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The Ediacara Member, South Australia: Lithofacies and palaeoenvironments of the Ediacara biota

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ABSTRACT

The Ediacara Member of the Rawnsley Quartzite in the Flinders Ranges (South Australia) has undergone considerable investigation due to its placement within the package of terminal Ediacaran sediments in the region and as the host sediments of the Ediacara biota fossils. A focus on palaeoenvironment reconstruction and taphonomy has seen a succession of lithofacies models presented. These have evolved with the expansion of recognised Ediacara biota localities and prevailing palaeontological methodologies. Much of the recent descriptive lithofacies work has focused on the Nilpena fossil site in the west of the Flinders Ranges. This location is particularly fossil-rich but does not represent a "typical" section through the Ediacara Member. The Ediacara Member elsewhere in the region contains up to six parasequences with total thicknesses varying from ten to 260 m. With the exclusion of the Ikara-Chace Range region, the majority of studied locations external to Nilpena do not show clear evidence for significant (canyon-scale), intra-member erosional features. In this study we review existing facies models for the Ediacara Member and compile a "best-fit" revised facies model by incorporating the modern facies interpretations (largely based at Nilpena) and previous basin-wide observations, models and stratigraphic sections. The revised model is assessed against a series of newly measured stratigraphic sections from across the basin. We propose the division of the wave-base facies into two facies, representative of the upper and lower storm wave-base environments respectively and the re-inclusion of a facies representative of a shoreface palaeoenvironment. Additional characters and identifiers for the facies have been incorporated to aid field identification, as the ability to identify facies of fossil-bearing isolated hand-specimens can allow fossils found on scree slopes to be traced back to source beds. Likewise, palaeoenvironmental interpretations are critical to the reconstruction of Ediacara biota habitat and preservational environments.

1. Introduction

1.1. Background

The Adelaide Rift Complex in South Australia is a north-south oriented fold belt deposited as a series of rifting cycles from the early Neoproterozoic until the Middle Cambrian (Preiss, 2000). The terminal Ediacaran and basal Cambrian sediments are well exposed in often continuous section throughout the Flinders Ranges region and provide an excellent opportunity to study the palaeontological and sedimentological record for the evolution of macroscopic life. This is well demonstrated by the naming of the Ediacaran Period (Fig. 1) after the initial site of Neoproterozoic fossil discovery in the region (Ediacara Hills) and designation of the basal Ediacaran Global Boundary Stratotype Section and Point at the base of the Nuccaleena Formation. (Knoll et al., 2006; Jenkins, 2007; Narbonne et al., 2012).

The Ediacara biota represent some of the earliest, complex life on Earth and pre-date the Cambrian radiation of animals. They were predominantly soft-bodied organisms and body plans include a range of enigmatic forms. Sessile taxa include frondose organisms such as the early eumetazoan *Arborea* (Dunn et al., 2019) and the tri-radially symmetrical *Tribrachidium* (Hall et al., 2018). Motile taxa most likely included *Dickinsonia* (Evans et al., 2019) and South Australia's state fossil emblem *Spriggina*. In South Australia, communities of these organisms are preserved within the Ediacara Member, often *in situ* over square-metre bedding surfaces at a

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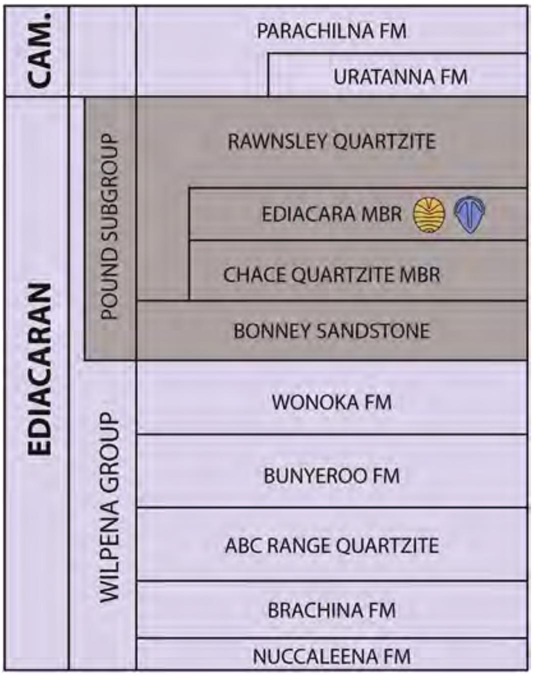

Fig. 1. Simplified Ediacaran and basal Cambrian (CAM.) stratigraphy of the central Flinders Ranges, South Australia.

number of fossil localities (Droser et al., 2017).

Due to the *in situ* preservation mode of the majority of fossils, a significant research focus has been on population and community-level palaeoecology. Such studies have been used to demonstrate community dynamics (Evans et al., 2018), response to environment (Paterson et al., 2017) and response to environmental disturbance (Reid et al., 2017). Palaeoecology studies focussing on the understanding of life habits and habitats of the Edicara biota require a thorough understanding of the palaeoenvironments in which the *in situ* communities are preserved.

Ediacara Member fossil sites are spread across a 20,000 km^2 region with a basin-parallel strike length of approximately 250 km. Despite this, recent work has focused on the Nilpena fossil site (Fig. 2; but see also Gehling, 1983, 2000) as it offers an unparalleled working laboratory for the study of Ediacaran palaeobiology and palaeoecology (see Droser et al., 2019). Included in this recent work have been revisions of the sedimentary lithofacies models for the Ediacara Member based primarily on the Nilpena location. This narrow focus for revisions of the sedimentological description of the Ediacara Member raises the issue of how representative the Nilpena site is of the broader basin. As a primary use of the Ediacara Member lithofacies models is to constrain the global life habitats for the Ediacara biota it is highly relevant to understand their occurrence and palaeoenvironments across the full breadth of the Adelaide Rift Complex basin. This contribution builds upon the basin-wide work of Gehling (1983, 2000) with a series of new measured stratigraphic sections to assess the most recent Ediacara Member lithofacies models in the context of the basin-wide sections. This allows us to provide a descriptive framework for mapping and logging of the Ediacara Member across the basin and subsequently will allow more representative and globally applicable palaeoenvironment characterisation for the Ediacara biota.

1.2. Regional setting and the Ediacaran preservational window

Sedimentary rocks of the Adelaide Rift Complex in South Australia preserve a near-continuous section throughout the late Neoproterozoic and early Cambrian. The base of the terminal Neoproterozoic Wilpena Group (Fig. 1) within the Adelaide Rift Complex is marked by the Nuccaleena Formation, a “cap carbonate” deposit which signals the transition from the last of the Cryogenian global glaciations into a succession defined by fluvial and shallow marine sedimentation. The Pound Subgroup (Fig. 1) comprises the red siliciclastic sediments of the Bonney Sandstone, disconformably overlain by the cleaner arenites and quartzites of the Rawnsley Quartzite. In turn, the Rawnsley Quartzite comprises the sand flat-to-supratidal Chace Quartzite Member, which is disconformably overlain by the fossiliferous shallow marine sediments of the Ediacara Member (Gehling, 2000). This in turn grades back into the sand flat-to-supratidal environment facies of the unnamed upper Rawnsley Quartzite unit. In the central Flinders Ranges the contact with the overlying Cambrian-aged Parachilna Formation is an obvious disconformity marked by vertical burrows of *Diplocraterion* (Jago et al., 2018). In the northern Flinders Ranges, the Ediacaran-Cambrian boundary is marked by the basal quartzite unit of the Uratanna Formation and the shallow channels and scours it cuts into the underlying upper Rawnsley Quartzite.

Although precise geochronological constraints do not exist for the Ediacara Member, biogeographic correlation with similar fossil assemblages in Russia for which reliable uranium-lead zircon geochronology exists place the likely age of the Ediacara Member at approximately 555 Ma (Martin et al., 2000). The richly fossiliferous horizons that mark the Ediacara Member signify a preservational window unlike any seen elsewhere in the fossil record. While Ediacaran fossils are known to occur at approximately 40 localities worldwide, and span a range of taxa and preservational styles, the Ediacara Member records the broadest morphological and taxonomic diversity (Droser et al., 2017). Ediacaran fossils are generally

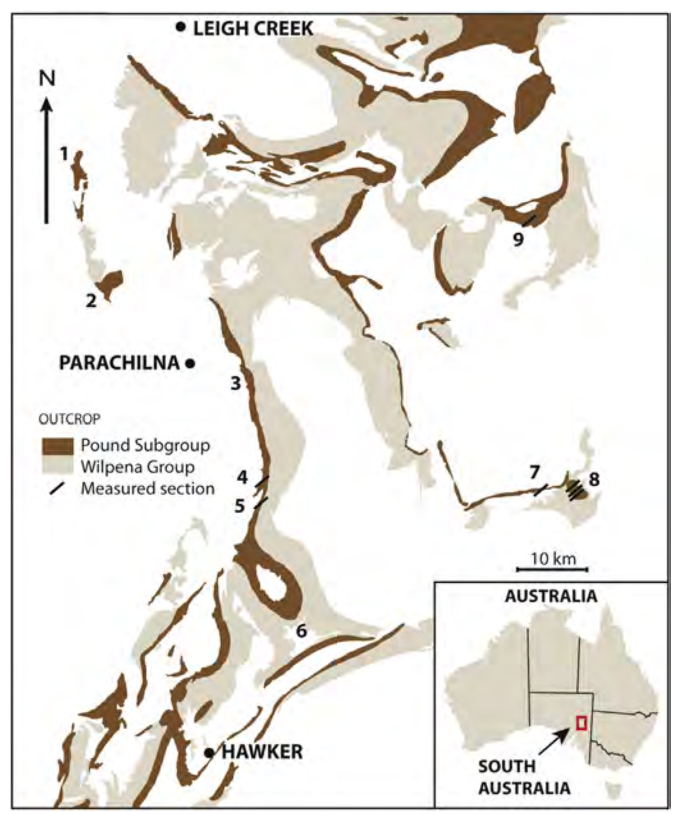

Fig. 2. Pound Subgroup outcrop of the Flinders Ranges region, South Australia. Sites discussed in this study: 1, Ediacara; 2, Nilpena; 3, Crisp Gorge; 4, Brachina Gorge; 5, Bunyeroo Gorge; 6, Ikara-Chace Range region; 7, Tooth Nob; 8, Reaphook Hill; 9, Mulga View.

recognised as members of one of three associations: the Avalon, White Sea or Nama (Narbonne, 2005; Waggoner, 1999, 2003). Interpretations for these assemblages have considered temporal, biogeographic and ecological/environmental factors to explain the variability, and while some sites, such as Mistaken Point (Newfoundland), represent unrivalled examples of a single assemblage, the Ediacara Member is now recognised for containing elements of all three assemblages (Gehling and Droser, 2013). This strongly supports the notion that these assemblages are environmentally controlled and represent ecological units, rather than temporal turnover or biogeographic zonation, highlighting the need for a greater emphasis on these physical environments and the relationships that the Ediacara biota had with them (Grazhdankin, 2004; Reid et al., 2018).

