AUSTRALIAN JOURNAL OF EARTH SCIENCES, 2016
http://dx.doi.org/10.1080/08120099.2016.1180322

Sedimentological interpretation of an Ediacaran delta: Bonney Sandstone, South Australia

J. W. Counts[a], F. Rarity[a], R. B. Ainsworth[a], K. J. Amos[a], T. Lane[a], S. Morón[a], J. Trainor[a], C. Valenti[b] and R. Nanson[a]

[a]Australian School of Petroleum, University of Adelaide, Adelaide, SA 5005, Australia; [b]Carnarvon Petroleum, Perth, 6872 WA, Australia

ABSTRACT

The type section of the late Ediacaran (*ca* 565 Ma) Bonney Sandstone in South Australia provides an opportunity to interpret a succession of Precambrian clastic sediments using physical sedimentary structures, lithologies and stacking patterns. Facies models, sequence stratigraphic analysis, and process-based architectural classification of depositional elements were used to interpret depositional environments for a series of disconformity-bounded intervals. This study is the first detailed published work on the Bonney Sandstone, and provides additional context for other Wilpena Group sediments, including the overlying Rawnsley Quartzite and its early metazoan fossils. Results show that the ~300 m-thick section studied here shows a progressive change from shallow marine to fluvially dominated sediments, having been deposited in storm-dominated shelf and lower shoreface environments, lower in the section, and consisting primarily of stacked channel sands, in a proximal deltaic environment near the top. Based on the degree of influence of wave, tidal or fluvial depositional processes, shallow marine sediments can be classified into beach, mouth bar, delta lobe and channel depositional elements, which can be used to assist in predicting sandbody geometries when only limited information is available. Sediments are contained within a hierarchical series of regressive, coarsening-upward sequences, which are in turn part of a larger basin-scale sequence that likely reflects normal regression and filling of accommodation throughout a highstand systems tract. Paleogeographic reconstructions suggest the area was part of a fluvially dominated clastic shoreline; this is consistent with previous reconstructions that indicate the area was on the western edge of the basin adjacent to the landward Gawler Craton. This research fills in a knowledge gap in the depositional history of a prominent unit in the Adelaide Rift Complex and is a case study in the interpretation of ancient deposits that are limited in extent or lacking diagnostic features.

ARTICLE HISTORY
Received 19 February 2016
Accepted 15 April 2016

KEYWORDS
sedimentology; highstand; delta; Adelaide Rift Complex; Bonney Sandstone; Flinders Ranges; Ediacaran

EDITORIAL HANDLING
Keyu Liu

Introduction

Over the past several decades, a variety of methods have been proposed to assist in determining the paleoenvironmental and paleogeographic settings of ancient sediments. In this paper, we provide a case study in interpreting a succession of Precambrian strata using a combination of methodologies, focusing on the classification and interpretation scheme described by Ainsworth, Vakarelov, and Nanson (2011) and Vakarelov and Ainsworth (2013), but also incorporating elements from Galloway (1975), Posamentier and Walker (2006), Reading (2009), and Walker (1984a). Unlike Phanerozoic depositional systems, Precambrian clastic sediments deposited before the evolution of complex life usually require interpretations to be based purely on physical processes, without the overprint of biogenic structures or the presence of diagnostic body fossils. The purpose of this study is to describe and interpret the type section of the Ediacaran Bonney Sandstone in Bunyeroo Gorge, South Australia, with the goals of: (1) applying modern interpretation techniques to gain a better understanding of the depositional environments in the formation, in order to better reconstruct the area's paleogeography at the time of deposition; (2) examining how these environments change over time in order to reconstruct the relative sea-level history and sequence stratigraphic setting of the region; and (3) assessing the effectiveness of a using combined interpretation methods when faced with a limited set of data.

With Precambrian rocks making up only 1.5% of surface rocks globally, similar systems are relatively rare worldwide when compared with their Phanerozoic counterparts (Blatt & Jones, 1975). Although the physical and chemical factors that affect sedimentation are still largely applicable to the Precambrian, the specific environmental conditions prevalent at the time were different from those today. The lack of multicellular life, differing atmospheric composition, and an increased rate of weathering and sedimentation affected the makeup and distribution of sedimentary environments (Bose et al., 2012). In addition, Precambrian deposits are biased overall towards craton interiors owing to the extensive tectonic modification of continental margins over time (Donaldson, Eriksson, &

CONTACT J. W. Counts john.counts@adelaide.edu.au

Altermann, 2009). Thus, the strata discussed here provide a unique opportunity to study an ancient succession of shallow-marine sediments on the margin of the Precambrian subcontinent that included Australia, which resulted from the Neoproterozoic fragmentation of the supercontinent Rodinia (Li et al., 2008).

In this study, we use aspects of several different, but mutually complementary methods in conjunction with one another to obtain a holistic view of a succession of clastic sediments. This approach to interpretation is warranted here because the data set consists solely of physical, inorganic sedimentary structures, lithologies and stratigraphic trends, with no trace or body fossils to assist in narrowing down the environmental setting. Interpretation of the section is also hampered by the paucity of detailed previous work on the formation and lack of detailed regional context for the section described here. A single outcrop section, however, can still result in significant new information, as interpreted depositional processes can reveal much about the larger depositional environments, paleogeography and geobody morphology of a region.

Background

Previous research

This study is the first detailed published work on the upper Bonney Sandstone, a clastic-dominated unit that was deposited on the Australia–East Antarctica subcontinent in the Ediacaran Period (Preiss, 1999). The subcontinent was formerly part of Rodinia, a supercontinent that existed as a stable landmass from around 1 Ga until around 850 Ma (Bogdanova, Pisarevsky, & Li, 2009). By the time of deposition of the sediments discussed here, this subcontinent was independent and would have existed at low latitudes, just north of the paleoequator (Li et al., 2008). Deposition of the Bonney Sandstone took place in the Adelaide Rift Complex, a Neoproterozoic to Cambrian basin on the margin of this subcontinent that began as a rift around 800 Ma. Beginning around 690 Ma, sag-phase deposition and continued Rodinian breakup led to the basin having an open oceanic connection to the east-southeast (present-day orientation; Preiss, 1990, 2000), and by the Ediacaran it had evolved into a passive margin (Preiss, 2000). The Adelaide Rift Complex is coeval with parts of the Amadeus, Georgina, Ngalia, Officer and Savory basins, which formed the much larger (2 million km^2) Centralian Superbasin across much of central Australia. Although generally not considered within the bounds of the larger Superbasin (Walter et al., 1995), the Adelaide Rift Complex shows many lithological similarities, and thus may have been a part of the Centralian depositional system. The modern-day Flinders Ranges expose several thousand metres of both clastic and carbonate basin-fill sediments, which were deposited in a variety of shelf, shallow-marine, and continental environments over the course of *ca* 300 Ma. Sedimentation began around 800 Ma and culminated in the Middle Cambrian (Jago, Gatehouse, Powell, Casey, & Alexander, 2010), although the absolute dates of many basin sediments are not clear and are interpolated from the few chronological markers that exist (Preiss, 2000). For a comprehensive summary of basin stratigraphy, see Preiss (1987).

Many sediments were affected by syndepositional diapir movement, where basal evaporites from the lowermost Callanna Group penetrated stratigraphically higher formations and in places pierced the surface (Dalgarno & Johnson, 1968; Kernen et al., 2012; Hearon, Rowan, Lawton, Hannah, & Giles, 2015; Counts & Amos, 2016). After the majority of sedimentation ceased in the Cambrian, the Delamerian Orogeny (514–190 Ma; Foden, Elburg, Dougherty-Page, & Burtt, 2006) intensely deformed basin sediments, resulting in folded and faulted strata now widely exposed in cross-section. These sediments are bounded to the west by the Gawler Craton and onlapping sediments of the Stuart Shelf, and to the east by the smaller Curnamona Cratonic Nucleus (Drexel et al., 1993). Both of these adjacent continental provinces would have been at least periodically subaerially exposed throughout much of basin history, with the basin fill being dominantly marine (Drexel et al., 1993; Preiss, 1987).

The Bonney Sandstone is a part of the Wilpena Group (Figure 1), whose base is at the Global Boundary Stratotype

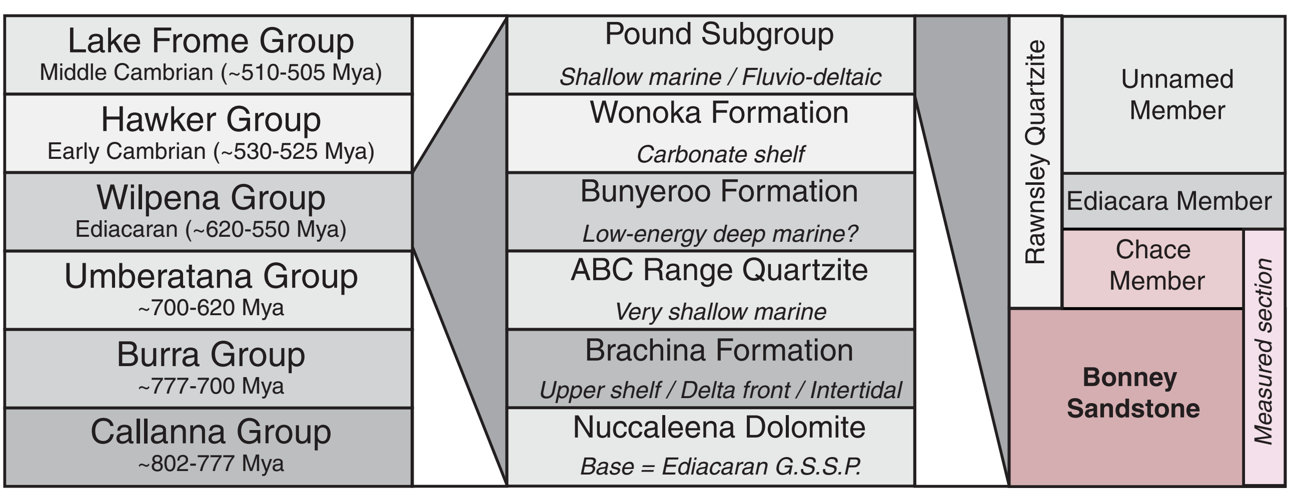


Figure 1. Stratigraphy of the Adelaide rift complex basin fill, showing the position of the Bonney Sandstone in relation to other units. A comprehensive description of all stratigraphic units can be found in Preiss (1987).

