Nature and significance of the Neoproterozoic Sturtian–Marinoan Boundary, Northern Adelaide Geosyncline, South Australia

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The Cryogenian succession of the Northern Flinders Ranges reveals a complex sedimentary record between the Sturtian and Marinoan glacial deposits. A major unconformity separates the Sturtian and Marinoan-aged sedimentary successions in the area. This forms a subaerial erosion surface with terrestrial and marginal marine infill directly above the Angepena and Balcanoona Formations in their respective localities. This exposure surface is here correlated with the previously documented submarine unconformity between the Yankaninna Formation and the underlying deep marine Tapley Hill Formation. This erosional event provides a chronostratigraphic marker horizon that coincides approximately with the previously defined Sturtian–Marinoan Time Series boundary in the Northern Flinders Ranges. These stratigraphic relationships also constrain lateral facies relationships between the Oodnaminta Reef Complex (Balcanoona Formation) and the Angepena Formation. Similarly, the shallow-water Weetootla Dolomite is correlated with the deeper water carbonates of the Yankaninna Formation.

KEY WORDS: Cryogenian, Sturtian, Marinoan, Umberatana Group, stratigraphy, Balcanoona Formation, Angepena Formation, unconformity.

INTRODUCTION

At least two very severe glaciations occurred during the Neoproterozoic (ca 750–630 Ma), and these are generally known as the Sturtian (older) and Marinoan (younger) glacial events. In addition, this general period of glacial activity (Cryogenian) almost certainly records the origin of metazoan animal life (e.g. Love et al. 2009; Maloof et al. 2010; Sperling et al. 2010). The Adelaide Geosyncline of South Australia contains a Neoproterozoic sedimentary succession that provides an outstanding record of the two major glacial events and the intervening interglacial sequence of the Cryogenian. However, there are few geochronological constraints on Cryogenian sediments of the Adelaide Geosyncline, where the Sturtian and Marinoan glacials were first recognised. Furthermore, there is now considerable uncertainty about how the Australian Sturtian and Marinoan glacial episodes relate to glacial succession on other continents (Calver et al. 2004; Allen & Etienne 2008). Usage of the Australian Sturtian and Marinoan terminology for Neoproterozoic glacial episodes worldwide appears now to be entrenched in the international literature. Such terminology is reasonable given the early development of knowledge on Neoproterozoic glacial deposits was heavily influenced by the Adeliean succession of South Australia (e.g. Chewings 1901; Howchin 1901; Mawson 1949). However, at present, the problems in global chronostratigraphic correlation of the Neoproterozoic glacial deposits inhibit usage of these terms internationally. Geochronological and stratigraphic studies of the Sturtian and Marinoan sediments of South Australia will contribute to improved understanding of this time period.

In this study, we examine the litho- and chronostratigraphic relationships of the interglacial succession between the Sturtian and Marinoan glacial deposits. We also examine the stratigraphic basis of the Sturtian and Marinoan Time Series (Mawson & Sprigg 1950), terms that are now used globally to denote the two major Neoproterozoic glacial episodes.

GEOLOGICAL SETTING AND AGE CONSTRAINTS

The Adelaide Geosyncline contains a Neoproterozoic to Cambrian aged sedimentary succession (the term ‘geo-
syncline’ is used as a non-genetic, historical term; see Williams et al. 2008). The basin consists of relatively undeformed sediments with a total stratigraphic thickness of over 12 km. This thick sedimentary succession has resulted from ongoing deposition beginning at ca 830 Ma and finishing in the Middle Cambrian (Coats & Bliss et al. 1971; Preiss 2000). The basin was subsequently deformed in the Delamerian Orogeny, which has been dated between ca 514 and 490 Ma (Foden et al. 2006). Age constraints for the Cryogenian Umbertana Group still remain poor due to a lack of volcanically derived deposits in the Adelaide System that can

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provide radiometric ages. A tuffaceous horizon within a terminal Sturtian glacial unit near Copley in the Northern Flinders Ranges gave a U–Pb zircon age of 659 ± 6 Ma (Fanning & Link 2008), which is supported by a Re-Os age of 643 ± 2.4 Ma from the overlying Tindelpina Shale of the Tapley Hill Formation (Kendall et al. 2006). There are no good age constraints for the Maroon glacial deposits (Elatina Formation), but correlation with other glacial successions of possible Maroon age from the Ghaub Formation in Namibia (Hoffmann et al. 2004) indicates an age of ca 635 Ma. However, there is considerable uncertainty in correlating the Australian Maroon with other ‘Maroon-age equivalents’ elsewhere. A recent study of in situ authigenic monazite grains from the Maroon-aged Enorama Shale gave a Th–U–total Pb age of 680 ± 23 Ma (Mahan et al. 2010). This date is inconsistent with those of both Kendall et al. (2006) and Fanning & Link (2008).

