A carbon isotope reference curve for ca. 1700–1575 Ma, McArthur and Mount Isa Basins, Northern Australia

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Abstract

Shallow marine Paleo- and Mesoproterozoic sedimentary successions are widely distributed in several major basins across northern Australia. The successions are only gently deformed, and their stratigraphy is relatively continuous, thus offering an ideal opportunity to document secular variations in carbon isotopes. Marine carbonate intervals from two of these major basins, the McArthur and Mount Isa Basins, have been sampled to document secular variation in δ13C from approximately 1700 to 1575 Ma. In all cases, the samples have been tied to a well established sequence stratigraphy which, along with U–Pb SHRIMP zircon dates, provides a time resolution of the order of 1 m.y. The data presented here thus provide the most comprehensive and best dated δ13C stratigraphy yet obtained from such ancient rocks. Diagenesis occurred early in the carbonate rocks from both basins with the result that fluid movements were restricted and primary carbon isotopic signatures were retained. The δ13C values from both basins vary within a very narrow range around a mean of −0.6‰, with extreme values seldom lying further than 1‰ from the mean. That is, the curves are essentially flat. The results of this study, combined with earlier studies on younger rocks, imply that the global ocean reached a state of equilibrium in the mid-Paleoproterozoic and remained stable for much of the following billion years. Current models of the ocean suggest that to maintain the carbon mass balance relatively low levels of tectonic activity would be required, which in turn suggests that the availability of nutrients, such as phosphorus, was stable and low. Prolonged nutrient stability may therefore have exerted a major influence upon the evolution of the biosphere over this time interval. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The stable isotopes 12C and 13C are fractionated during autotrophic fixation of CO2 and ultimately come into mass balance with the global ocean. Carbon isotopic ratios preserved in carbonate rock (δ13C) thus reflect the ancient biogeochemical cycle (Broecker, 1970; Hayes, 1983) and provide a record of secular variations within the global ocean through time. The pattern of secular variation of carbon for the last billion years of earth history is now relatively well documented. Major excursions of >2‰ have been documented globally and have been used to document both significant events in earth history and the earth’s biogeochemical history (e.g. Des Marais et al., 1992; Strauss et al., 1992; Kaufman and Knoll, 1995). Carbon isotopes have proved especially valuable...
in evaluating the critical time period around the Precambrian-Cambrian boundary (Brasier et al., 1994, 1996; Kaufman and Knoll, 1995; Pelechaty et al., 1996; Calver and Lindsay, 1998). The Neoproterozoic Era to Cambrian Period was a time of major biological, geological and environmental revolution (e.g. Knoll and Walter, 1992; Schopf and Klein, 1992; Brasier and Lindsay, in press). These revolutions were accompanied by major changes in the carbon cycle (e.g. Strauss et al., 1992; Kaufman and Knoll, 1995).

In spite of success in the use of the carbon isotopic record as an indicator of changes in the biogeochemical cycle in rocks younger than 1 Ga, there is relatively little information from older rocks. A reconnaissance survey of Paleoproterozoic to Mesoproterozoic rocks of the McArthur Basin (Plumb, 1991) suggests that $\delta^{13}C_{\text{carb}}$ values ranged between 0 and 1‰ (Veizer et al., 1992). Other studies suggest that there were few major biological, geological or environmental events during the Mesoproterozoic Era (e.g. Klein et al., 1992; Lowe, 1992; Schopf, 1992; Buick et al., 1995). $\delta^{13}C_{\text{carb}}$ values during the Mesoproterozoic appear to average around 1.5‰ with a variation about the mean of 0.5‰ (Buick et al., 1995; Knoll et al., 1995b). Similarly, Xiao et al. (1997) found that late Mesoproterozoic carbonate rocks from the north China Platform have $\delta^{13}C_{\text{carb}}$ values within a very narrow range.

Recently, Karhu and Holland (1996) have compiled available carbon isotope data for the earliest Paleoproterozoic and found evidence of a major positive excursion of ca. +12.0‰ in the interval from 2.22 to 2.06 Ga. They associate this distinctive excursion with a rise in atmospheric oxygen. Paleoproterozoic carbonate rocks younger than 2.06 Ga appear to have carbon isotopic values similar to those documented for the Mesoproterozoic, a conclusion consistent with earlier assessments (Schidlowski et al., 1983). However, the data were compiled from a number of sources and are poorly constrained both stratigraphically and in terms of absolute time.

In this paper, we test the hypothesis that $\delta^{13}C_{\text{carb}}$ values remain relatively flat between ca. 1.7 and 1.5 Ga through studies of well preserved carbonate rocks from two major Paleoproterozoic to Mesoproterozoic basins in northern Australia, the McArthur and Mount Isa Basins (Fig. 1).

2. Regional setting

Paleo- to Mesoproterozoic sedimentary rocks are widely distributed across the northwestern part of the Australian craton (Fig. 1). The exposed rocks form part of a series of relatively shallow, complex, polyphased basins including the Birrindudu, Kimberley, McArthur, Mount Isa and Victoria River Basins containing up to 10 km of sedimentary rocks (Plumb et al., 1990). These widely distributed basins exhibit many similarities in their stratigraphic successions, especially in the Paleo- to Mesoproterozoic, where regional unconformities separate apparently correlative megasequences that suggest common tectonic controls. Rb-Sr whole rock and zircon U-Pb ages from interbedded volcanics provide control on the regional timescale (Plumb et al., 1990; Page, 1997; Page and Sweet, 1998; Southgate et al., in press) (Figs. 2 and 3). The basins rest on crystalline basement generated during the Barramundi Orogeny, an event recognised across much of northern Australia (Page and Williams, 1988; Le Messurier et al., 1990; Needham and De Ross, 1990; Plumb et al., 1990; O’Dea et al., 1997). Beginning at approximately 1.8 Ga, large areas of the Australian craton, including the basins studied here, began to subside, possibly as a response to mantle instability and the intrusion of anorogenic granites at a time of the breakup of a putative Paleoproterozoic supercontinent (cf. Gurnis, 1988; Iudnurm and Giddings, 1988). The Proterozoic basins of northern Australia are unique in that much of the region has experienced only mild and often localised tectonic activity over the last 1.8 Ga (Plumb et al., 1990). Kerogen studies in the McArthur Basin indicate that the succession ranges from slightly over mature to sub-mature (Crick et al., 1988). Locally, hydrocarbons are preserved in situ in Mesoproterozoic source rocks (Powell et al., 1987). Further to the southeast in the Mount Isa Basin, large parts of the Mount Isa Block are only gently
deformed, and hydrocarbons have been encountered in a number of wells (McConachie et al., 1993). The sedimentary rocks of these two basins contain important microbiotas (Schopf and Klein, 1992), the oldest known biomarkers, including eukaryotic steranes (Summons et al., 1988; Summons and Walter, 1990), productive in-situ hydrocarbons (Powell et al., 1987; McConachie et al., 1993) and massive sulphate evaporites (Walker et al., 1977; Jackson et al., 1987; Des Marais et al., 1992). The basins thus provide an ideal setting for a detailed study of Paleoproterozoic isotopic signatures.

3. Basin-fill architecture

Stable isotopes are only of optimal value when placed within a well-constrained basin-fill architecture. Previous attempts to analyse stable isotopes in the McArthur Basin (Veizer et al., 1992) were limited by misinterpretation of the depositional environment of carbonate intervals (e.g. Emmerugga, Lynott, Yalco) as lacustrine (e.g. Brown et al., 1969; Logan and Williams, 1984; Lindsay et al., 1987; McConachie et al., 1993; Lindsay, 1987; McConachie et al., 1993; Lindsay and Wells, 1997; Sami et al., 1997). This led to a conflict in interpretation, with well-constrained isotopic data suggesting a marine environment, while facies analysis suggested a non-marine setting. Thus, to sample the basin fill to best effect, it is necessary to establish a comprehensive basin-fill architecture, both as an aid to understanding facies, and as a means of developing an effective timescale and, ultimately, a geohistory.

Sequence stratigraphic concepts provide the best means for defining the architecture of the basin fill by recognizing chronostratigraphic units (sequences) of genetically related lithofacies bounded by unconformities or their laterally equivalent conformities (sequence boundaries) (Vail, 1987).
Fig. 2. Composite δ¹³C_carb profile for the Paleoproterozoic to Mesoproterozoic McArthur and Nathan Groups from the Batten Trough (the main depocentre) of the McArthur Basin and the Karns Dolomite from the adjacent, but shallower, Wearyan Shelf area. Chronostratigraphy based upon Page and Sweet (1998) and Southgate et al. (in press).
Fig. 3. Composite δ¹³C_carb profile for the Paleoproterozoic Fickling Group, which lies close to the basin margin along the Murphy Inlier, and the McNamara Group, which lies further basinward, towards the main depocentre, in the Lawn Hill area of the Mount Isa Basin of northern Australia. Chronostratigraphy based upon Page and Sweet (1998) and Southgate et al. (in press).
et al., 1977a,b; Vail, 1987; Van Wagoner et al., 1987). However, these concepts were developed for much younger sedimentary rocks in passive margin settings. The McArthur and Mount Isa Basins are intracratonic basins that provide significantly different settings from those of a passive margin setting, but share much in common with other intracratonic settings (e.g. Amadeus Basin, Lindsay et al., 1993, 1987; Officer Basin, Lindsay and Leven, 1996).

