alexander and Gravestock 1990) (Fig. 22). This may indicate a cryptic disconformity between the Fork Tree Limestone and the Heatherdale Shale (that latter containing *P. janeae* Zone trilobites, e.g., *Atops* Emmons, 1844 (Jago et al., 1984) towards the top of the unit). If this were the case, the *M. etheridgei* Zone would be largely missing in the eastern Stansbury Basin. Alternatively, the deep water slope facies of the Heatherdale Shale may record relatively slow continuous basinal depositional cycles in environments that are devoid of the shelf-dominated shelly fauna that define the *M. etheridgei* Zone.
6.2.2 Molluscs

Early Cambrian molluscs and their biostratigraphic applications have been widely studied (Demidenko, 1999, Parkhaev, 2000, 2001, Parkhaev in Gravestock et al., 2001). In addition to the small shelly fossil scheme, Gravestock et al., (2001) established four informal molluscan zones based mostly on Stansbury Basin material (oldest to youngest): the *Pelagiella subangulata*, *Bemella communis*, *Stenotheca drepanoida*, and *Pelagiella madienesis* zones. Micromolluscan taxa typical of the *M. etheridgei* Zone in the Arrowie Basin include *Pelagiella subangulata*, *Anabarella australis*, *Mackinnonia rostrata* and *Pojetaia runnegari* Jell, 1980 in the Ajax and Wilkawillina limestones. This molluscan assemblage, in particular the occurrence of *P. subangulata* and *M. rostrata*, broadly correlates the *M. etheridgei* Zone with the *Pelagiella subangulata* Zone of Gravestock et al., (2001) in the Stansbury Basin, though the latter zone is poorly defined.

The *Bemella communis* Zone of Gravestock et al., (2001) is very problematic due to the poorly constrained biostratigraphic range and potentially flawed taxonomy of the eponym, thwarting correlation between basins. The stratigraphic range of *B. communis* on Yorke Peninsula is restricted to the lower Parara Limestone, which is approximately equivalent (based on typical *D. odyssei* Zone fauna – see above) with the lower Mernmerna Formation in the Arrowie Basin. However, in the Sellick Hill Formation on Fleurieu Peninsula, the stratigraphic range of *B. communis* ranges below the *Pelagiella subangulata* Zone, preceding the first occurrence of *Sunnaginia imbricata* and *Kulparina rostrata*. This very low stratigraphic occurrence of *Bemella communis* potentially compromises the biostratigraphic utility of this taxon, or at least suggests a detailed revision of this and similar species is required. Furthermore, Gravestock et al., (2001) identified ‘*B. communis*’ in the Mernmerna Formation of the Mulyungarie-2 core in the far eastern part of the Arrowie Basin, but this material was not figured, so the identification cannot be verified.
Early Cambrian molluscs are often exceedingly abundant; however, their taxonomy has been plagued by problems of preservation. Steinkerns are very common, but are often not sufficient for classification and therefore should be used with extreme caution in detailed biostratigraphic work. The difficulties associated with early Cambrian mollusc taxonomy and preservation has implications for the widespread use of molluscan taxa such as *P. subangulata* as indicators of major stratigraphic boundaries (Peng et al., 2012). Hence, in the current scheme they are relegated to accessory taxa.

6.2.3 Archaeocyaths

Archaeocyaths from Horse Gully on Yorke Peninsula were initially used by Etheridge (1890) to establish a Cambrian age for these limestones in South Australia and were the first group to undergo rigorous biostratigraphic treatment (Walter, 1967). Extensive systematic and biostratigraphic works (Kruse and West 1980; Gravestock, 1984, Zhuravlev and Gravestock, 1994) have established regional archaeocyathan biozones (Peng et al., 2012). Yet there are undoubted taxonomic difficulties. For example, Zhuravlev and Gravestock (1994) demonstrated that a single archaeocyath taxon (*Archaeopharetra irregularis* Taylor, 1910) may be confused with up to six other taxa throughout ontogeny. Identification complications along with high levels of endemism impede their applicability for global-scale biostratigraphic correlation.

A biostratigraphic scheme based on archaeocyaths from the Flinders Ranges (i.e., Wilkawillina Gorge and the Mt. Scott Range) was produced by Gravestock (1984) and later updated with material from Yorke Peninsula (Stansbury Basin) by Zhuravlev and Gravestock (1994). The sections in the Flinders Ranges intersect the lowermost Wilkawillina and Ajax limestones and contain highly diverse archaeocyathan taxa. Gravestock (1984) recognised...
two major assemblages, Faunal Assemblages I and II and three younger (minor) assemblages, III, IV and V; IV and V are only found in the Mt. Scott Range. Faunal Assemblage II was further subdivided into upper and lower parts (Fig. 22).

The oldest assemblage (Faunal Assemblage I) contains a maximum of 10 archaeocyath taxa, but only *Copleicyathus cymosus* Gravestock, 1984 and *Warriootacyathus wilkawillinensis* Gravestock, 1984 are restricted to this zone and are found in both the Wilkawillina and Ajax Limestone sections. At Wilkawillina Gorge, the incoming of archaeocyaths occurs in the lowermost Mt. Mantell Member, below a distinctive 10 m thick unfossiliferous ooid grainstone. The lower boundary of the *K. rostrata* Zone in the WILK section occurs in the basal Hideaway Well Member, ~20 m above the base of Gravestock’s Faunal Assemblage I and so the two zones have ~ 30 m of overlap through the Hideaway Well Member (Fig. 22).