The chronostratigraphic framework of the Neoproterozoic sediments of the Adelaide Geosyncline was first outlined by Lawson & Sprigg (1950), where the stratigraphy of their Adelaide System was divided into three chronostratigraphic groupings. These groups were named the Torrensian, Sturtian and Maroon Time Series. These sub-divisions were based on the apparent timing of the climatically distinct sedimentary successions of the regionally extensive glaciogene and redbed sediments as found in the Adelaide Geosyncline. The Torrensian-Sturtian boundary was placed at the first occurrence of glacial sediments within the Adelaidean succession (hence, named the Sturtian Glaciation), while the Sturtian-Maroon boundary was placed where redbed sediments (the Angepena Formation) were first encountered within the succession. The second and youngest glacial occur within the Maroon succession after this boundary transition (hence, named the Maroon Glaciation).

The terms Sturtian and Maroon have fallen into common usage when discussing other globally recognised late Neoproterozoic glaciations, despite occurring far away from the type locality of the Adelaide Geosyncline. We apply the Adelaidean Time Series nomenclature to exclusively denote each of the large glacial events found within the type locality. Considering the Sturtian and Maroon nomenclature is still applied to other global Neoproterozoic glacial successions, it is important to define the stratigraphic timing and characteristics of the Sturtian-Maroon boundary from where it was first described.

Mawson & Sprigg’s (1950) chronostratigraphic framework was subsequently modified by Thompson et al. (1964) who retained the Adelaide Time Series stage boundaries, but proposed the Adelaide System be grouped into large-scale chronostratigraphic units: the Callanma beds, Burra Group, Umberatana Group and Wilpena Group. Unit boundaries are closely related to the original Adelaide Time Series boundaries.

Mawson & Sprigg (1950) defined the Sturtian-Maroon Time Series boundary at the upper contact of the Brighton Limestone and the un-named overlying sedimentary successions ‘characterized by red-bed conditions which followed the widespread Sturtian glaciation.’ This formation boundary is generally gradational (even in the type section), and therefore difficult to constrain in a chronostratigraphic context, mostly because Mawson & Sprigg’s (1950) definition is more a litho-stratigraphic classification. The Time Series subdivision of Mawson & Sprigg (1950) was subsequently abandoned in later literature concerning the regional stratigraphy of the Adelaidean sediments (eg. Preiss 1987; Preiss et al. 1998) but the Sturtian–Maroon terminology has been widely used when discussing Neoproterozoic glaciations.

The lithostratigraphic boundary of the Nepouie and Upalima Subgroups (as defined by Preiss et al. 1998) of the Umberatana Group has largely replaced the Sturtian-Maroon Series boundary (as did the defunct Farina and Willohra Subgroups of Coats & Bliss 1971) since the basal Upalima Subgroup is placed at this boundary (Preiss et al. 1998). Preiss et al. (1998) identify the presence of the Sturtian–Maroon boundary in the Northern Flinders Ranges (Oodnaminta area), at the erosional surface found at the contacts of the upper Balcanoona Formation (the northern equivalent of the Brighton Limestone) and lower Yankinna Formation where they occur.

METHODS

To determine the depositional timing and stratigraphic positions of individual units of the interglacial Umberatana Group, stratigraphic sections were measured through the Nepouie and lower Upalima Subgroups in the northeastern Flinders Ranges. This was achieved by using a 1.5 m Jacob Staff in selected field localities. Field sites were selected based on their relative geographic positions in regard to outcrops of Balcanoona Formation; with particular focus around the reef margin outcropping at Oodnaminta. Specific localities (Figure 1) are in the vicinity of the following landmarks (with measured sections bearing that name); Nepouie Creek (NC), Mt Jacob (MJ), Woolltana Caves (WC), Arkaroola Quarry (AQ), Wortupa Well (WW) and Old Illinawortina (ILL). Stratigraphic columns were constructed to ascertain the relative timing of the various sedimentary deposits, and used to correlate lithological units found within the interglacial period of the Umberatana Group (Figure 2).

