Heavitree Quartzite, a Neoproterozoic (ca 800–760 Ma), high-energy, tidally influenced, ramp association, Amadeus Basin, central Australia

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The Neoproterozoic Heavitree Quartzite is widespread in the Amadeus Basin and has correlatives in all of the major central Australian intracratonic basins. The origin of the formation is enigmatic, not only because of its widespread sheet-like distribution and uniformity of composition, but also because intense silicification makes facies studies difficult. Recently discovered exposures at the eastern end of the basin are relatively free of diagenetic quartz allowing a detailed study of sedimentary structures and an understanding of the depositional architecture of the formation. The formation, which consists largely of pale-tan or white quartzose sandstone interbedded with rare laminated mudstone and conglomerate intervals, was deposited in at least four depositional sequences. The sheet-like nature of the sandstone results from an abundant supply of sediments deposited in a high-energy, open, shelf-like environment on a regionally subsiding, low-gradient ramp. Environmental settings switched both laterally and temporally between sand waves deposited by reversing tidal flow and higher velocity unidirectional currents involving dunes and plane beds. In the early stages of deposition, mud-dominated, tidal-flat environments alternated with higher energy, sand-dominated, tidally influenced settings. However, in the later stages of deposition a major eustatic sea-level fall moved base-level basinwards, earlier sediments were reworked by streams to form a ravinement surface, gravel was carried well into the basin and fines largely disappeared from the environment. Gravel deposition was followed by a return to high-energy, tidally influenced deposits involving large sand waves or dunes. Towards the top of the formation sand waves deposited by reversing tidal currents gradually decline and are eventually replaced by dunes deposited by unidirectional current flow. The transition to the shallow-marine, anoxic rocks of the Bitter Springs Formation is gradational in response to increased accommodation in a ramp setting which lacked a clearly defined shelf break. The Heavitree Quartzite was probably deposited as a direct response to the events surrounding the assembly and breakup of Rodinia, in particular peneplanation during regional uplift in response to a rising mantle plume followed by broad regional subsidence as the plume decayed prior to the breakup of the supercontinent. The large supply of quartz sand resulted from peneplanation associated with the rising plume and the lack of soil-stabilising vascular plants, an environmental setting with no modern analogue. The ultimate disposition of fines is not known but, given the environment of deposition, it is likely that they were removed during peneplanation and bypassed the sag basin completely.

Key words: Amadeus Basin, Heavitree Quartzite, Neoproterozoic, ramp setting, sequence stratigraphy.

INTRODUCTION

Thick, laterally persistent, mature, quartzose sandstone units with sheet-like geometries occur frequently in Neoproterozoic and earliest Palaeozoic basins but few have been described sedimentologically (Dott & Byers 1981; Walker 1985; Dott et al. 1986; Pettijohn et al. 1987; Fedo & Cooper 1990; Haddox & Dott 1990; Simpson & Eriksson 1990; Hamberg 1991; Tirsgaard 1993; Runkel et al. 1998). These sandstones are not only sheet-like and widely distributed but often have a specific stratigraphic context that relates to basin dynamics. They are typical of intracratonic basins and are often the first units deposited following the onset of subsidence or at the beginning of major phases of basin reactivation (Lindsay & Korsch 1989). They are not well understood from a sedimentological viewpoint but are important in that they provide information about the early stages of basin evolution. Many have been identified as having a shallow-marine origin but in some cases they have been interpreted as being fluvial and aeolian in whole or part (Runkel et al. 1998). Much of the uncertainty about details of their depositional setting has come from their unusually thin sheet-like geometries and a perceived need to invoke a mechanism other than shallow-marine currents to disperse the sediment over the extensive depositional areas (Pettijohn et al. 1987; Dott et al. 1986).

The Heavitree Quartzite, which is widespread in the Amadeus Basin of central Australia, is typical of these basal sandstones. Despite its topographic prominence throughout the region the formation received only limited attention during earlier field mapping programs (Wells et al. 1970), probably in large part because its uniform composition and high degree of silicification made facies analysis difficult. Consequently, little is known of the formation’s depositional setting.
Recently, outcrops of Heavitree Quartzite have been located on Limbala Station at the eastern end of the Amadeus Basin that are not as heavily silicified as elsewhere (Figure 3). The outcrops are part of a window of flat-lying Lower Neoproterozoic sedimentary rocks and Arunta Complex basement units exposed by low-angle thrust faulting related to the Palaeozoic Alice Springs Orogeny. This study, which is focused on these outcrops, is intended to provide some insight into the depositional processes involved and attempts to relate them to basin dynamics.