Putative body fossils have been reported from lower stratigraphic intervals within the late Precambrian succession of South Australia. These include a frond-like fossil from the terminal Cryogenian Seacliff Sandstone (Dyson, 1985; however see Jenkins, 1986), and examples of *Palaeopascichnus* from the Wonoka Formation (Haines, 2000). Other Australian locations, most notably the Arumbera Sandstone and Central Mount Stuart Formation in the Northern Territory have produced Ediacara-like fossils including *Arumberia banksi* (Gehling, 1999; Glaessner and Walter, 1975), *Skinnera brooksi* and *Hallidaya brueri* (Jenkins, 1981; Wade, 1969) in terminal Neoproterozoic deposits. However, such occurrences to date have been rare, and serve to highlight the exceptional preservational conditions that were present in the Ediacara Member.

Distinctive "Ediacara-style" preservation characterises the unit. The prevailing 'death mask' hypothesis was proposed by Gehling (1999) and requires the formation of a microbially-induced crust as means of preservation. After burial by sediment, the precipitation of iron minerals by iron and sulphate-reducing bacteria, presumed to be present in the pre-existing microbial mat structure (both above the organism and on the surrounding mat surface), formed a veneer-like, pyrite death-mask. This protected the soft-bodied organism from total compaction, and likely formed a parting surface along which lithified beds could split (Darroch et al., 2012; Gehling, 1999). This theory is supported by the fact that negative fossil impressions on bed soles are common and appear to be replacement casts infilled by sediment from below the organism, resulting in a negative hyporelief impression in the sole of the overlying bed and a counterpart, positive relief cast on the underlying bed (Glaessner and Wade, 1966). To date, however, there has been little supporting petrological evidence of pyritization from the Ediacara Member to support the notion that authigenic pyrite was extensive enough to be responsible for the quality and consistency of preservation over such large surface areas (but see Liu et al., 2019). A recent hypothesis proposed by Tarhan et al. (2016) suggests that preservation instead resulted from the rapid precipitation of silica cements from silica-saturated ocean waters. This model proposes that post-burial, organisms and the accompanying microbial mat were molded and cemented by the rapid nucleation of a silica film, prior to the significant decay of organic material. In a taphonomic window that closed with the appearance of significant silica biomineralisers, this process allowed for rapid preservation and the characteristic, finely-detailed fossils preserved in the Ediacara Member. Irrespective of the process, Ediacara-style preservation has permitted high-quality preservation throughout a range of palaeoenvironments, and of both *in situ* communities and transported body fossils (Gehling and Droser, 2013). The Ediacara Member therefore offers both a temporally and spatially restricted window into the world of the Ediacaran seafloor, one that closed rapidly with the onset of Phanerozoic bioturbation and consequently the disappearance of widespread microbial matgrounds (Bottjer et al., 2000; Callow and Brasier, 2009).

1.3. Depositional environment interpretations of the Ediacara Member

Several hypotheses have been offered to describe the depositional settings of the Ediacara Member and the preservational environments of the Ediacara biota at Flinders Ranges sites. Sprigg (1947, 1948) proposed a thanatocoenosis model for the Ediacara biota, consisting of pelagic organisms stranded, exposed and buried with the tide on the strandline or in tidal-flat environments. Conversely, Wade (1969, 1970) suggested that deposition and fossilisation occurred underwater in zones of reduced wave action sheltered behind rising diapirs. Goldring and Curnow (1967) offered three potential environments for deposition – offshore neritic, lagoonal and beach – but broadly dismissed the latter based on a lack of evidence to support the subaerial exposure of either the preserving sediments or the organisms themselves. This study argued for a partially-restricted bay environment to explain the reduction in hydrodynamic energy interpreted for the interval of fossiliferous sediment deposition, although not restricted to the extent of a lagoon. In contrast, Jenkins et al. (1983) favoured a model of lagoonal deposition, citing evidence for barrier wash-over deposits and several sedimentary characteristics suggestive of intertidal deposition, with organisms stranded and buried subaerialy.

A non-marine setting for the Ediacara Member (and consequently terrestrial habitat for the Ediacara biota) has also been proposed (Retallack, 2012, 2013). This model is based on the interpretation of Ediacara Member sediments as palaeosols and incorporates loess/aeolian and lagoonal facies based upon the interpretation of certain features including soil nodules and sand crystals. This hypothesis has been broadly disputed due to the multitude of sedimentary characteristics that support the standing interpretation of the Ediacara Member as a marine environment (see Callow et al., 2013; Tarhan et al., 2017; Gehling, 2000). The functional morphology of a number of Ediacaran taxa also strongly suggests a marine life habitat for these organisms (Xiao et al., 2013).

The concept and significance of underwater, *in situ* preservation was adopted by Gehling (1999, 2000), and accompanied the death mask hypothesis. Features including shrinkage cracks, which had previously been interpreted as evidence of subaerial exposure in tidal flat environments, were reinterpreted as sub-aqueous synaeresis cracks, and most likely related to the decay and contraction of a pre-existing microbial mat (Gehling, 2000; Gehling and Droser, 2012; Harazim et al., 2013; Plummer and Gostin, 1981). As well as introducing deeper water environments to the Ediacara Member facies arrangement, the notion of *in situ* preservation has helped make way for the application of a revised palaeoecological methodology to South Australian Ediacaran fossil surfaces (see Coutts et al., 2016; Droser and Gehling, 2015; Droser et al., 2006; Evans et al., 2018; Reid et al., 2017).

1.4. Lithofacies models

The Pound Quartzite was formalised by Forbes (1971) using a two-member nomenclature that designated the lower, predominantly-red sandstone unit as the Bonney Sandstone Member and the overlying white sandstone unit as the Rawnsley Quartzite Member. These were later amended by Jenkins (1975) to formations, thereby elevating the Pound Quartzite to the Pound Subgroup.

The unit now recognised as the Ediacara Member was first described by Sprigg (1947) as the "richly fossiliferous horizon" within the Pound Quartzite of the Ediacara Hills, on the western margin of the Flinders Ranges. Further exploration of the geographic range of the fossil beds was made by Wade (1970) who recognised the significance of the fossiliferous horizon as a relatively homogeneous stratigraphic interval within the broader Pound Quartzite across a range of exposures in the Flinders Ranges region. This unit was formalised as the Ediacara Member by Jenkins (1975), marking the middle portion of the Rawnsley Quartzite. Further amendments and a stratigraphic expansion were made by Gehling (2000) with the inclusion of additional lithofacies noted from previously unexplored sections at locations including Wilpena Pound and the Chace Range. The underlying Chace Quartzite Member was formalised as the lowest unit of the Rawnsley Quartzite by Reid and Preiss (1999).

Models describing the lithologic characteristics of Ediacara Member sediments have evolved with both the formalization of the sequence and the continued exploration of Pound Subgroup exposure throughout the Flinders Ranges (Fig. 3). The earliest facies model was proposed by Goldring and Curnow (1967), based on four measured sections and pre-existing drill core samples from the area south of Mt James in the Ediacara Hills. Their model defined three principal facies of the Rawnsley Quartzite (Fig. 3; Table 1).

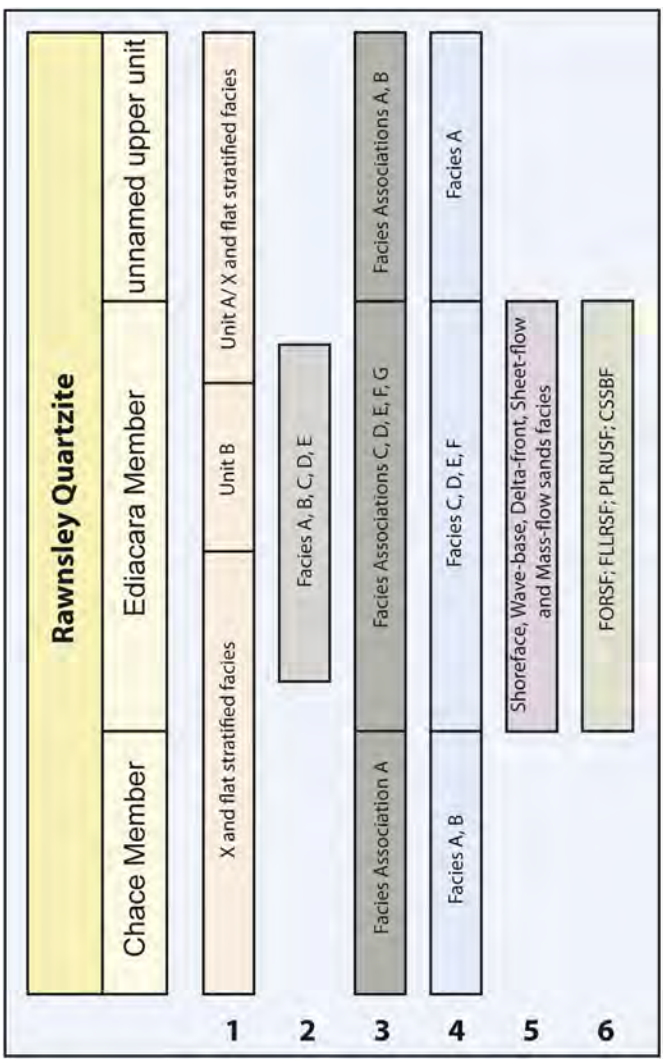

Fig. 3. Stratigraphic extent of previous Rawnsley Quartzite facies models. Note the stratigraphic extent of "Ediacara Member" facies has increased, particularly with the expansion of the Ediacara Member by Gehling (2000). Models: 1, Goldring and Curnow (1967); 2, Jenkins et al. (1983); 3, Gehling (2000); 4, Gehling and Droser (2012); 5, Gehling and Droser (2013); 6, Tarhan et al. (2017). For details of these models see also Table 1. ORSF = Oscillation-Rippled Sandstone Facies; FLLRSF = Flat-Laminated to Linguoid-Rippled Sandstone Facies; PLRUSF = Planar-Laminated and Rip-Up Sandstone Facies; CSSBF = Channelized Sandstone and Sand-Breccia Facies.

"Unit A" consists primarily of moderately to well-sorted orthoquartzites, and often massive, channel-fill sediments. "Unit B" is defined as the fossiliferous horizon comprising a mix of sandstones, siltstones and shales, some with clay or silty bed partings and undulose, rippled bed tops. This facies was interpreted as a relatively shallow, localised environment of lowered energy that was bounded gradationally above and below by the third facies, the offshore "cross stratified and flat stratified facies", comprising feldspathic sands characterised by trough cross-bedding and linguoid rippled bed tops. Although Unit B is presented as the principal fossiliferous horizon, it is noted that several specimens of *Pteridinium* were also identified from the cross stratified and flat stratified facies previously by Glaessner and Wade (1966). Located just below the main fossiliferous horizon, this observation serves as perhaps a precursor to the expanded range of Ediacara fossil preservation that was to be revealed by future exploration.