RESULTS

Tapley Hill Formation

The deep-water shales of the Tapley Hill Formation (as defined in the Northern Flinders Ranges by Coats; in Thompson et al. 1964) overlie the Sturtian glacials. Giddings et al. (2009) defined several informal chronostratigraphic units within the Tapley Hill Formation in the Northern Flinders Ranges. These informal units occur above the formally defined Tindelpina Shale Member (Coats; in Thompson et al. 1964) and, in order of oldest to youngest, are as follows: Siltstone Unit, Cyclic Unit, Quartz-Sandstone Unit and Transitional Shale Unit.
At Nepouie Creek (Figure 3, section NC), the Tapley Hill Formation begins with interbedded laminated dolomites and shales. This unit is recognised as the Tindelpina Shale Member as defined by Coats (in Thompson et al. 1964). The Tindelpina Shale Member is approximately 80 m thick in the Nepouie area and consists of finely laminated dolomites interbedded within non-calcareous shales. Dolomite interbeds are most abundant at the base of this unit becoming sparser upwards passing into very finely laminated shales. The lowest dolomite beds contain some coarse clastic material of sand to cobble-sized fragments in a dolomitic matrix. These beds grade upwards into thin silty and sandy dolomite interbeds separated by finely laminated shales. These shales of the Tindelpina Shale Member then grade into the Siltstone Unit, which consists of fine calcareous siltstones with thin cross-laminated intervals occupying a thickness of only around 40 m. The Cyclic Unit is not readily identifiable above the Siltstone Unit in this area. However, a 50 m thickness of calcareous shales is present in the stratigraphic position of the Cyclic Unit. Above this calcareous shale interval, a series of small-scale Bouma sequences mark the onset of the Quartz-Sandstone unit. The lowest of the turbiditic beds contain basal conglomerates of sandstones and carbonates corresponding to the A division of a typical Bouma sequence. The Quartz-Sandstone Unit in this area is particularly thick measuring ~230 m. This large thickness of the Quartz-Sandstone Unit (and particularly thin Cyclic Unit) suggests that it is a lateral equivalent of the Cyclic Unit found in other areas. The Transitional Shale Unit overlies the Quartz-Sandstone Unit and consists of ~320 m of calcareous shales with occasional thin (<10 cm) siltstone beds of possible turbiditic origin. The Transitional Shale Unit grades upwards into the basal stromatolitic limestones and dolomites of the Balcanoona Formation. The interbedded shale and
limestone lithology has preserved the basal stromatolites in a spectacular manner as domal and pseudo-columnar forms.

West of the Paralana Fault in the Wortupa Well area (Figure 4, section WW), ~70 m of the Tindelpina Shale Member occurs as a finely laminated dolomite facies, which grade up into interbedded carbonate and shale beds. The Siltstone Unit is found immediately above the Tindelpina Shale Member and occupies a thickness of 40 m. The Cyclic Unit is well developed in this area and consists of several (21) thin carbonate beds (each ~20 cm thick) spaced ~4–6 m apart within 107 m of calcareous shale. The Transitional Shale unit continues above the Cyclic Unit for some 260 m and hosts several sedimentary mega-breccia horizons. The base of these block horizons often has erosional bases. These mega-breccia horizons also contain large allochthonous blocks of Balcanoona Formation. These allochthonous blocks range in size from fist-sized clasts to blocks up to 300–400 m in diameter. These blocks are a result of mass wasting from the steep slope of a nearby reef margin (Giddings & Wallace 2009; Giddings et al. 2009).

Balcanoona Formation

In the northern Flinders Ranges, the Balcanoona Formation (as defined by Coats & Blisset 1971) is stratigraphically correlated to the stromatolitic and ooidal carbonates of the Brighton Limestone of the Mt Lofty Ranges and the Flinders Ranges. In its type section at Nepouie Creek (Figure 3, section NC), the Balcanoona Formation reaches a vertical thickness of approximately 150 m. Further north in the Mt Jacob (Figure 4, Section MJ) area, the Balcanoona Formation attains 280 m in thickness, and thickens to over 450 m where the outcrop terminates against the Paralana Fault, east of Arkaroola Homestead.

To the west of the Paralana Fault, the Balcanoona Formation attains a maximum thickness of over 1000 m, where it forms a carbonate platform that abruptly terminates as a reef escarpment north of Oodnaminta Hut where younger sediments onlap the escarpment (Giddings et al. 2009). This abrupt ‘thinning’ of the Balcanoona Formation has previously been interpreted as a submarine escarpment formed by erosion (Coats & Blisset 1971), at which Preiss et al. (1998) placed the Sturtian–Marinoan Boundary in the area. Recent investigations by Giddings et al. (2009) indicate that the submarine escarpment originally described by Coats & Blisset (1971) formed as a result of the termination of a large prograding reef margin. The carbonate platform of the Balcanoona Formation has prograded over the uppermost mega-breccia horizon hosted by the Transitional Shale Member of the Tapley Hill Formation.