REGIONAL SETTING

The assembly and breakup of Rodinia is well documented in the basin-fill architecture of the Neoproterozoic–Cambrian basins of central Australia (Amadeus, Officer, Ngalia and Georgina among other basins: Lindsay et al. 1987). These basins were initiated as a giant sag basin at ca 800 Ma (Lindsay et al. 1987; Lindsay & Korsch 1989; Powell et al. 1994; Walter et al. 1995; Lindsay & Leven 1996) (Figure 1). Subsidence was both uniform and slow over an area of $1.5 \times 3.0 \times 10^6$ km$^2$ (Lindsay & Leven 1996). Deep seismic profiling suggests that deep mantle processes were involved in the development of the sag basin (Lindsay & Leven 1996) an observation consistent with the build up of heat at the climax of the supercontinent cycle and the development and decay of a mantle plume. Upwelling of the plume initially caused domal uplifting of the continental lithosphere and regional peneplanation (Dam et al. 1998) which in turn led to thermal relaxation and widespread subsidence following the output of flood basalts and the cessation of plume activity (Zhao et al. 1994). The broad scope of the early stages of basin subsidence led Walter et al. (1995) to refer to this region as the Centraian Superbasin.

The Heavitree Quartzite was deposited, along with the associated Bitter Springs Formation (Lindsay 1987a), during the sag phase to form a megasequence (Lindsay & Korsch 1989). The depositional pattern was similar during the equivalent time interval in the Officer, Ngalia, Georgina and Savory Basins (Walter 1980; Deckelman 1995; Lindsay 1995; Lindsay & Leven 1996, Lindsay et al. 1987; Lindsay & Korsch 1989, 1991; Walter et al. 1995; Williams 1992, 1994) (Figure 2). Recent work by Grey and Blake (in press) suggests that sediments of similar age may have extended as far as the Wolfe Basin in the east Kimberley. The only evidence of the limits of the superbasin are in the Georgina and Ngalia Basins (where the succession is only present in the southern sub-basins) and perhaps in the Officer Basin. The northern limits of the superbasin are perhaps indicated in the Georgina Basin where sandstones interfinger with carbonate units and onlap basement highs (Walter 1980). Similarly, the Vaughan Springs Quartzite, which is the equivalent of the Heavitree Quartzite at the base of the Ngalia Basin succession, onlaps basement thereby indicating a possible northern limit to the superbasin. Palaeocurrent data from the Ngalia Basin suggest westward movement of sediments (Deckelman 1995). At the extreme eastern end of the Officer Basin the clastic Alinya Formation is replaced laterally by a carbonate association, thereby suggesting an eastern limit to the superbasin whereas seismic data along the southern margin of the Officer Basin suggest that the Alinya Formation thins and onlaps in that direction (Lindsay 1995). Westward the presence of conglomeratic deltaic units in the western Officer Basin is interpreted as reflecting a more marine setting in the eastern Officer Basin.
Basin (Savory Basin) may indicate a western limit to regional sedimentation (Williams 1992, 1994).

**AMADEUS BASIN**

The Amadeus Basin, which is typical of the Neoproterozoic intracratonic basins, lies at the centre of the Australian continental block to the south of Alice Springs and centred on longitude 132°E (Figure 3). It is a complex basin the evolution of which was influenced by a number of tectonic events (Korsch & Lindsay 1989; Lindsay & Korsch 1989, 1991; Shaw 1991; Lindsay 1993). It shares many similarities with the Officer Basin to the south (Gravestock & Lindsay 1994; Lindsay 1995; Lindsay & Leven 1996) and the Ngalia Basin (Deckelman 1995) to the north, and other Neoproterozoic intracratonic settings (Figure 1). The basin evolved in several distinct phases each of which produced a well-defined megasequence. The basin phases can be related to extrinsic causes, although the magnitude of the tectonic events underlying basin subsidence episodes varies (Lindsay & Leven 1996).

From east to west, its longest dimension, the Amadeus Basin extends for approximately 800 km, and contains a Neoproterozoic to Palaeozoic succession, which at its maximum exceeds 14 km in thickness (Figure 4). The well-preserved Neoproterozoic succession of the Amadeus Basin consists largely of shallow-marine rocks which rest unconformably on the Arunta and Musgrave Complexes. The total thickness of the Neoproterozoic succession averages close to 2000 m although in the northeast it may reach 3000 m (Wells et al. 1967, 1970; Lindsay & Korsch 1989; Lindsay 1993). Variations in the thickness of the Neoproterozoic succession and its distribution are discussed in more detail by Lindsay (1987a, 1993) and Lindsay and Korsch (1989).

**HEAVITREE QUARTZITE**

The Heavitree Quartzite (and correlative Dean Quartzite) is the earliest of the Neoproterozoic units in the Amadeus Basin and grades conformably into the carbonates and evaporites of the overlying Bitter Springs Formation. Together these two formations are among the most widely distributed units in the basin (158 000 km²). The most extensive outcrops of the Heavitree Quartzite are in the MacDonnell Ranges along the northern margin of the Amadeus Basin. The outcrops, which form a prominent erosional strike ridge, are almost unbroken from Kintore near the Western Australian border to the Simpson Desert in the east, a distance of 800 km. The strike ridge occurs...
along the upturned edge of the MacDonnell Homocline, a prominent structure formed along the length of the northern margin of the Amadeus Basin in response to foreland basin development during the Late Palaeozoic Alice Springs Orogeny. The main thrust controlling the formation of the basin margin lies within the Red Bank Zone a short distance to the north of the homocline (Shaw & Wells 1983).

