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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 $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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.

Keywords: Australia; Carbon; McArthur Basin; Mesoproterozoic; Mount Isa Basin; Oxygen; Paleoproterozoic; Sequence stratigraphy; Stable isotopes

1. Introduction

The stable isotopes ^{12}C and ^{13}C are fractionated during autotrophic fixation of CO_2 and ultimately come into mass balance with the global ocean. Carbon isotopic ratios preserved in carbonate rock ($\delta^{13}C_{carb}$) 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

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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 $\delta^{13}C_{carb}$ 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). $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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, polyphase 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; Wyborn, 1988; Pysklywec and Mitrovica, 1998; Idnurm 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

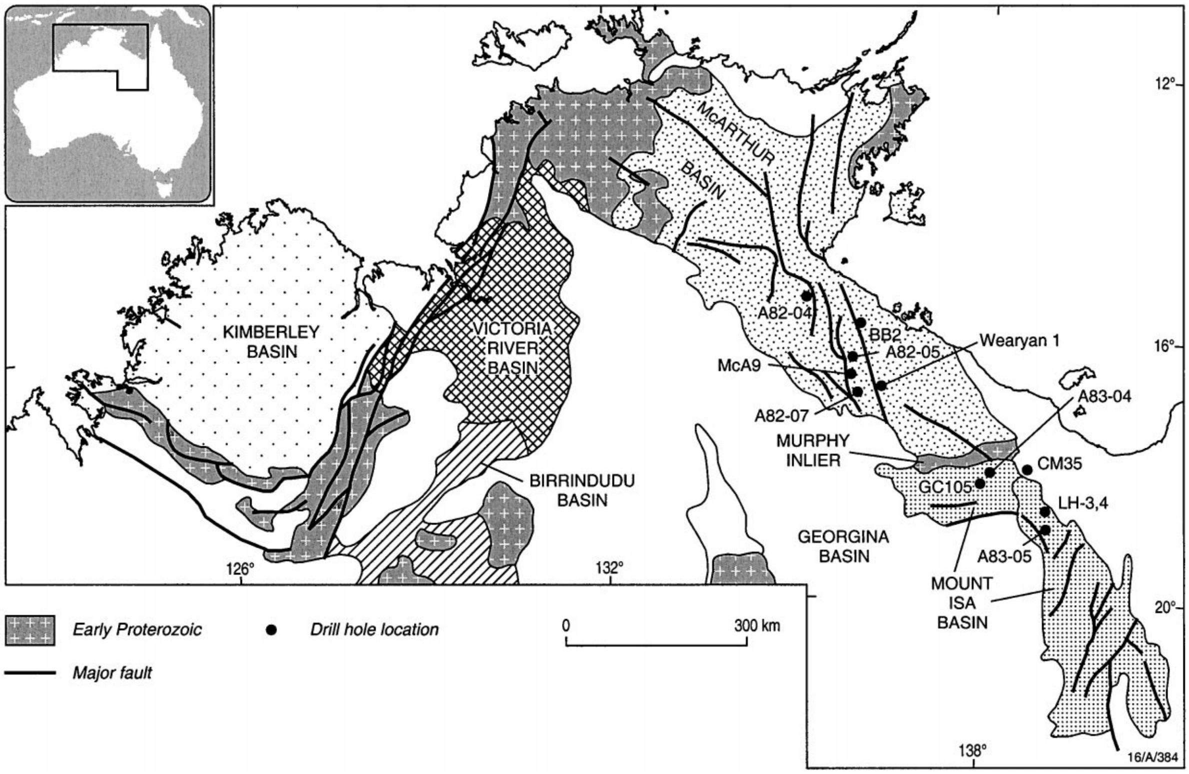


Fig. 1. Distribution of major Paleoproterozoic to Mesoproterozoic basins of northern Australia and the location of drill holes studied.

