The ca 2.74 Ga Mopoke Member, Kylena Formation: a marine incursion into the northern Fortescue Group?

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The ca 2.74 Ga Mopoke Member, Kylena Formation: a marine incursion into the northern Fortescue Group?

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The northern part of the Fortescue Group consists of interbedded flood basalts and sedimentary rocks that were deposited on the southern margin of the Pilbara Craton, Western Australia, during one or more periods of continental rifting between ca 2.78 and ca 2.63 Ga. Well-preserved sedimentary intervals within the group have yielded stable carbon and sulfur isotope data that have been used to infer changes in geobiological processes in the Neoarchean. However, the Fortescue Group is notable for being a predominantly subaerial succession, and it remains unclear whether data obtained from these intervals should be interpreted in the context of deposition in marine environments, possibly recording changes in the global ocean/atmosphere system, or in local and restricted lacustrine settings. Here, we describe the sedimentology, stratigraphy, stromatolites and stable carbon isotope geochemistry of the ca 2.74 Ga Mopoke Member, Kylena Formation, the oldest stromatolitic horizon in the Fortescue Group. This unit differs in terms of internal stratigraphic relationships, sedimentology, carbonate mineralogy and stable isotope geochemistry when compared with intervals of probable lacustrine origin in the overlying Tumbiana and Maddina formations. In contrast, we suggest that parts of the Mopoke Member may have been deposited under open marine conditions, or alternatively, in a lacustrine environment characterised by differing water chemistry and basement topography. Stromatolitic microfabrics described from other Fortescue Group stromatolites. Mud-draped ripples are common sedimentary features in the Mopoke Member, suggesting a tidal influence. Mopoke Member δ13Corg values are generally slightly positive, but also include some significantly depleted values, which may relate to the reoxidation of 13C-depleted organic matter. δ13Corg values average −36.7‰, consistent with Neoarchean marine units reported from elsewhere, but significantly less 13C-depleted than values reported from overlying lacustrine intervals in the Fortescue Group. We conclude that some features of Fortescue Group datasets relevant to the field of geobiology may be facies dependent, and that more work focusing on the overall depositional environments of the Fortescue Group is needed in order to appropriately interpret geobiological data reported from that group.

KEYWORDS: Neoarchean, tidalites, methanotrophy, microbially induced sedimentary structures, stromatolites, lacustine.

INTRODUCTION

Well-preserved Neoarchean sedimentary rocks of the Fortescue Group, Western Australia, have been used to investigate the evolution of the early biosphere. The Fortescue Group is known, among other things, for providing insights into the composition of the Archean atmosphere based on stable carbon and multiple sulfur isotopes (e.g. Pavlov et al. 2001; Ono et al. 2000; Eigenbrode & Freeman 2006; Thomazo et al. 2009), for insights into Archean microbial communities from stromatolites (e.g. Walter 1972, 1983; Packer 1990; Buick 1992; Awramik & Buchheim 2000), for reports of molecular biomarkers (e.g. Brocks et al. 1999; Rasmussen et al. 2008) and for cyanobacteria-like microfossils (Schopf & Walter 1983). Extremely low δ13Corg values reported from the group are generally interpreted as reflecting the incorporation of biomass derived from methane-cycling communities during a period of enhanced global methanotrophy in the Neoarchean (Hayes 1994).

Previous studies have focused on the ca 2720 Ma Tumbiana Formation. However, additional stromatolitic intervals are present in the Kylena, Maddina and Jeerinah formations. Whereas a lacustrine interpretation has been proposed for the stromatolitic Meentheena Member of the Tumbiana Formation (Lipple 1975; Walter 1983; Bolhar & Van Kranendonk 2007; Awramik & Buchheim 2009; Coffey et al. 2013; but see Thorne & Trendall 2001 and Sakurai et al. 2005 for differing interpretations), the depositional setting of stromatolitic intervals within the Kylena, Maddina and Jeerinah formations remain...
poorly constrained, and it is unclear whether data reported from these units should be interpreted in the context of deposition within global oceans, or in local and restricted lacustrine settings.