The Heavitree Quartzite is relatively uniformly distributed over large areas of the basin and averages 100–300 m in thickness (Figure 5). Onlap onto basement highs results in local thinning but there is no consistent pattern to suggest the location of the basin margin which, as discussed above, lay well beyond the bounds of the present erosionally defined Amadeus Basin. The formation is penetrated by a single petroleum exploration well, Magee...
1, where the formation is anomalously thin (4.6 m) over a local basement high (Wakefield-King 1994). Seismic data are limited as the formation is poorly imaged (Lindsay 1993) but, on a few sections, as many as seven persistent internal reflections can be identified, each defining a depositional cycle. A similar pattern for both internal structure and regional distribution has been observed for the equivalent interval (Pindar Sandstone) in the Officer Basin to the south (Lindsay & Leven 1996).

In spite of the extensive outcrop, detailed facies analysis of the Heavitree Quartzite has not been attempted previously because the intense silicification of the sandstone outcrops along the MacDonnell Ranges masks details of sedimentary structures. Recently discovered cliff exposures on Limbla Station (135°16’E, 23°59’S) approximately 145 km east of Alice Springs (Figure 3) are not as heavily silicified as elsewhere providing an opportunity to evaluate facies in greater detail.

The Limbla Cliffs outcrops are all basinward of the MacDonnell Homoclino and the deep-seated, steeply dipping thrust-fault complex that dominates the northern margin of the basin. The outcrops, which occur as part of a window of flat-lying Lower Neoproterozoic sedimentary rocks and Arunta Complex basement units exposed by low-angle thrust faulting related to the Palaeozoic Alice Springs Orogeny some distance from the basin-margin structures, suggest that silicification of the sandstones along the MacDonnell Ranges was associated with fluid movement along deep thrust faults, north of the MacDonnell Homoclino. It thus appears likely that large areas of the Heavitree Quartzite concealed in the subsurface may be less heavily cemented and thus have some petroleum reservoir potential. This observation is also consistent with local seismic images of the formation, which show significant velocity contrasts within the formation. In general, however, the formation is not clearly imaged seismically because of the overlying halite units in the Gillen Member of the Bitter Springs Formation (Figure 4).

The cliffs extend for more than 20 km along Pulya Pulya Creek and provide the location for five measured sections each 2.5 km apart (Figure 6). The sections are not complete because the upper part of the formation and the contact with the Bitter Springs Formation are covered by talus. However, in all cases, the lower part of the Heavitree Quartzite is almost completely exposed. Measured sections were complemented by a photomosaic of the cliff taken from a helicopter flying at the mid-level of the sections along the cliff front. The photomosaic allowed an evaluation of the lateral continuity of individual units between sections.

SEQUENCE AND FACIES ANALYSIS

The Heavitree Quartzite is a massive, laterally persistent unit that consists largely of pale-tan or white quartzose sandstone interbedded with rare laminated mudstone or conglomerate intervals. Despite being mapped as a continuous homogeneous sheet of quartzite it is, in fact, stratigraphically complex. Clark (1979) first noted that the type section of the formation at Heavitree Gap in Alice Springs (Figure 5) consisted of several units which he informally referred to as members. Significantly, units that are similar in terms of both lithology and facies associations can also be identified in the study area at Limbla. It is not known if they correlate directly but such well-defined cycles occurring over such large distances suggested the possibility that they are correlative depositional sequences (cf. Runkel et al. 1988).

The underlying premise of sequence analysis is that sediments are deposited as packages (sequences) of genetically related lithofacies bounded by unconformities or their correlative conformities (sequence boundaries) (Vail et al. 1977a, b, 1984). The lack of suitable fossils makes direct correlation difficult. However, facies discontinuities across sequence and systems-tract boundaries can be used as a means of defining the sequences (Grotzinger 1986; Lindsay 1987b; Lindsay et al. 1987; von der Borch et al. 1988; Lindsay & Korsch 1989). Similarly, special features, such as gravel lags along erosional surfaces, can be used as evidence to define sequence boundaries and evidence of reversal in water-depth trends can be used to identify maximum flooding surfaces. Terminology used in describing sequences is adapted from Vail (1987) and van Waggoner et al. (1987).