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 Paleo- to Mesoproterozoic 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; Jackson et al., 1987) rather than marine (cf. 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

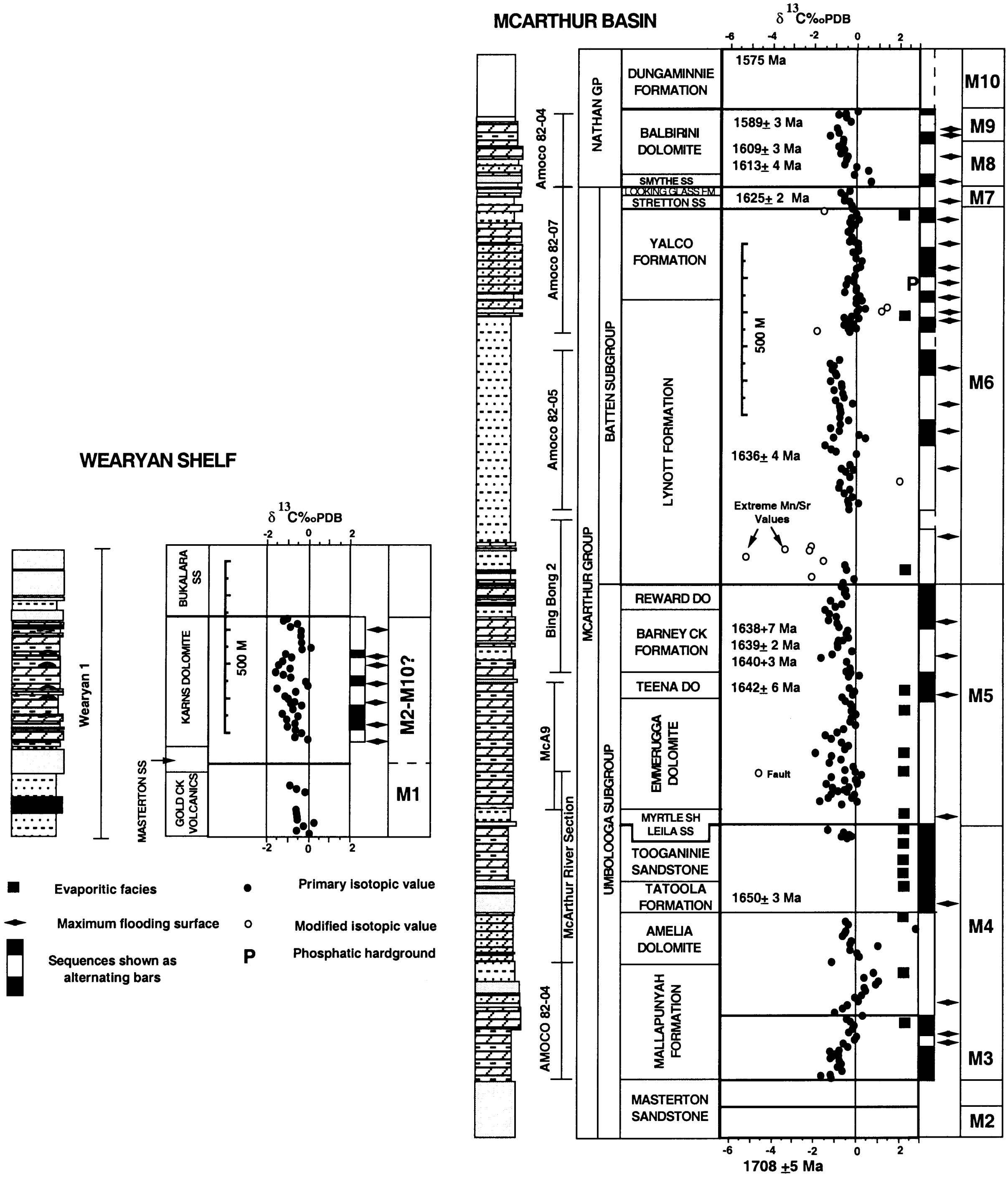


Fig. 2. Composite $\delta^{13}C_{carb}$ profile for the Paleoproterozoic to Mesoproterozoic McArthur and Nathan Groups from the Batten Trough (the main depocentre) of the McArthur Basin and the Karns Dolomite from the adjacent, but shallower, Wearyan Shelf area. Chronostratigraphy based upon Page and Sweet (1998) and Southgate et al. (in press).