Here, we examine the Mopoke Member, a laterally extensive stromatolitic carbonate horizon within the ca 2740 Ma Kylena Formation, the oldest stromatolitic horizon in the Fortescue Group. We compare it with demonstrably marine units described from other Archean formations and with intervals within overlying formations of the northern Fortescue Group, focussing on differences in mineralogy, sedimentology, stratigraphy and stable isotope geochemistry. The Mopoke Member is distinct from superficially similar Fortescue Group stromatolitic horizons in the Tumbiana, Maddina and Jeerinah formations, which are likely of lacustrine origin, and instead may have been deposited during a marine incursion into the northern Fortescue Group. We conclude that many of the observed differences between northern Fortescue Group units probably relate to the prevalence of locally variable lacustrine environments in this group, rather than to secular biological and/or environmental change during the Neoarchean.

Geological setting
The Fortescue Group is a succession of flood basalt and sedimentary rocks deposited on the southern margin of the Pilbara Craton, Western Australia (Figures 1, 2), from ca 2.78 Ga to ca 2.63 Ga, during one or more periods of rifting associated with extensive volcanism (Arndt et al. 1991; Blake 1993; Thorne & Trendall 2001; Blake et al. 2004). The Fortescue Group unconformably overlies Paleo- to Mesoproterozoic granite–greenstone basement and reaches a maximum local thickness of about 6 km (Thorne & Trendall 2001). Subaerial tholeiitic flood basalts are the predominant lithology, but the group also includes subordinate pillow basalt and basaltic tuff, felsic volcanic rocks, volcaniclastic rocks, clastic sedimentary rocks and stromatolitic carbonate.

Thorne & Trendall (2001) divided the Fortescue Group into four sub-basins for descriptive purposes (Figure 1). The northeast, northwest and Marble Bar sub-basins comprise the northern Fortescue Group, which is composed predominantly of subaerial basalt and siliciclastic rocks. The southern sub-basin lies to the south of the Fortescue River, has been more severely folded and metamorphosed, and consists mostly of pillow basalt and offshore sedimentary rocks: the supposed deeper-water lateral equivalents of Fortescue Group rocks preserved in the northern sub-basins. Metamorphism of the northwest and northeast sub-basins was limited to prehnite–pumpellyite facies (Smith et al. 1982).

The Kylena Formation and the Mopoke Member
The Kylena Formation (Smithies 1998; formerly the Kylena Basalt) consists of subaerial lava flows and thin units of carbonate, volcaniclastic and siliciclastic sedimentary rocks. Where present, the Kylena Formation

Figure 1 Map showing the extent of Fortescue Group outcrop in Western Australia and the Fortescue Group sub-basins of Thorne & Trendall (2001). Modified after Thorne & Trendall (2001).
disconformably overlies fluvial sandstone of the ca 2750 Ma (Blake et al. 2004) Hardey Formation, or unconformably overlies Paleo- to Mesoarchean basement rocks. The Kylena Formation is in turn disconformably overlain by pyroclastic and lacustrine deposits of the ca 2720 Ma (Blake et al. 2004) Tumbiana Formation.

The Mopoke Member (Williams 2007) is a thin horizon of carbonate, siliciclastic and volcaniclastic rocks...
(Figures 3, 4) separating two compositionally distinct lava flows of the Kylena Formation in the northeast sub-basin. Columnar jointing and pillow structures are locally developed in basaltic lava flows below the Mopoke Member in the Meentheena area (Figure 5). Upper Kylena Formation flows are generally thicker, consist of basalt and basaltic andesite, and were erupted under subaerial conditions (Williams 1999). Flows of both the upper and lower Kylena Formation are typically massive with highly vesicular, amygdaloidal and commonly scoriaceous flow tops. In the northeast sub-basin, the total stratigraphic thickness of the Kylena Formation ranges between 0 and ~600 m (Thorne & Trendall 2001) and the Mopoke Member is ~20 m thick. No radiometric dates are available for the Mopoke Member, but it is younger than ca 2740 Ma, the average of three dates obtained for the lower Kylena Formation (2749 ± 5, Nelson et al. 2006; 2741 ± 3, Blake et al. 2004; 2735 ± 6, Bodorkos et al. 2006), and older than the base of the overlying, 2727–2721 Ma Tumbiana Formation (Blake et al. 2004).