Because of the compositional uniformity of the formation sequence boundaries are subtle features. Other than the basement contact, the most distinctive surface visible in the Limbla sections is a major ravinement surface approximately 20–40 m above the basement contact. The surface is well defined, with several metres of relief, and is generally overlain by coarse fluvial conglomerate. Two other less prominent erosion surfaces are present in the section, one above the major erosion surface, the other below. Because of the abrupt facies changes across these surfaces they are interpreted to be sequence boundaries that break the formation into four depositional sequences (numbered 1 to 4, Figure 6). Sequences 2 and 3 are both divided into two lithologic components, designated A and B in each case, which define systems tracts.

Sequence 1

The basal surface of the Heavitree Quartzite cuts into metamorphic rocks of the Arunta Complex. Relief on this surface is significant, reaching tens of metres, and the overlying sedimentary units lap onto the palaeogeographic highs in the cliff section. Consequently, sequence 1 fills the lows in the basement erosion surface and is absent from the eastern end of the study area (sections 4 and 5).

Sequence 1, apart from a single thin mudstone unit at the base of section 2, consists dominantly of pale, fine- to medium-grained, quartzose sandstone with approximately 5% feldspar. The mudstone is thinly laminated and generally grey-green or purple, and becomes more sand-rich upwards. Asymmetric ripple marks are the most obvious sedimentary structure and these are sparsely distributed. Although thin and discontinuous in the Limbla Cliff sections, laminated mudstones in sequence 1 are extensive further west along the MacDonnell Ranges. Wherever they are encountered, the mudstones fill lows in the erosion surface.

In sections 1 and 3, sequence 1 is dominated by thick (>1 m) sandstone units with well-developed, low-angle,
Figure 6  Detailed sequence stratigraphy for the five sections of the Heavitree Quartzite measured at the Limbla Cliffs study area (see Figure 3 for section locations).
sigmoidal, cross-bedded foresets that are clearly outlined by lags of coarse (1 mm) sand grains and small pebbles (Figure 7). The foreset units are separated from each other by thin intervals of plane-bedded sandstone, an association also noted in the Lyell Land Group in Greenland (Tirsgaard 1993). In the midst of section 3, a single 2 m-thick sandstone unit, which consists of a single set of low-angle foresets, is prominent and notably different from the units described above. The foresets are sigmoidal and the dip of their surfaces is well below the angle of repose for the respective sand grain sizes (Figure 8c).

Many units, particularly those >3 m in thickness, show evidence of erosion manifested by truncation of cross-bedded sets. In some cases, where erosion has removed part of the bed, the foresets have undergone soft-sediment deformation and their upper parts have been overturned. These prominent thick sandstone units are a distinctive feature of the Heavitree Quartzite (Figure 7). Where they can be traced laterally, all of the sigmoidal foreset units pass gradationally into plane-bedded sandstone beds within a distance of 100–500 m. The upper part of the sequence in section 1 is dominated by plane-bedded sandstone that is coarser in grain size and has laminae outlined by 1 mm grains of sand. Facies relationship suggest that only the highstand systems tract of sequence 1 is present in the study area.

Figure 7 (a) Typical large-scale truncated sigmoidal foresets in the lower Heavitree Quartzite. (b) Simplified diagram showing the internal structure of large-scale sigmoidal cross-bedded foreset beds and sigmoidal foreset beds that occur interbedded with plane-bedded sandstones throughout the Heavitree Quartzite (cf. Tirsgaard 1993). Cross-bedded foreset units may be as much as 10 m thick but, when traced laterally, grade into plane-bedded sandstones. The larger cross-bedded foresets were deposited as sand waves that formed in a tidally influenced environment where there was a well defined, but not strong, asymmetry of tidal flow, such that sediment transport reverses with each tidal cycle but net sediment flow in one direction is well defined. The smaller sigmoidal foreset beds formed in migrating dunes under a unidirectional current. A slight increase in velocity caused a shift in deposition from sand waves or dunes to upper-flow-regime conditions and hence planar bedding. Penecontemporaneous deformation in the form of recumbent cross-beds is common and results from intense shear-stress generated by the high-velocity currents.
Sequence 2

The contact between sequences 1 and 2 is clearly defined by an abrupt facies change with much finer-grained mudstone of the latter resting on medium- to coarse-grained sandstone of sequence 1. The sequence boundary, although obviously continuous along the length of the cliff exposures, is not easy to follow because talus generally obscures the exposure. The sequence boundary at the base of sequence 2 has significant relief, probably of the order of tens of metres. Lithologically, the sequence consists of two units: 2A, a lower mud-rich unit; and 2B, an upper sand-dominated unit. The lower unit (2A), consists almost entirely of mudstone, most of which is well laminated. It begins with alternating red and green mudstone and siltstone in laminae of 1–5 mm. Higher in the succession poorly sorted sandstone laminae become more abundant and ultimately flaggy sandstone dominates the section toward the top. At some localities, notably sections 1 and 3 (Figure 6), sandstone beds interfinger laterally with the mudstone. The sandstone is moderately sorted, feldspathic and crudely laminated in 1 cm units. Poorly developed ripple marks, mudcracks and rain prints are present on the shaly bedding surfaces. Overall the units become coarser and laminae become thicker upward. Unit 2A is interpreted as the lowstand systems tract of sequence 2.