In contrast, Jenkins et al. (1983) defined a lithofacies model comprising five facies, broadly confined to the Ediacara Member (Fig. 3; Table 1). This incorporated an expanded number of study sites, including several measured sections on the western margin of the Flinders Ranges. Despite increasing the study area, the Ediacara Member was found to continue to crop out as the consistently heterolithic, fossiliferous portion of the lower Rawnsley Quartzite. Jenkins et al. (1983) described it as comprising repeated units of siltstones and medium to thickly-bedded sandstones featuring consistent lithological characteristics such as wave or current rippled beds, concretionary structures and clay galls, as well as the Ediacara biota itself. The five facies defined by Jenkins et al. (1983) were interpreted as spanning a range of shallow marine and intertidal environments, deposited during a phase of marine transgression and representative of a barrier bar and tidal lagoon complex, extending approximately 200 km parallel to the shallow Ediacaran coastline.

Following the lithofacies model developed by Gehling (1971, 1983), Gehling (2000) presented an expanded, detailed description of the facies associations based on analysis of a range of previously unstudied sections from across the Flinders Ranges, and presented new interpretations for the environments preserving the Ediacara biota (Fig. 3; Table 1). This included definition of the "Rawnsley sequence" as encompassing the Ediacara Member and the unnamed upper Rawnsley Quartzite unit as distinct from the underlying Chace Quartzite Member. This sequence was interpreted as a single depositional episode, bounded by a lower erosional contact with either the Chace Quartzite Member or, in some instances, the Bonney Sandstone below. Gehling (2000) outlined a total of seven facies associations; two of these incorporated the upper, unnamed Rawnsley Quartzite unit and underlying Chace Quartzite Member, with the remaining five describing the Ediacara Member. These broadly describe the Ediacara Member as an interval of fair weather-to storm-wave base and delta slope deposition, bounded vertically by coarser wave- and tide-reworked sediments indicative of a shallow, progradational setting.

With a renewed focus on the National Heritage-listed Nilpena fossil site, the work of Gehling and Droser (2012) placed a greater emphasis on environmental interpretations of the Ediacara Member and sought to develop those previously presented in Gehling (2000). The death-mask hypothesis introduced by Gehling (1999), which presented the concept of a microbially-bound mat substrate, was utilised to define six facies for the Rawnsley Quartzite (Table 1). These facies are based on depth-related associations of taxa assemblages and include specific microbial mat features characteristic of each zone, ranging from supratidal to below storm-wave base.

This model was subsequently narrowed to focus solely on the Ediacara Member (Gehling and Droser, 2013), and updated by condensing the six facies of Gehling and Droser (2012) into three

Table 1
Outlining key interpretive and descriptive facies characteristics of major models developed for the Rawnsley Quartzite and Ediacara Member.

Ediacara Member major lithofacies models								Depositional environment
Goldring and Curnow (1967)	**Unit A** Channel fill sediments incorporating massive, indurated orthoquartzite with undulose bed set soles and intraformational conglomerates.		**Unit B** Repeating units of lower, fossiliferous beds comprising thinly-bedded sandstones, silts and shales with interbedded silt partings and sand lenses grading into thicker, unfossiliferous beds of channel fill sediments and beds sets with well-developed ripple marks.			**Cross stratified and flat stratified facies** Fine-to-medium grained feldspathic sandstone exhibiting cross stratification and rare asymmetric ripples.		Sub-beach, offshore neritic zone of lowered hydrodynamic energy; restricted bay
Jenkins et al. (1983)	**Facies A** Unbedded-to-thinly bedded laminated, micaceous siltstones and fine grained quartz arenite displaying lenses or thin beds of medium-to-coarse grained arenite. Fossils rare.	**Facies B** Very thinly bedded or laminated micaceous siltstones and fine grained arenite, with thin, flaggy lenses of medium-to-coarse grained arenite. Commonly fossiliferous.	**Facies C** Flaggy or wavy bedded fine-to-medium grained orthoquartzite with occasional silty partings and oscillation or interference ripples. Restricted intervals contain mud cracks, clay galls, flat-top ripples and carbonate cemented beds. Fossiliferous.		**Facies D** Flaggy-to-thickly bedded, medium-to-coarse grained quartz arenite with silty bed partings. Fossils range from rare to abundant.	**Facies E** Thin-to-thickly bedded, massive quartz arenite forming sheet sands or lenticular, channel fills. Clay galls and concretionary structures approximating sand crystals. Sparingly fossiliferous.		Intertidal; barrier bar and tidal lagoon system
Gehling (2000)	**Facies Association A** Medium-to-coarse grained cross stratified feldspathic sandstone grading up into wavy-bedded with 'peetee' laminations. Sand rosettes interlayered with peetee beds.	**Facies Association B** Flat and cross stratified, medium-to-coarse grained clean sandstone marked by channellised and lenticular beds. Large cross stratified bed sets grade up into flat beds with current lineations and some ripple marks.	**Facies Association C** Massive channelized sandstone comprising very thick beds with little or no lamination. Medium-to-coarse grained. Basal brecciated units containing angular clasts of channel wall material.	**Facies Association D** Medium-to-coarse grained, massive amalgamated sandstone with deformed and foundered bed contacts. Large-scale ball and pillow structures and detached sand-balls in underlying silt beds common.	**Facies Association E** Laminated siltstone and fine-grained sandstone, commonly exhibiting thin sandy stringers with micro-cross laminations. South-eastern sections include 10–15 cm cycles of micro-turbidite units. Sparingly fossiliferous.	**Facies Association F** Upward thickening and coarsening, fossiliferous sandstone with interbedded siltstone. Wave and current rippled bed-top forms common. Sandstone beds are lenticular to continuous with smooth bed soles, either forming clean bed partings or containing silty interbed layers. Fossiliferous.	**Facies Association G** Medium-to-coarse grained feldspathic sandstone with thick beds of trough cross stratification. Flattened or spherical siliceous, white concretions are distributed throughout the unit.	Fossils deposited on delta slopes between storm and fair-weather wave base.
Gehling and Droser (2012) Gehling and Droser (2013)	**Facies A** Supratidal **Shoreface Sands** (?) Fossiliferous.	**Facies B** Intratidal **Wave-base Sands** Thin-bedded sandstone with rippled bed tops. Fossiliferous	**Facies C** Lower Shoreface **Delta-front Sands** Upward coarsening and thickening sets of laminated, silty sandstone. Fossiliferous	**Facies D** Fair-weather Wavebase **Sheet-flow Sands** Laterally continuous sandstone event beds with tool marks and planar lamination. Fossiliferous	**Facies E** Storm Wavebase **Mass-flow Sands** Very thickly-bedded lenticular sandstone with large scale ball and pillow structures grading into massive beds with exhibiting dewatering structures and scoured bed bases. Fossiliferous	**Facies F** Below Storm Wavebase		Shallow marine/deltaic succession Shallow marine
Tarhan et al. (2017)	**Oscillation-Rippled Sandstone Facies** Symmetric rippled, thin bedded, fine to coarse grained feldspathic quartz sandstone		**Flat-Laminated to Linguoid-Rippled Sandstone Facies** Upward coarsening and thickening sets; linguoid rippled; red silty sandstone	**Planar-Laminated and Rip-Up Sandstone Facies** Fine grained, planar laminated sandstone with tool marks and erosive bases	**Channelized Sandstone and Sand-Breccia Facies** Discontinuous, medium to coarse grained sandstone; ballad n pillow structures grading into massive beds; dewatering structures			Wave base/deltaic succession; below wave base including canyon fill
This study	**Concretionary Sands** Medium to coarse grained, medium to thick bedded arenite; asymmetric ripples and siliceous concretions		**Oscillation Ripple Sands** Thick laminate to thin bedded; medium to coarse grained arenite with symmetric or asymmetric ripples	**Combined Flow Ripple Sands** Hummocky rippled; thin to medium bedded, medium grained arenite plus shim layers.	**Current Ripple Sands** Thick laminate to thin bedded, moderately-to-poorly sorted arenite with low angle, discontinuous ripples	**Current Lineated Sands** Fine to medium grained arenite; current lineations and rare tool marks	**Channelised and Slumped Sands** Very thin to very thick bedded, medium to coarse grained arenite with amalgamated contacts; abundant soft sediment deformation structures and rosette structures	Shallow marine; shoreface to below wave base including lower deltaic; sediment gravity flow events

facies spanning shore-face sands to the deeper water delta-front sands (Fig. 3; Table 1). Also incorporated were two novel fossiliferous facies based on new fossil finds from Nilpena (see also Gehling, 2000). These facies, representing a package of sheet-flow, planar laminated sands and massive, slumped sandstones served to significantly expand the environmental range of the Ediacara biota. Several of these facies have subsequently been reviewed by Tarhan et al. (2017), but with a focus on descriptive, rather than interpretive, sedimentology (Fig. 3; Table 1). Again focussing on Nilpena, this model removes the Shoreface Sands facies of Gehling and Droser (2013), while renaming the remaining four facies to reflect the sedimentary features exclusive to each in outcrop. Interpretations place these facies in a zone extending from wave-base environments exhibiting oscillatory and combined-flow regimes to deeper-water environments of unidirectional or mass flow events (Tarhan et al., 2017).

2. Materials and methods

The update to the lithofacies model presented here is based on preceding Ediacara Member facies models from work focused on Nilpena (Gehling and Droser, 2012, 2013; Tarhan et al., 2017) and the basin-wide work of Gehling (2000) and has been applied to seven stratigraphic sections. A range of sites have been included due to the heterogeneous expression and extensive outcrop variation of the Ediacara Member. The measured sites are Bunyeroo Gorge and Brachina Gorge (in the Heysen Range), Mulga View, Tooth Nob and three sections in the Reaphook Hill area (Figs. 1 and 3). The summary of key facies identifiers (Table 2) is based on these sections.

Stratigraphic sections were measured at Brachina Gorge, Bunyeroo Gorge, Reaphook Hill, Tooth Nob and Mulga View. The sedimentological features of particular interest included grain size, sorting, composition and colour, as well as average bed thickness. Sedimentary structures recorded include bedforms such as ripples, cross laminations and cross bedding as well as the presence of lenses, and scour and fill channels. Secondary structures noted include siliceous concretionary structures and post-mineral rosettes. Units were assigned to lithofacies based on their lithological composition and identifiable sedimentary structures.