**Previous investigations**

Previous investigation of the Mopoke Member has been limited to brief lithological descriptions published in the explanatory notes accompanying Geological Survey of
Western Australia map sheets and reports (Williams 1999, 2007; Thorne & Trendall 2001; Farrel 2006; Williams & Bagas 2007), and a single sample of the Mopoke Member was analysed by Bolhar & Van Kranendonk (2007) as part of their trace elemental analysis of Fortescue Group carbonate rocks. This sample returned a trace-element distribution interpreted as a lacustrine signature, but there are no data on what stratigraphic level the analysed sample comes from within the member or the degree of alteration of this sample. Writing in explanatory notes, Williams & Bagas (2007) also considered the Mopoke Member to be lacustrine. In contrast, Thorne & Trendall (2001) proposed a marine origin for the Mopoke Member and described transgressive and regressive marine facies.

METHODS

Fieldwork was undertaken during seasons of 1 to 2 months duration in 2011 and 2013. Sections were measured with a Jacob's staff, a measuring tape and an Abney level. Hand samples were taken from outcrop in order to investigate lithology, microbialite microstructure and isotope geochemistry. Care was taken when sampling to avoid fractures, weathering rinds and recent cements. Geological thin-sections were prepared using standard petrographic techniques. Optical microscopy was performed using a Carl Zeiss Photomicroscope III and a Leica DM2500 running LAS 3.6 software. LA-ICP-MS, Raman and XRD analyses were performed at the UNSW Analytical Centre. Stable isotope analyses were performed by Environmental Isotopes Pty Ltd and the West Australian Biogeochemistry Centre.

LA-ICP-MS

Elemental information for each region/spot was collected using a New Wave NWR213 laser ablation unit coupled to a Perkin Elmer NexION 300D ICP-MS. Spot ablation of the geological thin-sections was performed using a frequency-quintupled Nd:YAG laser emitting a final pulse wavelength of 213 nm focused on the region of interest, with ablated material transported to the ICP-MS via a mixture of helium and argon carrier gas. Spot size was 50 µm for all analyses. The international NIST 61x series of standards was used for calibration. The following isotopes were analysed: 23Na, 24Mg, 27Al, 28Si, 32S, 39K, 43Ca, 55Mn, 57Fe and 88Sr. The experimental parameters were optimised to ensure an appropriate signal-to-noise ratio for each isotope and a reproducible signal.

Raman spectroscopy

Raman spectra were obtained from standard geological thin-sections using a Renishaw inVia Raman Microscope running Renishaw WIRE 3.2 software. Spot size was ~1.5 µm at 50x magnification using a 514.5 nm Argon ion laser with an 1800 gr/mm grating for all analyses. Spectra were identified using the RRUFF Project online database (http://rruff.info/).

XRD

Samples for bulk powder XRD analysis were selected on the basis of minimal alteration and fracturing. Samples were crushed and milled according to standard techniques before XRD analyses were performed using a PANalytical Xpert Multipurpose X-ray Diffraction System operating at 45 kV and 45 mA.

Stable isotopes

C and O stable isotope analyses of carbonates were performed using a GasBench II coupled with a Delta XL Mass Spectrometer (Thermo-Fisher Scientific). Three-point normalisation was used in order to reduce raw values to the international scale (Paul & Skrzypek 2007). Normalisation was performed based on international standards provided by IAEA: L-SVEC, NBS19 and NBS18. Values for international standards of carbon (δ13C) are according to Coplen et al. (2006). The external error of all δ13C and δ18O analyses is ±0.10‰.