Intracratonic basinal successions differ from passive margin successions in two major ways. First, intracratonic successions are polyphase, and second, the depositional sequences contained within the phases have very different geometries to their passive margin counterparts. Whereas passive margin successions are largely the product of a single major tectonic event, generally continental break-up, intracratonic basins preserve a much longer record of geologic time (300–500 m.y.) and are generally the product of several major tectonic events that may be either extensional or compressional. This results in a complex basin fill that consists of a series of depositional packages that have been referred to in the past as mesasequences (Lindsay and Leven, 1996). These packages are defined by major erosion surfaces that are often unconformable. They are thus not necessarily eustatically controlled depositional sequences in the strict sense of the definition (cf. Van Wagoner et al., 1987) but tectonically defined entities (cf. Sloss, 1963; Sloss and Speed, 1974).

Slow subsidence rates, low depositional slopes and shallow water depths collectively result in diminished accommodation within intracratonic basins. Consequently, the sequences deposited in these basins are extensive and thin, few have recognizable progradational geometries, and erosional unconformities generally have minimal topographic relief. Progradational geometries are only likely to occur during rapid subsidence when accommodation is significant (cf. Lindsay, 1987). During relative sea level lowstands, little or no accommodation may be available for sediment accumulation, and lowstand deposits are often poorly developed and areally restricted. Thus, intracratonic successions comprise stacked transgressive-highstand deposits separated by near planar unconformities or paraconformities; that is, maximum flooding surfaces commonly coincide with sequence boundaries or are stratigraphically close to them (Lindsay et al., 1993). In general, the depositional sequences are thin and poorly differentiated compared to their passive-margin counterparts (Lindsay, 1987; Lindsay and Korsch, 1989; Lindsay et al., 1993; Lindsay and Leven, 1996).

Intracratonic successions thus tend to have layer-cake stratigraphies, which means that sequence stratigraphies and lithostratigraphies frequently parallel each other. Variations in subsidence rates during basin evolution leave a distinctive fingerprint in the stacking patterns, potentially at least, identifying the tectonic regime active at the time (cf. Lindsay and Leven, 1996). The sequence boundaries thus provide timing marks produced by the imposition of short term sinusoidal cycles of eustasy on the longer term depositional patterns generated by tectonic controlled subsidence. Regional field studies in both basins combined with analysis of seismic sections (McConachie et al., 1993; Lindsay, 1998), drill core and wire line logs have been used to develop a regional basin-fill architecture. This framework, in combination with SHRIMP zircon dates (Page, 1997; Page and Sweet, 1998) from interbedded tuffs and paleomagnetic data (Idnurm and Giddings, 1995; Idnurm et al., 1995), provides age constraints that allow a time resolution of approximately 1 m.y. (Southgate et al., in press).

4. Sequence analysis

The basin framework used in the present study is adapted from Southgate et al. (in press). Ten basin phases or megasequences have been identified, each defined by major erosional unconformable surfaces that can be correlated regionally. The present study is based upon 12 drill cores, six from each basin and a supplementary outcrop section from the McArthur Basin where core was unavailable (Figs. 1–3). The cores and sections were selected to provide an isotope stratigraphy of all megasequences where carbonate sedimentation dominates. Correlative sections were sampled from
both basins on the basis that, if the isotopic signatures were similar, they were more likely to be primary (Figs. 2 and 3). Further, within each basin, we have sampled carbonate intervals from sections within the main depocentres and from thinner, more condensed sections closer to the basin margins, again on the premise that, if the signatures were similar in both deeper and shallower water environments, they were more likely to be primary and representative of the global oceanic signal.

Gamma-log interpretation and detailed analysis of core were used to establish a sequence stratigraphy for each drill hole or outcrop section thus allowing a direct tie with the previously established basin-fill architecture (Southgate et al., in press). Gamma logs, a mature tool widely used in the evaluation of petroleum reservoirs (Van Wagoner et al., 1991), have proved valuable in these ancient intracratonic settings where sequences are thin and facies variations subtle. Gamma rays are produced by natural radioactive decay of, for the most part, K, U and Th, although by far the largest proportion of the total count comes from the radiogenic breakdown of K. All three elements are strongly associated with the clay fraction of the sediments and to, some extent, with organic-matter complexes. Thus, with occasional exceptions such as tuffaceous horizons, or glauconite-rich intervals, gamma logs provide a valuable objective tool for evaluating subtle changes in lithology and facies within a vertical succession.

In their most obvious expression, depositional sequences occur as upward shallowing successions in which the clay fraction of the sediment declines upward in parallel with the shallowing depositional environment. Depositional sequences thus produce distinctive gamma-log patterns with sharp breaks in response to abrupt facies changes across sequence boundaries at their bases (e.g. M4 to M5, Fig. 14), followed by an initial increase in gamma-ray intensity (retrogradation), as the sea level rises and the environment deepens toward the maximum flooding, and finally a decrease in gamma intensity as the accommodation space fills, the succession progrades and the environment shallows (e.g. M5, Fig. 11 and M7, Fig. 13). As well as defining individual sequences, the ordered succession of sequences, that is the stacking patterns of the sequences, provides information on basin history. During times of increased basin subsidence, accommodation, and hence water depth, result in an overall increase in the deposition of fines thus producing a retrogradational stacking pattern in the resulting succession of sequences (e.g. M4, Fig. 8). The reverse is true as subsidence declines and water depth gradually decreases as the space is filled, producing a progradational stacking pattern (e.g. M8, Fig. 8). Where subsidence and sedimentation are in balance, aggradation occurs, and gamma logs cycle subtly with slight shifts in sedimentation in response to eustasy (e.g. Fig. 12). Gamma-log analysis thus provides a powerful technique for defining a sequence framework which, in combination with the larger-scale basin architecture, allows the development of a high resolution chronostratigraphic framework in which to evaluate chemostratigraphy. The sequence framework also provides a high degree of facies predictability (Van Wagoner et al., 1991).

While contemporaneous, the architectures of the McArthur and Mount Isa Basins are quite different. The McArthur Basin consists of a series of independent half grabens that were initiated by extension early in basin history, then amplified and finally inverted by later transpressional events (Jackson et al., 1987; Lindsay, 1998). The Mount Isa Basin in contrast has a much more open gamma logs provide a valuable objective tool for evaluating subtle changes in lithology and facies architecture with a thin basin margin succession preserved along the Murphy Inlier to the west that thickens rapidly towards a major depocentre in the east (Bradhaw et al., in press). The asymmetry of the basin led McConachie et al. (1993) to suggest that it was a foreland basin. In spite of their divergent architecture, second third and fourth order depositional sequences can be correlated across the fault controlled sub-basins of the McArthur Basin and into the broad open architecture of the Mount Isa Basin independent of structural controls. That such a refined sequence stratigraphy can be correlated in detail across such vast and tectonically diverse areas can only be explained if the sequences are eustatically controlled, which in turn implies that the basins were open to the global ocean and hence marine in nature (Southgate et al., in press). If the basins
were non-marine, the geometry of the depositional packages would be controlled by local tectonic events that would produce a discontinuous localised ‘sequence stratigraphy’ making regional correlation impossible.

The regional continuity of the sequence stratigraphy, along with data on facies associations, especially the vast platform carbonate associations, and distinctive gamma-log signatures, leaves no doubt that the basins were open to the global ocean. The abundance of glauconite, the presence of phosphatic hardgrounds and the distinctive facies signature of tidal associations throughout the succession in both basins provide conclusive evidence of a shallow marine depositional setting for most of the sedimentary rocks preserved in these two well-preserved ancient intracratonic basins.

5. Preliminary sample analysis

Given the extreme age of the rocks in the McArthur and Mount Isa Basins, it is important to establish, with some certainty, the primary nature of the $\delta^{13}$C_carb signature. Enough information is now available to show that Paleoproterozoic to Mesoproterozoic rocks may retain near primary carbon isotope compositions (e.g. Veizer et al., 1992; Buick et al., 1995; Knoll et al., 1995b). However, the passage of fluids during diagenesis and later mineralizing events can alter primary $\delta^{13}$C_carb values (Veizer, 1983; Fairchild et al., 1990; Kaufman et al., 1992; Marshall, 1993) such that samples must be screened. In this study, sample screening was carried out in four stages: by careful selection of sampling sites and samples, by thin section evaluation, followed by an analysis of key trace and major element associations and finally by assessment of the isotopic data.

With one exception (drill core GC105, Fig. 15), gamma logs were acquired for all drill cores and outcrop sections used in this study. Where downhole wireline logs were not available, natural gamma radiation was measured at 50 cm intervals on core and outcrop using a scintillation counter to construct a gamma-ray profile (cf. Chamberlain, 1984; Myers, 1989; Myers and Bristow, 1989; Aigner et al., 1995). The gamma logs were then used to evaluate facies and establish a sequence stratigraphy that was used for regional correlation. The carbonate dominated sequences in the two basins average 61 and 67 m in thickness in the Mount Isa and McArthur Basins, respectively. The minimum sequence thickness is approximately 40 m in both basins. During times of increased subsidence, sequences thickened to between 100 and 200 m, and stacking geometries became aggradational.

Sampling concentrated on cores from the less deformed parts of the basins and on lithologic intervals free from evidence of secondary alteration, especially signs of mineralisation. During preliminary work, drill core GC105 (Fig. 15) was sampled at 5 m intervals for its full length and at 1 m intervals for the upper 25 m in an attempt to evaluate small-scale secular changes. The isotopic signatures were found to be largely monotonic, which led us to establish a sampling interval of 10 m. In all, 6.8 km of core and section were examined and 576 samples collected for analysis to establish, with some certainty, the primary nature of the $\delta^{13}$C_carb signature. Enough information is now available to show that Paleoproterozoic to Mesoproterozoic rocks may retain near primary carbon isotope compositions (e.g. Veizer et al., 1992; Buick et al., 1995; Knoll et al., 1995b). However, the passage of fluids during diagenesis and later mineralizing events can alter primary $\delta^{13}$C_carb values (Veizer, 1983; Fairchild et al., 1990; Kaufman et al., 1992; Marshall, 1993) such that samples must be screened. In this study, sample screening was carried out in four stages: by careful selection of sampling sites and samples, by thin section evaluation, followed by an analysis of key trace and major element associations and finally by assessment of the isotopic data.