3. Results

3.1. Revised Ediacara Member lithofacies

Based upon our review of published and unpublished stratigraphic sections (e.g. Gehling, 1971) and new field observations, we suggest the Ediacara Member is best characterised by six lithofacies. These are representative of six shallow marine palaeoenvironments, broadly reflecting an environmental transition from a shoreface environment to offshore, below wave-base environments. All newly measured stratigraphic sections are presented in Fig. 3 and within-section facies relationships in Fig. 4. Significant variability is evident across a transect of sites, with Ediacara Member vertical thickness ranging from approximately 68 m at Bunyeroo Gorge to less than 10 m at Reaphook Hill sites. The Oscillation-Rippled Sandstone facies (Tarhan et al., 2017) has been revised and split into two lithofacies based on field data collected from a number of sites. We revise this lithofacies to Oscillation Ripple Sands facies, comprising characteristic crested or symmetrical ripples and thin, flaggy beds, and the Combined Flow Rippled Sands facies, which has hummocky or combined-flow ripples, finer grain size and thicker beds on average. We also include the Concretionary Sands facies, which does not crop out in all measured sections, but where present represents the coarse-grained and thickly-bedded sediments that sit just below the contact with the upper Rawnsley Quartzite. All lithofacies are found to be fossiliferous.

3.1.1. Concretionary Sands facies (CS)

The Concretionary Sands facies (CS) comprises thick (up to 25 m) packages of medium to coarse grained, well-sorted white quartz arenite or orthoquartzite. Generally, this facies is medium to very thickly bedded and planar, parallel laminated. Intervals may contain asymmetric-rippled bed-tops and low-angle or trough cross bedding, particularly in less thickly-bedded sections. In exposures including Brachina Gorge, Bunyeroo Gorge and the Chace Range, this facies commonly contains spherical to sub-spherical centimetre-scale, siliceous white concretions (Figs. 3 and 5). These are resistant marble-sized structures that either protrude from weathered bedding surfaces, or weather-out, leaving spherical cavities. In rare instances, concretions show some evidence (however weathered) of their former crystal structure (Fig. 6C). This facies is sparingly fossiliferous, with a near-total absence of body fossils compared to the remainder of Ediacara Member facies. Holdfast taxa are the most prevalent, with *Aspidella* preserved at a number of localities.

3.1.2. Oscillation Ripple Sands facies (ORS)

The Oscillation Ripple Sands facies (ORS) comprises the coarser-grained and flaggy-bedded portion of the Oscillation-Rippled Sand facies of Tarhan et al. (2017). It typically outcrops in bands less than 5 m thick, and commonly denotes a coarsening upwards and thinning of bed thickness from an underlying package of the

Table 2
Summary of key identifiers of Ediacara Member lithofacies.

Lithofacies	Defining structures	Bedform type	Common outcrop colour	Ave. bed thickness	Ave. grain size	Palaeoenvironment
Concretionary Sands	Asymmetric ripples; siliceous concretions	Wave ripples	White, orange	Medium-very thick bed	Medium- coarse	Shoreface
Oscillation Ripple Sands	Symmetric or asymmetric ripples	Wave ripples	White, pink	Thick laminate- thin bed	Medium- coarse	Fairweather wave base
Combined Flow Ripple Sands	Hummocky, blocky or rounded ripples	Combined wave and current ripples	White, maroon	Thin to medium bed, plus shims	Medium	Storm wave base
Current Ripple Sands	Low angle, discontinuous ripples	Current ripples	Maroon, khaki	Thick laminate- thin bed	Medium	Delta front- prodelta
Current Lineation Sands	Current lineations; scour marks; rip-up clasts	No ripples	White, grey	Thin- medium bed	Fine- medium	Grain flow events
Channelised and Slumped Sands	Soft sediment deformation, convolute contacts	Amalgamated beds and contacts	Maroon, white	Very thin- very thick bed	Medium-coarse	Mass sediment flow events

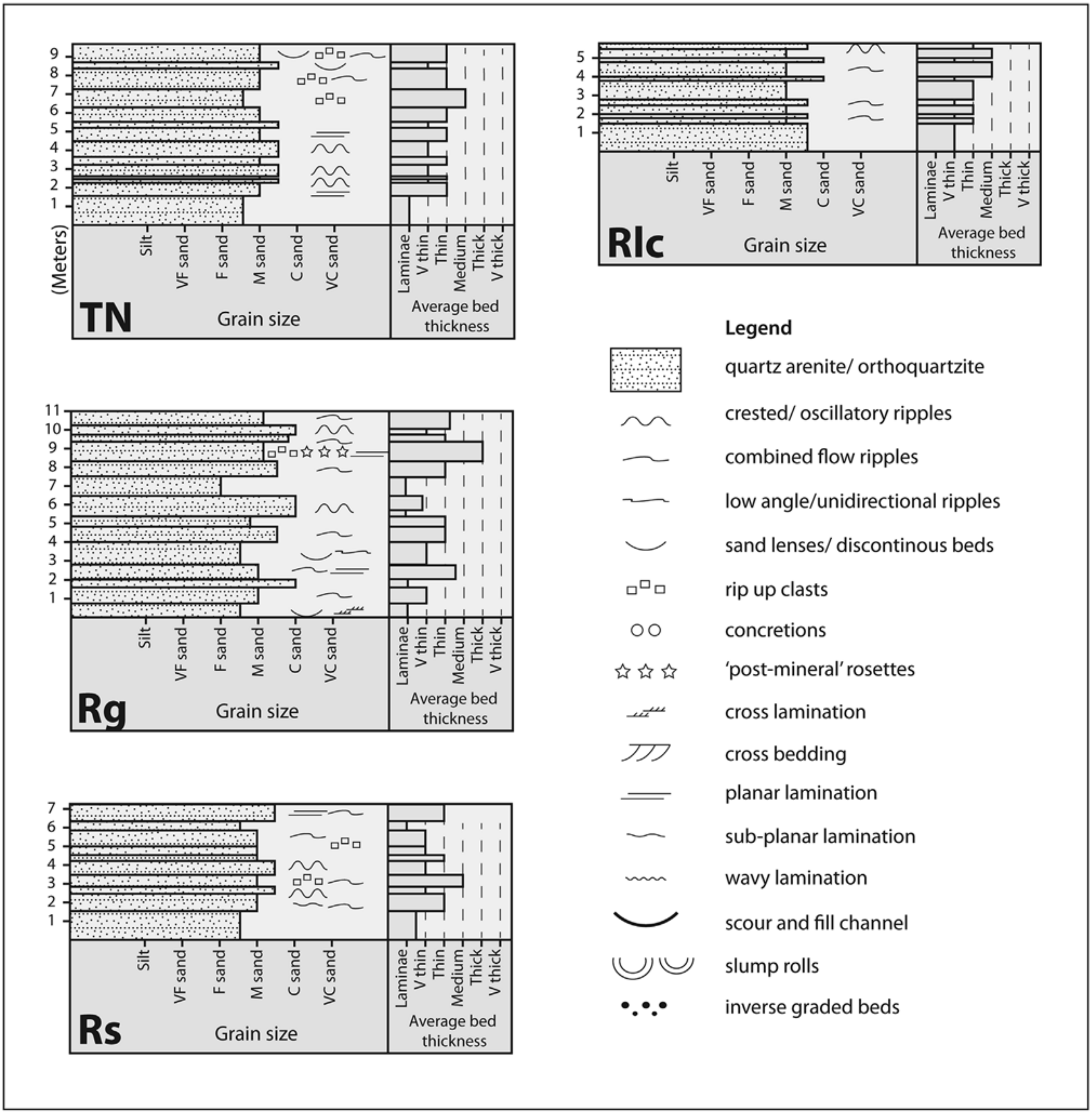

Fig. 4. Ediacara Member stratigraphic sections. TN, Tooth Nob; Rg, Reaphook gorge; Rs, Reaphook scholzite; Rlc, Reaphook little creek; BG, Bunyeroo Gorge; MV, Mulga View; BrG, Brachina Gorge.

Combined Flow Ripple Sands facies (CFRS). However, it is interbedded with the CFRS facies at some locations (Figs. 3 and 4). This facies comprises medium to coarse grained, well-sorted white arenites. Where weathering is less pronounced, it generally displays a ferruginous red or orange surface staining. Bed thickness is, on average, from thick laminated to thinly bedded, with thinner beds often wave-rippled or flaggy. Bed tops record high relief asymmetric to symmetric, often crested and bifurcated ripples. This facies is commonly fossiliferous, yielding *in situ* communities preserved on bed soles over large surface areas (for example Evans et al., 2017, 2018).

3.1.3. Combined Flow Ripple Sands facies (CFRS)

The CFRS is primarily a medium-grained, well-sorted, white arenite or orthoquartzite. On the southern margin of known outcrop of the Ediacara Member, at Devil's Peak, this facies is expressed as fine to medium-grained arenites. Ferruginous staining is common; beds often appear in outcrop as red or maroon in colour, and are typically thin to medium bedded with parallel, sub-planar laminations and rare cross-laminations. Bed tops preserve hummocky and undulose, rounded or blocky combined flow ripples. Laminate interbeds of fine to medium grain sandstone form parting laminations that are colloquially referred to as 'shim'. These laminae are commonly lenticular or discontinuous and crop out between the thicker sand beds in less weathered exposures. This facies is highly fossiliferous, recording an abundance of *in situ* taxa spanning a range of body plans. Fossiliferous bed sole surfaces are excavated to reveal semicontinuous to continuous surfaces of