Unit 2B consists largely of fine- to medium-grained, pale sandstone with 5–10% feldspar content. In the east, in sections 4 and 5, the unit is dominated by plane-beded sandstone. Further to the west large-scale planar cross-bedding is the dominant sedimentary structure. Prominent medium-tan sandstone beds 3-6 m-thick with low-angle (13–20°), large-scale, sigmoidal cross-bedded foreset units are present in sections 1 and 2. These units are underlain and overlain by plane-bedded sandstone (Figure 7) (cf. Tirsgaard 1993). Unit 2B is interpreted as the highstand systems tract for unit 2.

Sequence 3

The erosion surface at the base of sequence 3 has a relief of several metres and is defined by an abrupt facies change across the boundary. The sequence boundary can be followed without break for the full length of the cliffs. For convenience, the sequence can be described as two units. Unit 3A consists largely of purple or white coarse-grained sandstone and conglomerate the texture and geometry of which suggests that they are predominantly fluvial in origin. The unit varies considerably in thickness and comprises a succession of stacked channel-fill deposits. The channel-fill units contain trough cross-beds 20–30 cm thick. The conglomerate has a bimodal, or polymodal, grain-size distribution and consists of clasts of chert and quartz up to 2 cm in diameter in a matrix of coarse sandstone. The sandstone is quartzose with ~5% feldspar. Intraclast breccias of purple mudstone are abundant. The conglomerates pass conformably and gradationally upward into sandstones of unit 3B. Thin planar cross-beds, some with herringbone patterns that imply current reversals, are confined to a transition zone between units 3A and 3B. Gradation of facies results from a shift in depositional environment from fluvial (braided stream) to tidal which suggests that the maximum flooding surface lies within or just above this transitional zone such that unit 3A can be interpreted as the transgressive systems tract for sequence 3.

Unit 3B is dominated by well-developed, large-scale cross-beds with low-angle (16°) sigmoidal foresets. These large-scale, cross-bedded foreset units are underlain and overlain by plane-bedded sandstone (cf. Tirsgaard 1993) and laterally grade to plane-beded, fine- to medium-grained sandstone over distances of 100–500 m (Figure 7). Intraclast breccias are present on the sigmoidal foreset-bounding surfaces, and along the surfaces of the plane-bedded sandstones above and below the large-scale cross-bedded foreset units. Foresets preserved in the large-scale units (>2–3 m) are sigmoidal in shape, although the upper part of the foreset has been removed by erosion and at some localities has been overturned by soft-sediment deformation. Eastward, the large-scale, cross-bedded foresets are replaced by medium-grained sandstone that is thinly bedded (10–15 cm) and planar cross-bedded. The planar cross-beds occasionally show evidence of current reversals in the form of a herringbone pattern. Herringbone cross-bedding is most abundant in section 1 and is associated with tubular burrow-like structures that may be organic in origin or possibly due to water escape (Lindsay 1991). Unit 3B forms the highstand systems tract for sequence 3.

Sequence 4

The facies change defining the sequence boundary at the base of sequence 4 is not as distinctive as that of the other sequence boundaries. It is a relatively low-relief channelled...
surface which locally has a veneer of conglomerate. The conglomerate is bimodal or polymodal in grainsize and contains clasts up to 2 cm that are, for the most part, composed of resistant lithologies such as chert and quartz. This conglomeratic lag suggests that the surface is an erosional sequence boundary. Above the conglomerate is a 2 m-thick interval of cross-bedded, medium-grained sandstone below a transition into the main body of the succession. The bulk of sequence 4 consists of tan or purple, medium- to coarse-grained, quartzose sandstone. The sandstone is mostly plane bedded, although in the west some planar cross-beding is preserved. Intraclast breccias are present on bedding surfaces throughout the interval.

The contact of the Heavitree Quartzite with the overlying Bitter Springs Formation is generally covered in talus and, even where exposed at other localities along the MacDonnell Ranges, it is often faulted. The contact is, however, visible at Heavitree Gap close to the type section of the Heavitree Quartzite (Figure 5). There the Gillen Member (Figure 4) is conformable on the Heavitree Quartzite. A thick basal shale is overlain by interbedded dolostone and black or grey shale with occasional cross-bedded sandstone. Small, but well-developed stromatolites are locally developed at the top of the dolostone units (Lindsay 1987a). The transition from the Heavitree Quartzite to the Bitter Springs Formation is conformable and the boundary difficult to identify in outcrop. The change implies deepening upward from the clean quartzose sandstone of the Heavitree Quartzite to the black shale, sandstone and evaporites of the Gillen Member of the Bitter Springs Formation. Sequence 4 thus consists of a thin conglomeratic transgressive systems tract with a thick highstand systems tract dominated by planar bedded sandstones.