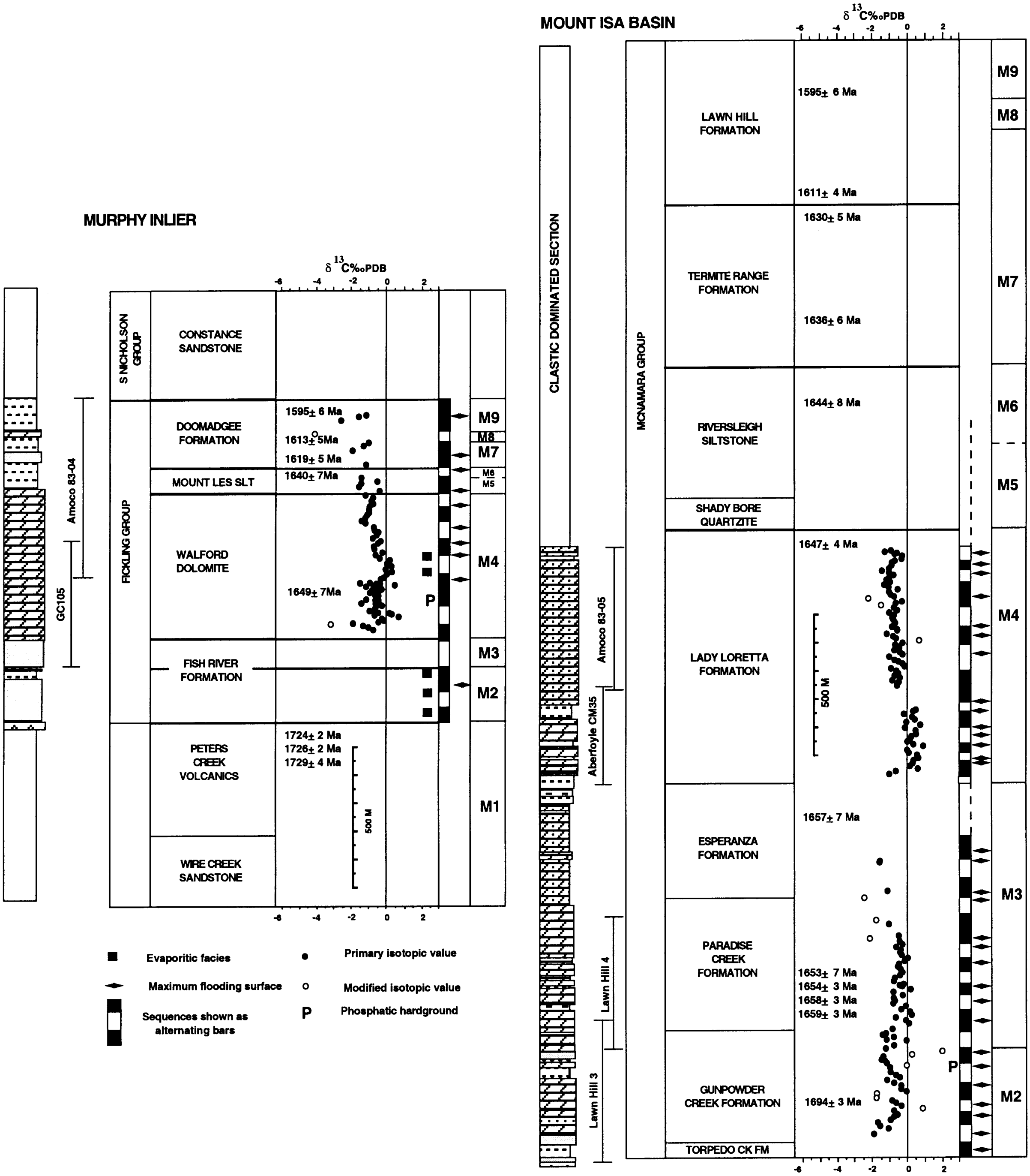


Fig. 3. Composite $\delta^{13}C_{carb}$ profile for the Paleoproterozoic Fickling Group, which lies close to the basin margin along the Murphy Inlier, and the McNamara Group, which lies further basinward, towards the main depocentre, in the Lawn Hill area of the Mount Isa Basin of northern Australia. 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 megasequences (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 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 (Bradshaw 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 (Table 1). Every fifth sample was subsampled for trace and major element analysis to aid in the analysis of diagenesis. Samples consisting of fine-grained micritic, microbial or, less frequently, oolitic carbonates were selected.