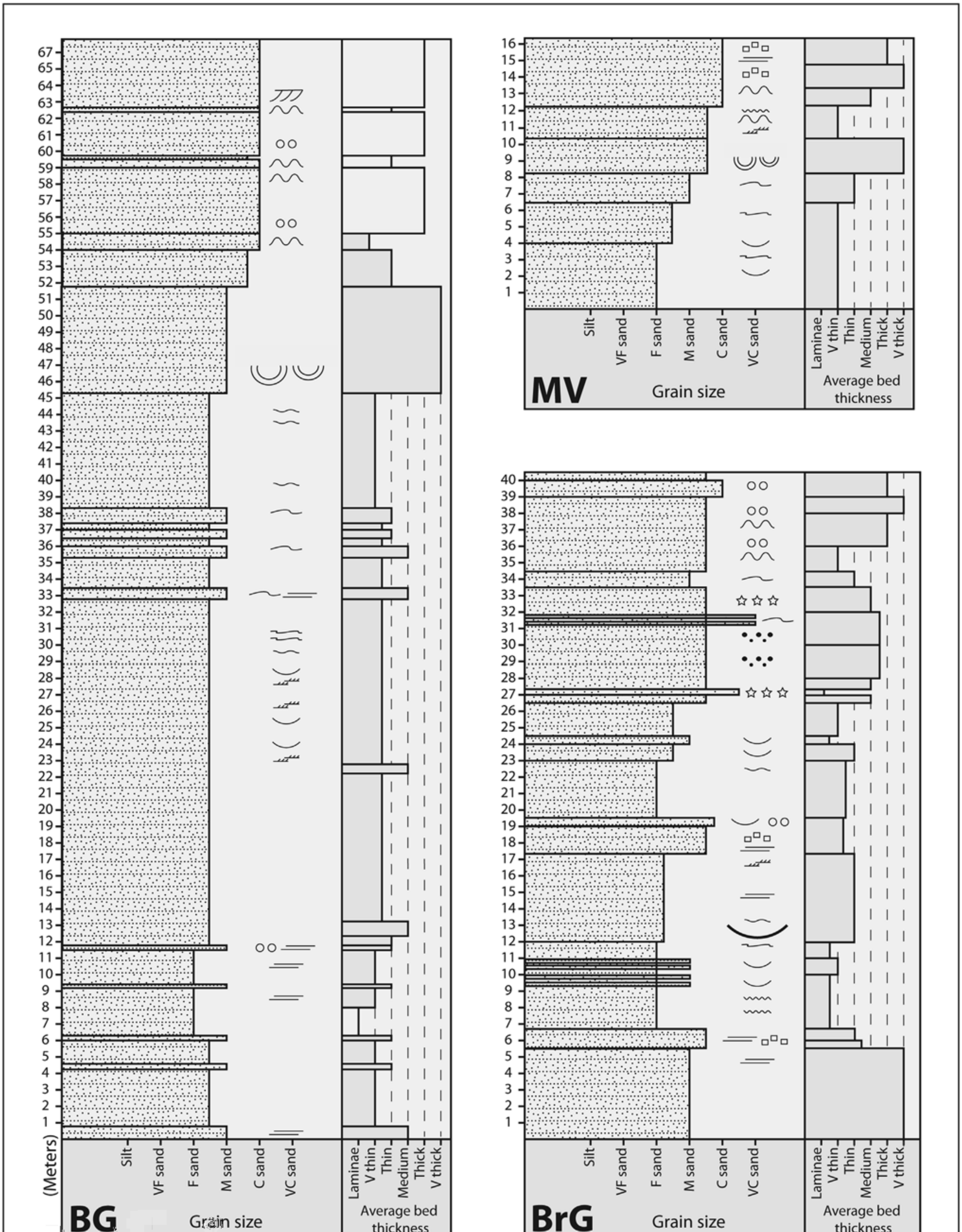

Fig. 4. (*continued*).

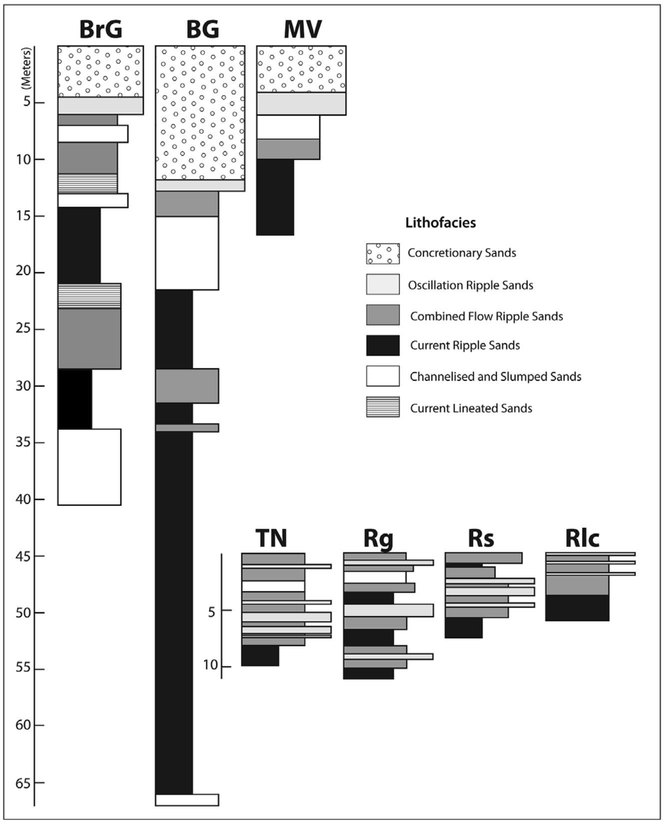

Fig. 5. Site-facies relationships of the Ediacara Member. BrG, Brachina Gorge; BG, Bunyeroo Gorge; MV, Mulga View; TN, Tooth Nob; Rg, Reaphook gorge; Rs, Reaphook scholzite; Rlc, Reaphook little creek. Top surfaces of each section represent the contact with the overlying upper Rawnsley Quartzite.

square-meter coverage of fossil communities (Reid et al., 2017).

3.1.4. *Current Ripple Sands facies (CRS)*

The Current Ripple Sands facies (CRS) comprises fine to medium-grained, poorly to well-sorted quartz arenite. It is commonly micaceous and often highly ferruginous, with maroon to purple-weathering in exposed outcrop. Where more recently exposed, shaly beds appear khaki coloured. This facies is relatively thinly bedded, commonly with thickly laminated to thin beds containing parallel to sub-planar wavy laminations. Bed surfaces may record low angle, unidirectional, continuous to lobate current ripples. At sites including Nilpena thick laminate to thin interbeds of medium grained, well sorted and clean sands interbed with the coarser material in discontinuous beds or lenses and contain cross laminations (Fig. 6). Specific horizons or sections can be relatively immature, coarse grained and poorly sorted, with very coarse, moderately well-rounded lithic clasts. Where fine to medium grained, it is commonly micaceous. This facies is commonly fossiliferous and records a range of *in situ* taxa preserved as bed sole impressions.

3.1.5. *Current Lineated Sands facies (CLS)*

The Current Lineated Sands facies (CLS) is white to grey weathering, well sorted quartz arenite or orthoquartzite. Grain size varies from fine to medium on the western margin of known outcrop at sites such as Nilpena and Ediacara, to medium or coarse grained in thicker sections through the Heysen Range. It is thin to medium and flat bedded, with a total absence of ripples or cross laminations. Bedding surfaces commonly record parting or current lineations, and more rarely, scour and flute casts. Rip-up clasts are common in discontinuous horizons, most notably on the tops of non-fossiliferous beds (Fig. 6). These commonly contain flat, rounded to sub-angular fine to medium grained sandstone clasts (Tarhan et al., 2017). However, rip-up clasts are also noted from all other facies, particularly at easterly sites, from both bed tops and bed bases. This facies is fossiliferous, with exposures at Nilpena yielding fine-grained surfaces preserving *in situ* communities (Hall et al., 2018; Paterson et al., 2017).

3.1.6. *Channelised and Slumped Sands facies (CSS)*

At localities including Nilpena and Bunyeroo Gorge and Brachina Gorge, the Channelised and Slumped Sands facies (CSS) forms the basal channel fill overlying the erosional contact of the Ediacara Member with the Chace Quartzite Member (Fig. 5). These erosional contacts represent decimetre-scale channels and regional kilometre-scale canyons that cut into the underlying Chace Member or, at Nilpena, into the Bonney Sandstone (Gehling and Droser, 2012). This facies is primarily medium to coarse grained, white to maroon weathering, moderately to well-sorted quartz arenite or orthoquartzite. Bed thickness is highly variable and ranges from very thin to very thick (up to 5 m thick), with internal bedding contacts commonly convoluted or amalgamated. Soft-sediment deformation is common and some outcrop-scale internal channelization is noted (Fig. 7). It is predominantly unlaminated, with minor planar laminations and occasional climbing ripple cross laminations (Gehling, 2000). Where the lower contact is with a package that is thinly bedded, finer grained sands such as the CRS, soft sediment deformation commonly involves scoured or convoluted bedding, ball and pillow structures or slump rolls (Fig. 7). Dewatering structures including dish and pillars are noted. At least one large scale (5 m diameter) slump and roll structure is noted at Bunyeroo Gorge. Secondary sedimentary structures resembling weathered out mineral rosettes are common at some sites (Fig. 7). These are present as hollow, centimetre-scale rosette structures distributed throughout a given bed and are noted from sites in the Heysen and Chace Ranges (Gehling, 2000). This facies is less fossiliferous than those recording *in situ* preservation in conjunction with a microbial mat substrate. Fossils in this facies are transported within sand beds, and are commonly distorted or torn (Fig. 7; see also Gehling and Droser, 2013).

3.2. *Regional variation of the Ediacara Member*

An isopach map of the Ediacara Member by Gehling (2000, Fig. 3) indicates two broad-scale northwest-southeast trending palaeovalleys and abundant, outcrop-scale channel incisions. This trend of erosion and deposition has resulted in the thickest stratigraphy occurring in the Heysen Range and Ikara to Chace Range region, while the thinnest successions are recorded on the eastern margin of the depositional area of the Ediacara Member at sites such as Mulga View and Reaphook Hill. In thickest sections, such as those in the Heysen Range, deposition is recorded as a series of parasequences. These are marked in outcrop by a series of upward coarsening and shallowing depositional cycles, the tops of which represent marine flooding surfaces (Gehling, 2000; Gehling and Droser, 2012). Bunyeroo and Brachina Gorge exhibit at least two shallowing-upwards parasequences, with the Bunyeroo Gorge section containing an extensive basal package of fine to medium grained, micaceous, thinly bedded, and khaki-to-purple weathering sands. The top of the youngest cycle at both sites includes a distinct package of thin, flaggy-bedded ORS facies and a capping package of CS.

In comparison, Reaphook Hill represents the most easterly exposure of the Ediacara Member. Measured sections are