Section and Point that defines the worldwide beginning of the Ediacaran period (Knoll, Walter, Narbonne, & Christie-Blick, 2006). It is the lowermost unit of the Pound Subgroup, immediately preceding the Rawnsley Quartzite, which hosts the well-known Ediacaran metazoan fossil assemblage. Youngest concordant zircon dates by Ireland, Flöttmann, Fanning, Gibson, and Preiss (1998) constrain Bonney deposition to no older than around 556 (±24 Ma) Ma. The formation is part of a large-scale shallowing-upward sequence (sequence Marinoan 4; Preiss, 2000) that encompasses sediments from the Bunyeroo Formation to the Rawnsley Quartzite, and terminates at the Ediacaran−Cambrian boundary. Below the Bonney Sandstone, the underlying Bunyeroo and Wonoka formations are composed primarily of clastic and carbonate mudstones, respectively, and the overlying Rawnsley Quartzite, including the Ediacara and Chace members, was deposited in a variety of shallow marine and intertidal environments (Gehling, 2000). In the revision of the Parachilna map sheet, Reid and Preiss (1999) revised the Bonney Sandstone to include sediments that had previously been in the Wonoka Formation, known as the Patsy Hill Member. These carbonates are not included in this study; here, we focus on the clastic sands and silty mudstones that make up the upper portion of the formation, as well as the lower portion of the Rawnsley Quartzite (the Chace Member).

Previous research on the formation either has been very general or has not been published in peer-reviewed literature. Forbes (1971) initially defined the type locality in Bunyeroo Gorge, but only provided brief lithological descriptions. The only detailed study to date is that of Gehling (1982), which included the Bonney Sandstone in an unpublished thesis primarily devoted to the context and paleontology of the Ediacaran faunal assemblage. Gehling (1982) measured the section we describe here, as well as many other Bonney Sandstone outcrops in the area; the two studies are compared below. He interprets the Bonney Sandstone as comprising seven individual facies, generally interpreted as having been deposited in tidally influenced, marginal-marine environments, usually in fining-upward sequences in delta lobes prograding basinward from the northwest. Most environments are interpreted as having been intertidal or subtidal, with a thin interval of alluvial deposition near the top of the formation.

Study area

The Bonney Sandstone section measured is exposed in Bunyeroo Gorge, South Australia (Figure 2; approximately −31.413341°S, 138.544719°E). At the field site the formation is striking approximately 035° and is tilted significantly, dipping ∼65°E. Here, Bunyeroo Creek cuts through the upper Wilpena Group at approximately 90° to strike, creating a cross-sectional view of the formation. Sediments comprising the Bonney Sandstone are exposed in the sub-vertical walls of the creek bed, permitting observations on a relatively continuous exposure of the formation.

Methodology

Stratigraphic units were measured with the use of a laser range-finder, tape measure and handheld GPS. Features measured included grainsize, average bed thickness, lithological and stratigraphic trends (e.g. small-scale fining-upward sequences), key surfaces, sedimentary structures and paleocurrent directions. Units were divided into facies based on the recurrence of lithological characteristics, generally a combination of both grainsize and sedimentary structures (Table 1). This separation was based on the interpreted depositional process responsible for each one. Facies that repeatedly occurred stratigraphically adjacent to one another were grouped into facies associations, which represent multiple depositional processes occurring within a continuous time frame (Table 2). Genetically related intervals within the formation were identified based on facies stacking patterns, fining- or coarsening-upward profiles in outcrop, and transgressive or erosive surfaces bounding such intervals. Once these features were identified, environments of deposition and specific depositional elements for each interval were interpreted primarily using methods described in Ainsworth et al. (2011), Vakarelov and Ainsworth (2013) and Walker (1984a).

Today, interpretation commonly utilises a facies models concept, well summarised by Walker (1979, 1984a), and Walker and James (1992). In this approach, sedimentary characteristics are used to define facies and facies associations, which are then assigned to a particular environment in the model, based on similarity to deposits observed in modern settings and inferences as to how such models would have been different in past conditions. Environments (e.g. delta front) contain a number of sub-environments (e.g., distributary mouth bars, channels, levees), each with a particular set of processes operating that allow deposits to be distinguished from one another. Facies models commonly take the form of idealised sequences of facies, block diagrams showing 3-D sediment relationships, or map-view schematics of sub-environments (Walker, 1984a). Galloway (1975) represented deltaic systems by a wave−tidal−fluvial ternary diagram, with each end-member of the spectrum representing a unique delta geomorphology associated with the process. This ternary diagram was expanded upon by Ainsworth et al. (2011) to incorporate all coastal environments and mixed-process systems, allowing intervals showing multiple processes to be classified as, for instance, 'wave-dominated, fluvially influenced, and tidally affected' (W*ft)*. Vakarelov and Ainsworth (2013) also placed an emphasis on the interpretation of stacking patterns at intra- and inter-parasequence scale, the nature of bounding surfaces as either transgressive or regressive, and a standardised classification of sedimentary units into a hierarchy of idealised depositional elements. All of these approaches are components of the interpretation discussed here.

Results and interpretation

Lithostratigraphic divisions

Bonney Sandstone sediments exposed in Bunyeroo Gorge are composed of a variety of clastic lithologies, with grainsizes

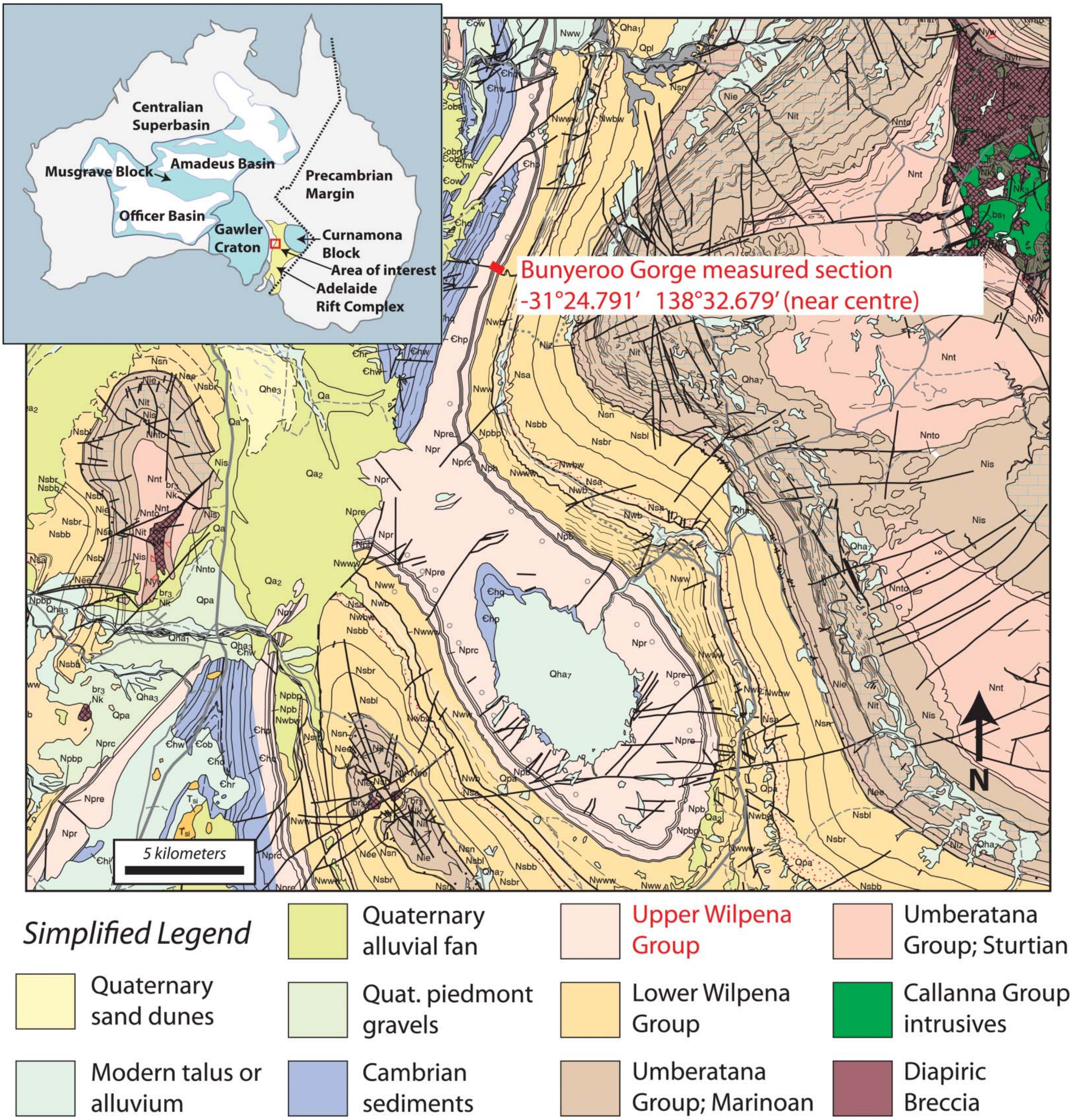


Figure 2. Detailed geological map of the study area and its position within Australia. Taken from Reid et al. (1999)