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Table 1
Sampling statistics for data from the McArthur and Mount Isa Basins

<table>
<thead>
<tr>
<th>Well, drillhole name</th>
<th>Total depth (m)</th>
<th>Carbonate carbon (Mean S.D.)</th>
<th>Oxygen (Mean S.D.)</th>
<th>Number of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>McArthur Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amoco 82-04</td>
<td>541.0</td>
<td>−0.37</td>
<td>0.62</td>
<td>59 3</td>
</tr>
<tr>
<td>Amoco 82-05</td>
<td>495.5</td>
<td>−0.63</td>
<td>0.54</td>
<td>45 1</td>
</tr>
<tr>
<td>Amoco 82-07</td>
<td>498.6</td>
<td>−0.20</td>
<td>0.50</td>
<td>52 0</td>
</tr>
<tr>
<td>Bing Bong 82 (NTGS)</td>
<td>442.9</td>
<td>−1.15</td>
<td>1.05</td>
<td>40 2</td>
</tr>
<tr>
<td>McA9 (BHP)</td>
<td>350.0</td>
<td>−0.79</td>
<td>0.58</td>
<td>35 0</td>
</tr>
<tr>
<td>McAthur R. Section</td>
<td>700.0</td>
<td>−0.63</td>
<td>0.94</td>
<td>32 0</td>
</tr>
<tr>
<td>Wooyan #1</td>
<td>843.3</td>
<td>−0.71</td>
<td>0.46</td>
<td>50 1</td>
</tr>
<tr>
<td>Mount Isa Basin</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CM35 (Aberfoyle)</td>
<td>549.0</td>
<td>−0.22</td>
<td>0.37</td>
<td>25 0</td>
</tr>
<tr>
<td>Amoco 83-04</td>
<td>597.6</td>
<td>−1.30</td>
<td>0.85</td>
<td>48 4</td>
</tr>
<tr>
<td>Amoco 83-05</td>
<td>582.2</td>
<td>−0.72</td>
<td>0.31</td>
<td>59 0</td>
</tr>
<tr>
<td>GC105 (Pasminco)</td>
<td>501.2</td>
<td>−0.70</td>
<td>0.59</td>
<td>58 0</td>
</tr>
<tr>
<td>Lawn Hill-03 (GSQ)</td>
<td>460.0</td>
<td>−0.75</td>
<td>0.81</td>
<td>33 1</td>
</tr>
<tr>
<td>Lawn Hill-04 (GSQ)</td>
<td>450.0</td>
<td>−0.53</td>
<td>0.42</td>
<td>40 1</td>
</tr>
<tr>
<td>Total</td>
<td>6771.3 m</td>
<td></td>
<td></td>
<td>576 13</td>
</tr>
</tbody>
</table>

* The second column associated with the number of samples on the right gives the number of samples that could not be analysed due to a low carbonate content. NTGS: Northern Territory Geological Survey; GSQ: Geological Survey of Queensland; BHP: Broken Hill Proprietary Limited.

intervals. The intimate association of the quartz grains with the laminated carbonate and the organic materials suggests that many of the quartz grains were trapped as they adhered to the surface of living bacterial mats. Most intraclasts are supported in fine grained micrite and show no evidence of deformation from compaction. The textures of the intraclasts, while varying slightly, are very similar to the surrounding lithologies, suggesting that they are locally derived and penecontemporaneously eroded. The localised nature of their origin was further supported by later detailed duplicate isotopic analyses, which show only a slight variation in δ13Ccarb and δ18Ocarb between clasts.

A few samples are predominantly oolitic with spaces between oolites largely filled by very fine-grained micrite. In general, the oolites are well preserved with their internal annular structure clearly visible. All are uniformly circular in cross-section, suggesting that they have not been deformed by compaction. A small proportion of the oolitic samples had original primary porosity (maximum 5%) between oolites, most of which has been filled by later chert and less frequently crystal-line quartz cement. Such cements are, however, rare.

Overall, the primary fabrics of the carbonates, especially the major platform carbonate units, are well preserved, suggesting that diagenesis, including dolomitisation and silicification, occurred early (cf. Veizer et al., 1992). Buick et al. (1995) drew similar conclusions for Mesoproterozoic carbonates in the Bangemall Basin. It therefore seems likely that the more massive carbonates in the Mount Isa and McArthur Basins were sealed to the passage of fluids during early diagenesis, thus retaining the primary δ13Ccarb signature.

Fe, Mn and Sr have all been used as a means of evaluating the effects of diagenesis. Mn/Sr and, to a lesser extent, Fe/Sr ratios have been regarded as a sensitive indicator of diagenetic alteration in carbonates because both Mn and Fe replace Sr during diagenesis (Brand and Veizer, 1980; Derry et al., 1992; Knoll et al., 1995a). Early work by Brand and Veizer (1980) suggested that samples with Mn/Sr ratios less than 2 were unaltered. However, more recent work by Knoll et al. (1995a) suggests that samples with values as high as 10
still produced reliable carbon isotope signatures. Given that the approach to the use of Mn/Sr ratios has generally been qualitative (Derry et al., 1994) their use should be evaluated more objectively. Regardless of their degree of diagenetic alteration, Sr values are low (35 ppm) in carbonate rocks throughout the Mount Isa and McArthur Basins. It is thus reasonable to expect that primary Mn/Sr ratios would be high under most circumstances. Synsedimentary Mn could be expected to occur in association with condensed intervals. However, Mn does not show a clear correlation with Al (Fig. 4C) or K, suggesting that it is independent of the clay fraction and is associated with other minerals (e.g. MnO₂) that are controlled by variations in Eh at the sediment water interface. It should, however, be noted that many preconceptions associated with the distribution of Mn or other elements in the sedimentary record are influenced by our experience with Phanerozoic sedimentary successions, which may not be entirely applicable in the biogeochemical setting of the Paleoproterozoic where the environment was less well oxygenated and bioturbation had not yet evolved (cf. Logan et al., 1995; Strauss et al., 1997).

The Mn/Sr ratios have a mean value of 39.2 which is high when compared with samples analysed from most other basins (e.g. Derry et al., 1994). The distribution of Mn/Sr values is polymodal (Fig. 4E) with most samples concentrating about the main mode at 10–15 and lesser modes at 30–35 and 55–60. A small number of samples, which lie well beyond these modes, are all associated with anomalous δ¹³C_Carb values (e.g. Bing Bong 2 drill hole, Fig. 11). The polymodal nature of the histogram indicates that Mn/Sr is a relatively independent variable and must be assessed for each locality if it is to be used as an indicator of diagenetic alteration. Our Fe/Sr and Mn/Sr cross-plot (Fig. 4D) shows that most samples cluster tightly, which suggests little alteration. The Fe vs. Al cross-plot (Fig. 4G) does not show a significant linear relationship, indicating that Fe, like Mn, is widespread throughout the lithologies. To some extent, Fe occurs in glauconite, which is relatively common throughout the section in both basins and often associated with transgressive systems tracts. However, potassium ferrocyanide staining suggests that there is little iron held in the carbonate mineral lattices. A histogram of Fe/Sr values (Fig. 4F) further suggests that Fe behaves much as Mn and is a relatively independent variable that should be evaluated for each locality. The histogram is polymodal, but only a few samples lie well beyond the main mode.

All samples analysed from the two basins are dolomitic, with Mg/Ca ratios of 0.60 ± 0.15. The tight clustering of Mg/Ca values about the mean suggests that the dolomitisation process had gone to completion throughout the succession in both basins and that similar conditions of diagenesis existed in both basins. Throughout the section, but especially where clastic lithologies dominate, micrites have also been silicified to varying degrees. The whole rock Si content of the samples ranges from 11 to 43% (mean ± 11.1%) although these figures include variable proportions from 5 to 10% clastic quartz. The diagenetic silica is very finely dispersed throughout the micritic matrix, suggesting that it is infilling pore space rather than replacing carbonate. As both the intraclasts and the oolites show little evidence of deformation to indicate compaction,
it seems likely that silicification of the micrite occurred during early diagenesis, thus filling the pores between the sub-microscopic carbonate grains and precluding compaction.

The data suggest that diagenetic processes, which are of critical importance to the interpretation of isotopic signatures, appear to have operated in a very different manner during the Paleoproterozoic to that which might be expected in Phanerozoic settings. Thin-section analysis of carbonate rocks from the Mount Isa and McArthur Basins shows that much of their primary fabric is well preserved. This, in conjunction with an evaluation of major and trace element chemistry, suggests that dolomitisation and silicification of these sediments occurred very early in their depositional history, an observation made during other studies of Proterozoic carbonates (cf. Veizer et al., 1992; Buick et al., 1995). A large proportion of the carbonates were deposited in shallow marine ramp settings, often in subtidal to peritidal environments. In an ecosystem lacking burrowing and grazing metazoa, newly deposited sea-floor sediments were likely to have been left undisturbed, with their surfaces strongly bonded by microbial mats. There was little primary porosity in the sediments because most intergranular spaces were filled by micrite during sedimentation. Since the micrite was not bioturbated, but actively bonded by microbial mats, current winnowing was inhibited. Only strongly erosive currents appear to have been effective in modifying the depositional interface. The sediments they eroded were clearly well consolidated because they were torn up as large, relatively rigid intraclasts. As diagenesis proceeded, at first through dolomitisation and then by silica infilling of pore spaces, the three-dimensional structure of the carbonate fabric was preserved and fluid flow through the well-bonded sediments was quickly precluded. This early diagenesis resulted in the ‘locking-in’ of primary δ13C_carb signatures.