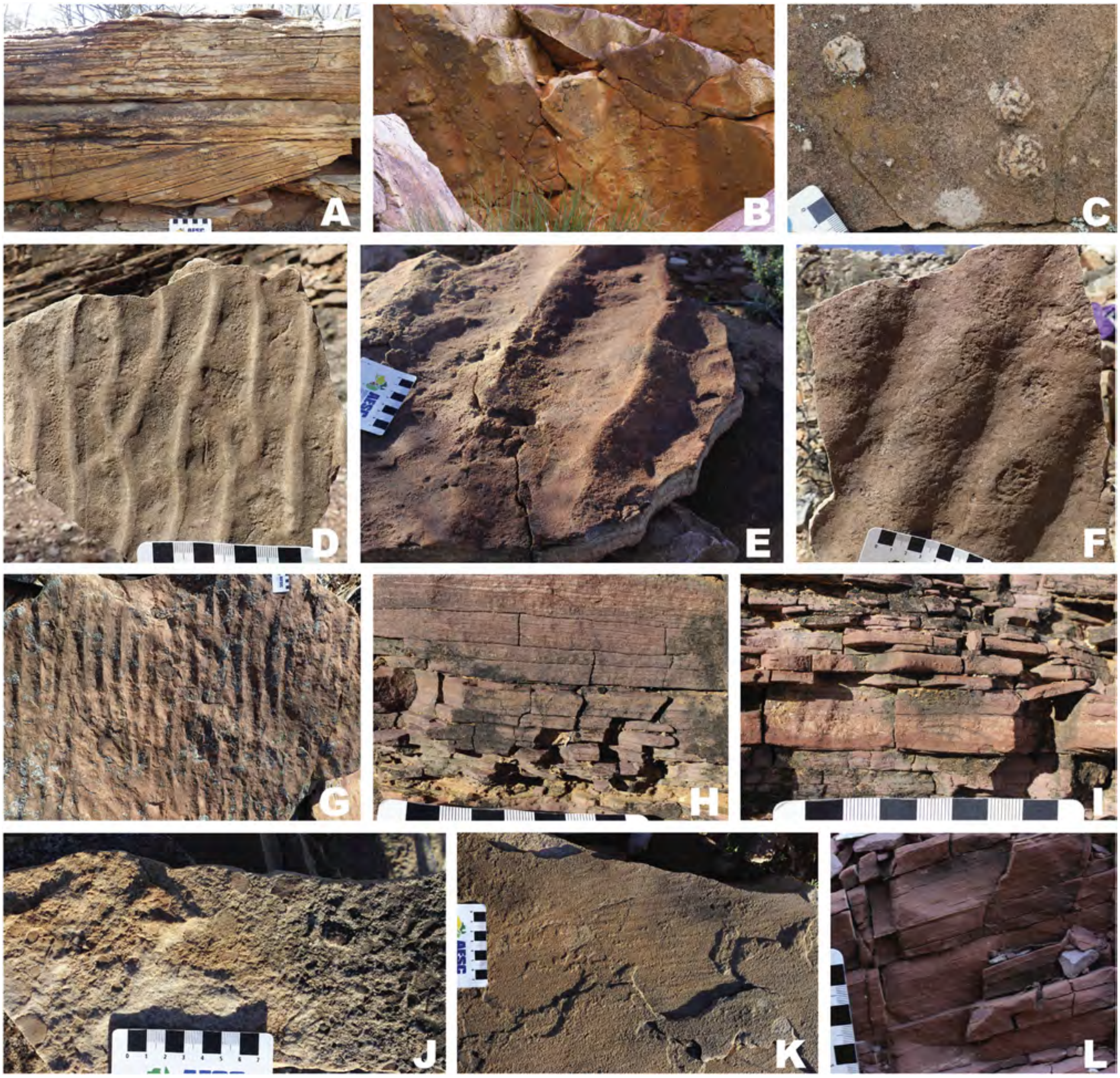

Fig. 6. Characteristics and common bedforms of the Ediacara Member. Cross bedding on the scale of (A) is largely absent, this example is from the unnamed upper Rawnsley Quartzite, which overlies the Ediacara Member. B, siliceous concretions from the Concretionary Sand facies; C, siliceous concretions with remnant original crystal structure; D, small scale, symmetric and bifurcated ripples with microbial mat textures from the Oscillation Ripple Sand facies (ORS); E, bed top, symmetric and crested ripples typical of the ORS; F, bed base wave ripple impressions from the ORS; G, sharp-crested shallow water ripples; H, thin and discontinuous lenses of coarse, clean sand in the Current Ripple Sand facies (CRS); I, cross laminations in the CRS; J, bed top rip-up clasts in the Current Lineated Sand facies (CLS); K, Bed base current lineations of the CLS; L, lensed sand interbeds in the CRS. Scales are in centimeters.

informally named Reaphook gorge (31°23′5.86″S, 139°17′10.54″E), scholzite creek (31°23′21.22″S, 139°17′29.98″E) and little creek (31°23′28.25″S, 139°17′34.31″E). Here thickness is less than 15 m, and outcrop is dominated by medium to coarse grained, hummocky or flaggy sand beds. This trend in thickness is also noted for Tooth Nob, which also comprises a restricted package of predominantly medium to coarse-grained, hummocky to flaggy-rippled beds.

At these sites, the Ediacara Member contains a restricted shallowing-upwards sequence which disconformably overlies the Chace Quartzite Member beginning with a package of the CRS. This rapidly shallows and fluctuates between the lower CFRS wave-base and the upper ORS, and is then truncated by the overlying cross bedded, feldspathic sandstone facies of the upper Rawnsely Quartzite. At Reaphook Hill, sections along a north to south transect thin rapidly from three restricted shallowing cycles to just one (Fig. 5E,F,G). In comparison with Heysen Range sites and Mulga View, a capping package of flaggy ORS and shoreface CS is absent.

The Ediacara Member at Mulga View is expressed primarily as medium-grained sands with a thickness of approximately 16 m. The section coarsens and shallows, with the exception of a package of contorted and slumped medium grained sand beds at some exposures signifying a spatially restricted return to slightly deeper environments before continued coarsening and shallowing.

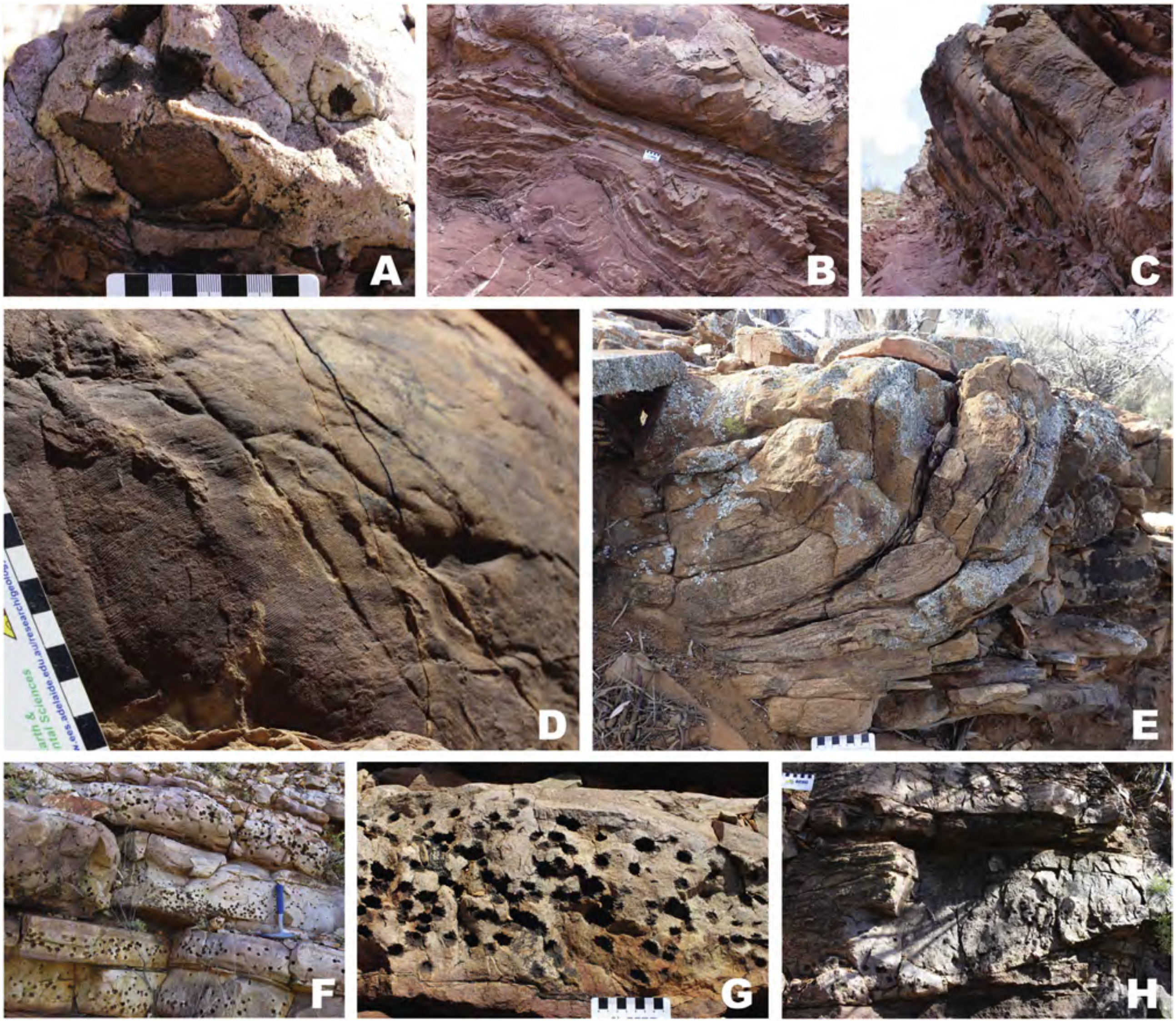

Fig. 7. Characteristics of the Channelised and Slumped Sand facies (CSS). A, Multiple bed base rip-up clasts and interbed post-mineral rosettes; B, Soft sediment deformation of Current Lineated Sand facies (CLS) beds by overlying CSS sediments and slump rolls; C, Serial slump rolls overlying CLS sediments; D, Transported specimen of *Dickinsonia* sp. preserved on slump roll base; E, slump roll cross section view; F, G, interbed post-mineral rosettes; channelized rosette-bearing CSS sediments overlying Combined Flow Ripple Sand facies beds. Scales are in centimeters.

4. Discussion

4.1. Facies models

A facies model should act as a norm for comparison of sedimentary sequences across regions, as a framework and guide for observations, a predictor for new sites or situations and a basis for interpretation of the environment that it represents (Walker, 1976). With correct interpretation, a model should provide a distinction between facies that reflects a significant difference in temporal and/or spatial depositional conditions (Counts et al., 2016). Facies models are generally considered at the broad environment of deposition scale (e.g. turbidite fan, carbonate ramp) but, for the purposes of the lithofacies model presented here, a finer scale of focus is used (e.g. wave-base or delta-front environment). This is done as the motivating factor for addressing the environmental setting/s of the Ediacara Member is to provide a framework for the habitat environment of the Ediacara biota. The lithofacies model presented here can then act as the basis for future work focused on the basin evolution and structure of the Ediacara Member. Although the ultimate aim of the lithofacies model is to allow for environmental interpretation, we agree with Tarhan et al. (2017) that facies names should reflect identifiable physical characteristics rather than palaeoenvironmental interpretations (see Table 1). This is to best communicate key features and encourage the field identification of characteristics as a means for distinguishing facies (Hubbard et al., 2009).

The presentation of this revised facies model is also motivated by the need for a model that can be used across the Flinders Ranges for field identification of all facies and their sedimentary environments. This is particularly timely as there is renewed focus on palaeontological investigations across the Flinders Ranges as a whole, as opposed to a localised focus on the Nilpena region (see Counts et al., 2016; Coutts et al., 2016; Reid et al., 2017). The primary differences between the facies model offered here and other models are:

1. The separation of the two previously unified wave-base depth facies (ORS and CFRS; see Results section).
2. The inclusion of the Concretionary Sands facies, which reintroduces the capping, shoreface environment sediments that are present at the majority of exposures.
3. The inclusion and discussion of regional variation across a range of Ediacara Member sites.