ranging from silty mudstones to granules. Sandstones are dominant; the mean grainsize of sandstones increases overall up-section, from dominantly very fine- to fine-grained or very fine-grained near the base, to medium-grained near the top. Sandstones in most intervals, however, are rarely coarser than fine-grained, and range from cleaner quartz arenites to muddy, feldspathic sandstones, with occasional granule stringers present. At the scale of outcrop observations, sandstone beds were most commonly tabular and continuous. The outcrop is only incipiently weathered at creek level; sandstone beds commonly weather in relief, forming small ridges perpendicular to the creek bed, with finer-grained intervals forming reentrants. The few instances where channel forms or scours were observed were noted on the log. The section is approximately 270 m thick, including the Chace Member (Figures 3, 4), and the Bonney Sandstone can be divided into three general lithological divisions: (1) a lower division, about 75 m thick, consisting of interbedded fissile silty mudstones and very fine-grained sandstones, in decimetre-scale beds contained within coarsening-upward packages; (2) a middle unit composed almost entirely of amalgamated sandstones, also about 75 m thick, which can be described as a single, vertically interconnected sandstone containing few or none of the mudstones seen in the lower Bonney Sandstone; and (3)

Table 1. Facies found in the Bunyeroo Gorge section of the Bonney Sandstone. Colour of facies column corresponds to that seen in Figures 3 and 4.

#	Facies	Sub-facies/ Description	Representative Photo	Depositional Process
1	Massive/ Planar Siltstones and Mudstones	1a: Massive 1b: Planar-laminated		Gravitational settling; low-energy deposition
2	Planar and Low-angle Laminated Sandstone	2a: Low-angle to planar laminated 2b: with asymmetric ripples 2c: with cross-stratification		Dominated by upper flow regime (high-energy), with some lower flow regime bed-forms (unidirectional)
3	Sandstone with Interference Ripples	May also occur with with low-angle and planar lamination		Flow in more than one direction; two sets of unidirectional currents operating within a short time frame; lower flow regime
4	Sandstone with Symmetrical Ripples	4a: Symmetrical ripples only 4b: with low-angle and planar lamination		Oscillatory flow caused by wave action
5	Cross-stratified Sandstone	Trough or tabular cross-stratification, sometimes with planar laminae, without additional sedimentary structures		Down-current migration of dunes due to unidirectional flow
6	Hummocky Cross-stratified Sandstone	Visible HCS, without other sed. structures		Combination of oscillatory and unidirectional flow
7	Heterolithic Strata (mud/sand)	7a: Interlaminated (mm) 7b: Interbedded (cm-scale) 7c: Interbedded (dm-scale) May also have asymmetric ripples.		Alternating low/high energy over a range of time scales.

Table 2. Facies associations found in the Bunyeroo Gorge section of the Bonney Sandstone. Colour of facies association row corresponds to facies column in Figure 3; facies colour corresponds to that seen in Figures 3 and 4.

Facies Association	*Constituent Facies*	*Interpretation*
A	7B/7C 5	Storm-dominated lower shoreface
B	1B 2A 7B 5	Lower shoreface
C	4B 7A/7B 3	Distal upper shoreface
D	2A/ 2B 4B 5 6	Proximal upper shoreface
E	2A/2B/2C 5	Channel fill / Proximal delta fan

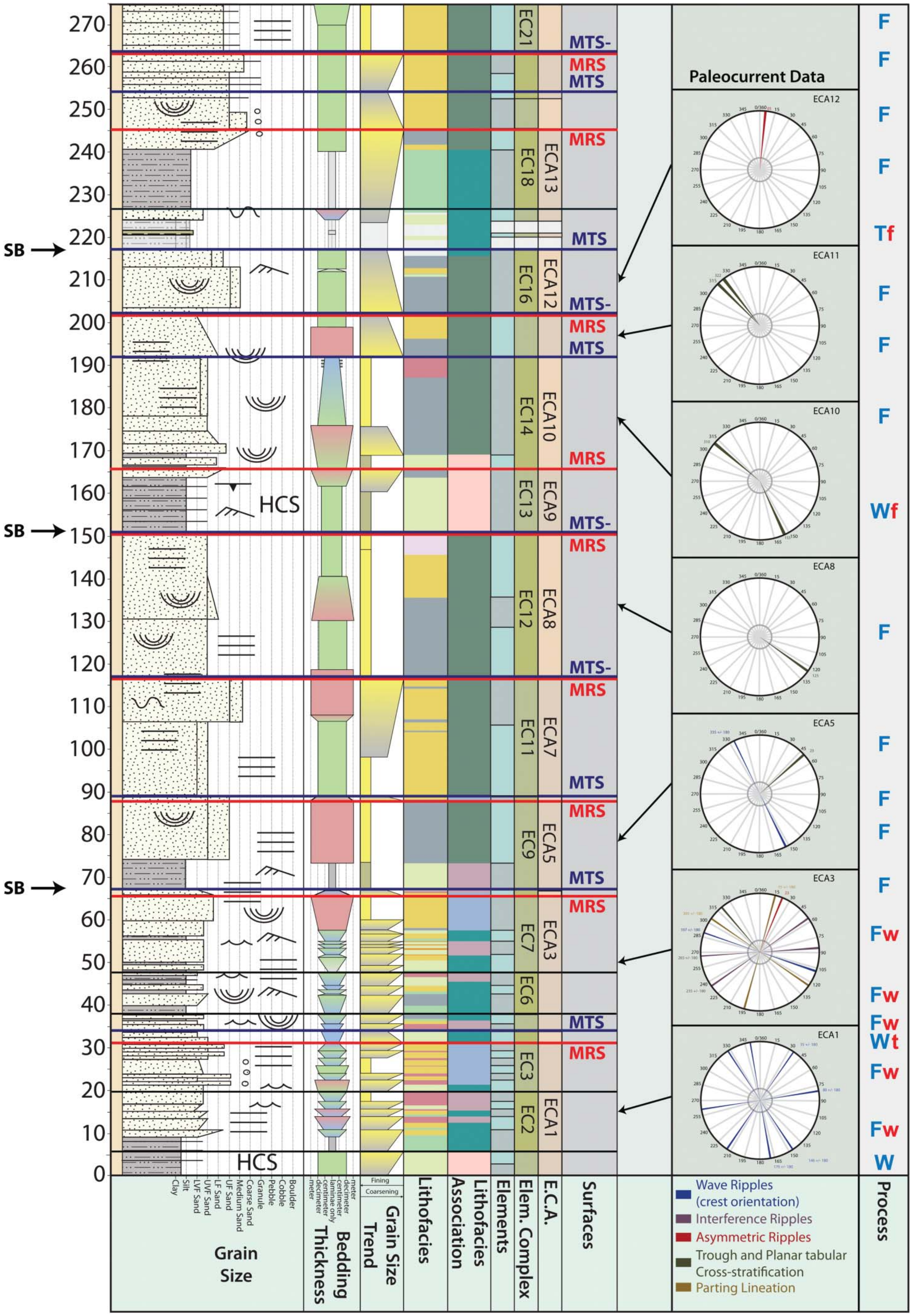


Figure 3. Summary log and paleocurrents. For detailed information, see complete log in Figure 4 and interpretations in Tables 1, 2 and 4. SB, sequence boundary; EC, element complex; ECA, element complex assemblage; MTS, maximum transgressive surface; MRS, maximum flooding surface; HCS, hummocky cross-stratification.