Gravestock (1984, p. 3) noted the presence of minor shelly fossils such as a ‘large’ *Kutorgina* sp. (which is most likely to be *Askepasma saproconcha*), in addition to hyoliths and chancelloriids in Faunal Assemblage I. Gravestock (1984) does not report any supplementary shelly fossils from his Lower Faunal Assemblage II, but the boundary between Faunal Assemblages I and II is reported to contain a fossiliferous band with *Chancelloria* Walcott, 1920 and the bivalve mollusc “*Fordilla*” Barrande, 1881 (most likely to be *Pojetaia runnegari*, as *Fordilla* is unknown from Australia.

The *M. etheridgei* Zone is broadly correlated here to Gravestock’s (1984) Lower and Upper Faunal Assemblage I (Fig. 22). The upper boundary of Faunal Assemblage II terminates at the Flinders Unconformity (Wilkawillina Gorge). In Wilkawillina Gorge, *Micrina etheridgei* is noted up to 30 m above the unconformity, but below the Mermnema Formation (referred to as the Parara Limestone by Gravestock 1984). This section must
represent the Second Plain Creek Member of the Wilkawillina Limestone, as it is the only member of the Wilkawillina Limestone deposited post-Flinders Unconformity and it is restricted to the Bunkers Graben (Clarke, 1986b). Gravestock (1984) notes the presence of a variety of brachiopods and Lapworthella, suggesting either M. etheridgei Zone or perhaps lower D. odyssei Zone.

Zhuravlev and Gravestock (1994) updated the original archaeocyath scheme of Gravestock (1984) and proposed three formal zones (from oldest to youngest): the Warriootacyathus wilkawillensis, Spirillicyathus tenuis and Jugalicyathus tardus Assemblage Zones. Importantly, these zones were based on Stansbury Basin material, utilising many of the stratigraphic sections that were later used to construct the SSF scheme of Gravestock et al., (2001). The Warriootacyathus wilkawillensis Zone can be approximately correlated with the K. rostrata Zone, as it is essentially similar to archaeocyath FA I of Gravestock (1984), and was correlated with Daily’s Faunal Assemblage 1 (Zhuravlev and Gravestock, 1994). The overlying Spirillicyathus tenuis Zone includes archaeocyaths and accessory SSF that correlate it with Gravestock’s (1984) Lower Assemblage II and the lowermost parts of Daily’s (1956) Faunal Assemblage 2. The youngest zone, the Jugalicyathus tardus Zone, is best represented in the Flinders Ranges and is approximately equivalent to Gravestock’s (1984) Upper Assemblage II, and slightly overlaps the A. huoi trilobite Zone. These younger archaeocyath zones are equivalent to the M. etheridgei Zone. The Flinders Unconformity caps the Jugalicyathus tardus Zone in the Flinders Ranges. Strata above this zone contain SSF and trilobites such as Pararaia tatei (Woodward, 1884) and P. bunyerooensis Jell in Bengtson et al., 1990, but no archaeocyath zones are defined (Zhuravlev and Gravestock, 1994). Zhuravlev and Gravestock (1994) identify two younger intervals with recognisable archaeocyaths; the Syringocnema favus beds and the Archaeocyathus abacus beds, which correlate with the D. odyssei Zone.
6.2.4 Acritarchs

One of the potential advantages of acritarch biostratigraphy in the Arrowie Basin is that taxa have been retrieved from the lowest siliciclastic strata such as the Uratanna and Parachilna formations, as well as thin shale beds within the Woodendinna Dolostone that do not preserve shelly fossils. However, like archaeocyaths, difficulties with the systematics of acritarchs sometimes confound confident identification of biozones (see discussion by Khomentovsky and Karlova, 1993). Biostratigraphic zonation of early Cambrian acritarchs from South Australia was developed by Zang in Gravestock et al., (2001), Zang et al., (2001), and Zang et al., (2007). Seven acritarch assemblage zones have been developed for the lower Cambrian of South Australia (Zang et al., 2007), ranging from the latest Ediacaran, throughout the lower Cambrian (Terreneuvian–Series 2) to the Series 3, Stage 4–5 boundary. Acritarch Zones 1, 2 and 3 encompass pre-shelly units (Uratanna and Parachilna formations).

The acritarch biozonation established by Zang et al., (2007) is a composite scheme based on material from both the Stansbury and Arrowie basins. However, because these coeval basins were deposited under different depositional regimes it is not always easy to recognise and correlate these zones. For example, acritarchs from Assemblage Zone 4 (Skiagia ornata Zone) are known from the lower Kulpara Limestone (Stansbury Basin), while Assemblage Zone 5 (Skiagia ciliosa-Corollasphaeridium aliquolatum Zone) is based on material from the Wilkawillina Limestone in the Arrowie Basin. Despite being based on Stansbury Basin material, Assemblage Zone 4 (Skiagia ornata Zone) ranges from the upper parts of the Woodendinna Dolostone to the lower Wilkawillina Limestone (A. huoi Zone) in the Arrowie Basin (Zang et al., 2007, fig. 18, pg.166), therefore encompassing pre-shelly strata, in addition to the K. rostrata Zone and potentially also part of the M. etheridgei Zone.
The lower and upper boundaries of Acritarch Zone 4 in the Arrowie Basin are poorly
constrained due to a lack of detailed sampling in the interval between Zones 4 and 5 (Zang et
al. 2007).