In order to aid field identification of the facies, a guide of primary characteristics for each facies has been produced (Table 2). It is anticipated this will be useful in the identification and correlation of *in situ* outcrop and hand specimens and may be especially valuable where fossils are present. Of particular importance in identifying Ediacara Member material is the location of beds from which float material (loose, weathered out blocks) is derived, as a single fossiliferous hand specimen may then yield an entire bed surface, if it can be located. Similarly, many fossil specimens in museum collections around the world are now isolated from information on their host sequence but the presented guide will allow for designation of their host facies in some instances. This guide utilises bedforms and sedimentary structures which are widespread at field sites, but characteristic of a given facies. Commonly identifiable lithological features, such as grain size and bed thickness are demonstrated here to be quite variable within a single facies (see also Gehling, 2000), so spatial variability in the expression of a given facies should also be considered.

4.2. Facies interpretations

Flow regime models that describe fluvial and marine environments are well established (Clifton et al., 1971). As a package of sediments representative of a shallow, prograding system the majority of Ediacara Member facies most likely record a set of heterogeneous palaeoenvironments from the wave-dominated shoreface, through wave-base to delta-front and/or pro-delta environments (Droser et al., 2017). As a result, various bedforms are specific to a given facies and are therefore suggested for use in facies identification. Bedforms present in the majority of this zone are subject to the lower part of the Lower Flow Regime (Dalrymple and Choi, 2007). Where the predominant energy source is derived from wave action, as in the CS facies and ORS facies, preserved bed-top ripples are generally symmetrical in profile with deep and narrow troughs displaying occasional bifurcation and commonly sharp, continuous crests (Dumas et al., 2005). Asymmetric wave ripples preserve a profile with a relatively shortened lee slope and similar deep troughs. These are indicative of oscillatory flow processes where flow is stronger in one direction than the other. These bedforms therefore suggest sediment deposition within a zone of relatively shallow oscillatory flow, consistent with the coastal shoaling zone of the lower shoreface and/or an upper fair-weather wave base environment (Testik et al., 2006). The relatively coarse grain size, maturity and presence of asymmetric ripples in the CS suggest that this facies was broadly deposited under the influence of upper wave-action swash and backwash and is representative of a shoreface environment.

While the ORS facies contains thin, flaggy, predominantly symmetrically-rippled beds indicative of an upper wave-base environment, the CFRS facies is characterised by broad, rounded, asymmetric and often-discontinuous ripples, which form under the influence of combined wave and current action (Yokokawa et al., 1995). Combined flows result from the action of a unidirectional flow, such as a current or gravity flow and the oscillatory flow of wave action. They are most likely the result of increased wave energy during periods of storm activity (Dumas et al., 2005). This suggests the CFRS facies was deposited above the storm-weather wave base boundary and subject to periods of exposure of combined wave and current action, present during storm activity (Dumas et al., 2005).

Current ripples of the CRS have a lower relief relative to the wave ripples of the Ediacara Member, a steeper lee-side flank, and tend towards lobate rather than sinuous. In outcrop, they are generally evident as small, asymmetric ripples in often micaceous, thinly bedded purple sands. This facies is finer-grained than the CS, ORS and CFRS facies and deposition is interpreted to have occurred as a steady fall below wave-base and be affected by current flow processes only. The majority of deposited sediments likely represent the average 'background' sedimentation for the basin, rather than the result of storm activity or sediment-gravity flows as observed for the majority of other Ediacara Member facies (Dalrymple and Choi, 2007; Gehling, 2000). The occurrences of intermittent horizons of coarse-grained, immature sediments are however suggestive of a fluvial sediment source.

The remaining two facies (Current Lineated Sand facies and Channelised and Slumped Sand facies) are interpreted to be the result of sediment-gravity flows involving event-style deposition of sediments reworked from in-shore and delta-front/pro-delta zones and record sedimentary structures characteristic of their deposition. The CSS facies contains abundant structures indicative of soft-sediment deformation (see Results and Fig. 7) that are visible in outcrop in most instances and make an excellent diagnostic tool. This facies is interpreted as sands deposited by a mass-flow event, and in contrast with the often underlying CRS was likely deposited rapidly. The soft-sediment deformation structures, including convoluted interbed contacts and dish and pillar structures, suggest there was little lag time to allow for sufficient dewatering to occur between deposition of successive beds (Gehling, 2000). The CLS facies, despite a notable absence of ripple bedforms, contains characteristic bed-top rip-up clasts and current lineations (see Results and Fig. 6). This facies represents deposition under the influence of episodic, unidirectional grain flow events, as suggested by inverse grading present in this facies at the Brachina Gorge Section II site (see Fig. 4; see also Gehling, 2000; Lowe, 1982; Tarhan et al., 2017).

4.3. Implications

4.3.1. Facies relationships

The measured sections presented here demonstrate that the thickest sections within the Ediacara Member depositional zone are present through the Heysen Ranges, while Gehling (2000) also shows that relatively thick deposition also occurred through the Ikara-Chace region. In contrast, sections on the eastern margin at Reaphook Hill and Tooth Nob (Fig. 5) highlight significant thinning of the Ediacara Member towards the east with dominantly wave-base environments represented by the preserved stratigraphy.

In the thickest sections, the bulk of deposition occurred in the CRS facies below wave base (see Fig. 5), with sediments comprising comparatively iron and mica-rich, often poorly sorted and relatively less mature sands. This may suggest that the bulk of sediments was introduced into the system from a relatively local fluvial source, and that the shallow, coastal marine facies (CS, ORS, and CFRS) then constitute the mature, reworked sediments of this system. We further suggest that the sediments comprising the CSS facies are at least in part derived from the delta front-to-pro delta environments of the CRS facies, and are representative of sediment-gravity flow events involving the bulk movement of unconsolidated sediment down or across the delta-front or pro-delta face. This is evidenced by the two thickest sections in the Heysen Range (Bunyeroo and Brachina Gorges; Figs. 4 and 5), where the CRS directly overlies CSS sediments. Likewise, we suggest that the CLS facies represents serial sediment-gravity flow events of sediment downslope from the cleaner, more mature sediments of the shallower coastal marine facies (CS, ORS and CFRS). However, this model does not account for the rapid base level fluctuations required to increase water depth sufficiently for both the CSS and CLS facies to be deposited below wave-base (in some instances) and then returned to previous depositional conditions. While this contribution is focused on the sedimentary environments present for the purpose of palaeoecology study, there remains further work to be undertaken investigating the basin structure and evolution.

4.3.2. Palaeoecology

Clear interpretations of, and definitions between, palaeoenvironments is central to Ediacaran palaeoecology. In the majority of instances, Ediacaran fossils are representative of soft bodied, enigmatic organisms unlike those recorded in Phanerozoic deposits. Many of these fossils, with no clear extant analogues, represent problematic taxa. By incorporating an understanding of habitat environment into the study of these taxa, a broader understanding of population and community structure has begun to emerge (for example Gehling and Droser, 2013). This in turn aids understanding of these enigmatic organisms, and supports the traditional (but limited) taxonomic approaches in the allocation of these taxa to biological groups. Palaeoenvironment habitat information may help infer tolerances to abiotic environmental factors such as average water depth, high or low energy regimes or frequency of disturbance events. Of great importance therefore is the distinction between *in situ* and *ex situ* fossil material, and which lithofacies are most likely to preserve fossils which represent the organisms within their life habitats. We suggest that the CSS facies, which commonly preserves fossils including *Pteridinium* within sand event beds, or crumpled and torn *Dickinsonia* on the base of beds, represents a lithofacies of transported material only, with all organisms having been transported from other lithofacies representative of life habitats. In situ preservation appears most likely to have occurred in the ORS, CFRS, CRS, and CLS lithofacies, while the CS lithofacies requires further investigation (see Reid et al., 2018). Better understanding of these environments within the Ediacara Member will in turn aid broader comparisons between habitat and preserving environments with other Ediacaran localities globally.

5. Conclusions

The Rawnsley Quartzite has a rich history of investigation that continues to provide a working framework for the exploration and interpretation of the Ediacara biota. Despite comprising a package of macroscopically homogeneous medium to coarse grained siliciclastics, the Ediacara Member contains a host of lithological characteristics which allow for palaeoenvironmental analysis of the life habitats and preserving environments of the Ediacara biota. A recent, renewed focus on a broader spread of Flinders Ranges Ediacara fossil sites and the potential for nomination of World Heritage status has led to greater interest in Ediacara Member localities at sites external to the Nilpena-Ediacara area (however see Gehling, 1971). Considering the sizeable geographic range of Ediacara Member outcrop within the greater Flinders Ranges region, models seeking to describe the sedimentology, palaeoenvironments and geologic evolution must include data from multiple localities across the broader region. Accurate identification of Ediacara Member lithologies is critical to promoting the expansion of research in this field and continued scientific dialogue about the Ediacara biota.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2019.09.017.