Prior to isotopic analysis, thin sections were studied to assess the effects of diagenesis and determine the suitability of samples for further analysis. Thin sections were stained using alizarin red-S and potassium ferricyanide to help identify Ca- and Fe-rich carbonates (Green, 1993). In thin section, most samples consist of alternating layers of laminated stromatolitic and micritic carbonate. The stromatolitic layers comprise very-fine-grained, laminated carbonate, including remnants of the original microbial mats. Organic material, mostly in the form of fragments of microbial mat, but also as finely dispersed carbon, are present in most carbonate samples. Organic carbon content is generally low but is quite variable, with TOC values (total organic carbon, weight per cent) reaching 10% in some samples. The micritic interlayers contain angular intraclasts and quartz grains, the latter being most abundant in samples from thin carbonate beds in clastic dominated

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

Well/ drillhole name	Total depth (m)	Carbonate carbon		Oxygen		Number of samples	
		Mean	S.D.	Mean	S.D.		
McArthur Basin							
Amoco 82-04	541.0	−0.37	0.62	−6.26	1.17	59	3
Amoco 82-05	455.5	−0.53	0.54	−5.91	1.63	45	1
Amoco 82-07	498.6	−0.20	0.50	−7.92	1.29	52	0
Bing Bong #2 (NTGS)	442.9	−1.15	1.05	−6.11	0.94	40	2
McA9 (BHP)	350.0	−0.79	0.58	−7.99	1.06	35	0
McArthur R. Section	700.0	−0.63	0.94	−6.64	1.82	32	0
Wearyan #1	843.3	−0.71	0.46	−6.08	0.98	50	1
Mount Isa Basin							
CM35 (Aberfoyle)	349.0	0.22	0.37	−8.51	0.48	25	0
Amoco 83-04	597.6	−1.03	0.85	−7.79	1.12	48	4
Amoco 83-05	582.2	−0.72	0.31	−8.24	1.04	59	0
GC105 (Pasminco)	501.2	−0.70	0.59	−7.09	0.99	58	0
Lawn Hill-03 (GSQ)	460.0	−0.75	0.81	−8.73	1.64	33	1
Lawn Hill-04 (GSQ)	450.0	−0.53	0.42	−7.90	0.92	40	1
Total	6771.3 m				Total	576	13

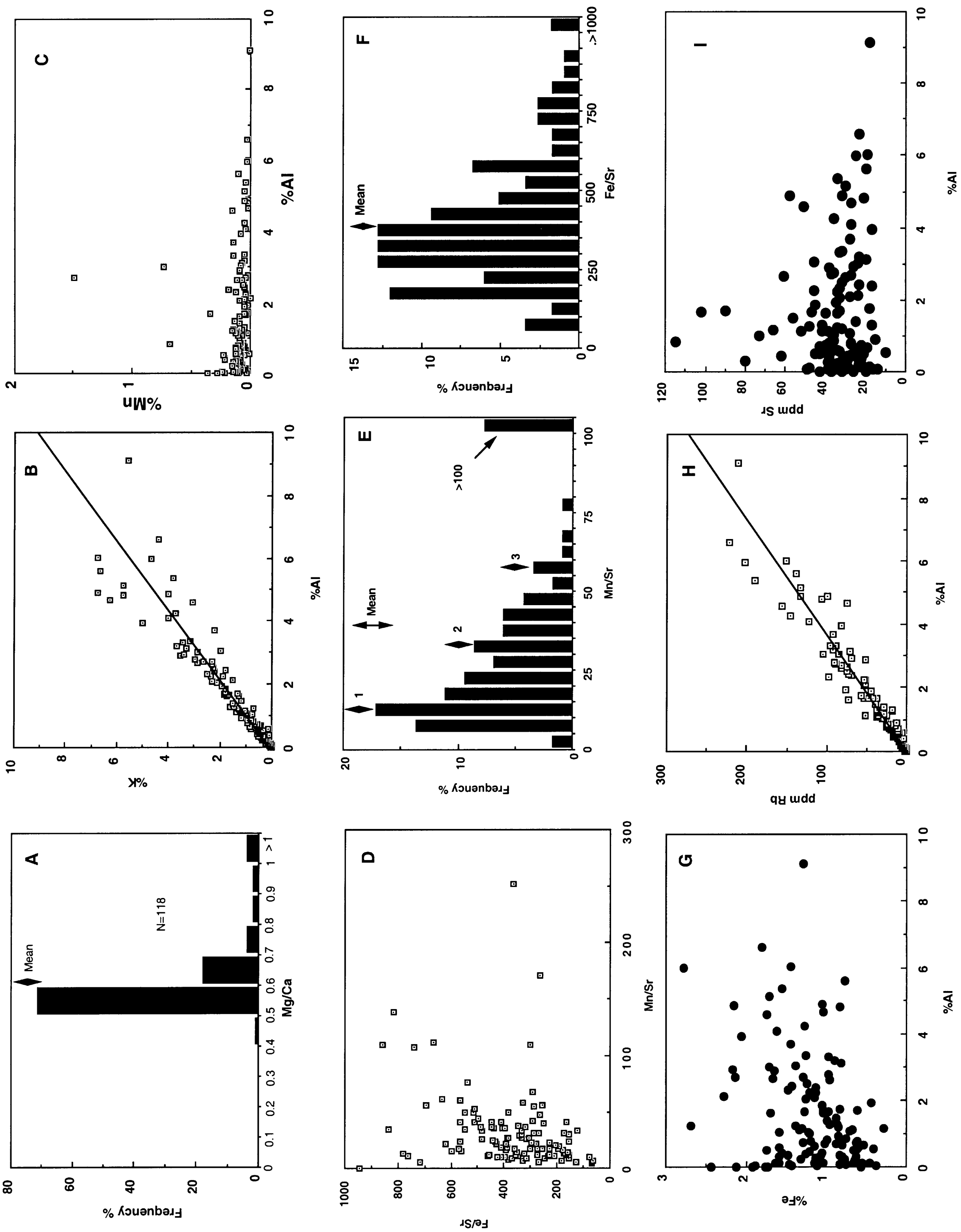
[a] The second column associated with the number of samples on the right gives the number of samples that could not be analysed due to a low carbonate content. NTGS: Northern Territory Geological Survey; GSQ: Geological Survey of Queensland; BHP: Broken Hill Proprietary Limited.