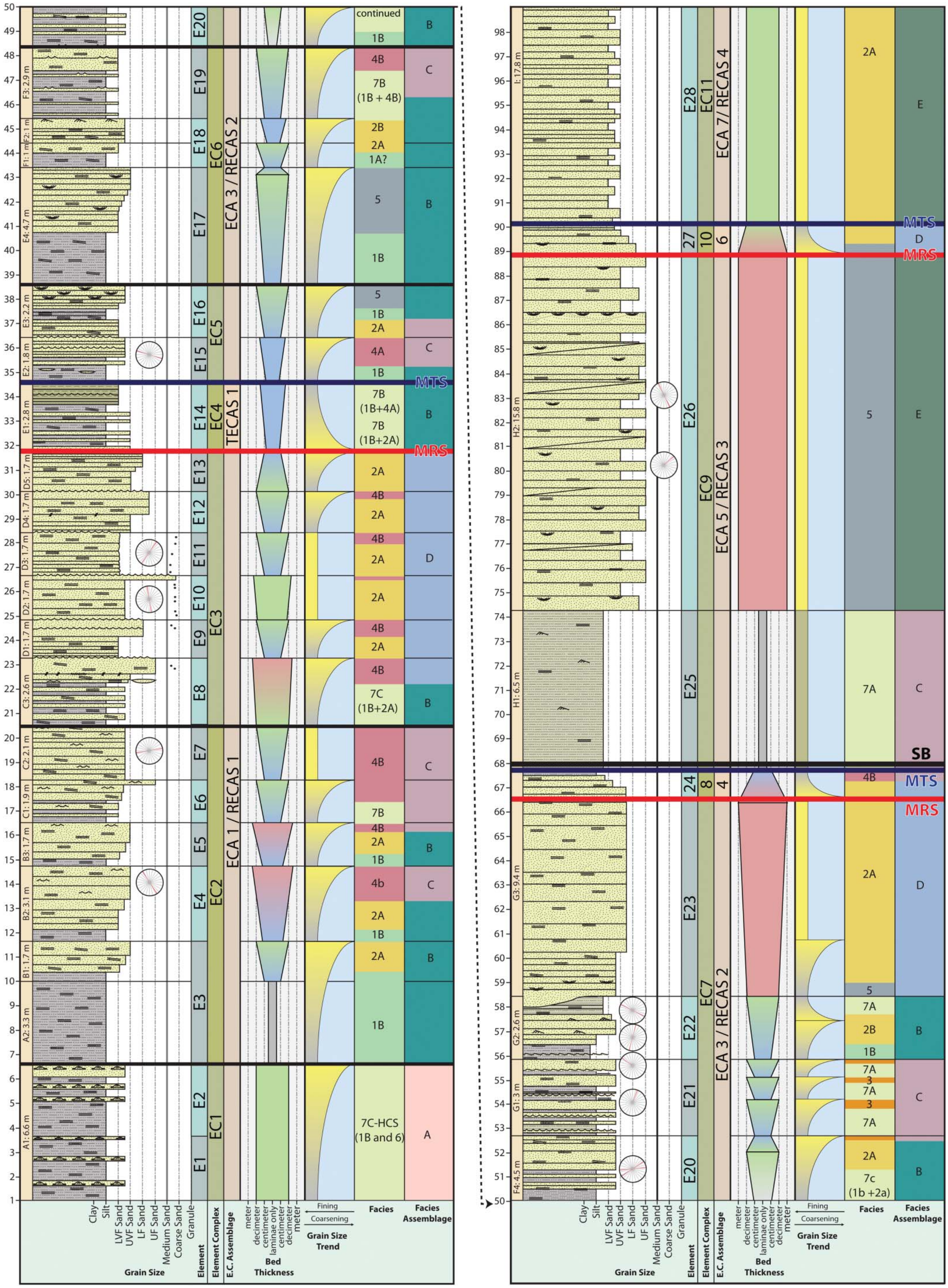


Figure 4. Stratigraphic column of the Bonney Sandstone in Bunyeroo Gorge, showing lithologies, parasequences and parasequence boundaries, grainsize and thickness trends across beds, facies and facies associations.

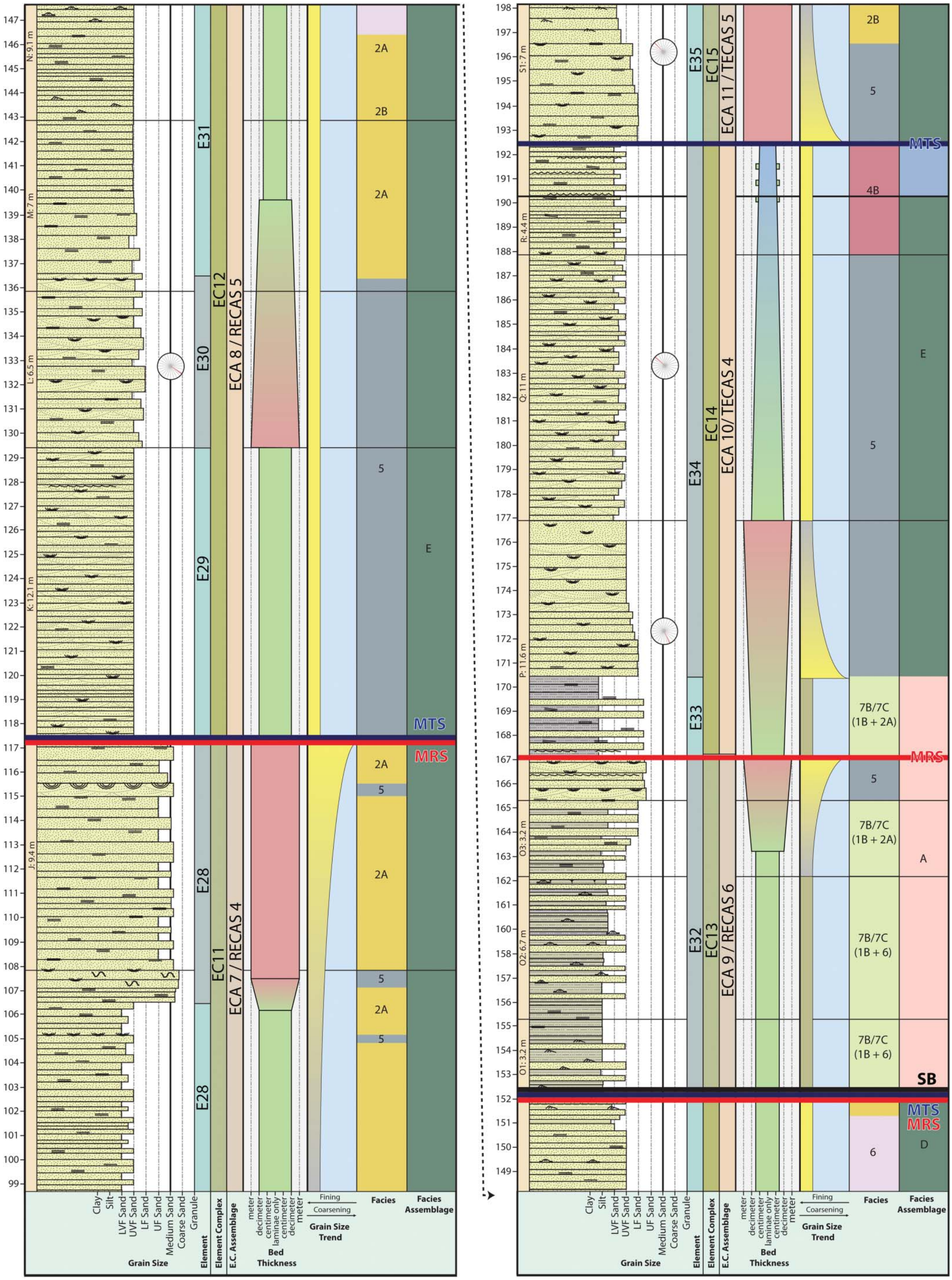


Figure 4. (Continued).

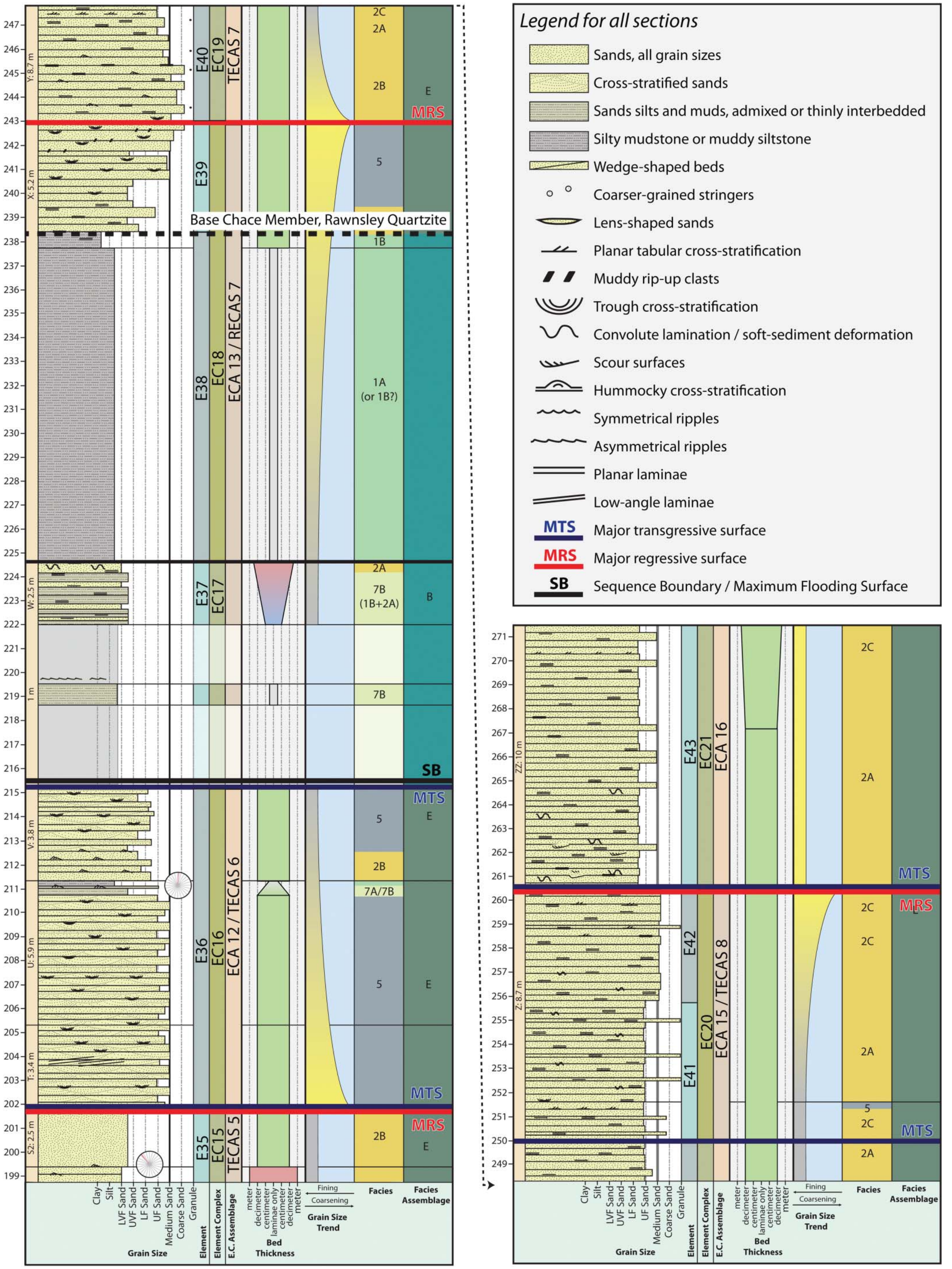


Figure 4. (Continued).

an upper heterogeneous interval, ~85 m thick with lower-quality exposure, consisting of muddy siltstones interbedded with sandstones on a metre scale. These divisions are independent of genetic or sequence stratigraphic boundaries, but are useful for correlation. A similar tripartite division was observed by Gehling (1982). Gehling (1982) also notes that the overlying Chace Member of the Rawnsley Quartzite is separated from the Bonney Sandstone by a non-erosive unconformable contact, which he identifies as a type 2 sequence boundary based on the change in sedimentary character from muddy, reddish sandstones to cleaner light coloured sands. The upper sandy unit described here (at 239 m and above) is recognised as a lithological boundary and interpreted to be the Chace Member on the basis of Gehling's (1982) regional work; however, our specific interpretations as to the depositional environment and nature of the contact differ.