References

Bottjer, D.J., Hagadorn, J.W., Dornbos, S.Q., 2000. The Cambrian substrate revolution. GSA Today (Geol. Soc. Am.) 10 (9), 1–7.
Callow, R.H.T., Brasier, M.D., 2009. Remarkable preservation of microbial mats in Neoproterozoic siliciclastic settings: implications for Ediacaran taphonomic models. Earth Sci. Rev. 96 (3), 207–219.
Callow, R.H.T., Brasier, M.D., McIlroy, D., 2013. Discussion: "were the Ediacaran siliciclastics of South Australia coastal or deep marine?" By Retallack et al., Sedimentology, 59, 1208-1236. Sedimentology 60 (2), 624–627.
Clifton, H.E., Hunter, R.E., Phillips, R.L., 1971. Depositional structures and processes in the non-barred high-energy nearshore. J. Sediment. Res. 41 (3), 651–670.
Counts, J.W., Rarity, F., Ainsworth, R.B., Amos, K.J., Lane, T., Moron, S., Trainor, J., Valenti, C., Nanson, R., 2016. Sedimentological interpretation of an Ediacaran delta: Bonney Sandstone, South Australia. Aust. J. Earth Sci. 63 (3), 257–273.
Coutts, F.J., Gehling, J.G., García-Bellido, D.C., 2016. How diverse were early animal communities? An example from Ediacara Conservation Park, Flinders Ranges, South Australia. Alcheringa 40 (4), 407–421.
Dalrymple, R.W., Choi, K., 2007. Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth Sci. Rev. 81 (3), 135–174.
Darroch, S.A., Laflamme, M., Schiffbauer, J.D., Briggs, D.E.G., 2012. Experimental formation of a microbial death mask. Palaios 27 (5), 293–303.
Droser, M.L., Gehling, J.G., 2015. The advent of animals: the view from the Ediacaran. Proc. Natl. Acad. Sci. U. S. A. 112 (16), 4865–4870.
Droser, M.L., Gehling, J.G., Jensen, S.R., 2006. Assemblage palaeoecology of the Ediacara biota: the unabridged edition? Palaeogeogr. Palaeoclimatol. Palaeoecol. 232 (2–4), 131–147.
Droser, M.L., Tarhan, L.G., Gehling, J.G., 2017. The rise of animals in a changing environment: global ecological innovation in the Late Ediacaran. Annu. Rev. Earth Planet Sci. 45 (1), 593–617.
Droser, M.L., Gehling, J.G., Tarhan, L.G., Evans, S.D., Hall, C.M., Hughes, I.V., Hughes, E.B., Dzaugis, M.E., Dzaugis, M.P., Dzaugis, P.W., Rice, D., 2019. Piecing together the puzzle of the Ediacara biota: excavation and reconstruction at the Ediacara National Heritage site Nilpena (south Australia). Palaeogeogr. Palaeoclimatol. Palaeoecol. 513, 132–145.
Dumas, S., Arnott, R., Southard, J.B., 2005. Experiments on oscillatory-flow and combined-flow bed forms: implications for interpreting parts of the shallow-marine sedimentary record. J. Sediment. Res. 75 (3), 501–513.
Dunn, F.S., Liu, A.G., Gehling, J.G., 2019. Anatomical and ontogenetic reassessment of the Ediacaran frond Arborea arborea and its placement within total group Eumetazoa. Palaeontology 62 (5), 851–865.
Dyson, I.A., 1985. Frond-like fossils from the base of the late Precambrian Wilpena Group, South Australia. Nature 318 (6043), 283.
Evans, S.D., Dzaugis, P.W., Droser, M.L., Gehling, J.G., 2018. You can get anything you want from Alice's Restaurant Bed: exceptional preservation and an unusual fossil assemblage from a newly excavated bed (Ediacara Member, Nilpena, South Australia). Aust. J. Earth Sci. 1–11.
Evans, S.D., Droser, M.L., Gehling, J.G., 2017. Highly regulated growth and development of the Ediacara macrofossil *Dickinsonia costata*. PLoS One 12, e0176874.
Evans, S.D., Gehling, J.G., Droser, M.L., 2019. Slime travelers: early evidence of animal mobility and feeding in an organic mat world. Geobiology 17 (5), 490–509.
Forbes, B., 1971. Stratigraphic subdivision of the Pound Quartzite (late Precambrian, South Australia). Trans. R. Soc. S. Aust. 95, 219–225.
Gehling, J.G., 1971. The Geology of the Reaphook Hill Area, Flinders Ranges, South Australia. Adelaide University unpubl. BSc Honours thesis.
Gehling, J.G., 1983. The Sedimentology and Stratigraphy of the Late Precambrian Pound Subgroup, Central Flinders Ranges, South Australia. Adelaide University. Unpubl. BSc Masters Thesis.
Gehling, J.G., 1999. Microbial mats in terminal Proterozoic siliciclastics; Ediacaran death masks. Palaios 14 (1), 40–57.
Gehling, J.G., 2000. Environmental interpretation and a sequence stratigraphic

framework for the terminal Proterozoic Ediacara Member within the Rawnsley Quartzite, South Australia. Precambrian Res. 100 (1), 65–95.
Gehling, J.G., Droser, M.L., 2012. Ediacaran stratigraphy and the biota of the Adelaide geosyncline, South Australia. Episodes 35 (1), 236–246.
Gehling, J.G., Droser, M.L., 2013. How well do fossil assemblages of the Ediacara biota tell time? Geology 41 (4), 447–450.
Glaessner, M., Walter, M., 1975. New Precambrian fossils from the Arumbera Sandstone, Northern Territory, Australia. Alcheringa 1 (1), 59–69.
Glaessner, M.F., Wade, M., 1966. The late Precambrian fossils from Ediacara, South Australia. Palaeontology 9 (4), 599–628.
Goldring, R., Curnow, C., 1967. The stratigraphy and facies of the late Precambrian at Ediacara, South Australia. J. Geol. Soc. Aust. 14 (2), 195–214.
Grazhdankin, D., 2004. Patterns of distribution in the Ediacaran biotas: facies versus biogeography and evolution. Paleobiology 30 (2), 203–221.
Haines, P.W., 2000. Problematic fossils in the late Neoproterozoic Wonoka Formation, South Australia. Precambrian Res. 100 (1–3), 97–108.
Hall, C.M.S., Droser, M.L., Clites, E.C., Gehling, J.G., 2018. The short-lived but successful tri-radial body plan: a view from the Ediacaran of Australia. Aust. J. Earth Sci. 1–11.
Harazim, D., Callow, R.H.T., McIlroy, D., Lokier, S., 2013. Microbial mats implicated in the generation of intrastratal shrinkage ('synaeresis') cracks. Sedimentology 60 (7), 1621–1638.
Hubbard, B., Cook, S., Coulson, H., 2009. Basal ice facies: a review and unifying approach. Quat. Sci. Rev. 28 (19), 1956–1969.
Jago, J.B., Gehling, J.G., Betts, M.J., Brock, G.A., Dalgarno, C.R., García-Bellido, D.C., Haslett, P.G., Jacquet, S.M., Kruse, P.D., Langsford, N.R., Mount, T.J., Paterson, J.R., 2018. The Cambrian system in the Arrowie Basin, Flinders Ranges, South Australia. Aust. J. Earth Sci. 1–26.
Jenkins, R.J.F., 1975. An Environmental Study of the Rocks Containing the Ediacara Assemblage in the Flinders Ranges. Australian Geological Convention, Abstracts, Adelaide, pp. 21–22.
Jenkins, R.J.F., 1981. The concept of an 'Ediacaran Period' and its stratigraphic significance in Australia. Trans. R. Soc. S. Aust. 105 (4), 179–194.
Jenkins, R.J.F., 2007. 'Ediacaran' as a name for the newly designated terminal Proterozoic period. Geological Society, London, Special Publications 286 (1), 137–142.
Jenkins, R.J.F., Ford, C.H., Gehling, J.G., 1983. The Ediacara member of the Rawnsley Quartzite: the context of the Ediacara assemblage (late Precambrian, Flinders Ranges). J. Geol. Soc. Aust. 30 (1–2), 101–119.
Jenkins, R.J.F., 1986. Are enigmatic markings in Adelaidean of Flinders Ranges fossil ice-tracks? Nature 323 (6087), 472.
Knoll, A.H., Walter, M.R., Narbonne, G.M., Christie-Blick, N., 2006. The Ediacaran Period: a new addition to the geologic time scale. Lethaia 39 (1), 13–30.
Liu, A.G., McMahon, S., Matthews, J.J., Still, J.W., Brasier, A.T., 2019. Petrological evidence in support of the death mask model for Ediacaran soft-bodied preservation in South Australia. Geology 47 (3), 215–218.
Lowe, D.R., 1982. Sediment gravity flows: II Depositional models with special reference to the deposits of high-density turbidity currents. J. Sediment. Res. 52 (1), 279–297.
Martin, M.W., Grazhdankin, D.V., Bowring, S.A., Evans, D.A.D., Fedonkin, M., Kirschvink, J., 2000. Age of Neoproterozoic bilatarian body and trace fossils, White Sea, Russia: implications for metazoan evolution. Science 288 (5467), 841–845.
Narbonne, G.M., 2005. The Ediacara biota: neoproterozoic origin of animals and their ecosystems. Annu. Rev. Earth Planet Sci. 33 (1), 421–442.
Narbonne, G.M., Xiao, S., Shields, G.A., Gehling, J.G., 2012. The Ediacaran Period. The Geologic Time Scale 413–435.
Paterson, J.R., Gehling, J.G., Droser, M.L., Bicknell, R.D., 2017. Rheotaxis in the Ediacaran epibenthic organism *Parvancorina* from South Australia. Sci. Rep. 7, 45539.
Plummer, P., Gostin, V., 1981. Shrinkage cracks: desiccation or synaeresis? J. Sediment. Res. 51 (4), 1147–1156.
Preiss, W., 2000. The Adelaide Geosyncline of South Australia and its significance in Neoproterozoic continental reconstruction. Precambrian Res. 100 (1), 21–63.
Reid, L.M., Holmes, J.D., Payne, J.L., García-Bellido, D.C., Jago, J.B., 2018. Taxa, turnover and taphofacies: a preliminary analysis of facies-assemblage relationships in the Ediacara Member (Flinders Ranges, South Australia). Aust. J. Earth Sci. 1–10.
Reid, L.M., García-Bellido, D.C., Payne, J.L., Runnegar, B., Gehling, J.G., 2017. Possible evidence of primary succession in a juvenile-dominated Ediacara fossil surface from the Flinders Ranges, South Australia. Palaeogeogr. Palaeoclimatol. Palaeoecol. 476, 68–76.
Reid, P., Preiss, W., 1999. Parachilna map sheet. South Australian Geological Survey Geological Atlas 1, 54–13.
Retallack, G.J., 2012. Were Ediacaran siliciclastics of South Australia coastal or deep marine? Sedimentology 59, 1208–1236.
Retallack, G.J., 2013. Ediacaran life on land. Nature 493 (7430), 89–92.
Sprigg, R.C., 1947. Early Cambrian (?) jellyfishes from the Flinders Ranges, South Australia. Trans. R. Soc. S. Aust. 71 (2), 212–224.
Tarhan, L.G., Droser, M.L., Gehling, J.G., Dzaugis, M.P., 2017. Microbial mat sandwiches and other anactualistic sedimentary features of the Ediacara Member (Rawnsley Quartzite, South Australia): implications for interpretation of the Ediacaran sedimentary record. Palaios 32 (3), 181–194.
Tarhan, L.G., Hood, A.S., Droser, M.L., Gehling, J.G., Briggs, D.E., 2016. Exceptional preservation of soft-bodied Ediacara Biota promoted by silica-rich oceans. Geology 44 (11), 951–954.
Testik, F., Voropayev, S., Balasubramanian, S., Fernando, H., 2006. Self-similarity of asymmetric sand-ripple profiles formed under nonlinear shoaling waves. Phys. Fluids 18 (10), 108101.
Wade, M., 1969. Medusae from uppermost Precambrian or Cambrian sandstones, central Australia. Palaeontology 12 (3), 351–365.
Wade, M., 1970. The stratigraphic distribution of the Ediacara fauna in Australia. Trans. R. Soc. S. Aust. 94, 87–104.
Waggoner, B., 1999. Biogeographic analyses of the Ediacara biota: a conflict with paleotectonic reconstructions. Paleobiology 25 (4), 440–458.
Waggoner, B., 2003. The Ediacaran biotas in space and time. Integr. Comp. Biol. 43 (1), 104–113.
Walker, R.G., 1976. Facies models 1. General introduction. Geoscience Canada 3 (1).
Xiao, S., Droser, M., Gehling, J.G., Hughes, I.V., Wan, B., Chen, Z., Yuan, X., 2013. Affirming life aquatic for the Ediacara biota in China and Australia. Geology 41 (10), 1095–1098.
Yokokawa, M., Masuda, F., Endo, N., 1995. Sand particle movement on migrating combined-flow ripples. J. Sediment. Res. 65 (1), 40–44.