Acritarch Assemblage Zone 5 (Skiagia ciliosa-Corollasphaeridium aliquolumum
Zone) occurs in the lower Wilkawillina Limestone (Yalkalpo-2 drillcore, 782.7–732.3 m;
Zang et al., 2007). Zang et al., (2007) report Micrina etheridgei, Dailyatia (species not
identified) and A. huoi from Assemblage Zone 5, therefore correlating it with Faunal
Assemblage 2 of Daily (1956), the Jugalicyathus tardus Zone of Zhuravlev and Gravestock
(1994), and the M. etheridgei Zone of the present study.

6.3 Officer Basin

In contrast to the richly bioclastic carbonates in the Arrowie Basin, the depositional
regime in the Officer Basin during the early Cambrian was dominated by mixed siliciclastics
with carbonates and evaporites (Gravestock, 1995). The few early Cambrian shelly fossils
described from the Officer Basin are known only from drill cores through the Ouldburra
Formation (Gravestock et al., 1997). The Ouldburra Formation and the coeval Relief
Sandstone were deposited as part of sequence tracts €1.1 to €1.3 that are broadly coincident
with the entire Hawker Group in the Arrowie Basin (Gravestock and Hibburt 1991;
Gravestock, 1995).

The Manya-6 drill core (Ouldburra Formation) has yielded cranidia and librigenae of
the redlichiid trilobite Abadiella officerensis Jago and Dunster, 2002 between 967.7–970.13
m depth (Jago et al., 2002a). Additional trilobite fragments were recovered from an interval
between 889–1263 m in this core suggesting an age no older Cambrian Stage 3. The oldest
fossils in this core are indeterminate sponge spicules (at 1391 m) (Gravestock et al., 1997).

Archaeocyath-microbial build-ups also occur in the interval 399–654 m in the Marla-6 drill core which yielded hyoliths, sponge spicules and “ostracods” (probably bradoriids) (Gravestock et al., 1997, p. 94).

Poor preservation of most fossil material from the early Cambrian of the Officer Basin makes precise biostratigraphic correlation with the Arrowie Basin difficult. However, the occurrence of *Abadiella officerensis* may correlate with the occurrences of the congeneric *A. huo*i in the Arrowie Basin. Zang et al. (2007) also reported acritarchs from the *Skiagia ciliosa-Corollasphaeridium aliquolumum* Zone (acritarch Assemblage Zone 5) from the Manya-6 drillcore, suggesting that this part of the succession may be broadly correlated with the *M. etheridgei* Zone or possibly the *D. odyssei* Zone in the Arrowie Basin.

6.4 Amadeus Basin, Northern Territory

The lower Cambrian Todd River Dolostone in the Amadeus Basin, central Australia is richly fossiliferous (Wells et al., 1967). The unit consists of thinly bedded calcareous sandstones interbedded with thin dolostone beds (Laurie and Shergold, 1985). Early investigation into the shelly fauna from the Todd River Dolostone revealed archaeocyaths associated with “*Micromitra etheridgei*” (=*Micrina etheridgei*) in the lower parts of the unit (Wells et al., 1967). Hyoliths, brachiopods and trilobite fragments were noted in upper stratigraphic levels (Wells et al., 1967; Wells et al., 1970; Laurie, 1986).

The Todd River Dolostone type section (and cores 25, 26 and Rodinga 5 drilled by the Bureau of Mineral Resources) produced a rich fauna including *Dailyatia ajax*, *Micrina etheridgei*, *Eccentrotheca* sp., chancelloriid spicules, *Sachites* sp., *Thambetolepis* Jell 1981 (=
Sinosachites sp., Edreja Koneva 1979 (=Eodicellomus) sp., Lingulella sp., Pelagiella sp., indeterminate trilobites, and other indeterminate shelly fossils (Laurie and Shergold, 1985). A nearby locality (NT600) also produced a well preserved fauna described by Laurie (1986). This material included both mitral and sellate sclerites of M. etheridgei (Laurie, 1986). This locality also produced well preserved Dailyatia specimens; material figured by Laurie (1986) depicts D. ajax sclerites (Laurie, 1986, fig. 6A-I, 7A, C, D, F). The fauna also includes other tommotiids such as Paterimitra pyramidalis and Eccentrotheca cf. kanesia Landing, Nowlan and Fletcher, 1980 (later identified as probable L sclerites of P. pyramidalis by Larsson et al., 2014), and another kennardiid species, Kennardia reticulata Laurie, 1986.

A single shell attributed to Pelagiella sp. was recovered from NT600 in the Todd River Dolostone, in addition to a brachiopod fauna that includes Askepasma toddense Laurie, 1986, Edreja aff. distincta Koneva, 1979 (= Eodicellomus sp.) and Lingulella (=Eoobolus spp.). This combination of taxa, in particular the presence of Micrina etheridgei, Eccentrotheca, Askepasma toddense and additional lingulid brachiopods enables confident correlation between the Todd River Dolostone and the M. etheridgei Zone age strata in the Arrowie Basin.

6.5 Georgina Basin, Northern Territory and Queensland

The Red Heart Dolostone in the Georgina Basin is broadly coeval with the Todd River Dolostone in the Amadeus Basin (Laurie and Shergold, 1985). The BMR Hay River 11B core intersected 9.8 m of Red Heart Dolostone and yielded a phosphatic shelly fauna that included Dailyatia ajax, chancelloriids and Edreja-like (= Eodicellomus sp.) brachiopods and ?Ramenta sp. (Laurie and Shergold, 1985). A diverse fauna, including Dailyatia ajax, ?Tannuolina etheridgei (=Micrina etheridgei), ?Edreja sp., Paterina sp., Lingulella sp.,
indeterminate orthid brachiopods, micromolluscs such as *Yochelcionella* sp., hyoliths, echinoderm fragments and chancellorids, was also recovered from the Errarra Formation (Mopunga), which was synonymised with the Red Heart Dolostone (Laurie and Shergold, 1985; Dunster et al., 2007). This shelly assemblage, particularly the occurrence of *M. etheridgei*, correlates the Red Heart Dolostone with strata encompassing the *M. etheridgei* Zone in the Arrowie Basin.