Altogether, the data suggest that diagenetic alteration resulted in dolomitisation and silicification, occurred early, precluding the passage of later fluid events through the carbonate intervals and locking in the primary carbon isotopic signatures. Overall, the results emphasise the importance of preliminary sample selection. Thin section and microfacies analysis are of almost equal importance. Mn, Fe and Sr provide valuable support for the above but they must be evaluated on a site-by-site basis if they are to provide useful results.

6. Analytical method

Core samples were examined both macro- and microscopically for lithologic variation. Selected portions of carbonate were cleaned and analysed using a VG Isogas PRISM mass spectrometer attached to an on-line VG Isocarb preparation system (cf. Brasier et al., 1996). The reproducibility of the replicate standards was better than 0.1‰ for δ13C_carb and δ18O_carb. Calibration to PDB standard via NBS 19 and Cambridge Carrara marble was performed daily using the Oxford in-house standard (NOCZ, Brasier et al., 1994). Results from 13 samples were of poor quality due to their low carbonate content and were ultimately rejected (Table 1). Duplicate analyses were performed to evaluate isotopic variation between the various carbonate phases (up to six phases were analysed). In general, the differences between phases were minimal and within analytical error. Duplicate δ13C_carb analyses varied by between 0.01 and 0.30‰, and δ18O_carb values ranged between 0.5 and 0.9‰. Overall, the results show that the isotopic composition within samples is relatively uniform. Duplicate analyses were also performed on all samples that exceed the mean δ13C_carb value for any one core by more than one standard deviation. In general, the more extreme values occurred in samples that had low carbonate contents.

δ18O_carb has been used as an indicator of diagnostic alteration (Brand and Veizer, 1980; Derry et al., 1992) and provides valuable support for major and trace element evaluations. δ18O_carb values generally become more negative in response to diagenetic effects, which can often be recognised from covariance on δ13C_carb/δ18O_carb cross-plots (Figs. 5 and 6). In general, however, the cross-plots of our data show that most samples from the Mount Isa and McArthur Basins cluster tightly around mean δ13C_carb values of close to −0.5 and
Fig. 5. $\delta^{13}$C$_{carb}$ vs. $\delta^{18}$O$_{carb}$ cross-plots for data from McArthur Basin drill core. Note that most values cluster relatively tightly around $\delta^{13}$C$_{carb}$ values close to $-0.5\%o$. Most altered values lie well beyond two standard deviations from the main clusters of points. Some covariance is apparent in Amoco 82-05 and 82-07 drill cores and the McArthur River outcrop section, suggesting minor alteration. Regression lines are significant at the 95% level of confidence.
Fig. 6. $\delta^{13}C_{\text{carb}}$ vs. $\delta^{18}O_{\text{carb}}$ cross-plots for data from Mount Isa Basin drill cores. Note that most $\delta^{13}C_{\text{carb}}$ values cluster relatively tightly close to $-0.5‰$. Some covariance is apparent in the Pasminco GC105, Lawn Hill 3 and Amoco 82-05 drill cores, suggesting minor alteration although most correlations, notably in Lawn Hill 3, are associated with single divergent points. Regression lines are significant at the 95% level of confidence.
$\delta^{18}O_{\text{carb}}$ values of around $-8$ to $-6$ (Table 1). Some linear correlation can be seen to occur in five of the drill holes and in samples from the McArthur River Section, but the strength of the correlation frequently relates to conspicuous outlying samples that are obviously altered. In some cases, such as in Bing Bong 2 drill hole (Fig. 5), the outlying values can be associated with other indicators of alteration such as extreme Mn/Sr values.

Finally, while $\delta^{13}C_{\text{carb}}/\delta^{18}O_{\text{carb}}$ cross-plots provide useful information, the best indication of alteration in the $\delta^{13}C_{\text{carb}}$ data comes from the presence of anomalous outlying values. Where single $\delta^{13}C_{\text{carb}}$ values depart abruptly from the overall isotopic trend, especially when the deviation is negative, samples should be treated with care and evaluated against other indicators. Frequently, such deviant values also have anomalous $\delta^{18}O_{\text{carb}}$ values and high Mn concentrations.

7. McArthur Basin

The McArthur Basin covers an area of 180 000 km$^2$ in the central northern region of the Australian craton (Fig. 1). It is a complex polyphase intracratonic basin containing a Paleoproterozoic to Mesoproterozoic mixed carbonate and clastic depositional succession with minor volcanics that locally exceeds 10 km in thickness. The basin is bounded to the southeast by the Murphy Inlier, which also separates it from the Mount Isa Basin. In the northwest, the basin is limited by the older Pine Creek Geosyncline, while to the northeast, it is bounded by the Arnhem Block. The full extent of the basin is unknown as large areas extend beneath the Georgina Basin (cf. Lodwick and Lindsay, 1990), the Carpentaria Basin and the Arafura Sea (Jackson et al., 1987; Plumb et al., 1990; Haines et al., 1993).

The McArthur Basin was initiated at approximately 1.8 Ga as a sag basin. Subsequent extension of the weakened crust, beginning at approximately 1730 Ma, led to the development of a series of normal faults and half grabens within zones defined laterally by major strike-slip fault complexes (the Batten Trough). The half grabens were initially filled by a volcaniclastic sedimentary succession with associated bimodal volcanics. During subsequent basin subsidence, which occurred initially in response to thermal recovery and later to episodes of compression/transpressional reactivation ending at approximately 1575 Ma, the Batten Trough accumulated a mixed carbonate and clastic succession exceeding 8 km in thickness (McArthur and Nathan Groups, Jackson et al., 1987). A major change in basin and regional dynamics between 1575 and 1500 Ma led to inversion of the thickened succession overlying the half grabens and extensive erosion of earlier depositional units. Structural inversion was followed some time later by deposition of a further 3 km of shallow marine clastic sediments of the Roper Group which were, in turn, deformed by later structural events.

As in many intracratonic basins, the stratigraphy of the McArthur Basin is complex (Fig. 2). Subsidence rates were generally low, and sediment supply was variable so that depositional successions vary considerably in thickness. The six drill holes described in the following sections were selected to provide a relatively comprehensive stratigraphic coverage of the thickest part of the basin fill in the main depocentre (Batten Trough) and some coverage of the thinner section exposed on the Wearyan Shelf.

7.1. Wearyan Shelf

The Wearyan Shelf (Fig. 1) appears to have remained a topographic high through most of the basin’s history (Jackson et al., 1987). Consequently, the sediments preserved in this area are mostly shallow marine carbonates that are difficult to correlate directly with the thicker succession preserved in the nearby sub-basins.

7.1.1. Wearyan 1 drill hole

Wearyan 1 drill hole (Fig. 7) lies close to the western margin of the Wearyan Shelf (Fig. 1) where the Proterozoic succession is concealed beneath the Georgina Basin succession. The drill hole penetrated 374 m of carbonate rocks of the Karns Dolomite and a further 260 m of clastic rocks and basic volcanics and volcaniclastics associated with the Masterton Sandstone and the Gold
Creek Volcanics (Table 1). The Karns Dolomite consists largely of dolostone, which is in part stromatolitic, interbedded with dolomitic and quartzose sandstone and red shale. Casts of evaporite minerals are abundant. The complexity of the gamma log and the sharply defined sequence boundaries, as indicated by abrupt increases in the gamma count, suggests that the formation was deposited during a number of basin phases or sea level cycles and probably reflects a long period of sedimentation in a platform setting during which sedimentation cycled from subtidal to peritidal conditions. This is consistent with the suggestion by Jackson et al. (1987) that the Karns Dolomite correlates with either the Nathan or McArthur Group or both and thus may include rocks deposited during megasequences M4 to M10.

The $\delta^{13}C_{\text{carb}}$ curve is almost monotonic within the Karns Dolomite (Fig. 7) with values ranging from a minimum of $-2.0$ to $0\%$. The $\delta^{18}O_{\text{carb}}$
signature for the Karns Dolomite is more complex than the carbon curve, suggesting that diagenesis has played a major role in its evolution. However, a cross-plot of carbon and δ¹³C_carb and δ¹⁸O_carb values in a similar range to the Karns Dolomite (Fig. 7).

7.2. Batten Trough

In the Batten Trough, which is the major depocentre adjacent to the Wearyan Shelf (Fig. 1), the McArthur Basin succession is much thicker and has been divided into four lithostratigraphic groups, in ascending order: the Tawallah, McArthur, Nathan and Roper groups (Jackson et al., 1987). The Tawallah and Roper groups consist largely of clastic sediments and were not analysed. The McArthur Group consists of more than 4000 m of evaporitic carbonate rocks and shale with minor sandstone, whereas the Nathan Group consist of dolostone, sandstone and shale with a total thickness of 1500 m (Fig. 2). These two groups range in age from ca. 1700 to 1575 Ma and include megasequences M2–M10 (Page, 1997; Page and Sweet, 1998; Southgate et al., in press). The five drill holes sampled in this part of the basin provide a coverage of most formations within the two groups with the exception of a gap in the lower part of the McArthur Group, which was sampled in outcrop (McArthur River Section) (Fig. 2).