Organic matter C isotope analyses were performed on samples that were first washed and had weathering rinds removed by sawing. They were then crushed using a hammer and placed in a rock mill. Powdered samples were digested in hydrochloric acid to remove carbonate. Approximately 500 mg of powdered rock sample was reacted with 10% HCl at room temperature overnight and then rinsed and dried overnight at 50°C. The high carbonate content and low organic C content required this step to be repeated up to three times. Dried rock power was weighed in tin cups for analysis of δ13C values and C concentrations using a modified Europa Roboprep CN Elemental Analyser (EA) attached to a Finnigan Mat Confo III and Finnigan 252. Samples were then analysed relative to internal gas standards that were calibrated using international carbon isotope standards NBS-22 (δ13C = −30.03‰ VPDB; Coplen et al. 2006) and IAEA-CH6 (δ13C = −10.45‰ VPDB). Microanalysis standard B2105 was run to calibrate for concentration and as an unknown. Values are reported in permil (%) relative to the international standard VPDB, which is defined by the International Atomic Energy Agency standard IAEA-NBS19 (δ13C = +1.95‰; Coplen et al. 1995).

THE MOPOKE MEMBER

Lithology

The Mopoke Member consists primarily of dark grey-coloured stromatolitic limestone and dolomite (Figure 3) and thinner units of calciturbite/calcisiltite, calcareous mudstone, siltstone, sandstone and black chert. Four lithofacies are defined here for descriptive purposes (L1 to L4, Figure 6). L1 consists of flat to wavy-laminated carbonate hosting large domical stromatolites (Figure 7a-c). It is typically ~1 m thick, but varies in thickness over distances of several hundred metres. It reaches a maximum thickness of 3 m at locality 5, where it hosts large domical stromatolites with up to 20 cm of synoptic relief. In the Meenthena area (Figure 1) L1 may be as little as ~10 cm thick. Coarsely laminated carbonate of L1 has encrusted pre-existing topography, including basalt cobbles derived...
from lower Kylena Formation lava flows (Figure 7a). Bulk powder XRD spectra indicate L1 is predominantly calcite and 5–10 wt% silica. The microfabric of both domical and stratiform laminated carbonate in L1 consists of coarsely recrystallised spar and dolospar intersected by stylolites and/or multiple generations of radiating blades of radiaxial calcite (Figure 7d–f). The radiaxial calcite commonly occurs in conspicuous, isopachous laminae visible in outcrop (Figure 7d). Some occurrences are associated with dissolution breccia (Figure 7f). LA-ICP-MS spot analyses of radiaxial calcite yielded values of ~10 000–15 000 ppm Mg, ~800–1000 ppm Fe and ~100–1000 ppm Sr. Edgewise tabular carbonate clasts, in places reworked into rosettes, also occur within L1 (Figure 8a). The first few centimetres of L1 are locally pervasively silicified and rich in siliciclastic grains. Dolomite inclusions visible in thin-section indicate some of the silica has replaced a carbonate lithology. This style of silicification in the base of L1 has occasionally resulted in the high-fidelity preservation of detrital and kerogenous laminae in microstromatolites (Figures 8b, 9).

L2 is generally less than 30 cm thick and consists of planar-laminated calcareous siltstone/shale (Figure 8c). L3 consists of irregularly silicified microbial laminae (Figure 8d, e) in recrystallised dolostone and limestone, and a minor siltstone and sandstone component preserving microbially induced sedimentary structures (Figure 8f). In thin-section, the replacive silica of L3 surrounds islands of relict spar and dolospar, resulting in a clotted texture that is visible at low magnification (Figure 10a, b). Zones where silicification has proceeded further have the appearance of massive black chert in outcrop and scattered dolomite rhombs floating in a microcrystalline silica matrix in thin-section (Figure 10c). Silicification occasionally appears to conform to bedding (Figure 10d), but for the most part is discordant. Kerogen visible in thin-sections occurs in black-coloured streaks and blobs in both carbonate stromatolites and in replacive silica zones.