In its type section at Nepouie Creek (Figure 3), the Balcanoona Formation can be divided into an upper and lower unit; the lower unit consists of stromatolitic limestone and dolomites. The upper units consist of dolomitised ooid grainstones in which fenestrae are
Figure 3 Detailed stratigraphic section of the Nepouie Creek area demonstrating informal lithological members of the Tapley Hill Formation.
Figure 4 Compiled stratigraphic sections of the Mt Jacob, Wortupa Well and Illinawortina regions. Dashed lines represent chronostratigraphic correlations between respective sections.
Further north near Arkaroola Homestead, the unit consists of the lower stromatolitic and upper fenestral ooidal facies with large bedding-parallel, often planar sheet cavities (after Shinn 1983) containing abundant fibrous cements. The sheet cavity grainstone units of the Balcanoona Formation grade laterally into fenestral or birdseye grainstones in the Arkaroola–Mt Jacob–Nepouie regions. These birdseye cavities of the Balcanoona Formation are in-filled with primary fibrous marine cements, followed by a secondary sparry burial cements (Figure 5a, b).

The stratigraphic section measured at Wortupa Well (Figure 4, section WW), west of the Paralana Fault system, transects the reefal platform ~10 km south of Oodnaminta Hut. Here, the total thickness of the Balcanoona Formation is 740 m thickening to the north to over 1000 m (Giddings & Wallace 2009). Several internal reef litho-facies are identified in this transect; a basal fore-reef talus or slope deposit, overlain by a lower biological (non-stromatolitic) reef-core or skeletal framework, which then grades into an upper stromatolitic framework. The sheet cavity bearing grainstone facies overlies the stromatolitic framework. These sheet cavity grainstones laterally thin and eventually pinch out in the vicinity of Oodnaminta Hut behind the reef margin.

**Angepena Formation**

The Angepena Formation (Coats & Blissett 1971) is a series of interbedded red dolomitic mudstones and pink to buff weathering dolomites. In the study area, the formation is only present east of the Paralana Fault in the Nepouie–Mt Jacob region. The Angepena Formation conformably overlies the Balcanoona Formation with a gradational contact. The total thickness of the formation as measured is 552 m thick (west of Mt Jacob; Figure 4, stratigraphic section MJ) and is unconformably overlain by the Weetootla Dolomite.

Typical lithologies found within the Angepena Formation are pink dolo-mudstones and oolitic grainstones and buff stromatolitic dolomites. The lower portion of the formation is characterised by red to maroon, finely laminated dolomitic muds. These are regularly

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**Figure 5** Outcrop photographs of primary sedimentary features of the Balcanoona and Angepena formations. (a) Sheet crack of the platformal facies of the Balcanoona Formation. Arrows indicate: P, primary multi-generation isopachous marine cements lining planer sheet cavities and S, secondary burial sparry cements infilling the remaining cavity space of sheet cavities. 2 cm coin for scale. 30°25′27″S, 139°15′39″E. (b) Birdseye fenestrae cavities in the Balcanoona Formation congregating along bedding planes where they may form poorly developed sheet cavities. Geological hammer for scale. 30°22′09″S, 139°23′03″E. (c) Tepee structures of the Angepena Formation. Geological hammer for scale. 30°22′14.5″S, 139°22′40″E. (d) Intraclassic conglomerates and tepee structures in carbonates of the Angepena Formation. Conglomeratic clasts are often formed of pink silty dolomites and then encased in a red mud matrix. Note the planar erosion surface cutting the irregular surface and crests of tepees. A 2 cm coin is shown for scale. 30°22′14.5″S, 139°22′40″E.
interbedded with cyclic pink dolomite beds (<2 m thick). The pink/maroon colour is due to a hematite content of up to 10% (Coats & Blisset 1971). The pink mudstones and dolomites contain abundant rip-up clast horizons, mud cracks and tepee structures (Figure 5c, d). The tepee morphology is generally of the embryonic to mature type (Assereto & Kendall 1977). Tepees are nearly always accompanied by intraclast breccias in their immediate vicinity. While still dominated by pink dolomite lithologies, the upper portion of the formation contains buff-coloured stromatolitic dolomites. These stromatolite beds become more common towards the top of the formation, which is capped by a 25 m thickness of grey, relatively featureless silty shale. The shale is unconformably overlain by the Weetootla Dolomite, the thickness and regularity of dolomite beds becoming more prominent both up section and to the north.