Facies analysis and interpretation

Within this lithostratigraphic framework, sediments can be divided into seven distinct facies, summarised in Table 1. Facies are composed of mudstones, interbedded heterolithic sandstones and silty mudstones, and sandstones containing a variety of sedimentary structures. Facies are distributed unevenly throughout the section, with the thickness of coarsening-upward intervals being much smaller (2–4 m) in the lower 75 m, and increasing to tens of metres in the middle and upper units, with some exceptions.

Based on the fine-grained nature of Facies 1, these sediments are most likely the product of gravitational settling (Ashley, 1990). Occasional thin sandstone laminae may be the result of episodic deposition in an overall low-energy environment (cf. Colquhoun, 1995; Swift, Hudelson, Brenner, & Thompson, 1987). Planar-laminated sandstones in Facies 2 are likely the product of upper flow regime and unidirectional flow (Cheel, 1990), and also contain rare asymmetric ripples (Facies 2b) or cross-stratification (Facies 2c), indicating that flow became turbulent and dropped into the lower flow regime. Sandstones with asymmetric interference ripples (Facies 3) indicate two directions of flow affecting the same bedform, whereas symmetrically rippled sandstones (Facies 4), indicate oscillatory flow conditions that suggests the presence of waves (Reading, 2009). Linear wave ripple crests are not strongly orientated in a particular direction, ranging from north–south to east–west. In Facies 5, tabular, cross-stratified sandstones denote relatively high-energy conditions, and uncommon scours indicate erosive events or channelisation. Paleocurrent readings on these troughs are most commonly northwest–southeast, but are more likely to only show an apparent direction and are thus less reliable than direct measurements from bedding-plane views. Hummocky cross-stratified sandstones in Facies 6 are the product of both unidirectional and oscillatory flow affecting the same sediment surface (Dumas & Arnott, 2006). Heterolithic strata in Facies 7 indicate rapidly changing depositional conditions over a relatively short time-scale. This facies is subdivided based on the scale of interbedding, which is a product of the time frame and sedimentation rate in which these alternating lithologies were deposited.

Recurring combinations of facies can be grouped into six facies associations (Table 2). Although facies are interpreted to the level of a specific, direct process, the presence of multiple facies occurring together can be a better indicator of the overall environment and larger-scale mechanisms responsible for deposition. Each facies association is interpreted to represent a general depositional environment, with each being a unique combination of individual facies. Based on the presence of thin, hummocky cross-stratified sandstones interbedded with silty mudstones, Facies Association A is interpreted as a storm-dominated lower shoreface. Silty mudstones are likely the result of normal, background sedimentation, and hummocky cross-stratified sandstones are likely event deposits affected by storm waves but below the reach of fair weather waves. This is similar to other storm-dominated shelves described by Walker (1984b) and Basilici, de Luca, and Poiré (2012). Facies Association B is similar in that it only occurs in the lower part of the section and also contains thick packages of silty mudstones, but it does not contain the abundant Hummocky cross-stratification (HCS), found in Facies Association A, would indicate substantial storm influence. Mudstones in Facies Association B are commonly overlain by sands containing trough cross-stratification, asymmetric ripples and planar to low-angle laminae. It is thus also interpreted as lower shoreface, below normal wave base, although potentially closer to the shoreline given its proximity to sands. Upper shoreface environments are represented in Facies Associations C and D, with C being somewhat deeper and more distal owing to higher mud/shale content. Facies Association D consists primarily of thick amalgamated sandstones with little mudstone content, commonly in tabular beds with wave ripples indicating a more proximal area of deposition. These sediments are similar to shoreface sands described by Feldman, Fabijanic, Faulkner, and Rudolph (2014) and Lambiase and Tulot (2013), and may have been deposited in a foreshore environment near the tops of shallowing-upward intervals where low-angle and planar-laminated sands become the dominant sedimentary structures. In Facies Association E, sandstones are almost entirely composed of high-energy unidirectional flow indicators such as dune-scale cross-stratification. However, neither sediments rarely have evidence of fluvial processes like channel scours, lateral accretion surfaces or a fluvial-style stratigraphic architecture. Thus, these sediments are interpreted as in the marine environment but with some degree of fluvial influence, i.e. a proximal deltaic environment such as a delta front or delta fan, with some degree of channelisation inferred, but not directly seen in the study area.

Within the formation, the abundance of mudstones decreases upward, as reflected in the described facies and affecting their interpretation (Figures 3, 4). Some upper and middle Bonney sediments (e.g., intervals 75–150 m and 165–217 m) are lacking in basal mudstones, and the sandstone unit thickness is highest in the middle part of the

Table 3. Brief definitions of architectural categories. Taken from Vakarelov and Ainsworth (2013).

Element (E)	An architectural unit that represents the smallest unique, identifiable geomorphological feature and its subsurface equivalent, from which larger-scale architectural units are built.
Element Complex (EC)	An architectural unit that represents a grouping of genetically related elements and element sets that were deposited under similar process conditions in the same part of a depositional system. Element complex boundaries can occur along strike and along dip direction and are marked by the presence of distinct stratigraphic surfaces or abrupt facies boundaries.
Element Complex Assemblage (ECA)	An architectural unit that is formed by a group of genetically related element complexes (or element complex sets if such are defined) that can cumulatively be considered to have been formed under similar process conditions. ECAs are conceptually similar to depositional systems.

section. Environments of deposition based on facies associations are interpreted as generally becoming progressively shallower upward, being dominated by more distal marine environments at the base, shallow marine sediments in the middle, and fluvial-deltaic sediments at the top.

Process and architectural classification

Vertical trends in grainsize and facies stacking patterns allowed the identification of a series of intervals that are separated by interpreted transgressive and regressive surfaces (shown in Figures 3, 4). These intervals can be identified at a variety of hierarchical levels and have been classified into a series of categories: elements, element complexes (ECs) and element complex assemblages (ECAs)—that are fully defined in Vakarelov and Ainsworth (2013) and reproduced in Table 3. Categories are also hierarchical; elements, for example, can be grouped together to form an element complex, and element complexes can be further grouped into ECAs. All categories may display stratigraphic trends that may allow them to be considered parasequences, as the term does not contain a scale in its definition.

Applying this scheme to our data sets, element-scale intervals usually comprise a series of metre-scale coarsening-upward sediments with silty mudstones at their bases and amalgamated sandstones at their tops, or simply comprise amalgamated sandstones. In element complexes and ECAs, elements are usually stacked atop one another, with the overall sand content of these smaller units increasing upward and forming coarsening-upward profiles at scale of tens of metres. Surfaces bounding the intervals are commonly sharp, and marked by a change from sandstones to mudstones or sandstones to finer-grained sandstones upward.

Once identified, shallow marine sediments within ECs were classified as to the primary, secondary or tertiary process operating in the interval—either wave, tidal, or fluvial—denoted by a *Wft* acronym with initials representing the respective amount of influence (Figure 5; Ainsworth et al., 2011). Each interval was thus assigned a stacking pattern

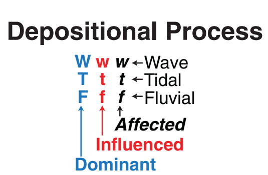


Figure 5. Notation scheme for relative influence of wave, tidal and fluvial processes.

(transgressive or regressive) and ranking of process order (e.g. *Fw*), which was then used to determine the possible range of architectural units (e.g., mouth bar, delta lobe, etc.) using those categories defined by Vakarelov and Ainsworth (2013). From these, the most likely EC was selected.

Interpretation of stacking patterns and architectural elements

The distributions of facies and facies associations within each coarsening-upward or fining-upward interval are shown on the stratigraphic columns. Intervals were classified as either transgressive or regressive based on the sequence of interpreted depositional energies and environments as determined from the constituent facies and facies associations. Most intervals are interpreted as regressive owing to their overall coarsening-upward and shallowing-upward profile. These are commonly bounded by composite surfaces that represent both maximum flooding and maximum regression. Alternatively, regressive ECAs may be separated by very thin transgressive, fining-upward intervals (transgressive element complex assemblages, or TECAs), interpreted to represent the remnants of thicker transgressive deposits that have mostly been eroded during the overlying regressive interval. Thick amalgamated sands overlie many TECAs and are interpreted as channels or proximal deltaic deposits; these may be infilling incised valleys cut during transgression. Valleys are primarily filled by these sands during subsequent regressive intervals, as most of the underlying transgressive deposits are eroded as fluvial sands prograde basinward. Higher in the section (above ~165 m), subtle fining-upward trends in amalgamated sands may represent gradual or minor transgressions but do not return the system to fully marine conditions. Base-level changes reflected in TECAs and regressive ECAs (RECAs) are contained within four major regressive intervals, separated by three maximum flooding surfaces at 68, 152 and 215 m from the base of the formation. These intervals comprise multiple ECAs and are interpreted as sequences, and their bounding surfaces as sequence boundaries. In the single section measured here, the contact between the Bonney Sandstone and Chace Member (at 238 m) cannot clearly be identified as a sequence boundary and is interpreted as a continuation of the regressive sequence beginning at the base of ECA 13. The Chace Member has a slight increase in grainsize compared with the units below, reflecting the continued shallowing-upward trend throughout the formation, but otherwise was not observed to have substantial differences from many of the underlying sands. Throughout the section, regressive ECs and regressive ECAs are interpreted to represent progradational, regressive shoreline pulses, with rapid relative sea-level transgressions between them. Deposition of individual elements is likely not a product of regional base level change, but instead may represent lateral, localised changes in the locus of deposition resulting from lobe-switching or avulsion.