L4 is composed predominantly of laminated calcareous mudstone and siltstone featuring desiccation cracks, symmetrical ripple cross-lamination and mud drapes (Figure 10e, f). Ripple crests are slightly sinuous, peaked to slightly rounded and occasionally bifurcate, with wavelengths 1 to 3 cm and amplitudes <8 mm. The predominant carbonate mineral in L4 is micritic calcite. L3 and L4 commonly repeat up to three times before the end of outcrop. Tuff, reported in the explanatory notes of multiple GSWA map sheets (e.g. Hickman 1983; Williams 2007; Williams & Bagas 2007), was not found to be a significant component of the Mopoke Member at the localities investigated, although a basaltic agglomerate is present at locality 1.

**Stratigraphy**

A series of sections were measured along the roughly north–south-trending extent of Mopoke Member outcrop in the northeast sub-basin (Figures 4, 11). The minimum measured thickness of the Mopoke Member ranges between 3 and 15 m and a maximum thickness of ~20 m can be estimated for sections in the Meentheena area. There is a slight thickening of units away from the Yilgalong Granitic Complex in a northerly direction. A southerly thickening away from the same paleotopographic high is not apparent in the southernmost sections measured. The southernmost locality logged for this study is located approximately 67 km
northwest of Nullagine, where the Mopoke Member is of similar composition and stratigraphy to the other localities. The northernmost locality logged is in the hinge of the Oakover Syncline, where the basal portion of the Mopoke Member consists of several metres of planar-laminated siltstone/shale. Overlying units are consistent with the stratigraphy of sections logged to the south. At other localities, the lowermost unit of the Mopoke Member is either a coarsely laminated stromatolitic carbonate or a thinly bedded intraformational conglomerate or lithic sandstone deposited in the topographic lows of lava flows. Where not preceded by shale or conglomerate, the lowermost bed of L1 lies conformably upon vesicular basaltic flow tops that show minimal reworking. With the exception of locality 1 (where there is an agglomerate), the uppermost unit of the Mopoke Member is L3 or L4 at all localities investigated. The internal stratigraphy of the Mopoke Member is laterally consistent, with centimetre-thick beds (for example, the calcilutite layers in L2) traceable laterally over distances of more than 50 km. The dip of Mopoke Member units is consistently less than 15° across the entire northeast sub-basin and relates to the gentle folding responsible for large-scale geological
Figure 8 (a) Edgewise conglomerate clasts in L1. (b) Thin-section photomicrograph showing a silicified microstromatolite in a siliciclastic lens near the base of L1. Scale bar = 1 mm. (c) Laminated siltstone/mudstone (L2) with white-coloured calcilutite banding. (d) Partially silicified microbial laminations in L3. (e) Partially silicified stromatolites in L3. (f) Bedding-plane exposure of L3 with microbially induced sedimentary structures.
structures such as the Oakover Syncline and Meentheena Centrocline.

**Stable isotopes**

Limited stable carbon and oxygen isotope data are shown in Figure 6 and Table 1. $\delta^{13}$C$_{\text{carb}}$ values range from $-2.8\%$ to $2.0\%$ VPDB with a single outlier at $-5.6\%$. The spread in values correlates to lithological variation (Figure 6): values obtained from L1 cluster between $1.2\%$ and $1.8\%$ (mean = $1.6\%$); those from L2 between $-2.8\%$ and $-2.6\%$ (mean = $-2.7\%$); those from L3 between $-5.6\%$ and $2.0\%$ (mean = $-0.7\%$); and a single value of $-1.5\%$ was obtained for L4.

$\delta^{18}$O$_{\text{carb}}$ values range from $-21.2$ to $-17.4\%$ VPDB (mean = $-19.3\%$) (Figure 6). Samples that appeared in outcrop to be more severely altered were observed to yield the most $^{18}$O depleted values. There is no significant correlation between $\delta^{18}$O$_{\text{carb}}$ and $\delta^{13}$C$_{\text{carb}}$ values (coefficient of correlation = 0.13).

$\delta^{13}$C$_{\text{org}}$ values for carbonate samples range from $-40.7\%$ to $-29.8\%$ VPDB (mean = $-36.3\%$). There is a trend of increasing $^{13}$C-depletion upsection from L1 towards L4 (Figure 6). A single $\delta^{13}$C$_{\text{org}}$ value of $-46.8\%$ was obtained from a sample of pervasively silicified kerogenous stromatolitic material collected from the base of L1 (Figure 9).