At the contact between the Balcanoona and Angepena formations, interbeds of Balcanoona Formation-type lithologies (sheet-cracked fenestral grainstones) occur within pink dolomitic muds and dolomites of the Angepena Formation (i.e. the Angepena Formation has a conformable and gradational contact with the underlying Balcanoona Formation). The sheet cracked grainstones of the Balcanoona Formation increase in thickness and abundance to the north, and this suggests the Balcanoona and Angepena formations are lateral equivalents (Figure 6).

**Yankaninna Formation**

Finely laminated calcareous silts and grey micritic limestone are characteristic of the Yankaninna Formation (as defined by Coats; in Thompson et al. 1964). Where the Yankaninna Formation occurs in basinial environments (at Illinawortina and Oodnaminta; Figure 4) it disconformably overlies the Transitional Shale Unit of the Tapley Hill Formation (Giddings et al. 2009). At Illinawortina, laminated micritic limestone beds occur within calcareous silts and shales. These laminated limestones units usually outcrop as two or three regionally persistent bands. The lower Yankaninna Formation also commonly displays soft sediment deformation and slump structures. Near Oodnaminta Hut, the calcareous silts, shales and limestones of the Yankaninna Formation onlap the platform margin of the Balcanoona Formation (Giddings & Wallace 2009; Giddings et al. 2009). The uppermost carbonate unit contains giant ooids (up to 8 mm in diameter) where it onlaps the Balcanoona Formation.

**Weetootla Dolomite Member**

The Weetootla Dolomite Member (of Coats & Blisset 1971) unconformably overlies the Angepena Formation east of the Paralana Fault. This unit is approximately 140 m thick in the Wooltana Caves area (Figure 7, stratigraphic section WC) and consists of two limestone beds separated by a ~25 m-thick horizon. At Wortupa Well, two limestone beds unconformably overlie the Balcanoona Formation. While not previously recognised, these limestone beds display similar lithologies and stratigraphic relationships to the Weetootla Dolomite. These limestone beds are assigned to the Weetootla Dolomite.

The lower basal contact of the Weetootla Dolomite is an unconformity in both the Wooltana Dolomite and Wortupa Well areas (Figure 3, stratigraphic sections, MJ, WW; Figure 7, WC, WWa). This unconformity surface has several metres of erosional relief. Infilling erosional depressions on the unconformity are lenticular masses of poorly sorted, rounded quartz gravels (2–10 mm in size) and sands that also include large lithic fragments of yellow dolomite up to 20 cm in diameter (Figure 8a). In the Wooltana Caves area, the gravel succession is overlain by approximately 60 m of grey limestones and yellow dolomites. The limestone beds are mainly composed of densely packed large or giant ooids (often up to 1 cm in size) with lesser stromatolitic limestones. The upper limestone bed also contains a thin (<0.5 m thickness) basal gravel and grain component (1–5 mm grain-size), which quickly passes into limestones. This upper limestone bed is approximately 45 m thick and is dominated by giant ooids and stromatolites. The Weetootla Dolomite Member conformably grades into calcareous shales and silts of the overlying Amberoona Formation.

On the western side of the Paralana Fault, a very similar succession directly overlies the Balcanoona Formation. South of Oodnaminta Hut near Wortupa Well, a series of limestone beds are interbedded with calcareous silts (Figure 7). Here, this unit is separated from the Balcanoona Formation by an unconformity. This succession is approximately 70 m thick in this area but the thickness can vary laterally due to the relief on the unconformity (Figure 8b). This unit consists of a basal clastic conglomerate containing poorly sorted, rounded quartz gravels (1–10 mm in grain-size) with a minor component of sub-rounded lithic yellow dolomite fragments. Overlying the conglomerate are up to three beds of sandy and stromatolitic limestones. These limestone beds are usually 10 to 20 m thick and are separated by calcareous silts. Calcareous shales and silts of the Amberoona Formation conformably overlie this unit.

**Amberoona Formation and Enorama Shale**

The Amberoona Formation (as defined by Coats; in Thompson et al. 1964) is a series of grey-coloured, fine-grained, calcareous silts and shales gradationally overlying the Yankaninna Formation and Weetootla Dolomite. The unit is devoid of any pure carbonate beds with the exception of some poorly developed stromatolite beds in the Illinawortina area. The Amberoona Formation rarely develops a stratigraphic thickness of over 100 m where it occurs above shallow water carbonate successions. In basinial settings such as Illinawortina the Amberoona Formation reaches a stratigraphic thickness of over 240 m.