7. CORRELATION OUTSIDE AUSTRALIA

The difficulties surrounding global correlation of lower Cambrian pre-trilobitic strata based on SSF occurrences have been well documented (see Steiner et al., 2004, 2007; Landing et al., 2013), and are largely due to faunal provincialism and facies dependence of many key taxa. Therefore, high resolution correlation of this scheme outside of East Gondwana is problematic. The aim of this contribution has been to establish a workable regional biostratigraphic scheme. Various faunal elements (mostly at genus level) from the South Australian shelly biozones have been identified that link the successions most closely to strata in China (Fig. 23).

7.1 *Kulparina rostrata* Zone

The low diversity fauna of the *K. rostrata* Zone are highly endemic, which limits correlation outside of East Gondwana. However, in the Stansbury Basin, *Kulparina rostrata* partially overlaps with the tommotiid *Sunnaginia imbricata* over a relatively short interval (2.5 m) in Facies D of the upper Sellick Hill Formation (unpublished data), providing potential global correlation for the lower part of the *K. rostrata* Zone. *Sunnaginia* has a wide
distribution in the early Cambrian, with previous reports from lower Cambrian strata in England, Siberia, Avalonian North America and Mongolia (see Murdock et al., 2012 and references therein). However, *Sunnaginia* has not been recovered from the Arrowie Basin, possibly due to a lack of suitable facies.

7.2 *Micrina etheridgei* Zone

In China, the *S. flabelliformis-T. zhangwentangi* Assemblage Zone is succeeded by the *Parabadiella huoi* trilobite Zone which correlates directly with the *A. huoi* Zone in South Australia (Jago et al., 2002b; Paterson and Brock, 2007). Whilst there is continued debate about the generic assignment of this species (see Landing et al., 2013 for discussion), there is general agreement that *A. huoi* and *P. huoi* are conspecific. Hence, there is strong correlation between the trilobitic upper part of the *M. etheridgei* Zone and the *P. huoi* zone in China.

Traditionally, the *A. huoi* Zone is considered to be younger than the *Profallotaspis* and *Fallotaspis* zones in Siberia (see Peng et al., 2012, fig. 19.3; Landing et al., 2013, fig. 4), though Yuan et al., (2011) indicated the *Parabadiella* Zone in China can be interpreted as time-equivalent to the *Eofallotaspis* Zone in Morocco and the *Profallotaspis jakutensis* Zone in Siberia. The correlation chart of Landing et al., (2013, fig. 4) indicates *Fallotaspis bondoni* (Neltner and Poctey 1950) from southern Morocco is late Issendalenian (*Choubertella–Daguinaspis* Zones) in age, which is ~519 Ma (Peng et al., 2012, fig. 19.11). The *Abadiella huoi* (= *Parabadiella*) Zone is lower Nangaoan (= upper Atdabanian, *sensu* Landing et al., 2013), which is therefore slightly younger (ca. 518 Ma) (Peng et al., 2012, fig. 19.11). Therefore, *Abadiella* and *Fallotaspis* Hupe, 1953 may well have been contemporaneous, but occurring in different trilobite provinces (see Fig. 23).
In South China, the first appearance of *Micrina xiaotanensis* Li and Xiao, 2004 overlaps with the last appearance of *Sinosachites flabelliformis* He, 1980 and *Lapworthella rete* Yue, 1987 in the lower Yuanshan Formation (Li and Xiao 2004). The last occurrence of *L. rete* defines the upper boundary of the *S. flabelliformis-T. zhangwentangi* Assemblage Zone in South China (Steiner et al., 2007). Thus, co-occurrence of *Micrina, Lapworthella* and halkieriid sclerites (likely to be *Sinosachites*) in the *M. etheridgei* Zone can be correlated with the upper part of the *S. flabelliformis-T. zhangwentangi* Assemblage Zone in China.

*Lapworthella rete* and *Conotheca brevica* Qian, Xie and He, 2001 have been reported from the Marcory Formation, southern France, which Devaere et al., (2014a) correlates with the *S. flabelliformis-T. zhangwentangi* Assemblage Zone in China based on co-occurrence of the taxa in both localities. Hyoliths are abundant in the AJX-M section which includes taxa such as *Triplicatella disdoma* Conway Morris in Bengtson et al., 1990 (Skovsted et al., 2014b), and *Cupitheca holocyclata* Bengtson in Bengtson et al., 1990 (Skovsted et al., 2016), and probable conothecids. They co-occur with *Lapworthella* in the *M. etheridgei* Zone providing a temporal link with the Marcory Formation, southern France and the *S. flabelliformis-T. zhangwentangi* Assemblage Zone in China.

Some brachiopods that first appear in the *M. etheridgei* Zone also have a global distribution. *Eoobolus*, for example, is widely dispersed, but this genus is currently poorly defined and probably represents a “wastebasket” taxon that is very long ranging, which currently limits biostratigraphic application (Ushatinskaya, 2012). In addition, *Askepasma transversalis* Peng, Zhao, Qin, Yan and Ma, 2010 from the lower Cambrian Balang Formation, eastern Guizhou is the only occurrence of the genus outside Australia (Peng et al., 2010). However, in the Balang Formation, this taxon co-occurs with *Redlichia chinensis* Walcott, 1905. In Australia, *Redlichia* occurs in younger strata (Series 2, late Stage 4) (Laurie, 2006), and hence is unlikely to correlate with the zones described herein.
Furthermore, the illustrated specimens have a more prominent pedicle beak than either *Askepasma toddense* or *A. saproconcha* and do not display the reticulate microornament diagnostic of the genus, leaving identification and correlation of these specimens in doubt.