**INTERPRETATIONS**

Sedimentary features of the Mopoke Member suggest an upwards-shallowing, shallow marine depositional environment.

**L1**

L1 probably represents a marine transgression over the basaltic lava plain of the lower Kylena Formation. The stromatolites suggest this facies was deposited in the photic zone, and in a minimum of 20 cm of water as
Figure 10 (a) Clotted fabric resulting from the replacement of spar (left of image) by silica in L3, shown in transmitted light. Scale bar = 1 mm. (b) Transmitted light thin-section photomicrograph in cross polarised light showing silica replacing dolospark in L3, an intermediate stage in the advancement of the clotted fabric shown in (a) and (c). Scale bar = 1 mm. (c) Thin-section photomicrograph montage in reflected light showing dolomite rhombs floating in a clotted fabric related to the near-complete diagenetic silicification of microbial laminae in L3. Scale bar = 1 mm. (d) Partially silicified microbial laminations in L3. Note the concordance of silica with bedding. (e) Mud drapes on small-scale ripple cross stratification in L4. (f) Small scale, bifurcating symmetrical ripple cross-stratification in L4. Increments on Jacob’s staff are 10 cm.
constrained by the synoptic relief of stromatolitic laminae (Donaldson 1976). 'Rosettes' of reworked edgewise conglomerate clasts imply deposition above storm wave base (Kazmierczak & Goldring 1978). Pervasive silicification seen in the basal portion of L1 at some localities appears to have been relatively early, as it has resulted in the preservation of kerogen and microbial fabrics (Figure 8b) that have elsewhere been obliterated by recrystallisation. The fabric of L1 carbonate, which is dominated by spar, dolospar and isopachous calcite crusts, is comparable with previously reported shallow water Neoarchean marine units (e.g. Sumner & Grotzinger 2004), but distinct from the exclusively micritic fabrics reported from other Fortescue Group stromatolitic carbonates (e.g. Walter 1972; Coffey et al. 2013).

Much of the radiaxial calcite in L1 (Figure 7d–f), which has not been reported from other Fortescue Group units, appears to be primary, or at least a replacement of a phase growing at the sediment–water interface in that it has nucleated on areas of pre-existing topography and has formed laterally extensive, isopachous laminae that are onlapped by detrital grains (cf. Kendall 1985; Wilson & Dickson 1996). Where radiaxial calcite in the rock record has been interpreted as a primary marine precipitate (e.g. Schroeder & Purser 1986), it is commonly considered a proxy for generally warm, high CaCO\textsubscript{3} saturation and high pCO\textsubscript{2} conditions consistent with proposed models of the Neoarchean environment (e.g. Grotzinger & Knoll 2003; Dauphas & Kasting 2011). There are no definitive sedimentological features in L1 discriminating between marine and lacustrine settings, but the lateral continuity of facies is unlike the regular lateral facies changes reported from many modern lakes and from the Meentheena Member in the overlying

Table 1 Stable isotope values for Mopoke Member samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>δ\textsuperscript{13}C\textsubscript{carb} % VPDB</th>
<th>δ\textsuperscript{18}O\textsubscript{carb} % VPDB</th>
<th>δ\textsuperscript{13}C\textsubscript{org} % VPDB</th>
</tr>
</thead>
<tbody>
<tr>
<td>YOS1</td>
<td>Stromatolitic carbonate (L1)</td>
<td>1.23</td>
<td>−19.82</td>
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<tr>
<td>2.5.11.2</td>
<td>Irregularly silicified stromatolitic carbonate (L3)</td>
<td>−5.68</td>
<td>−19.90</td>
<td></td>
</tr>
<tr>
<td>3.5.11.2</td>
<td>Irregularly silicified stromatolitic carbonate (L3)</td>
<td>2.08</td>
<td>−19.81</td>
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<td>Green shale (L2)</td>
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<td>−19.51</td>
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<td></td>
<td>−29.8</td>
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<td>−20.71</td>
<td>−37.2</td>
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<td>Laminated calcareous siltstone (L4)</td>
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<td>−19.40</td>
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<tr>
<td>30.5.11.7</td>
<td>Stromatolitic carbonate (L1)</td>
<td>1.89</td>
<td>−18.46</td>
<td>−32.5</td>
</tr>
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</table>
Tumbiana Formation, which is probably lacustrine (Awramik & Buchheim 2009).