Green and grey shales of the Enorama Shale (as defined by Dalgarno & Johnson; in Thompson et al. 1964) conformably overlie the Amberoona Formation. A defining feature of the unit is the presence of three thin, but very distinct stromatolitic limestones beds of the Wundowie Limestone Member found towards the base of the Enorama Shale. The Wundowie Limestone...
Figure 6 Geological map of the area northeast of Arkaroola Quarry (see inset box from Figure 1).
Member was originally placed within the Angepena Formation (Coats & Blisset 1971), but then later revised as belonging to the Enorama Shale (Preiss et al. 1998). Above the Wundowie Limestone Member, the lithology returns to a fine-grained shale until the heavily eroded sequence boundary of the overlying glaciogenic Elatina Formation.

DISCUSSION

Stratigraphic relationships

The stratigraphic relationships of carbonate units within the interglacial succession of the Umberatana Group are complex. The relationships between units such as the Balcanoona, Angepena and Yankaninna formations, as well as the Weetootla Dolomite, are problematic.

In its type section, east of the Paralana Fault at Nepouie Creek, the Balcanoona Formation has been described by Mawson (1934), Coats & Blisset (1971) and Preiss (1987). Although technically first named by Coats & Blisset (1971), the Balcanoona Formation is recognised as belonging to Mawson’s (1934) Munyallina beds. The transect of Mawson’s stratigraphic section is located east of Mt Jacob. Mawson (1934) identified the lower algal limestones and upper oolitic dolomites of the Balcanoona Formation, which corresponds to units 3 (upper), 4, 5, 6 and 7 (lower) of the Munyallina beds (in Coats & Blisset 1971). In this section, the Angepena Formation then overlies the Balcanoona Formation and corresponds to units 6, 7, 8, 9 and 10 of Mawson’s Munyallina succession (in Coats & Blisset 1971). However, Coats & Blisset (1971) regard the Weetootla Dolomite and Wundowie Limestones as upper members of the Angepena Formation. Coats & Blisset (1971) did...
not recognise the presence of the Amberoona Formation. In the type area of the Angepena Formation south of Arkaroola, the Amberoona Formation gradationally overlies the Weetootla Dolomite, and the Wundowie Limestone is now regarded as a member of the Enorama Shale.

Past stratigraphic placements of the Angepena Formation consider the formation as developing in stratigraphic intervals that elsewhere in the basin are occupied by the Amberoona Formation and Enorama Shale (Coats & Blisset 1971). The Angepena Formation and its members were grouped into the Willochra Subgroup. The Elatina Formation is regarded as capping the Angepena Formation and its constituents. However, in a regional stratigraphic context, the units of the Willochra Sub-Group (of Coats & Blisset 1971) excluding the Elatina Formation, on the whole, were considered lateral equivalents to the Amberoona Formation. Similarly, Preiss (1987) regarded the Angepena Formation as occupying the stratigraphic position of the Amberoona Formation and Enorama Shale, but also suggested that the upper portions of the Angepena Formation intertongue with the Etina Formation some distance away from the type section. However, both authors recognise that the basal Angepena Formation intertongues with the uppermost Balcanoona Formation in the type area.

Our research suggests that the stratigraphic relationships of the Angepena Formation with the underlying and overlying units necessitate a re-evaluation of previous stratigraphy (eg. Coats & Blisset 1971; Preiss 1987). The gradational lateral and vertical interfingering contacts between the Angepena and Balcanoona formations suggest that the Angepena Formation does not simply overlie the Balcanoona Formation but is instead a lateral facies variant of the Balcanoona Formation (according to Walthers Law of the correlation of facies, in Middleton 1973). The absence of the Angepena Formation in the area of the Oodnaminta Reef Complex is therefore not surprising.

Moving northwards from Nepouie Creek towards Arkaroola, the Angepena Formation begins to thin laterally while also becoming highly gradational in its basal 100 m with the Balcanoona Formation as illustrated in the stratigraphic section at Arkaroola Quarry (Figure 9) and geological map of the area (Figure 6). The interbedded dolomites within the Angepena Formation become more apparent to the north with individual beds also increasing in thickness. The pink mudstones also become more carbonate-rich in this direction. While this vertical thinning of the Angepena Formation takes place, the underlying Balcanoona Formation then increases considerably in thickness. This increase in thickness of the Balcanoona Formation is accompanied by the appearance of reef framework litho-facies in the basal section of the Balcanoona Formation. This framework consists of the same non-stromatolitic and stromatolitic frameworks as observed in the Oodnaminta Reef complex and suggests that as the Balcanoona Formation becomes more reefal, conditions are no longer suitable for deposition of the Angepena Formation. The northwards thickening trend of the Balcanoona Formation has previously been interpreted as fault thickening resulting from smaller splay fault that branch off the main Paralana Fault, where the Balcanoona Formation is thrust up on the Angepena Formation (Coats & Blisset 1971; Coats 1973). Field mapping in this region (Figure 6) confirms the presence of several faults in the vicinity of the contact between the Balcanoona and Angepena formations. However, the displacement observed on these faults is insufficient to account for the apparent thickness variations above. Instead, the interbedding of the upper Balcanoona and lower Angepena formations increases across this fault. The upper Balcanoona Formation in this area also takes on a pink hue, further suggesting lateral facies relationships between the two formations. Here, fenestral Balcanoona Formation is also found interbedded within the Angepena Formation. Regardless of fault activity in this area, this interbedding of the Balcanoona and