7.2.1. Amoco 82-04 drill hole

Amoco 82-04 is the westernmost of the McArthur Basin drill holes sampled in this study (Fig. 1) and penetrates some of the oldest (M3 and M4) and youngest (M8 and M9) units of the basin succession (Fig. 8) including the Mallapunyah Formation from the lower McArthur Group plus the Smythe Sandstone, and Balbirini Formation from the Nathan Group. Generally, TOC values are low (less than 0.05%) throughout the core, although three samples from dark dolomitic shale in the lower Mallapunyah Formation (450 m depth) have values close to 0.5% (Dorrins and Womer, 1983).

The Mallapunyah Formation is a distinctive red-bed unit consisting of shale, siltstone, sandstone and dolostone with abundant evidence for evaporitic conditions in the form of halite and gypsum casts and cauliflower cherts (Haines et al., 1993). A sharp break in the gamma log at the mid-point in the Mallapunyah Formation indicates the start of a new basin phase. Above the break, the gamma count increases as the sequences backtrack in the deepening environment. Muir (1979) suggested that the formation was deposited in a sabkha setting, which is generally consistent with our interpretation of the evaporitic facies from the drill core, although we would suggest, given the regional continuity of the unit and the maturity of the sandstones, that the environment was somewhat more open than might be expected in a sabkha setting. Six depositional sequences can be identified from the gamma-log signature for the Mallapunyah Formation (Fig. 8).
Fig. 8. δ¹³C_carb and δ¹⁸O_carb stratigraphy of the Amoco 82-04 drill hole from the McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

d13C-carb and d18O-carb stratigraphy of the Amoco 82-04 drill hole from the McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

declines as the basin fill progrades. The gamma-log data suggest that the Smythe Sandstone consists of a single depositional sequence with a pronounced transgressive conglomerate at its base, followed abruptly by silty sandstone, which grades to well-sorted sandstone towards the top of the formation (Fig. 8). Pietsch et al. (1991) suggest that these widespread sandstones are braided stream deposits. The blocky shape of the gamma-log curve, however, shows that, while the lower conglomerates may be non-marine, later sediments form part of a major high-energy, marine transgression, as indicated by the rapidly increasing gamma intensity (cf. Haines et al., 1993).

The Balbirini Formation consists largely of dolarenites with subordinate silty sands and dololutes. A well-developed karst surface divides the formation between megasequences M8 and M9, indicating a significant hiatus. The gamma-log values from the lower Balbirini Formation decline gradually in intensity to the M8/M9 sequence boundary, indicating that it is part of a shallowing
upward marine succession. Above the mega-
sequence boundary, dololitites are more abun-
dant, and the formation is aggradational. Rapid
swings in the gamma intensity indicate the highly
cyclical nature of the rocks, much as encountered
in the Amelia or Emmerugga Dolomites.
Stromatolites are found throughout the formation,
although they are more abundant towards the top,
while oolitic and intraclast intervals occur sporadi-
cally throughout. Although Jackson et al. (1987)
suggested a continental sabkha origin for the
Balbirini Formation, because of the common evap-
ortic textures, gamma-log and facies analysis sug-
gest a more open tidal or peritidal origin in a
broad platform setting for large parts of the
formation.

\[ \delta^{13}C_{\text{carb}} \text{ values within the Nathan Group begin with moderately heavy values of around } +0.6 \text{‰ at the base, declining to ca. } -1.0 \text{‰ at the karst surface within the Balbirini Formation that defines the M8-M9 boundary, and increasing again to near 0.0 \text{‰ at the top of the core (Table 1, Fig. 8). } \delta^{18}O_{\text{carb}} \text{ values are more discontinuous, showing shifts of as much as 2.0‰, especially in M9.} \]

7.2.2. McArthur River section

Drill core was not available for rocks included in
megasequences M4 and part of M5, which
include much of the lower Umbolooga Sub-group
(Fig. 2). Consequently, a composite outcrop sec-
tion was measured and sampled in the McArthur
River area at the southern end of the Batten
Trough (Figs. 1 and 9). Three formations in this
interval are carbonate-rich; the Amelia Dolomite,
the Tooganinie Formation and the Emmerugga
Dolomite. The type sections of the Amelia and
Emmerugga Dolomites (Jackson et al., 1987) and
a nearby section of the Tooganinie Formation were
sampled.

The Amelia Dolomite, which consists of
approximately 170 m of stromatolitic dololutite
and dolarenite, is the oldest pure carbonate unit
in the McArthur Basin and forms the highstand
of a major depositional sequence that includes the
underlying Mallapunyah Formation. As indicated
by the gamma logs, the carbonates of the Amelia
Dolomite are highly cyclical and consist of thin
(5–20 m) stacked parasequences (Fig. 9). The par-
asequences consist of a generally shallowing
upward cycle of basal intraclasts and oolitic dolo-
stones, locally showing evidence of desiccation in
the form of both halite and gypsum casts, followed
by domal, columnar and then laminar stromato-
lites. Domal stromatolites are replaced by larger
complex Conophyton bioherms (Jackson et al.,
1987) in some intervals. Stromatolites decline in
importance higher in the succession. The para-
sequences are largely aggradational, as indicated
by the gamma log (Fig. 9). As well as evidence of
halite and gypsum, the formation also includes
massive beds of ‘sideritic marble’, which have been
interpreted as siderite replacement of evaporitic
gypsum, some of the earliest evidence for wide-
spread deposition of sulphate evaporites (Walker
et al., 1977; Jackson et al., 1987).

The Amelia Dolomite was deposited in a shal-
low marine subtidal to peritidal environment
during a period of slow and uniform subsidence.
The setting is perhaps best described as a broad,
shallow, evaporitic platform rather than the more
restricted sabkha setting suggested by Jackson
et al. (1987). The formation is terminated abruptly
by a sequence boundary at the contact with the
Tatoola Sandstone.

The Tooganinie Formation, along with the
underlying Tatoola Sandstone, forms a second
major depositional sequence at the top of M4. The
gamma log (Fig. 9) indicates that the basal
sequence boundary lies in the upper part of the
Amelia Dolomite, and the basal few meters of the
transgressive systems tract are largely dololutite
and dolarenite deposited in a backstepping envi-
ronment. Within the Tatoola Sandstone, the trans-
gressive systems tract consists of very fine to fine
grained, flaggy sandstone, which, as indicated by
the reversal of the gamma log, grades to medium
coarse grained, thick-bedded sandstone and
dolostone at the maximum flooding surface. This
thicker bedded sandstone interval at the base of the
highstand grades rapidly upward to the Toogannie Formation. A combination of struc-
tures including halite casts and hummocky cross-
stratification in the lower sandstones of the Tatoola
Sandstone suggests a high-energy environment in
a modest depth of water near storm wave base but
in a restricted basinal setting. Thicker bedsets and
trough cross-bedding in the upper sandstone unit along with the declining intensity of the gamma-log pattern suggest shallowing to a subtidal environment at the base of the Tooganinie Formation.

The Tooganinie Formation is a shale dominated interval with thin dolostone units throughout. Like the Amelia Dolomite, the formation is highly cyclic, consisting of a succession of aggrading...
parasequences, as indicated by the rapid cycling but general vertical progression of the gamma log. The parasequences, which range from 5 to 15 m thick, begin in shale and grade upward to thin but massive stromatolitic dolostone. Because of the shaly nature of the parasequences, they are more clearly defined on the gamma logs than in the Amelia Dolomite. Casts of large halite hoppers are abundant throughout the formation, generally in the coarser parts of the clastic intervals. Due to poor outcrop, we were only able to sample the upper 30 m of this formation. Like the Amelia Dolomite, the Tooganinnie Formation was deposited in a shallow marine, often evaporitic, platform setting with sediments being deposited in subtidal to peritidal environments.

The Lela Sandstone, Myrtle Shale and Emmerugga Dolomite form a large-scale depositional sequence at the base of M5. The Lela Sandstone consists of coarse grained dolomitic sandstone that grades upwards to the red-brown siltstones of the Myrtle Shale. The form of the gamma log suggests a deepening of the water above a thin transgressive sandstone overlying the sequence boundary at the base of the Lela Sandstone to the maximum flooding surface just above the base of the Myrtle Shale. The Myrtle Shale is progradational to the base of the Emmerugga Dolomite, which is largely aggradational. The Emmerugga Formation consists of stromatolitic and brecciated dolostone with minor intervals of siltstone and shale including some evidence of evaporites. Both the facies/lithology and the gamma log show that sedimentation throughout the formation was cyclical (Fig. 10), especially in the lower part of the formation, although parasequence boundaries are not obvious. Cycles most commonly consist of laminated dololutite followed by domal stromatolites, although locally, large Conophyton bioherms appear in the middle of the formation (Jackson et al., 1987). Halite casts are present in both the Myrtle Shale and the Emmerugga Dolomite, suggesting a restricted basin. The Emmerugga Dolomite is a platform carbonate deposited in a tidal to subtidal and peritidal setting, which at times became evaporitic, as part of a shallow marine ramp during a period of slow basin subsidence.

The isotopic data from the McArthur River outcrop section show more effects of alteration than almost all the other sections. Carbon and oxygen cross-plots (Fig. 5) show a modest linear covariance and some scatter about the mean values. In part, this may reflect weathering of the outcrop but more likely relates to the higher clastic component, especially in the Tooganinnie Formation, and to their association with a highly evaporitic environment. In spite of this, the carbon values follow a relatively predictable path with only a few values lying outside a narrow range from −2.0 to 0.0‰. A relatively large single point positive excursion in the Amelia Dolomite may be related to diagenetic replacement of gypsum. A relatively negative carbon isotope value at the base of the Emmerugga Dolomite comes from a thin carbonate unit in a largely clastic interval and is suspected to reflect alteration during the passage of later fluids.