**L2**

L2 may have been deposited in a deeper-water environment below the zone of carbonate precipitation (cf. Murphy & Wilkinson 1980; Treece & Wilkinson 1982). A deeper, lower-energy environment for L2 is supported by the absence of current-generated sedimentary features and evidence for subaerial exposure, such as desiccation cracks. The distinctive pair of white-coloured calcite layers in the thinly bedded unit of L2 that interrupts L1 (Figure 8c), may represent a brief return to carbonate precipitating conditions, perhaps in events similar to the ‘whittings’ observed in some modern settings (e.g. Hodell et al. 1998). The thickening of L2 towards locality 1 (Figure 11) suggests a basin that deepened towards the northeast, in contrast to a previously proposed southward thickening of the Kylena Formation into its supposed southerly equivalent, the Boongal Formation (Thorne & Trendall 2001).

**L3**

The decreasing synoptic relief of stromatolites in L3 implies a shallower minimum water depth than in L1. The small-scale domical and conical stromatolites and microbially induced sedimentary structures in L3 are commonly associated with shallow-water facies (cf. Porada & Bouougri 2007). The laminated, reticulate surfaces preserved in marly sediment (Figure 8f) are similar to reticulate structures reported from both ancient and modern bacterial mats (e.g. Shepard & Sumner 2010; Flannery & Walter 2011). Most of the silica in this unit is interpreted to be of late diagenetic origin, given the textural relationships seen in thin-section, which indicate it post-dates the coarse recrystallisation of the carbonate comprising stromatolitic laminae.

**L4**

Desiccation cracks and small scale, bifurcating, symmetrical (wind-generated) ripple cross-lamination suggest a very shallow water to periodically exposed depositional setting for L4. The double mud drapes deposited on ripples may reflect a regime of semi-diurnal tides (cf. De Boer et al. 1989). Horizontal sections showing a gradation into thicker mud drapes (visible in Figure 10e) may represent deposition during neap tides, when current velocities were lower and the transport of sand did not take place (cf. Eriksson & Simpson 2000; Williams 2000; Mazzunder & Arima 2005).

**Stable isotopes**

Archean marine δ13C values are generally near zero (Veizer et al. 1989, 1990). Values from L1 in the Mopoke Member are also near zero. However, some values from L2, L3 and L4 are significantly 13C depleted (−5.6 to 2.0%). The depleted values may relate to diagenetic alteration and the early or late remineralisation of associated organic carbon, which is significantly depleted (−40.7 to −29.8%). This hypothesis is supported by the visibly most recrystallised sample yielding the lowest value (−5.6%). Alternatively, some of the observed δ13C variation in L2, L3 and L4, especially towards positive values, may be primary. The positive values may represent a previously undocuemed marine exursion, or if this part of the Mopoke Member represents a periodically restricted (e.g. lagoonal) setting, the values could be related to fluctuating water levels and/or rates of organic matter burial. More data are needed. δ18O values are consistently depleted (−21.2 to −17.4%), suggesting alteration via 18O depleted meteoric waters (Walls et al. 1979). The decreasing δ13Corg values upsection, from −29.8% in L1 to −40.7% in L4 (Figure 6) may be related to the increased burial of methanotrophic biomass in an increasingly restricted setting, an interpretation consistent with the shallowing upwards environment suggested by sedimentological features. L1 yielded the most enriched δ13Corg values, which are comparable with average marine values reported from throughout the geologic record, whereas L2, L3 and L4 yielded lower values that are closer to those reported from overlying, lacustrine units of the Fortescue Group (e.g. Awramik & Buchheim 2009; Coffey et al. 2013).