Figure 8 Outcrop photograph (a) and labelled aerial photograph (b). (a) Lithic dolomite boulder encased within coarse gravels found infilling erosional troughs above the Balcanoona Formation in the Wortupa Well area. 67 mm lens cap for scale. 30°25′52″S, 139°15′18″E (b) Interpreted aerial photograph of the karst surface eroding a broad shallow channel into the Balcanoona Formation in the Wortupa Well area. Stratigraphic section WWa is marked for reference. BFm, Balcanoona Formation; WDol, Weetootla Dolomite, WD, Weetootla Dolomite beds 1 and 2; AFm, Amberoona Formation; ESh, Enorama Shale; W, Wundowie Stromatolite Beds 1, 2 and 3.
Angepena formations is purely a stratigraphic relationship.

Although the Balcanoona and Angepena formations display distinctly different sedimentary lithologies (reef vs redbed sedimentation), both formations are considered to have formed in shallow to very shallow marine environments. Furthermore, the main carbonate constituent in both the upper Balcanoona Formation and Angepena Formation is ooidal grainstones. The Balcanoona Formation is interpreted as a high-energy peritidal and shallow marine deposit, while the Angepena Formation displays typical low-energy peritidal, mudflat type deposits including abundant mudcracks and tepee antiforms (Assereto & Kendall 1977; Kendall & Warren 1987). If deposition of the Angepena and Balcanoona formations is contemporaneous, then the Angepena Formation may simply represent a shallow to paralic coastal facies that was situated behind the platform margin and backreef facies of the Balcanoona Formation (see Figure 10 for schematic environmental reconstruction). Such depositional regimes illustrating shoreward transition from barrier reef platformal carbonates to shoreline redbeds have also been documented from the Permian successions of the Delaware Basin in West Texas and New Mexico (Silver & Todd 1969).

The Yankaninna Formation is a calcareous shale and siltstone unit that disconformably overlies the Tapley Hill Formation in deep-water area of the basin. Its base is always defined by two, often three, distinct limestone beds that interbed with calcareous siltstones and shales. In the Oodnaminta area, these limestone beds lap upon the reef escarpment of the Balcanoona Formation. The Yankaninna Formation is then conformably overlain by Amberoona Formation in basinal environments of the northern Flinders Ranges.

To the east of the Paralana Fault near Wooltana Caves, two well-defined stromatolitic and ooidal limestones unconformably overlie the Angepena Formation. These limestone beds have been previously named the Weetootla Dolomite Member (Coats & Blissett 1971) and were considered as a subunit of the Angepena Formation. However, investigation in this study indicates that the Weetootla Dolomite Member is separated from the Angepena Formation by an unconformity. The Weeootla Dolomite is conformably overlain by silty shales of the Amberoona Formation, suggesting that the Weeootla Dolomite is more closely related to the Amberoona Formation than the Angepena Formation.

In the Wortupa Well area west of the Paralana Fault, two to three sandy stromatolitic limestone beds occur (interbedded with calcareous silts and shales) unconformably overlying the Balcanoona Formation. These limestone beds occur laterally across the entire shallow water platform of the Oodnaminta Reef Complex. These limestones are then conformably overlain by the Amberoona Formation. We interpret this shallow water interbedded limestone succession as directly correlating with the Weeootla Dolomite Member, and hence suggest it be named as such.

These limestone beds also directly correlate with the basinal limestone beds of the Yankaninna Formation where they onlap onto the platform margin of the Oodnaminta Reef Complex. Therefore, the Weeootla Dolomite Member is here considered a direct lateral equivalent of the deeper water Yankaninna Formation. This stratigraphic relationship further supports the time and lateral equivalency of the Angepena and Balcanoona Formations (and the upper Tapley Hill Formation as their basinal equivalent).