7.2.3. McA9 drill hole

The McA9 drill hole (Table 1) is located in the central eastern McArthur Basin (Fig. 1) and penetrates a significant part of megasequence M5 including the upper 290 m of the Emmerugga Dolomite (approximately 620 m thick) and the basal 60 m of the Teena Dolomite (total thickness 94 m; Haines et al., 1993) (Fig. 10).

The Emmerugga Dolomite, which is described in detail above, consists for the most part of aggrading parasequences in this section. The Teena Dolomite abruptly overlies the Emmerugga Dolomite with a thin unit of coarse-grained quartzose sandstone at the base. The gamma log suggests that a sequence boundary lies just below the sandstone and that the transgressive systems tract begins with the deposition of carbonates at the top of the Emmerugga Dolomite. The section above the basal sandstone consists of laminated, grey dololinite and dolomitic siltstone with calcite pseudomorphs of gypsum (Coxco Member; cf. Jackson et al., 1987). The Teena Dolomite was deposited in a platformal carbonate setting which was somewhat more evaporitic than the carbonates facies of the preceding Emmerugga Dolomite. The
backstepping facies indicated by the increasing
gamma log intensity, however, suggests increasing
water depth.

$\delta^{13}C_{\text{carb}}$ values begin at close to $-1.7\%$ at the
base of the core and increase to $-0.2\%$ at the
base of the Mitchell Yard Member, in general
correspondence with increasing evidence for evap-
orite conditions (Fig. 10, Table 1). A single value of
$-4.6\%$ at 260 m depth lies close to a major
fault plane, suggesting alteration due to later fluid
flow. $\delta^{18}O_{\text{carb}}$ values are much more varied
(Table 1), as expected. As in previous cores, there
is a decrease in the $\delta^{18}O_{\text{carb}}$ value (to $-8.71\%$)
immediately below the sequence boundary beneath
the base of the Teena Formation and an increase
again above the boundary (to $-6.2\%$).

7.2.4 Bing Bong 2 drill hole

Bing Bong 2 drill hole (Fig. 1) penetrated parts of
megasequences M5 and M6 including the upper
part of the Teena Formation (Coxco Member),
the Barney Creek Formation, Reward Dolomite
and the lower part of the Lynott Formation
(Fig. 11). The boundary between the two mega-
sequences is defined by a shift in the gamma-ray curves, which indicates an increase in accommodation above the boundary. The gamma log shows that two major depositional sequences occur within M5 above the sharply defined sequence boundary at the top of the Teena Dolomite (Fig. 11). The first encompasses the lower 120 m of the Barney Creek Formation, and the second includes the upper part of the Barney Creek Formation and the Reward Dolomite. The earliest lowstand sediments associated with the lower Barney Creek Formation consist of grey silty dololutite and dolomitic siltstone. In places, these are highly carbonaceous with TOC values locally as high as 8% near the base. The lowstand units are carbonaceous and pyritic throughout and grade upward from silty sediments at the base to dololutite and dolarenites of the highstand. The second lowstand interval at the top of the Barney Creek Formation consists of grey dolomitic siltstone and silty dololutite with black carbonaceous shales, which are also pyritic and carbonaceous throughout. It passes gradationally upwards to more massive lighter grey dololutites and dolarenites of the Reward Dolomite, which forms the highstand systems tract.

A sharp break at the top of the Reward Dolomite implies an increase in accommodation, which defines the beginning of M6. The gamma log suggests that the Lynott Formation is an
incomplete sequence with only the lowstand systems tract being intersected. This lowstand is made up of a series of thin backstepping parasequences consisting of silty dololutite, grey dolomitic alithine and carbonaceous shale much like the lowstands of the two earlier sequences. A fall in gamma-log intensity at the top of the core suggests that the highstand lay directly above.

The sequences each represent major shallowing-upward cycles during which sedimentation began in a restricted, anoxic, clastic-dominated setting and then shallowed upward to a carbonate platform setting in which subtidal, tidal and peritidal environments may be present. The setting shares many similarities with Grand Cycle carbonates of the Cambrian in western North America (e.g. Mount and Signor, 1992) and depositional sequences in the Cambrian of western Mongolia (Lindsay et al., 1996). Carbonate banks were able to nucleate and expand as the rate of sea level rise decreased towards the end of the highstand and the supply of clastic sediments was reduced (Lindsay et al., 1996).

$\delta^{13}C_{\text{carb}}$ values in the Teena Dolomite to the Reward Dolomite (Fig. 11) from megasequence M5 fall within a narrow range, but data from megasequence M6 in the Lynott Formation are less consistent. Two anomalously light values are associated with very high Mn/Sr values (Fig. 11), suggesting that they are the product of later alteration. The $\delta^{13}C_{\text{carb}}$ curve crosses sequence boundaries without interruption. The $\delta^{18}O_{\text{carb}}$ data are more consistent than in most cores sampled.

7.2.5. Amoco 82-05 drill hole

The Amoco 82-05 drill hole intersects the Lynott Formation (megasequence M6) (Figs. 1 and 12) which is lithologically relatively homogeneous, consisting of dark shales, dolomitic shales and dolarenites. The formation consists of thin, upward-fining parasequences that are clearly delineated by the rapid swings in gamma intensity. In core, the parasequences all have sharply defined bases and begin with shales then grade upward to dolarenites. Gamma-log data also indicate stacking of the parasequences into large-scale (ca. 200 m) cycles forming subtle depositional sequences (Fig. 12). Overall, the facies and gamma-log data suggest that subsidence rates increased abruptly at the start of the deposition of the Lynott Formation, leading to increased accommodation and to the localised deposition of tempestites in an increasingly anoxic environment that ultimately became aggradational. The organic carbon content of the Lynott Formation is low; only seven of the 36 samples from the formation have TOC values greater than 0.5%, with the highest having 1.3% (Dorrins and Womer, 1983).

$\delta^{13}C_{\text{carb}}$ values are relatively consistent throughout the Lynott Formation in contrast to the values encountered at the base of the formation in Bing Long 2 drill hole. $\delta^{13}C_{\text{carb}}$ values range from ca. $-0.3\%$ to $-1.0\%$ (Table 1, Fig. 12). The high $\delta^{13}C_{\text{carb}}$ value at 365 m lies outside the trend of the rest of the data and is associated with a high $\delta^{18}O_{\text{carb}}$ value, suggesting that it is probably not primary. $\delta^{13}C_{\text{carb}}$ data are somewhat more variable than the $\delta^{13}C_{\text{carb}}$ values.

7.2.6. Amoco 82-07 drill hole

Amoco 82-07, the eastern-most drill hole sampled from the McArthur Basin (Fig. 1), penetrates four formations tentatively identified as the Lynott Formation (Donnegnan Member?), Yalco Formation, Stretton Sandstone and Looking Glass Formation, and a small section at the base of the Balbrin Dolomite (Fig. 13). The core thus samples the upper part of megasequence M6, all of M7, although in a condensed form, and the lower part of M8.

An increase in gamma intensity at the base of the Yalco Formation suggests increasing accommodation at this stage of basin development. Gamma-log and core analysis suggests that the Yalco Formation forms a series of thin depositional sequences that consists of thinly interbedded stromatolitic dololutite and dolarenite with some thin pyritic black shale (Fig. 13). The formation was deposited in an anoxic, shallow-marine setting that gradually shallowed upward to produce a more massive dolomitic highstand. A single TOC analysis from the lower Yalco Formation yielded 0.5% (Dorrins and Womer, 1983).

The Stretton Sandstone and overlying Looking Glass Formation form a single sequence that represents megasequence M7 at this location. The Stretton Sandstone consists of fine sandstone, thin
Fig. 12. $^{13}$C$_{carb}$ and $^{18}$O$_{carb}$ stratigraphy of the Amoco 82-05 drill hole from the middle McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

dolostone units and siltstone and gradually become more sand-rich towards the top of the formation. The formation is glauconitic and has hummocky cross-stratification (Haines et al., 1993), suggesting deposition in a marine setting close to the storm wave base. A low TOC value was recorded in a single analysis from the Stretton Formation of 0.5% (Dorrins and Womer, 1983). The Looking Glass Formation consists largely of stromatolitic dololutite and dolarenite deposited in a shallow marine platform-carbonate setting. Together, the Stretton Sandstone and looking Glass Formation form a single shallowing-upward sequence with a rapid increase in the gamma count indicating a thin transgressive systems tract with a long slow decline in the gamma curve towards the Looking Glass dolostones that form the top of the sequence. The gamma-log and facies successions follow much the same pattern as seen in the Barney Creek Formation sequences, where sedimentation began in a deeper-water, clastic-dominated setting that graded to a carbonate-dominated platform setting as the clastic sediment supply was gradually eliminated. The Balbirini Dolomite at this locality is very similar in terms of facies, lithology and gamma-log response to that encountered in Amoco 82-04 (Fig. 8). Two TOC analyses from the Balbirini Dolomite yield values of 1.3% for dolomitic siltstones at the maximum flooding surface and 0.4% from some Stretton Sandstone and looking Glass Formation dolostones that form the top of the Yalco Formation are what cleaner dololutites in the hightstand (Dorrins and Womer, 1983). Weakly defined phosphatic hardgrounds associated with a maximum flooding surface near the base of the Yalco Formation are the only phosphorus-rich intervals identified in the McArthur Basin.
Fig. 13. $\delta^{13}C_{\text{carb}}$ and $\delta^{18}O_{\text{carb}}$ stratigraphy of the Amoco 82-07 drill hole from the upper McArthur and Nathan Groups, McArthur Basin, northern Australia. For key, see Fig. 10.