Sediments have varying degrees of wave, tidal and fluvial influence, although definitively tidally influenced sediments are rare, and most intervals can be classified as regressive and fluvially dominated. This results in a narrow range of morphological possibilities for the shallow marine deposits making up each interval. Lower Bonney shallow marine sandstones in ECAs 1−3, for instance, predominantly comprise sedimentary structures generated by unidirectional, upper flow regime currents. Symmetrical wave ripples are also present, but are considered to be a secondary process, and are orientated in a variety of directions, suggesting complex shoreline geometry, changing shoreline orientation or a variety of non-parallel sand bodies affected by shoaling waves. These features, combined with the stacked small-scale, coarsening-upward elements, suggest that these intervals are composed of a series of fluvial mouth bars, deposited in a marine environment with at least moderate wave influence. Individual mouth bars are represented by the sandy tops of each element, with the shaly bases marking a return to quieter, lower shoreface conditions. Sandstones in ECAS 4−8 all consist of fluvially dominated processes, with little or no evidence that indicates substantial influence from other processes. These intervals consist almost entirely of planar, low-angle and trough cross-stratified amalgamated sands. Although these sedimentary structures can be found in a range of depositional settings, the conspicuous lack of features characteristic of other processes indicates that these sands are likely the infill of channels in a proximal fluvio-deltaic setting. The lack of coastal plain fines, potential overbank deposits, lateral accretion surfaces and other characteristics of a fully continental setting indicate that these sands, while strongly fluvial in origin, were still deposited in the marine realm where channels are no longer tightly confined. ECA 9 marks a return to more distal deposition, and the heterolithic beds with HCS show the additional influence of tidal and wave processes. In the upper Bonney Sandstone, the increasingly coarse grainsizes, granule stringers, and cross-stratified sandstones of ECAs 10−16 suggest that these sediments continue a formation-scale coarsening-upward trend and may be even more proximal than those below. The northwest−southeast directionality of paleocurrents in ECAs 8−10 indicate channels orientated in those directions, with bidirectionality possibly resulting from tidal influence. Bidirectional paleocurrents are not seen in the same bed and measurements may be biased owing to the orientation of outcrop exposures, so a tidally influenced channel is not the preferred interpretation. Unlike other intervals, ECA 13 is fine-grained and poorly exposed, and may represent another significant flooding event. On a formation scale, the Bonney Sandstone is thus interpreted here as transitioning from wave-dominated, lower shoreface environment at its base, to a series of distal, marine, delta mouth bars in the lower portion, to proximal fluvio-deltaic channel sands near the top (Table 4). ECs and ECA categories in the Bonney Sandstone are detailed in Table 4, along with a schematic graphic of each element complex, after Vakarelov and Ainsworth (2013). Note that these elements apply only to shallow marine portions of each sequence, and some ECAs only contain a single element complex. Table 4 shows the evidence used to determine the range of processes, the constituent facies and the variety of options considered for each element complex interval.

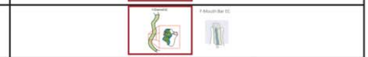
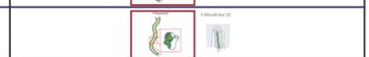
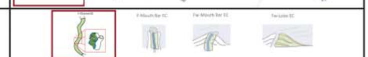
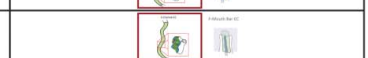
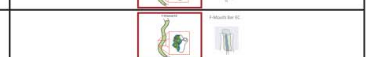
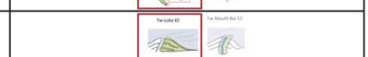
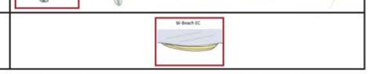
Discussion

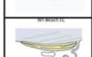
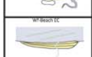
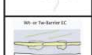
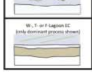
Regional implications and significance

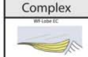
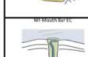
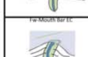
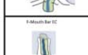
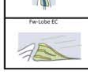
The presence of a fluvial-deltaic system in the Bonney Sandstone provides further context regarding basin evolution and paleogeography in the Adelaide Rift Complex. The Bonney Sandstone and Chace Member of the Rawnsley Quartzite are the only units in the Wilpena Group to show evidence of fluvial processes (Preiss, 1987), likely marking a maximum regressive interval within the group. However, definitive evidence of subaerial exposure (e.g., mudcracks) was not seen, although fine-grained sediments are generally not present at the tops of regressive intervals. An alternative explanation for fine-grained mudstones higher the section is that they result from overbank, coastal-plain deposition or marginal marine, low-energy processes; however, no characteristics exist in these intervals that are definitively diagnostic. Although a red colour persists throughout the Bonney Sandstone and has been recently used as supporting evidence of extensive subaerial exposure (Retallack, Marconato, Osterhout, Watts, & Bindeman, 2014), red shales are not necessarily indicative of terrestrial environments (Tarhan, Droser, & Gehling, 2015). No other indications of paleosol formation were seen in the section measured here, despite it being less than 10 km from the Brachina Gorge section described by Retallack et al. (2014) as containing multiple paleosol horizons. Many of the lines of evidence for a subaerial interpretation of other Wilpena Group sediments have also been called into question (e.g., Callow, Brasier, & McIlroy, 2013), and we consider the Bonney Sandstone in the study area to have been fully deposited in the marine realm. The presence of tidally influenced facies, although not definitive, suggests that the basin was linked to the larger ocean and not completely restricted.

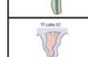
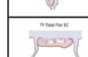
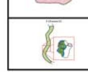
On a large scale, the formation-level shallowing-upward trend seen in the Bonney Sandstone is likely the result of continued progradation and progressive infilling of accommodation in the basin, resulting in increased exposure of upper formation sediments to shoreface and continental processes. Shallowing-upward systems composed of multiple, increasingly proximal parasequences are characteristic of highstand systems tracts (Van Wagoner et al., 1988), as sediments prograde into the basin and fill up available accommodation; this is interpreted to be the case here (Figure 6). As neither parasequences nor systems tracts are defined by their scale, this formation could also be interpreted as consisting of multiple highstand

Table 4. Summary and classification of shallow marine depositional elements. Graphical representations of ECs from Vaklerov and Ainsworth (2013). Stratigraphic locations of ECs and ECAs are shown on the measured sections in Figures 3 and 4.