PALAEOCURRENT ANALYSIS

Palaeocurrent orientations in the Heavitree Quartzite are complex and difficult to interpret unless care is taken to separate the different scales and types of current structure (Figure 8). Cross-bedding is the major current structure preserved in the Heavitree Quartzite, although poorly developed asymmetric ripple marks are present in some beds (Figure 6). Thick beds of sandstone (1–10 m) with low-angle, cross-bedded, sigmoidal foresets are the most distinctive form of cross-bedding, although small- and large-scale planar cross-beds and trough cross-beds are also abundant.

Trough cross-beds show the main direction of sediment transport to have been to the north or northwest onto what is now the exposed Arunta Complex. Asymmetric ripple marks (Figure 8d) suggest a similar transport direction, although they have a larger spread in measured directions than the cross-beds. Low-angle, large-scale, sigmoidal foresets (Figure 8c) indicate accretion to the southwest at right angles to trough cross-bed (Figure 8a) orientations. Significantly, orientations of low-angle, large-scale, cross-bedded foresets are similar to the those measured on sigmoidal foresets from thinner beds (i.e. without cross-beds) (Figure 8c). Planar cross-beds suggest palaeoflow directions to the northwest but have a larger spread in measured directions than the trough cross-beds. Small-scale, planar cross-beds (Figure 8b) indicate palaeoflow directions to the northeast at right angles to the main direction of sediment transport, and in the opposite direction to large-scale foreset accretion, implying that the origin of the small-scale planar cross-beds is related to large-scale foreset development and that both are probably tidal in origin. Locally, the small-scale, planar cross-beds also form heringbone patterns thereby implying that there were periods of short-term current reversal. Clark (1979) found similar palaeocurrent patterns further west from the present study area in the vicinity of Alice Springs.

The interpreted palaeocurrent directions are consistent with the isopachs of the Heavitree Quartzite, which indicate thickening of the formation towards the west (Figure 5). Data from the Ngalia Basin to the north also show a westward movement of sediments (Clark 1979) implying that the sediments accumulated in a series of parallel east–west-oriented sub-basins.

DISCUSSION

Thick, mature, quartzose sandstone units with tabular geometries and very little mudstone are characteristic of Late Neoproterozoic and earliest Palaeozoic successions (Dott & Byers 1981; Dott et al. 1986; Pettijohn et al. 1987; Fedo & Cooper 1990; Haddox & Dott 1990; Simpson & Eriksson 1990; Hamberg 1991; Tirsgaard 1993). The Heavitree Quartzite, which is typical of these sandstones, is predominately quartzose and was deposited as four depositional sequences. The sequences consist of thin transgressive systems tracts overlain by a thicker tabular highstand systems tract. The most conspicuous sedimentary structures are planar cross-beds, large foresets (1 m thick), large-scale, low-angle, sigmoidal, cross-bedded, foreset units (3–10 m thick), and plane-bedded units. Asymmetric ripple marks are present in most settings but are generally poorly developed and poorly preserved in the Heavitree Quartzite.

Beds up 10 m thick consisting of individual sets of low-angle sigmoidal cross-bed sets are a distinctive feature of the Heavitree Quartzite. Internally they are characterised by three orders of bedding surfaces: (i) primary erosional bedding surfaces at the base of the units; (ii) well-defined low-angle sigmoidal surfaces defining the foresets; and (iii) somewhat steeper cross-beds bundled within the foresets. Overall, the general form, scale and internal structure of these units suggests they formed in a tidally influenced or tidally dominated environment as flow-transverse sand waves of a type referred to by Allen (1980) as class IV sand waves. Such structures are formed in settings where there is a well defined, but not strong, asymmetry of tidal flow, such that sediment transport reverses with each tidal cycle, but net sediment flow in one direction is well defined. Class IVA sand waves also form in settings where large-scale flow separation occurs above the face of the advancing structure allowing the development of steep foreset slopes and repeated avalanching. Thus, the sand wave migrates in a clearly defined direction, but erosive rounding of the sandwave crest occurs during tidal reversal producing the characteristic sigmoidal shape of the foresets. Pebble and intraclast lags on foreset-bounding surfaces suggest that they are reactivation surfaces and add further support to
there being a tidal component involved in the deposition of these thick beds.