The $\delta^{13}C_{\text{carb}}$ signature of the Amoco 82-07 drill core is surprisingly consistent. Most samples have values close to zero or are slightly negative. Three samples that lie outside the trend (at 90, 416 and 430 m depth) have light $\delta^{18}O_{\text{carb}}$ values, suggesting early diagenetic alteration. The $\delta^{13}C_{\text{carb}}$ curve for megasequences M6–M8 is thus quite flat. Throughout the drill core, $\delta^{18}O_{\text{carb}}$ values are more erratic than $\delta^{13}C_{\text{carb}}$ values but do not suggest high levels of diagenetic modification.

8. Mount Isa Basin

The Mount Isa Basin is the erosional remnant of a major Proterozoic intracratonic basin (McConachie et al., 1993) that extended over more than 120,000 km$^2$ of north central Australia (Fig. 1). Much of the basin margin has either been erosionally removed or is concealed beneath the younger Georgina, Carpentaria and Eromanga Basins. It is only in the northwest, where the younger basin sequences onlap the Murphy Inlier, that the original basin margin is preserved (Fig. 3). In the main depocentre, to the southeast, the basin fill is more than 11 km thick. Deposition of the basin fill was initiated shortly before 1.7 Ga (Page, 1997; Page and Sweet, 1998; Southgate et al., in press) in response to a major rifting event associated with bimodal volcanism and intrusion of anorogenic granites (Wyborn, 1988) and ceased prior to 1.5 Ga in response to the Isan Orogeny, a regional tectonic event (O’Dea et al., 1997).
The basin-fill architecture of the Mount Isa Basin is complex and consists of several mega-
sequences separated by major erosional surfaces, most of which are immediately overlain by a
transgressive sandstone unit (McConachie et al., 1993). The basal megasequence consists of contin-
ental tholeiitic volcanics intercalated with clastics and minor carbonates. The overlying mega-
sequences, which include the McNamara and Fickling Groups, consist of ramp carbonates
together with their deeper-water equivalents to the south which grade upward into a clastic dominated
succession. Finally, the South Nicholson Group, which rests on a major erosion surface at the top
of the McNamara and Fickling Groups, is domi-
nated by rocks of fluvial origin. Overall, the archi-
tecture and facies distribution of the sedimentary
fill of the Mount Isa Basin is very similar to that
of the McArthur Basin.

The preservation of the basin margin along the
Murphy Inlier provides an opportunity to compare
the condensed/abbreviated onlapping section with
the more distal section from the Lawn Hill Platform which lay closer to the basin’s main
depocentre. The Fickling and McNamara Groups, which contain significant carbonate intervals, thus
provide a distal and proximal view of basinial facies
during the major period of basin evolution and
allow direct comparison with the McArthur and
Nathan Groups of the McArthur Basin.

8.1. Murphy Inlier

The Fickling Group, where it onlaps the
Murphy Inlier (Fig. 1), consists of four forma-
tions: the Fish River Formation, Walford
Dolomite, Mount Les Siltstone and Doomadgee
Formation (Fig. 3). The succession along the
Murphy Inlier is highly condensed with pro-
nounced erosion surfaces separating major basin
phases. In spite of this, most of the major basin
phases are represented in the section even though
somewhat abbreviated. The few thin carbonates
included in the volcanoclastic Fish River
Formation (megasequences M2 and M3) are gen-
erally completely silicified and not relevant to the
present study. Two drill holes penetrate the upper
part of the group, Amoco 83-04 and Pasminco
GC105 (GC=Gorge Creek) providing coverage
for megasequences M4-M9.

8.1.1. Amoco 83-04 and Pasminco GC105 drill
holes

The Amoco 83-04 drill hole penetrates the
largely siliciclastic Doomadgee Formation (M7-
M9) and Mount Les Siltstone (M5 and M6) as
well as the upper part of the Walford Dolomite
(M4) (Fig. 14). The GC105 drill hole penetrates
the lower part of the Walford Dolomite (M4) and
extends a short distance into the upper Fish River
Formation (M3) (Fig. 15). Major erosion surfaces
(sequence boundaries) separating the formations
indicate large time breaks (Lindsay and Wells,
1997; Page, 1997; Page and Sweet, 1998; Southgate
et al., in press).

Together, the two drill holes provide a complete
sampling of the approximately 400 m thick
Walford Dolomite, which locally represents
the whole of megasequence M4 (Figs. 14 and 15). The
formation consists almost entirely of dolostone
with only minor interbeds of dark green shale and
siltstone (5-10 cm thick). The dolostones are
largely stromatolitic or microbial laminites with
less frequent packstone or wackestone intervals
and halite casts at the base of some cycles. The
facies define shallowing upward parasequences,
from 50 to 100 m thick, which were deposited in a
tidal to peritidal ramp setting. A single elevated
phosphorus value (1300 ppm) suggests that phos-
phatic hardgrounds are present in the Walford
Dolomite. Because of the nature of the deposi-
tional setting, sequence boundaries within the
formation are not well defined, although the gamma
log outlines subtle stacking patterns that suggest
sequences. TOC values (N = 14) throughout the
Walford Dolomite are generally less than 0.1%,
with only one sample reaching 0.6% (Dorrins
et al., 1983).

The Mount Les Siltstone, which is 84 m thick,
consists largely of interbedded fine-grained sand-
stone, siltstone and shale with occasional thin
dolostone beds, which tend to be more abundant
lower in the formation. It gradually shallows
upward with more massive sandstone and siltstone
units at the top. Pyrite occurs in small amounts
throughout the formation but is more abundant
in the lower part. Minor rip-up clasts and dewater-
Fig. 14. $\delta^{13}$C_carb and $\delta^{18}$O_carb stratigraphy of the Amoco 83-04 drill hole from the Fickling Group adjacent to the Murphy Inlier, Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 14. $\delta^{13}$C_carb and $\delta^{18}$O_carb stratigraphy of the Amoco 83-04 drill hole from the Fickling Group adjacent to the Murphy Inlier, Mount Isa Basin, northern Australia. For key, see Fig. 10.

ing structures occur throughout, and low-angle cross-beds are present at 270 m. Gamma-log data show that the formation includes a complete depositional sequence plus part of the lowstand systems tract of a second sequence, the top of which has been removed by erosion (Fig. 14). Outcrop close to the drill hole indicates that the formation may consist of as many as three depositional sequences suggesting significant topographical relief on the upper sequence boundary (Lindsay and Wells, 1997). Although four of the six TOC analyses from the Mount Les Siltstone are low (0.1–0.2%), dark shale samples from the maximum flooding surfaces associated with the lower and upper sequences reach 3.0 and 1.6%, respectively (Dorrins et al., 1983).

The Doomadgee Formation consists largely of thinly bedded dolostone, shale, siltstone and sandstone in variable proportions resting on a thin basal conglomerate formed of silicified clasts of
Walford Dolomite (Lindsay and Wells, 1997). The only observed sedimentary structures were rare cross-beds and some slump folding. Pyrite occurs throughout the sequence. TOC values ($N = 20$) are generally less than 0.5% throughout the Doonmadgee Formation except for five values from dark shales at, and just below, the maximum flooding surface in the lowermost sequence which reach 1.5% (Dorrins et al., 1983).

Gamma-log data suggest that the formation consists of at least two complete depositional sequences and part of a third that were deposited in shallow-marine, upward-shallowing settings (Fig. 14). The three sequences are the proximal facies of the attenuated megasequences M7-M9. The transgressive systems tract of the lower sequence (M7) was deposited in a shallow marine setting above the wave base. As the gamma logs indicate, the transition to the highstand is abrupt, with a shift to a more basinal, perhaps shoreface, setting. The highstand shows strong evidence of a normal upward-shallowing succession passing from the shoreface to a more proximal near shore environment, followed ultimately by coastal plain sediments at the top. The second sequence, which is the only indication of M8 along this part of the Murphy Inlier, consists of a thin dolostone. The upper sequence (M9) is a fine grained clastic-dominated interval deposited above the storm-wave base.
Although isotopic data from this drill hole show considerable spread, they provide no evidence for covariance between \( \delta^{13}C_{\text{carb}} \) and \( \delta^{18}O_{\text{carb}} \) (Fig. 6). \( \delta^{13}C_{\text{carb}} \) values show a greater variance than \( \delta^{18}O_{\text{carb}} \) (Table 1). Extreme \( \delta^{18}O_{\text{carb}} \) values range from \(-10.4\%o\) to \(-5.5\%o\) due to the increased potential for diagenetic alteration in the more permeable clastic units higher in the section. \( \delta^{18}O_{\text{carb}} \) values from the Mount Les Siltstone are the most negative \((-8.92 \pm 1.05\%o\)), whereas \( \delta^{18}O_{\text{carb}} \) values for the Doomadgee Formation \((-7.53 \pm 0.89\%o\)) are slightly heavier than the mean \( \delta^{18}O_{\text{carb}} \) values for carbonate units \((-7.75 \pm 1.02\%o\)). The \( \delta^{13}C_{\text{carb}} \) values range from \(-4.6\%o\) to \(1.6\%o\), with most values confined to a narrow range between \(-2.0\%o\) and \(0.0\%o\) (Table 1). The least variable \( \delta^{13}C_{\text{carb}} \) values come from the massive carbonates of the Walford Dolomite and the most extreme values from thin carbonate beds of the clastic dominated Doomadgee Formation (Figs. 14 and 15). Stratigraphically, the \( \delta^{13}C_{\text{carb}} \) values show an oscillatory decrease upward through the Walford Dolomite from around \(0\%o\) at the base to close to \(-2\%o\) at the top.