Bradoriid fauna have often been used to distinguish Cambrian biogeographic provinces (Siveter and Williams, 1997; Melnikova et al., 1997; Williams and Siveter, 1998; Hou et al., 2002; Williams et al., 2007; Topper et al., 2011b). Australian bradoriid assemblages bear close taxonomic similarities (at the genus level) with those from South China (Topper et al., 2007, 2011b; Betts et al., 2014), though genera in Australia are typically correlated to older strata. For example, *Jiucunella* was thought to be endemic to China until the recent description of *Jiucunella phaseola* from the Arrowie Basin (Betts et al., 2014). *Jiucunella phaseola* is restricted to the *M. etheridgei* Zone in South Australia. In South China, the morphologically similar *Jiucunella paulaula* is restricted to the slightly younger *Eoredlichia*-Wutingaspis Zone in the Qiongzhusian Formation in Chengjiang County, Yunnan (Hou & Bergström, 1991; Hou et al., 2002).

Similarly, *Jixinlingella* was only known from the lower Cambrian Shuijingtuo Formation (*Eoredlichia*-Wutingaspis Zone), Shaanxi, central China (Lee 1975; Zhang 2007) before *Jixinlingella daimonikoa* was described by Betts et al. (2014) from the *M. etheridgei* Zone. In addition, *Neokunmingella cf. minuta* ranges from the *Eoredlichia*-Wutingaspis Zone in the Qiongzhusi Formation to the *Palaeolenus* Zone in the Canglangpu Formation in South China (Hou et al., 2002). *Neokunmingella shuensis* is also recorded from the *Eoredlichia*-Wutingaspis Zone in Southern China (Zhang, 2007). In the Arrowie Basin, *Neokunmingella moroensis* appears to represent an older occurrence, being restricted to the *M. etheridgei* Zone in the MORO and MOG sections.
8. CONCLUSION

This new biostratigraphic scheme applies the widely adopted methodology of defining only lower boundaries based on first occurrences of diagnostic fossils in a stratigraphic section, which simplifies both the definitions and visual representation of the zones. Unrecognised time-breaks between zones (e.g. boundary between the *M. etheridgei* and *D. odyssae* zones) can confound accurate identification of biozone boundaries, frustrating correlation at regional (and global) scale. This is further supports the need for integrating multi-proxy datasets, particularly biostratigraphy and chemostratigraphy to calibrate and circumvent shortcomings of relative dating methods.

Definition of internationally acceptable boundaries for lower Cambrian chronostratigraphic subdivisions remains unresolved, especially the base of Stages 2, 3 and 4. Many previous biostratigraphic schemes for Australia have utilised Siberian stages (e.g. Kruse et al., 2009) or the depositional sequence sets of Gravestock and Cowley (1995).

Resolving this issue ultimately hinges on the resolution of biostratigraphic ranges of shelly fauna through regional, basin-scale sequences.

Absence of trilobites below the Cambrian Series 2, Stage 3 *Abadiella huoi* trilobite Zone means that other faunal groups must be employed to fill this biostratigraphic gap in East Gondwana. Schemes based on acritarchs (Zang in Gravestock et al., 2001; Zang 2001; Zang et al., 2007), archaeocyaths (Gravestock, 1984; Zhuravlev and Gravestock, 1994) and ichnofossils (Droser et al., 1999) have been used with varying success. Biozones based on shelly fossils have great potential to fill the pre-trilobitic gap in Australia and contribute meaningfully to lower Cambrian regional and global correlation.

Measured sections have yielded abundant shelly fossils from the Wilkawillina, Wirrapowie and Ajax limestones, the biostratigraphic ranges of which are predictable and
repeatable across the basin. This has resulted in the establishment of three new biozones (in ascending order): the *Kulparina rostrata* Zone, *Micrina etheridgei* Zone, and the *Dailyatia odyssei* Zone. The *D. odyssei* Zone is associated predominantly with the Mernmerna Formation (and equivalent strata) and will be documented in greater detail in a subsequent paper. These zones intersect the fossiliferous part of the Hawker Group in the Arrowie Basin, South Australia and allow robust correlation both within the basin and with coeval depocentres such as the Stansbury, Amadeus, Georgina and Officer basins. The endemic nature of many of the taxa utilised in this scheme, restrict global correlation. However, faunal correlation with China is enabled through occurrences of several cosmopolitan shelly fossil genera (and species), indicating that the *K. rostrata* and *M. etheridgei* zones correlate with the Meishucunian *S. flabelliformis-T. zhangwengtangi* Assemblage Zone in China. Therefore, the Australian zones range from the upper Terreneuvian Series, Stage 2 to Series 2, Stage 3.

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References


Clarke, J.D.A. 1986b. Stratigraphy and sedimentology of the upper part of the Wilkawillina Limestone, Wilkawillina Gorge, Flinders Ranges. Quarterly Geological Notes - Geological Survey of South Australia 100, 2-7.


Cobbold, E.S., 1921. The Cambrian horizons of Comley (Shropshire) and their Brachiopoda, Pteropoda, Gasteropoda and etc. The Quarterly Journal of the Geological Society of London 76, 325–386.