Element Complex Assemblage	Element Complex	Features indicating depositional Process			Grain size and bed thickness trends	Constituent Facies	Constituent Facies Associations	Most Likely Depositional Processes	Possible Architectural Classifications
		Wave	Tidal	Fluvial					
ECA 16 / ?	EC21	Planar- to low-angle lamination, planar tabular cross-stratification	Planar- to low-angle lamination, planar tabular cross-stratification	Planar- to low-angle lamination, planar tabular cross-stratification, small scours	Trends not apparent	2	E	F	
ECA 15 / TECAS 8	EC20	Planar- to low-angle lamination, planar tabular cross-stratification	Planar- to low-angle lamination, planar tabular cross-stratification	Planar- to low-angle lamination, planar tabular cross-stratification	Sandy, faintly coarsening-upward profile	5, 2	E	F	
ECA 14 / TECAS 7	EC19	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification, planar tabular cross-stratification	Trough cross- stratification, Planar- to low-angle lam., Asymmetric ripples, planar tabular cross-strat.	Sandy fining-upward profile	2	E	F	
	EC18		Heterolithic beds	Asymmetric ripples	Sands at top, coarsening-upward from thick muds	1, 2, 5	E, F	F	
ECA 13 / RECAS 7	EC17	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification, Asymmetric ripples	Trends not apparent	2, 7	F	Tf Ft	
ECA 12 / TECAS 6	EC16	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification, Asymmetric ripples	Sandy fining-upward profile	1, 2, 5, 7	E, F	F	
ECA 11 / TECAS 5	EC15	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification, Asymmetric ripples	Sandy fining-upward profile	2, 5	D, E	F	
ECA 10 / TECAS 4	EC14	Planar- to low-angle lamination, trough cross-stratification, symmetrical ripples	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Sandy fining-upward profile	4, 5, 7	A, D	F Fw	
ECA 9 / RECAS 6	EC13	HCS, Planar- to low-angle lamination, trough cross-stratification	Heterolithic beds	Asymmetric ripples trough cross-stratification	Single large-scale coarsening-upward interval	7, 5	A	Wf Tf	
ECA 8 / RECAS 5	EC12	Planar- to low-angle lamination, trough cross-stratification, HCS	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Trends not apparent	2, 5, 6	D	F Fw	
ECA 7 / RECAS 4	EC11	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Single sandy, large-scale coarsening-upward interval	2, 5	D	F	
ECA 6 / TECAS 4	EC10	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Sandy fining-upward profile	2, 5	D	F	
ECA 5 / RECAS 3	EC9	Planar- to low-angle lamination, trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification	Trough cross-stratification, Planar- to low-angle lamination, wedge-shaped, discontinuous beds	Single large-scale coarsening-upward interval	7, 5	C, E	F	
ECA 4 / TECAS 3	EC8	Planar- to low-angle lamination	Planar- to low-angle lamination	Planar- to low-angle lamination	Fining-upward profile	2, 4	C, D	F	
ECA 3 / RECAS 2	EC7	Symmetrical Ripples, interference ripples, Planar- to low-angle lamination	Interference ripples planar- to low-angle lamination, heterolithic beds	Scour/erosive surfaces asymmetric ripples	Series of coarsening- and thickening-upward intervals, with increasing sand content upward	1, 2, 3, 5, 7	B, C, D	Fw	
	EC6	Symmetrical Ripples, Planar- to low-angle lamination, Trough cross-stratification	Planar- to low-angle lamination, trough cross-stratification, heterolithic bedding	Planar- to low-angle lamination, trough cross-stratification	Series of coarsening- and thickening-upward intervals	1, 2, 4, 5, 7	B, C	Fw Wf	
	EC5	Symmetrical Ripples, Planar- to low-angle lamination, Trough cross-stratification	Planar- to low-angle lamination, Trough cross-stratification	Planar- to low-angle lamination, Trough cross-stratification	Two coarsening-upward intervals	1, 2, 4, 5	B, C	Fw Wf	
ECA 2 / TECAS 1	EC4	Planar- to low-angle lamination	Planar- to low-angle lamination, Heterolithic beds	Planar- to low-angle lamination	Fining-upward profile	7	B	Wt Tw	
	EC3	Symmetrical Ripples, Planar- to low-angle lamination	Planar- to low-angle lamination	Planar- to low-angle lamination	Series of coarseningand thickening-upward intervals, usually sand-dominated			Fw Wf	
	EC2	Symmetrical Ripples, Planar- to low-angle lamination	Planar- to low-angle lamination	Planar- to low-angle lamination	Series of coarsening- and thickening-upward intervals, with increasing sand content upward	1, 2, 4, 7	B, C	Fw Wf	
ECA 1 / RECAS 1	EC1	HCS	Heterolithic beds		Increasing sand upward	7	A	W	
See detailed stratigraphic column in Figure 3		Primary depositional process	Secondary depositional process	Tertiary depositional process	See detailed stratigraphic column in Figure 3	See Table 1	See Table 2	W w *w* ←Wave T t *t* ←Tidal F f *f* ←Fluvial ***Affected*** Influenced Dominant	See Vakarelov and Ainsworth (2013) = Preferred Interpretation

Element Complex	Definition
	*W Beach*- Shore-parallel linear unit with very little or no influence from rivers and tides. Includes foreshore as well as both lower and upper shoreface facies
	*Wt Beach*- Shore-parallel linear unit; linear coastline where foreshore is extended by tides and intertidal bars are formed.
	*Wf Beach*- Shore-parallel linear unit; linear coastline supplied by small rivers but without any shoreline protrusion; fluvial sediments reworked by waves
	*Wt or Tw Barrier*- Barrier EC forming in areas with higher tidal range; increased heterogeneity due to tidal channels and associated washover facies
	*W, T, or F Lagoon*- EC that forms landward of a barrier and shoreward of the mainland, consisting of sediment that fills lagoon after the onset of regression

Element Complex	Definition
	*Wf Lobe*- Delta lobe forming laterally to Mouth Bar Element Complex due to along-shore migration of sediment from wave action; always next to MB
	*Wf Mouth Bar*- Central portion of delta lobe, reworked by wave action to be more elongate along shore than Fluvially dominated MBs
	*Fw Mouth Bar*- Central portion of delta lobe along ansemi-protected coast with little or no tidal influence, elongated along shore, moderately heterogeneic
	*F Mouth Bar*- Fan-like deposits containing numerous individual mouth bars, or elongate sandy systems that are separated by indistributary units
	*Fw Lobe*- Delta lobe, lateral to Mouth Bar, supplied by fluvial sedient with some degree of wave reworking. Represents a single pulse of shoreline progradation.

Element Complex	Definition
	*Tf, Twf, or Tfw Mouth Bar*- Mouth bar (delta lobe) significantly reworked by tidal action; moderate heterogeneity
	*Tf Lobe*- Delta lobe forming laterally to Mouth Bar Element Complex, often between two distributary channels
	*Tf Tidal Flat*- Broad area periodically inundated by tides, usually containing both muds and sands, may be cut by tidal channels
	*Tw Tidal Flat*- Broad area periodically inundated by tides, usually containing both muds and sands, less fluvial influence than *Tf*
	*F Channel*- Channel belt; all deposits realted to the migration and formation of single channel bodies. Not tidally influenced, occurs on delta plain and upstream

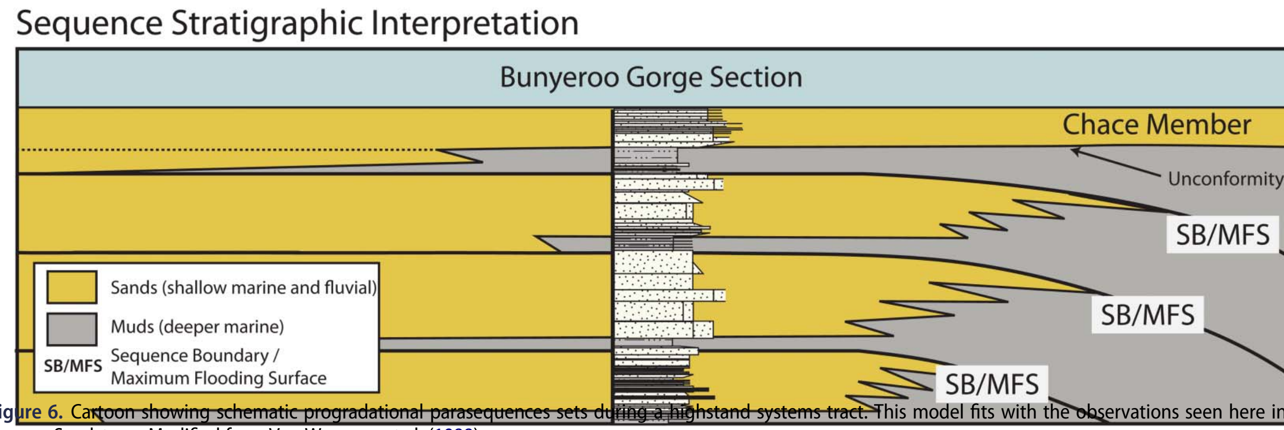


Figure 6. Cartoon showing schematic progradational parasequences sets during a highstand systems tract. This model fits with the observations seen here in the Bonney Sandstone. Modified from Van Wagoner et al. (1988).

systems tracts, stacked atop one another, with sequence boundaries in between. Sequence boundaries are defined by their regional nature, and thus a full sequence stratigraphic interpretation is beyond the scope of this study. The tentative regional correlation in Figure 7, however, suggests that these surfaces may indeed be regionally extensive. Gehling (2000) interprets the top of the Bonney Sandstone as a type 2 sequence boundary, but does not recognise internal sequences within the Bonney Sandstone based on his regional mapping.

Flooding events and generation of new accommodation space at all scales may be due to a number of possible mechanisms but are most likely related to either eustatic sea-level change or changes in regional tectonic subsidence. As the sediments were likely adjacent to a continental craton on the margin of a former rift basin with a very thick fill, it is likely that subsidence was substantial and rapid in the area. In addition, Wilpena Group sediments in the basin show no evidence for rapid (1 Ma-scale or less) global sea-level and climate