The identification of the regional unconformity located at the base of the Weeootla Dolomite and the submarine unconformity identified at the base of the Yankaninna Formation suggest that these unconformities also directly correlate. The basal unconformity of the Weeootla Dolomite as it outcrops east and west of the Paralana Fault displays a near-identical depositional record. Both these horizons outcrop with basal conglomerates consisting of quartz gravels and abundant lithic dolomite fragments. These conglomerates are then overlain by the Weeootla Dolomites. In the deep water succession, allochthonous blocks sourced from the Oodnaminta Reef Complex occur in the identical stratigraphic horizon at the base of the Yankaninna Formation. This indicates that mass
wasting of the reef margin occurred at the same time as sub-aerial exposure, karstification and conglomeratic deposition on top of the Oodnaminta reefal platform. This unconformity provides a regional chronostratigraphic marker horizon that is well developed east and west of the Paralana Fault in basinal, platformal and coastal settings. This previously unrecognised widespread unconformity probably developed from eustatic processes. This regional exposure and erosion event corresponds closely with the cessation of growth of the Oodnaminta Reef Complex. Such a large regression could result from significant global cooling as suggested by Giddings et al. (2009) in which conditions for such large-scale reef development became unsuitable, and subsequently the entire platform would also become sub-aerially exposed. Interestingly, the occurrence of the lower non-stromatolitic skeletal framework of the Oodnaminta Reef Complex is not found above the unconformity. Such an abrupt decline in reef-building frameworks from Phanerozoic reefs is often attributed to the onset of glacial expansion and global cooling (Stanley 1988a, b). When this evidence of biological decline is coupled with the observed regressive features (subaerial erosion) it may indicate that glacioeustatic processes were active during this otherwise interglacial succession. Alternatively, the regression at the top of the Oodnaminta Reef may represent a regional tectonic event.

**Implications for the Sturtian–Marinoan boundary in the Northern Flinders Ranges**

Preiss (1987) placed the Sturtian–Marinoan boundary at the contact between the Balcanoona and Angepena formations. Later attempts to redefine the Sturtian–Marinoan boundary in the Northern Flinders Ranges (Preiss et al. 1998) placed it on the sequence boundary that forms as an ‘erosional channel cut into the Balcanoona Formation near Oodnaminta Hut.’ This position, however, is not on the contact of the Balcanoona and Angepena formations (Mawson & Sprigg’s 1950, definition requiring the boundary be placed at the first appearance of redbed sediments). Although this boundary placement does not follow the original definition of Mawson & Sprigg (1950), we suggest that it does mark an appropriate position for the Sturtian–Marinoan boundary in the Northern Flinders Ranges. However, in a regional context, simply placing the Sturtian–Marinoan boundary on the upper contact of the Balcanoona Formation creates a highly diachronous time-stage boundary. Therefore, we suggest that a more practical point for chronostratigraphic subdivision
between Sturtian and Marinoan Time would be the regressive erosional surface located at the base of the Weetootla Dolomite and the Yankaninna Formation. The sub-aerial and sub-marine erosion at the base of these respective units marks a significant regional sequence boundary in the Northern Flinders Ranges. It is not clear if this erosion surface is a local unconformity caused by tectonic effects, or if it is a regional eustatic sequence boundary that can be located around the entire Adelaide Geosyncline. If this sequence boundary does reflect glacioeustatic drawdown, then evidence of this significant regression may be found elsewhere in the Adelaide Geosyncline and within other Australian Neoproterozoic basins.

CONCLUSIONS

The extensive carbonate platforms of the Balcanoona Formation and red-bed successions of the Angepena Formation are lateral facies of each other, and therefore considered as time equivalent formations. The Balcanoona Formation forms in the shallow to deep marine conditions where it commonly forms large prograding reef complexes with well-developed back-reef lithofacies. The Angepena Formation exhibits characteristics typical of a peritidal mudflat (coastal) deposit, interpreted as the most shoreward facies located behind the extensive platform and barrier margins of the Oodnaminta Reef Complex found within the Balcanoona Formation.

The Weetootla Dolomite overlies the Oodnaminta Reef Complex and may be directly correlated with deep marine deposits of the Yankaninna Formation. A regionally widespread erosion surface is present at the base of both the Weetootla Dolomite and Yankaninna Formation. This sub-aerial (and submarine) erosion surface found in the mid Umberatana Group represents a significant and important unconformity in the Northern Flinders Ranges. This unconformity probably developed as a result of marine regression and as such provides a new and useful chronostratigraphic marker that can further constrain ages (relatively date) of many units within the Umberatana Group. This regression also broadly correlates with the Sturtian–Marinoan boundary of the Adelaidean System.

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