Demidenko, Y. E. 1999. Skeletnye problematichnye ostatki iz nizhuego kembriya Yuzhnoy Avstralii (Skeletal problematic remains from the lower Cambrian of South Australia). Avtoreferat dissertatsii kandidata geologo-nimeralogicheskikh nauk, Moscow, Moscow State University (unpublished, in Russian).


Cambrian ichnofabric and trace-fossil record in siliciclastic rocks of South Australia. 
*Geology* 27, 625-628.

Potential of the southern Georgina Basin. Northern Territory Geological Survey, 

Emmons, E. 1844. The Taconic System: Based on Observations in New-York, 

Formation (Cambrian), western Nevada, USA. *Palaeogeography, Palaeoclimatology, 
Palaeoecology* 295, 236–244.

Etheridge, R. 1890. On some Australian species of the family Archaeocyathinae. 
Transactions of the Royal Society of South Australia 13, 10-22.

of Paleontology* 66, 558-562.

faunal connection with Australia. *Journal of Paleontology* 64, 692-700.

Society of Turkey* 20, 35–48 (in Turkish with English abstract).

13*, 87-98.

Lethaea* 67, 55-118.

Geyer, G. and Shergold, J.H. 2000. The quest for internationally recognized divisions of 


Howchin, W., 1922. A geological traverse of the Flinders Ranges from the Parachilna Gorge to the Lake Frome Plains. Transactions of the Royal Society of South Australia 46, 46-82.


Laurie, J.R., 2006. Early Middle Cambrian trilobites from Pacific Oil and Gas Baldwin 1 well, southern Georgina Basin, Northern Territory. Memoir of the Association of Australasian Palaeontologists 32, 127.


Steiner, M., Li, G., Qian, Y. and Zhu, M. 2004. Lower Cambrian small shelly fossils of northern Sichuan and southern Shaanxi (China), and their biostratigraphic importance. *Geobios* 37, 259-275.


Tate, R., 1892. The Cambrian fossils of South Australia. *Transactions of the Royal Society of South Australia* 15, 183-189.
Taylor, T.G., 1910. The Archaeocyathinae from the Cambrian of South Australia with an account of the morphology and affinities of the whole class. Memoir of the Royal Society of South Australia, 2, 55-186.


Yue, Z. 1987. The discovery of Tannuolina and Lapworthella from Lower Cambrian in Meishucun (Yunnan) and Maidiping (Sichuan) sections. Professional Papers of


Zhu, M., Babcock, L. and Peng, S.-C. 2006. Advances in Cambrian stratigraphy and
paleontology: Integrating correlation techniques, paleobiology, taphonomy and
paleoenvironmental reconstruction. Palaeoworld 15, 216-222.

Australia and archaeocyathan Early Cambrian zonation. Alcheringa 18, 1-54.

Captions

Fig. 1. Extent of Arrowie Basin, South Australia showing Cambrian outcrop and locations of
measured sections.

Fig. 2. AJX-M stratigraphic section through the Ajax Limestone in Mt. Scott, north-western
Flinders Ranges. Ranges of key shelly fossil taxa through the Micrina etheridgei Zone and
the Dailyatia odyssei Zone are shown. AJX-M has trilobite control; extent of the Abadiella
huoi and Pararaia tatei Zones are shown. Abundance data is given in Appendix 1.

Fig. 3. AJX-N stratigraphic section through the Ajax Limestone in Mt. Scott, north-western
Flinders Ranges. Ranges of key shelly fossil taxa through the Micrina etheridgei Zone are
shown. Abundance data is given in Appendix 2.

Fig. 4. MORO stratigraphic section through the Parachilna Formation, Woodendinna
Dolostone and Wilkawillina and Wirrapowie limestones in the Arrowie Syncline, northern
Flinders Ranges. Ranges of key shelly fossil taxa through the K. rostrata Zone and the
Micrina etheridgei Zone are shown. Abundance data is given in Appendix 3.

Fig. 5. MOG stratigraphic section through the Wirrapowie and Wilkawillina limestones,
Mernmerna Formation and Nepabunna Siltstone in the Arrowie Syncline, northern Flinders
Ranges. Ranges of key shelly fossil taxa through the Micrina etheridgei Zone and the
Dailyatia odyssei Zone are shown. Note the Flinders Unconformity is not developed in the Arrowie Syncline and the succession is largely continuous between the Wirrapowie Limestone and the Mernmerna Formation. Abundance data is given in Appendix 4.

Fig. 6. WAR stratigraphic section through the Wirrapowie Limestone in the central Flinders Ranges. Ranges of key shelly fossil taxa through the K. rostrata Zone are shown. Abundance data is given in Appendix 5.

Fig. 7. BALT stratigraphic section through the Parachilna Formation, Wilkawillina Limestone and the Billy Creek Formation in the Bunkers Range, central Flinders Ranges. The Flinders Unconformity represents erosion of the upper Winnitinny Creek Member and non-deposition of the entire Mernmerna Formation, hence the D. odyssei Zone is not present in the BALT section. Ranges of key shelly fossil taxa through the K. rostrata Zone and the Micrina etheridgei Zone. Abundance data is given in Appendix 6.