While the large, cross-bedded, sigmoidal foreset units are distinctive and indicative of a tidally-influenced environment other associated structures offer considerable insight into temporal and areal variation in fluid flow. These distinctive thick sandstone units can be traced laterally into plane-bedded sandstones or thinner units with simple sigmoidal foresets or planar cross-beds. Palaeocurrent data show that the foreset directions of both simple foreset units (1 m thick) and the cross-bedded foreset units (3–10 m thick) lie at right angles to the trough cross-bed current directions suggesting that they were longshore currents. Similarly, the alternation of these units with plane-bedded units suggests a high-energy setting shifting periodically to an upper-flow-regime environment similar to that documented by Tirsgaard (1993) in the Lyell Land Group of northeast Greenland. High current velocities are also consistent with the intraclast breccias in the plane-bedded units and on the sigmoidal cross-bedded foresets of the thicker sandstone beds. Overall, the associations suggest that the 1 m-thick sigmoidal foreset units are the product of migrating dunes (class IIA: Allen 1980) and that they, and the plane-bedded units, indicate a shift in the flow regime involving both, a shift to predominantly unidirectional flow (dunes), and a progressive increase in current velocity ultimately into an upper-flow-regime environment (plane beds) (Allen 1980). Similarly, the truncation of sigmoidal foresets by horizontally bedded units and the presence of recumbent cross-bedded foresets is indicative of erosion involving high-shear stresses associated with an upper-flow-regime environment and deposition of plane beds.

At the other extreme, when currents were more tidally influenced and had greater asymmetry, herringbone cross-stratification was developed. This occurred in sequence 3 of the Heavitree Quartzite in the transitional facies between the transgressive systems tract and the highstand as rising sea-level flooded the ravinement surface and tidal conditions reappeared. Above the herringbone cross-stratified interval sedimentary structures reflecting higher current velocities and lower flow asymmetry reappear.

Thickness variations in sequence 1, and the transgressive systems tract of sequence 2, suggest that initially sedimentation was controlled by local bedrock topography as tidally influenced systems deposited their sediment load in depressions in thesubsiding landscape. Mudcracks and rain prints imply that those settings were frequently exposed subaerially. The tidal flat deposits coarsen upwards and are overlain by sand-dominated complexes, that involved large-scale sandwaves, dunes and plane-bed sands, deposited in a high-energy environment. The accumulating tidal sediments do not completely blanket the underlying topographic basement surface but lap onto the remaining highs. The presence of an evaporitic interval (Treuer Member) in the Vaughan Springs Formation of the Ngaila Basin (Deckelman 1995) emphasises the arid nature of the regional climate at the time of deposition.

The erosion surface at the base of sequence 3 records a significant event in basin evolution. The base-level shift resulted in regional erosion with the development of relatively deep channels and the redistribution of relict sediments northward into the basin by braided streams. As a consequence gravel was transported deep into the basin where it was deposited as channel fill in the ravinement surface. Clasts in the conglomerates are relatively small and are mostly resistant lithologies suggesting long distances of transport. The bimodal nature of the grainsize of the gravel implies that the streams were heavily laden, which is also consistent with an overall braided-stream origin. The continuity of the ravinement surface, and the existence of a similar surface in the type sections at Alice Springs (Figure 5), suggests that it formed in response to a sea-level fall and a major basinward shift of base-level. While there is no direct evidence that the surfaces are regionally correlative recent work by Runkel et al. (1998) on a similar environmental setting suggests that it is likely.

Above the fluvially deposited conglomerate facies in sequence 3, sedimentary rocks are predominantly subtidal in origin. Locally, shales, presumably deposited in a tidal-flat setting, are preserved but they are of minor importance. Indications are that water depths increased rapidly following the sea-level low at the start of sequence 3 and that this deepening trend continued to the Bitter Springs Formation. Along with this deepening trend evidence of a strong tidal influence gradually declines such that sequence 4 was deposited in large part by unidirectional currents. This gradual and conformable transition to the Bitter Springs Formation is consistent with deposition in a ramp setting where there is no clearly defined shelf break. The absence of lowstand systems tracts associated with three of the four Heavitree Quartzite sequences is also consistent with a ramp setting (Lindsay 1987b).

Overall, the analysis suggests that an abundant supply of clastic sediment was delivered to a shallow, open shelf-like, regionally subsiding, low-gradient, ramp setting by heavily laden braided streams. Dispersal of the sediment was almost certainly aided by major sea-level shifts which, during lowstands, allowed sediment to be carried into the basin. However, the high-energy shallow-marine environment into which the sediments were transferred was more than capable of dispersing the large volumes of sediment to form the extensive sheet-like sand bodies that are typical of the formation. In the early stages of deposition strong reversing tidal currents played a major role but as water depths increased unidirectional currents became dominant.