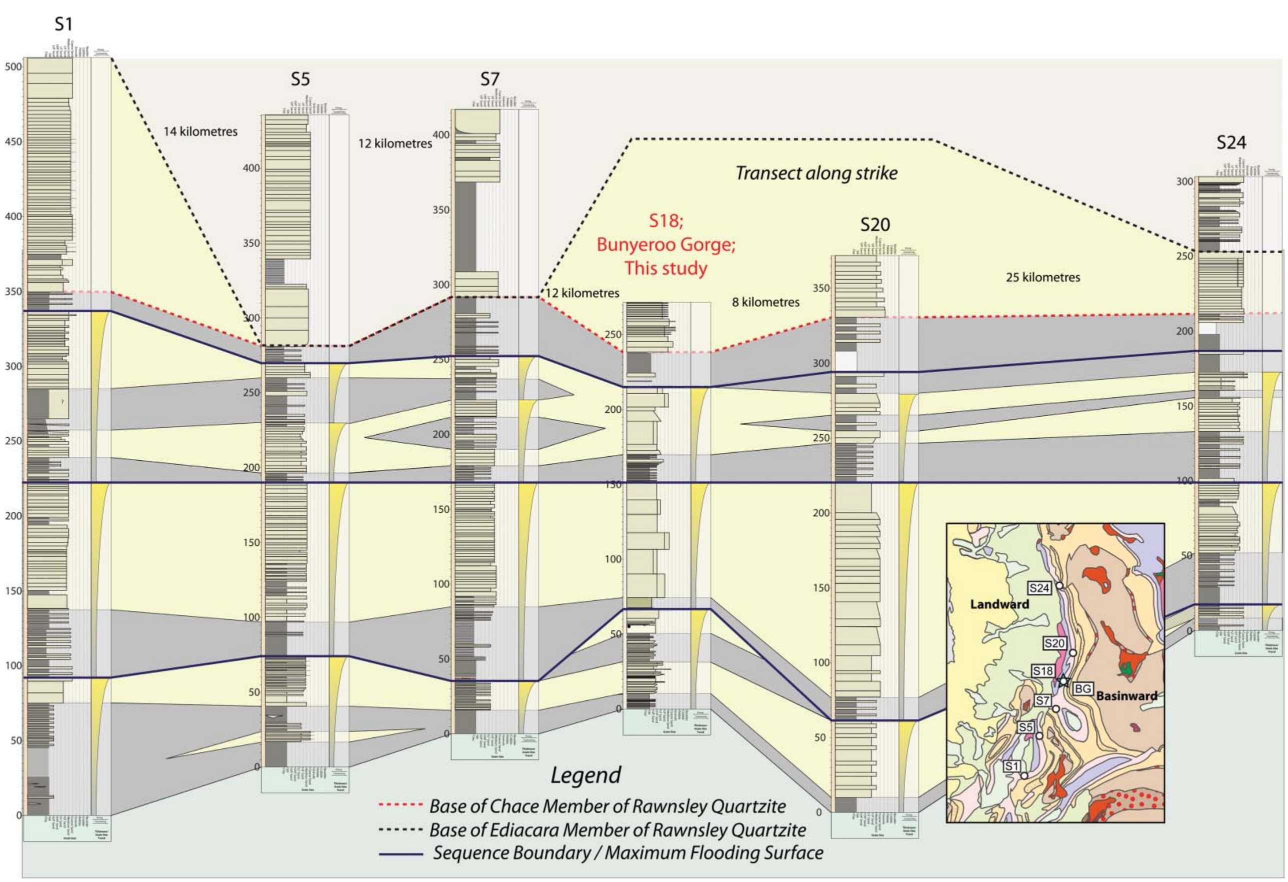


Figure 7. Correlation with Gehling's (1982) Bonney Sandstone measured sections. Locations shown in inset map.

fluctuations, as in, for example, the early Permian (Miller, McCahon, & West, 1996). However, without extensive sequence stratigraphic correlation, a definitive cause of relative sea-level fluctuations cannot be established. It is also possible that parasequences are the result of an autocyclic process that is not related to sea-level change. In a fluvial-deltaic shallow marine system, parasequences can be generated by lobe-switching and lateral shifting of facies near river mouths (Swift, Phillips, & Thorne, 1992). This is interpreted as being the most likely case with the smaller elements and ECs.

Correlations by the authors using five of Gehling's (1982; appendix) measured sections of the Bonney Sandstone are useful in demonstrating along-strike consistency of internal lithostratigraphic divisions across approximately 70 km, providing a way of estimating the size of depositional units present (Figure 7). While individual beds cannot be correlated across these sections, general divisions and maximum flooding surfaces can be. Based on regional paleogeography, it is likely that the north–south transect defined by these points is roughly parallel to the paleoshoreline. The paleocurrent data in Gehling (1982) show a range of currents in cross-stratification in all directions except west, a result similar to the collated paleocurrents seen here. Both this study and that of Gehling (1982) recognise the overall shallowing-upward nature of the formation, and a comparison of the same measured section between the two studies over 30 years apart shows that most observations are in agreement, although some interpretations differ. Notably, most intervals were interpreted by Gehling (1982) as being fining-upward, rather than coarsening as described here. Additionally, lower Bonney sediments were interpreted by Gehling (1982) as having a substantial degree of tidal influence; instead, the section is interpreted here as being dominated by fluvial processes with only a small contribution from waves and tides. The 'petee' structures described in the Chace Member were not observed in the section measured here. Since these features are thought to be related to evaporite crystallisation and expansion within sands, they are critical to Gehling's (1982, 2000) intertidal interpretation for this unit. In our observations, this unit's lithologies consist only of cross-stratified and planar-laminated, granule-bearing sands, and as such it is interpreted to be similar to the high-energy deltaic channel-fills seen elsewhere in the mid- to upper Bonney Sandstone.

Zircon data from Ireland et al. (1998) indicate a Grenville-age source of these sandstones, possibly from the Musgrave province to the north, indicating that fluvial input from the Gawler Craton was likely minor. Thus, the deltaic system seen here most likely originated in another part of the basin, rather than coming directly from the landmass directly west of the study area. As the possible origin of sands is far to the north, a northern origin for the locus of the delta is favoured, and would be consistent with more north–south paleocurrents for unidirectional flow indicators seen here. These sediments may have entered from the northern part of the semi-restricted basin and been transported southward along the western basin margin. The widespread occurrence of very similar facies in distal Bonney Sandstone equivalents (e.g., Punkerri Sandstone, Arumbera Sandstone; Grey & Calver, 2007) suggests a widespread interval of shallow marine conditions across Australia, which can now be better compared with the continental margin where the section here was deposited.

Approaches to sedimentological interpretation with limited datasets

This study demonstrates the benefit of a multi-faceted approach to interpretation in sedimentary successions that are lacking in certain diagnostic criteria or context, limited in exposure, or on which few previous studies have been conducted. Ideally, interpretation would incorporate many lines of evidence: geochemistry, ichnology, stratigraphic context, regional correlations, paleontology, etc. In the section described here, the lack of these sources of information necessitates that individual facies be the building block for further analyses. When interpreted correctly, the distinction between two facies is a meaningful separation that reflects a fundamental difference in the depositional conditions over time and/or space. In some cases, a single facies alone can substantially restrict the range of possible depositional environments; facies may show a process directly responsible for sediment emplacement that is unique to certain environments (oscillatory flow, for example, which is limited only to environments occurring within wave base). In other instances, information about the variety of these processes operating (in the form of facies associations) is needed to understand a particular depositional setting. Stratigraphic occurrence of two or more facies together, however, does not inherently create a meaningful facies association. Adjacent juxtaposition of facies may cross sequence or parasequence boundaries, and environments may rapidly shift between one facies and another. Thus, when assigning facies associations, some degree of interpretation is required that takes into account the processes expected to co-occur in a given environment. Once assigned, facies associations can be applied to standard facies models to allow for the interpretation of large-scale environments (delta front, shoreface, etc.).

Facies models provide an archetype from which interpretation can be based on, which can take on a range of forms. However, sedimentary successions in the 'real world' rarely conform perfectly to idealised spatial or stratigraphic models of facies occurrence, creating uncertainty in interpretation. The system of architectural classification defined by Vakalerov and Ainsworth (2013) provides a way to deal with this uncertainty. By providing a fixed set of depositional elements at a hierarchy of levels for each process (W–T–F)-stacking pattern (transgressive/regressive) combination, unlikely interpretations are eliminated as possibilities. The scale of parasequences seen here requires interpretation at the level of the element complex, an architectural unit representing a group of smaller elements deposited under similar process conditions in the same part of a depositional system. Thus, uncertainty in interpretation in the Bunyeroo Gorge section is expressed as a narrow range of possible ECs, which are based on extensive observations in a variety of modern and ancient sediments. This process-based classification applies only to shallow marine deposits as it is built to assist in the interpretation of petroleum reservoir geometries in the subsurface. It does not contain architectural elements for sedimentary deposits in deepwater or shelfal systems, nor for those in continental or fluvial environments. As such, in real-world sedimentary successions, a mixed approach to interpretation is required, incorporating both an architectural classification and assumptions using facies models. In addition to inherently promoting uncertainty owing to deviation from a rarely occurring ideal, facies models alone do not fully describe all aspects of a sedimentary succession. Properties at both larger and smaller scales exist that assist in putting together a complete picture of the interval in question. Lower shoreface environments, for example, may encompass both mudstones and amalgamated sandstones at the top, and contain sedimentological trends within and across the lower shoreface facies association. The process-based analysis of parasequences applied here (Vaklerov & Ainsworth, 2013) also provides a way to add additional information to an interpretation based on facies associations. The 25 defined ECs provide more precise information on the morphology of geobodies within a given environment than the more general facies associations; e.g., subclasses of the shoreface environment include beach, lobe, mouthbar, etc. This is important in the prediction of stratigraphic and spatial architecture of these units, which are potential reservoir analogues. This method also allows for transparency at all stages of the interpretation process (shown in Table 4), permitting the reader to better understand the available evidence and the ways that conclusions were drawn.

Conclusions

The Bonney Sandstone section in Bunyeroo Gorge provides an opportunity to demonstrate that reasonable, reproducible interpretations can be made in a sedimentary succession that consists solely of lithologies and physical sedimentary structures. The formation in the study area is part of a progradational, fluvially dominated deltaic system with minor influence from wave and tidal processes, and increasing proximality over time. Identified depositional elements include proximal fluvial-deltaic channels, fluvial mouth bars, tidally and fluvially influenced delta lobes, and wave-dominated shorefaces, as determined using both facies models and process-based architectural classification. Sediments are primarily contained within regressive intervals on a scale of tens of metres, bound by composite maximum transgressive–regressive surfaces, although in some cases, these surfaces are separated and a transgressive interval is preserved. Four major shallowing-up sequences are found in the formation, separated by three maximum flooding surfaces. The results shown here provide new information regarding the paleogeographic and sea-level history of South Australia, and also provide context for the early metazoan fossil assemblage in the overlying Ediacara member, which immediately postdates the sediments described here.

Acknowledgements

This research is supported by a University of Adelaide International Postgraduate Research Scholarship and the AAPG Nancy Setzer Murray Memorial Grant. This paper forms TRAX manuscript number 347. Access to field localities was granted by DEWNR scientific research permit Q26318-1. We acknowledge the traditional inhabitants of the land on which this research was conducted.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

J. W. Counts http://orcid.org/0000-0001-7374-6928

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