Fig. 8. MMT stratigraphic section through the Wilkawillina Limestone and Mernmerna Formation in the Bunkers Range, central Flinders Ranges. The Flinders Unconformity (FU) occurs at horizon MMT/295.5 where the Third Plain Creek Member of the Mernmerna Formation (P. bunyeroensis trilobite zone) lies unconformably on the Winnitinny Creek Member of the Wilkawillina Limestone. Hence, the Six Mile Bore and Linn's Springs members of the Mernmerna Formation are missing. The D. odyssei Zone is indicated by the occurrence of Stoibostrombus crenulatus but does not represent the true base of the zone due to the FU. Abundance data is given in Appendix 7.

Fig. 9. WILK (Wilkawillina Limestone type section) stratigraphic section through the Woodendinna Dolostone, Wilkawillina Limestone and Mernmerna Formation in the Bunkers Graben, central Flinders Ranges. The Flinders Unconformity (FU) in the WILK section represents a time break between the Winnitinny Creek and Second Plain Creek members of
the Wilkawillina Limestone. The true base of the *D. odyssei* Zone is difficult to ascertain due to the unknown time gap represented by the “reddened horizon”. Additional sampling between the horizons immediately above and below the FU will clarify boundaries. Abundance data is given in Appendix 8.

Fig. 10. 10MS-W stratigraphic section through the Parachilna Formation, Wilkawillina Limestone and the Mernmerna Formation in the south-eastern Bunkers Graben, central Flinders Ranges. Ranges of key shelly fossil taxa through the *K. rostrata* Zone and the *Micrina etheridgei* Zone are shown. Abundance data is given in Appendix 9.

Fig. 11. CR1 stratigraphic section through the Wirrapowie Limestone in the Chase Range, southern Flinders Ranges. Ranges of key shelly fossil taxa through the *K. rostrata* Zone and the *M. etheridgei* Zone are shown. Abundance data is given in Appendix 10.

Fig. 12. Correlation of all stratigraphic sections within the Arrowie Basin based on stratigraphic extent of the *K. rostrata* Zone, the *Micrina etheridgei* Zone and the *Dailyatia odyssei* Zone.


Aa (Betts et al., 2014), Wilkawillina Limestone (HWM), SAM P53171. T, MMT/126.5.

Winnitinny Creek Member (WTCM) of the Wilkawillina Limestone, SAM P53172. U,

MORO/881.6, Wilkawillina Limestone (WTCM), SAM P53173. V, MORO/730.0,

Wilkawillina Limestone (HWM), SAM P53174.


Fig. 15. *Eccentrotheca helenia* and *Micrina etheridgei* typical of the *M. etheridgei* Zone. A-I, *E. helenia*. A, MOG/210.0, Winnitinny Creek Member (WTCM) of the Wilkawillina
Limestone, SAM P53194. B, D, MMT/237.5, Wilkawillina Limestone (WTCM), SAM P53195. SAM P53197. C, MORO/881.6, Wilkawillina Limestone (WTCM), SAM P53196. E, MMT/231.0, Wilkawillina Limestone (WTCM), SAM P53198. F-H, MOG/42.8,
Wirrapowie Limestone, SAM P53199, SAM P53200, SAM P53201. I, MMT/237.5,

Fig. 16. Askepasma toddense and Eoobolus sp. from the M. etheridgei and D. odyssei Zones.
microornament AJX-M/274.0, Ajax Limestone, SAM P53226. S and U, *Eooobulus* sp. dorsal
valve with pustulose microornament AJX-M/368.0, Ajax Limestone, SAM P53227.


rhomboid scales, MOG/114.1, Wirrapowie Limestone, SAM P53276. P, *M. anthelios* spine,
MORO/889.0, Wilkawillina Limestone (WTCM), SAM P48697. Q, *M. anthelios* spine,
MOG/15.0, Wirrapowie Limestone, SAM P53277. S, *Jixinlingella daimonikoa*, conjoined
shields (holotype) MORO/1043.0, Wirrapowie Limestone, SAM P48683. U, *J. daimonikoa*
left shield, MORO/1043.0, Wirrapowie Limestone, SAM P48684.

Fig. 20. Bradoriid fauna from the *M. etheridgei* Zone and the *D. odyssei* Zone. A-D,
*Parahoulongdonella bashanensis*. A-B, left shield, CR1/500.0, Wirrapowie Limestone SAM
P53278. C-D, left shield, RC/102.0, Wirrapowie Limestone, SAM P53282. E-F, *Quadricona*
*madonnae*, both from the Wirrapowie Limestone. E, conjoined specimen, RC/252.9, SAM
BALC/580.0, Winnitinny Creek Member (WTCM) of the Wilkawillina Limestone, SAM
CR1/589.7, Wirrapowie Limestone, SAM P53281. L(O) and P, *Spinospitaella coronata* all
from BALC/580.0, Wilkawillina Limestone (WTCM). L, close up of spine tip from (O). O,
broken spine, SAM P53284. P, broken spine with abraded ornament, SAM P53287. M-N.S.
coronata shield fragment from ER9/0.0, Wirrapowie Limestone, SAM P44806.