The deposition of the Heavitree Quartzite appears to have occurred in an environment in which there was a fine balance between accommodation and sediment supply. Generally, the two were almost in balance but, over time, supply was unable to keep pace with accommodation such that water depth gradually increased. This suggests the tectonic setting was important in controlling architecture as all the evidence points to synchronous subsidence over a vast area of the Australian craton. The release of the large volumes of clastic material into the depositional environment may well relate to doming and peneplanation (Dam et al. 1998) associated with the initiation of the mantle plume as continental accretion climaxed. A relatively local origin for the clastic material present in the Heavitree Quartzite is supported by detrital zircon U–Pb ages (Zhao et al. 1992). Present reconstructions of Rodinia (Weil et al. 1998) also suggest a major orogenic belt to the south associated with Antarctica, potentially a major source of
sedi-ment. Although simple land plants appeared early in earth history (Gutzmer & Beukes 1998) the lack of soil-stabilising vascular plants in the Neoproterozoic was also important in determining the abundant sediment supply (Tirsgaard 1993) a point amplified by the presence of braided stream deposits at the base of sequence 3.

While there are no equivalent modern depositional settings for comparison, the Heavitree Quartzite has much in common with other Proterozoic quartzites, such as the Jura Quartzite of western Scotland (Anderton 1976), the Lower Sandfjord Formation of northern Norway (Levell 1980) and the Lyell Land Group of northeast Greenland (Tirsgaard 1993) all of which are interpreted as tidal associations. The abundant presence of large-scale, cross-bedded foresets suggests that the regional depositional setting involved a shallow, high-energy tidally influenced environment with a marine shelf being the best modern analogue (Anderton 1976; Smith & Taverner-Smith 1988; Smith 1992). This interpretation is consistent with the shallow nature of these intracratonic settings. The lack of fines is consistent with the high-energy environment and suggests that they bypassed the sag basin to be deposited elsewhere, perhaps marginally to the ancient supercontinent (Pettijohn et al. 1987). The fact that there is no evidence of the preservation of the lowstand systems tracts of three of the four sequences is consistent with deposition in a ramp setting. Work on younger depositional sequences in the basin has shown that lowstand systems tracts are more likely to be preserved during periods of rapid subsidence especially in a foreland basin setting where an equivalent to the shelf/slope break develops (Lindsay 1987b).

Finally, any understanding of the deposition setting during Heavitree Quartzite time is still limited by our inability to correlate regionally. Observations, both in the Limbла study area and from along the length of the MacDonnell Range, suggest that depositional sequences may persist over large distance, which is consistent with evidence of slow subsidence. It thus seems likely that deposition occurred simultaneously over vast areas with a large supply of sediment being rapidly dispersed by strong currents.

CONCLUSIONS

The Heavitree Quartzite and correlative formations, which are preserved at the base of the Neoproterozoic intracratonic successions across large areas of the Australian continent, record deposition in a sag basin that subsided synchronously across much of the Australia Craton over a time interval of ~40 million years (Gravestock & Lindsay 1994). The following general conclusions regarding the deposition of the basal sandstones in these basins can be drawn:

(1) The Heavitree Quartzite was, for the most part, deposited in a high-energy, open, shelf-like, tidal setting in which currents were alternately asymmetric (tidally reversing) and unidirectional.

(2) Deposition, and thus formation architecture, was controlled by regional subsidence and linked to sea-level changes to produce at least four well-defined sequences. The distinctive sheet-like form of the sandstones of the Heavitree Quartzite is a result of a large sediment input into a high-energy depositional environment on a subsiding low-gradient ramp.

(3) Broad similarities in the stacking patterns within the formation observed at widely separated localities suggest the possibility that sequence boundaries may be correlative over large areas of the basin. There is as yet no direct evidence that this is so, but studies of similar facies elsewhere suggest it is likely (Runkel et al. 1998) and it is consistent with the depositional setting.

(4) The abundance of quartzose sand relates to basin mechanics associated with mantle-plume formation (Dam et al. 1998) enhanced by the lack of soil-stabilising vascular plants (Tirsgaard 1993). The ultimate dispersal of fines is not known but they appear to have bypassed the high-energy depositional environment of the sag basin. Their ultimate destination can only be determined through a better understanding of the palaeogeography of Rodinia (Weil et al. 1998).

(5) Accommodation and an abundant sediment supply were almost in balance during deposition of the formation. This fine balance associated with the low-gradient ramp setting over vast areas of the basin appears to be a direct result of basin mechanics associated with mantle-plume decay relating to the assembly and dispersal of Rodinia.

(6) Over the long term, subsidence gradually outstripped sediment supply, water depths increased and the tidal influence declined. This ultimately led to a decline in the clastic sediment supply and, because of the low-gradient ramp setting and the lack of a clear shelf break, the transition to the carbonate-dominated Bitter Springs Formation was gradual and conformable.

(7) Silicification, one of the main impediments to petroleum exploration in the Heavitree Quartzite, may be localised along the MacDonnell Homocl ine as a result of fluid movement along deep-seated thrust faults. Basinward from the homocl ine silicification may be less intense suggesting the possibility of improved petroleum reservoir quality. This, in association with anoxic black shales of unknown hydrocarbon source potential at the base of the overlying Bitter Springs Formation, suggests that the interval is worthy of further study.

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