### 8.2. Lawn Hill area

The sedimentary fill of the Mount Isa Basin increases significantly in total thickness southeast of the Murphy Inlier (McConachie et al., 1993). Seismic reflection data indicate that some units present along the Murphy Inlier simply increase in thickness towards the depocentre, whilst new units appear overlapping the major sequence bound-aries closer to the main depocentre (Bradshaw et al., in press). The total thickness of the McNamara Group varies locally from 8 to 11 km. In the Lawn Hill area, the McNamara Group can be divided into two units (Andrews, 1996) (Fig. 3). The lower unit of the McNamara Group is a mixed carbonate and clastic assemblage that includes the Torpedo Creek Quartzite, Gunpowder Creek Formation, Paradise Creek Formation, Esperanza Formation and Lady Loretta Formation (M2-M4). The upper unit of the McNamara Group is predominantly clastic and includes the Shady Bore Quartzite, Riversleigh Siltstone, Termite Range Formation and the Lawn Hill Formation (M5-M9). The megasequence boundary at the base of the upper unit of the McNamara Group (basal M5) is directly overlain by the transgressive Shady Bore Quartzite, which highlights the start of a major phase in the development of the Mount Isa Basin (Domagala et al., 1997; Krassay et al., 1997). Subsidence rates increased abruptly, thereby increasing accommodation and water depth. Almost all of the thickness variation in the McNamara Group occurs in a single unit of the Riversleigh Siltstone, which varies from 800 to 3200 m in thickness (Andrews, 1996) as a direct response to the onset of the renewed phase of subsidence.

The present study is focused on isotopic signatures preserved in carbonates that occur predomi-nantly in the lower units of the McNamara Group. Four drill holes penetrate parts of the Paradise Creek, Esperanza and Lady Loretta formations.

#### 8.2.1. Lawn Hill 3 and 4 drill holes

Lawn Hill 3 and 4 drill holes (Fig. 1, Hutton, 1983) are stratigraphically overlapping drill holes that together penetrate the Paradise Creek Formation, the Gunpowder Creek Formation and the basal sands of the Torpedo Creek Quartzite before passing into the basement (Yeldham Granite) (Fig. 16) and provide isotopic signatures for megasequence M2 and much of M3.

The Torpedo Creek Quartzite consists of thin basal polymict conglomerates followed by well-sorted quartzose sandstones with minor siltstones. An inflection in the gamma log above the contact with the Yeldham Granite shows that the Torpedo Creek Quartzite forms a thin fluvial basal trans-gressive systems tract followed by a series of gradually fining or backstepping shallow marine sandstone units that grade conformably into the basal Gunpowder Creek Formation. The lower Gunpowder Formation begins in fine-grained sandstone containing graded units (tempestites) but grades to dolomitic siltstone and dololutite. The gamma count at first increases along with the fining clastic units to a maximum flooding event before decreasing as the formation becomes more dolomite. The basal Gunpowder Creek Formation was deposited in a shallow marine shoreface clastic...
Fig. 16. d\(^{13}\)C\(_{carb}\) and d\(^{18}\)O\(_{carb}\) stratigraphy of the Lawn Hill 3 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Setting but overlies a predominantly fluvial, clastic transgressive unit, the Torpedo Creek Quartzite.

Six further depositional sequences, all of which consist of tidal and peritidal ramp/platform carbonates, are documented in the gamma log (Fig. 16). The lower four sequences are largely aggradational units reflecting declining accommodation space in the upper part of megasequence M2. The sequence boundary between M2 and M3 is indicated by the rapid increase in gamma intensity resulting from an increase in deposition of fines as accommodation increases. Above the M2/M3 boundary, two thin, shallowing-upward, progradational sequences form the base of M3, each beginning in deeper-water clastic sediments and grading upward to tidal and peritidal carbonates, reflecting increasing accommodation at the start of M3. The gamma log for one of the sequences at the base of M3 (see Fig. 16) shows a pronounced maximum flooding surface. Phosphatic hard grounds with P levels in excess of 4500 ppm associated with this condensed interval are the earliest phosphates in the basin.

The Paradise Creek Formation (Fig. 17) consists of thinly bedded and laminated stromatolitic dolostone, dolomitic siltstones and occasional sandstone and chert interbeds. The formation is highly cyclic, as indicated by the gamma log, and consists of thin (10–20 m) stacked parasequences that begin in finer dolomitic siltstone and grade upward to more massive stromatolitic dolostones at the top. The parasequences are bundled into sequences (ca. 100 m thick) that are also evident in the gamma-log signature. The overall aggradational...
Fig. 17. $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

Fig. 17: $\delta^{13}$C<sub>carb</sub> and $\delta^{18}$O<sub>carb</sub> stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.
Fig. 18. $\delta^{13}$C and $\delta^{18}$O stratigraphy of the Amoco 83-05 drill hole from the middle McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key see Fig. 10.

from within the main body of the formation above the ore-equivalent horizon, probably within the lower sequence identified by McConachie et al. (1993), while the CM35 drill hole intersected the formation lower in the succession. Together, the two cores provide isotopic data for a significant proportion of megasequence M4.

The Lady Loretta Formation consists of thinly bedded stromatolitic dolostone with some interbeds of dololutite and fine sandstone. The formation is highly cyclic, with small-scale cycles ca. 10–30 m thick (parasequences) and longer-term cycles of ca. 200 m (sequences) (Figs. 18 and 19). The smaller cycles begin with dololutites and intraclast breccias at their base and dolarenites with stromatolites and, less commonly, oolites towards the top. McConachie et al. (1993) interpreted the formation to have been deposited in a tidal to deep marine shelf setting with slope margin bypass deposits. The environment was character-
ised by periodic subaerial exposure and development of oolitic and stromatolitic banks. Seismic and gamma-log data support this interpretation and suggest deposition in a ramp setting in which sea level cycles played a prominent role in fine-tuning local facies associations. A total of 34 analyses from the Lady Loretta Formation suggest that TOCs are low throughout the formation. With the exception of one sample that reached 2.0%, the remaining samples all had values less than 0.2% (Dorrins et al., 1983).

$\delta^{13}C_{\text{carb}}$ values are relatively consistent throughout the cored section of the formation (Fig. 18, Table 1). The $\delta^{13}C_{\text{carb}}$ data from the CM35 drill hole are among the heaviest of all the drill holes sampled (Table 1) with all but five samples having values greater than 0‰ (Fig. 19). The Lady Loretta Formation is aggradational so that facies variations are minimal throughout the interval. The relatively featureless nature of the $\delta^{13}C_{\text{carb}}$ curve is thus consistent with the unvarying facies, suggesting that the primary signature is unaltered. The $\delta^{18}O_{\text{carb}}$ curve is similarly featureless, which is consistent with the cross-plot that shows the data to be very tightly grouped about the mean with no evidence for covariance (Fig. 6).

9. Conclusions

Regional analysis of facies and sequence stratigraphy provides conclusive evidence that the sedimentary successions preserved in the McArthur and Mount Isa Basins were deposited in a shallow marine environment that, for most of the time, was in communication with the global ocean. Diagenesis of the carbonate rocks, including dolomitisation and silicification, occurred early, thereby sealing the rocks to fluid movement and retaining the primary oceanic $\delta^{13}C_{\text{carb}}$ signatures. Stable isotope data from the McArthur and Mount Isa Basins therefore provide, for the first time, a comprehensive $\delta^{13}C_{\text{carb}}$ curve for the late Paleoproterozoic and early Mesoproterozoic Eras. Isotopic data from the shallower stable shelf environment of the Wearyan Shelf are very similar to data from the deeper sub-basins of the McArthur Basin (Fig. 2). In the Mount Isa Basin, data from
the main depocentre also reveal a pattern similar to data from the basin margin (Fig. 3). The validity of the δ¹³C_carb curves presented here is further strengthened by the fact that the data are from adjacent basins and thus provide important basic information on the state of the Paleoproterozoic global ocean.

Composite isotope curves for the two basins (Figs. 2 and 13) show that δ¹³C_carb values lie within a relatively small range throughout most of the time interval. Values from both basins average −0.6‰ and seldom lie more than 1‰ either side of the mean. The mean δ¹³C_carb values for the two basins are essentially the same statistically (95% confidence level), with means of −0.59‰ and −0.65‰ in the McArthur and Mount Isa Basins, respectively. As might be expected, the δ¹⁸O_carb values appear to have been much more sensitive to the passage of meteoric waters than the δ¹³C_carb values. δ¹⁸O_carb values average −7.3‰ for all data from both basins. The results confirm earlier speculation (cf. Des Marais et al., 1992) that δ¹³C_carb values varied within narrow limits during the period from approximately 1.7 to 1.5 Ga, much as in the later Mesoproterozoic Era (Buick et al., 1995; Xiao et al., 1997), that is the δ¹³C_carb curve is essentially flat. To maintain the carbon mass balance within such narrow constraints, relatively low levels of tectonic uplift may be required, which is consistent with the present understanding of global tectonics (Des Marais et al., 1992). As we have discussed elsewhere (Brasier and Lindsay, 1998), these conclusions also suggest that the limited availability of biolimiting nutrients such as phosphate and nitrate could have brought about strong evolutionary pressures towards symbiotic association and the development of autotrophic eukaryotes.

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