Fig. 21. Typical shelly fauna associated with the *Dailyatia odyssei* Zone. A-G and K,
*Lapworthella fasciculata*. A, MOG/264.7, Winnitinny Creek Member (WTCM) of the
Wilkawillina Limestone, SAM P53292. B and K, MOG/912.0, Mernmerna Formation, SAM
P53293. C, AJX-N/382.4, Ajax Limestone, SAM P53294. D, MMT/268.0, Wilkawillina
Limestone (WTCM), SAM P53295. E, MOG/905.4, Mernmerna Formation, SAM P53296. F,
MMT/268.0, Wilkawillina Limestone (WTCM), SAM P53297. G, MMT/265.1, Wilkawillina
MOG/912.0, Mernmerna Formation, SAM P53299. I and J, MOG/905.4, Mernmerna
Formation, SAM P53300, SAM P53301. M-O, *Dailyatia odyssei*, all C1 sclerites from the

Fig. 22. Regional correlation of the K. rostrata, M. etheridgei and the Dailyatia odyssei zones. The assemblages can be confidently correlated between the Arrowie Basin and the western Stansbury Basin (Yorke Peninsula), eastern Stansbury Basin (Fleurieu Peninsula) based on co-occurrence of key fauna. Position of previous schemes utilising shelly fossils (Daily 1956) and archaeocyaths (Gravestock 1984) are also included. Note uncertainty of shelly fossil zonation in the Heatherdale Shale is due to lack of fauna. Dashed lines indicate boundaries are uncertain. Undulating lines indicate unconformities.

Fig. 23. Correlation of the K. rostrata and M. etheridgei zones with South China utilising key cosmopolitan genera. Figure adapted from Steiner et al (2007, figs 11 and 12); Yuan et al (2011, table 2); Peng et al. (2012, fig. 19.11); Yang et al (2013, fig. 5). Further global correlation is hindered by lack of cosmopolitan species in the K. rostrata and M. etheridgei zones. Dashed lines indicate boundaries are uncertain. Undulating lines indicate unconformities.

Author biographies
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John R. Paterson is a Professor of Earth Sciences and currently an Australian Research Council Future Fellow at the University of New England (UNE) in Armidale, New South Wales, Australia. He graduated with a BSc (Hons) (2001) and PhD (2005) from Macquarie University in Sydney. He completed postdoctoral studies at the South Australian Museum, Adelaide (2005) and Macquarie University (2006) before his appointment as a Lecturer at UNE in 2007. His main research interests include Cambrian faunas from East Gondwana, especially the Emu Bay Shale Konservat-Lagerstätte of South Australia. He has served as Secretary of the Association of Australasian Palaeontologists (AAP; 2006-2010), is currently a corresponding member of the International Subcommission on Cambrian Stratigraphy, and serves on the editorial boards of the peer-reviewed journals Alcheringa, AAP Memoirs and Zootaxa. He was recently awarded the 2016 Anton Hales Medal by the Australian Academy of Science.
Jim Jago is currently Adjunct Professor within the School of Natural and Built Environments, Mawson Lakes Campus, University of South Australia. Jim joined the South Australian Institute of Technology in 1971 and has continued at SAIT/University of South Australia. He is an Honorary Research Associate with the South Australian Museum. His main research interests are in Cambrian biostratigraphy, particularly of Tasmania, South Australia and Antarctica, and in the stratigraphy and sedimentology of the Cambrian of South Australia. He is a voting member of the Cambrian Subcommission.
Sarah M. Jacquet is a PhD student in the Department of Biological Sciences, Macquarie University in Sydney, Australia. She graduated with a BSc. (majoring in Palaeobiology) with Honours (2012) from Macquarie University. Her honours project focused on shelly fossil assemblages, palaeoenvironments and faunal dynamics of lower Cambrian carbonates from the north-east Flinders Ranges, South Australia. Her doctorate research now aims to better understand the early evolution and radiation of the Mollusca from the lower Cambrian of East Gondwana. This broad focus is channelled into various fields of interest including taxonomy, biostratigraphy, taphonomy and early ontogeny of ancestral macro- and micromolluscs.
Christian B. Skovsted is Senior Curator of invertebrate palaeontology at the Swedish Museum of Natural History, Stockholm, Sweden. From 2014 he also serves as Editor of *GFF*, the scientific journal of the Geological Society of Sweden. He received his PhD from Uppsala University in 2004 with a thesis concerning the Early Cambrian fauna of Small Shelly Fossils (SSF) from North East Greenland. Since then he has expanded his work to include Cambrian SSF faunas from all parts of the globe. In recent years he has mainly concentrated on the scleritome structure and taxonomy of the problematic *tommotiids,* a group of multi-plated fossils which have turned out to be closely related to brachiopods.
Timothy P. Topper is a postdoctoral researcher at the Swedish Museum of Natural History, Stockholm, Sweden. His interests are devoted to unravelling the events surrounding one of the most profound phases of evolutionary change in the history of life on Earth, the Cambrian Explosion. He studied Geology and Palaeontology at Macquarie University and obtained his PhD in 2010 at Macquarie University; a thesis focused on Cambrian shelly faunas of South Australia. Since then his research has expanded to include fossil assemblages from Sweden, Denmark, Greenland and North America. Recently his focus is directed towards understanding the palaeoecology of the brachiopods in the Burgess Shale Lagerstätte. Soon he will relocate to Durham University where his work will lead him to the Cambrian deposits of North Greenland.
Glenn A. Brock is an Associate Professor of Palaeobiology in the Department of Biological Sciences, Macquarie University, New South Wales, Australia. His interdisciplinary research program focuses on detailed exploration of the Cambrian Radiation of animal life which heralds the emergence and rapid diversification of the major animal body plans and the birth of animal-based ecosystems. He has served as Honorary Editor (1996-2000) of Alcheringa, the Australasian journal of Palaeontology and President (2007-2010) of the Australasian Association of Palaeontologists (AAP). Internationally, he has been a visiting Scholar/Professor at the Institute of Advanced Studies, Durham University, UK and the Department of Earth Sciences, Uppsala University Sweden. He is a corresponding member of the International Subcommission on Cambrian Stratigraphy, and has been part of the organising committee of major palaeobiological congresses – including co-chairing the 1st International Palaeontological Congress in Sydney (2002).