**Overall depositional environment**

With the exception of L2 (planar-laminated calcareous siltstone/shale), all lithofacies appear to have been deposited under shallow water conditions, with sedimentary features in lithofacies overlying L2 suggestive of upwards shallowing. Karst features affecting all carbonate facies are the result of periods of prolonged subaerial exposure during the deposition of L3 and L4.

Some parts of the Mopoke Member somewhat resemble a less extensive version of the Meentheena Member (Tumbiana Formation), and some of the same arguments that have been employed to infer a lacustrine setting for the Tumbiana Formation may be used to suggest a similar setting for these parts of the Mopoke Member, including deposition within a largely subaerial succession, the prevalence of symmetrical ripple cross-lamination and the absence of assuredly marine sedimentary features. However, much of the Mopoke Member is distinct from other stromatolitic units of the Fortescue Group (including the Meentheena Member) in terms of carbonate mineralogy, stratigraphy and sedimentology. The balance of probabilities currently favours a marine interpretation for at least part of the Mopoke Member based on the following observations:

- The succession of centimetre-scale lithofacies may be traced laterally across the entire extent of outcrop (100+ km). This is not a characteristic generally associated with shallow water lacustrine deposits, which typically exhibit frequent lateral and vertical facies changes (Platt & Wright 2009). Frequent lateral facies changes are observed in the Meentheena Member (Tumbiana Formation), which is considerably thicker yet consists of lenticular units that for the most part cannot be traced laterally over distances of more than a few kilometres (cf. Awramik & Buchheim 2009).
• Spar, dolosparradial calcite (Figure 7d–f) are conspicuous features of the Mopoke Member and distinguish it from micritic limestone members of the overlying Tumbiana and Maddina formations (cf. Walter 1983; Awramik & Buchheim 2008). In this respect, the Mopoke Member bears a closer resemblance to demonstrably marine early Precambrian formations from which isopachous sea-floor crusts, fans and dolomite are commonly reported, and where micrite is rare (e.g. Beukes 1987; Grotzinger & Knoll 1995, 2003; Sumner 1995; Sumner & Grotzinger 2004).

• Although lava flows overlying the Mopoke Member are subaerial and in some places thick enough to form columnar joints, there is some pillow basalt in the lower Kylena Formation. In contrast, the lava flows that underlie fluvial and lacustrine sedimentary rocks of the Tumbiana, Maddina and Jeerinah formations are exclusively subaerial.

• The double mud drapes observed in L4 are best accounted for by tidal influences.

• Comparatively high $\delta^{13}$Corg values obtained from the Mopoke Member are consistent with values reported from Neoarchean carbonate units deposited in shallow water marine environments (e.g. Fischer et al. 2009). These values contrast with the extremely low values (down to $\sim$60%o) reported from overlying lacustrine units in the Fortescue Group.

• The trace-elemental analyses of Bolhar & Van Kranendonk (2007), interpreted as suggestive of a lacustrine depositional environment, are stratigraphically unconstrained. Trace element analyses may have been compromised by alteration of the selected samples by meteoric waters, which is suggested by the consistently depleted stable oxygen isotope data reported here.

CONCLUDING REMARKS

A periodically restricted lacustrine environment, which differed in terms of basement topography and water chemistry when compared with other lacustrine units of the Fortescue Group, is one possible depositional environment for the Mopoke Member. However, the mineralogoy, sedimentology, stratigraphy and stable carbon isotope geochemistry is most consistent with a marine depositional environment. $\delta^{13}$Corg values for the Mopoke Member are more enriched in $^{13}$C than those reported from overlying lacustrine intervals in the Fortescue Group and closer to Archean units known to be of marine origin, suggesting a facies control on the $^{13}$C-depletion of organic matter in the Fortescue Group. We conclude that differences in carbonate mineralogy and stable isotope values reported from the northern Fortescue Group may represent local variations in restricted settings rather than globally significant biological and/or environmental change during the Neoarchean. Paleobiological data obtained from the northern Fortescue Group should thus be carefully considered in the context of depositional environments.

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