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 $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ 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 crystalline 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 $\delta^{13}C_{carb}$ 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


A
Frequency %
Mg/Ca
Mean
N=118
B
%K
%Al
C
%Mn
%Al
D
Fe/Sr
Mn/Sr
E
Frequency %
Mn/Sr
Mean
1
2
3
>100
F
Frequency %
Fe/Sr
Mean
>1000
G
%Fe
%Al
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ppm Rb
%Al
I
ppm Sr
%Al

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. MnO_2) 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 $\delta^{13}C_{carb}$ 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 ferricyanide 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 (Fig. 4A) 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 = 15.0 ± 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,

Fig. 4. Geochemical evaluation of carbonates analysed for $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$. (A) Histogram of Mg/Ca values showing a tight clustering of the data around a mean of 0.60 ± 0.15. (B) Cross-plots of K and (C), Mn vs. Al. The strong linear relationships indicate that both P and K are associated with clay minerals and hence maximum flooding surfaces. (D) Analysis of Mn and Fe in relation to Sr suggests little covariance. (E) Mn/Sr values are polymodal, suggesting that primary values are quite variable areally and temporally. Small numbers of samples with Mn/Sr values that lie well beyond the main modes and are clearly altered. (F) Histogram of Fe/Sr is also polymodal suggesting relative independence of stratigraphy. (G) Cross-plot of Fe vs. Al does not show a significant covariance, suggesting that Fe is relatively independent of lithology and is widespread throughout the section. (H) and (I) show that Rb is strongly associated with Al and thus the terrigenous component of the rocks, whilst Sr is independent and presumably associated with the carbonate component. All regression lines shown are significant at the 95% level of confidence.

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 $\delta^{13}C_{carb}$ signatures.

Altogether, the data suggest that diagenesis, including 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 $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$. 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 $\delta^{13}C_{carb}$ analyses varied by between 0.01 and 0.30‰, and $\delta^{18}O_{carb}$ values ranged between 0.5 and 0.9‰. Overall, the results show that the isotopic composition within samples is relatively uniform. Replicate analyses were also performed on all samples that exceed the mean $\delta^{13}C_{carb}$ 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.

$\delta^{18}O_{carb}$ has been used as an indicator of diagenetic alteration (Brand and Veizer, 1980; Derry et al., 1992) and provides valuable support for major and trace element evaluations. $\delta^{18}O_{carb}$ values generally become more negative in response to diagenetic effects, which can often be recognised from covariance on $\delta^{13}C_{carb}/\delta^{18}O_{carb}$ 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 $\delta^{13}C_{carb}$ values of close to -0.5 and

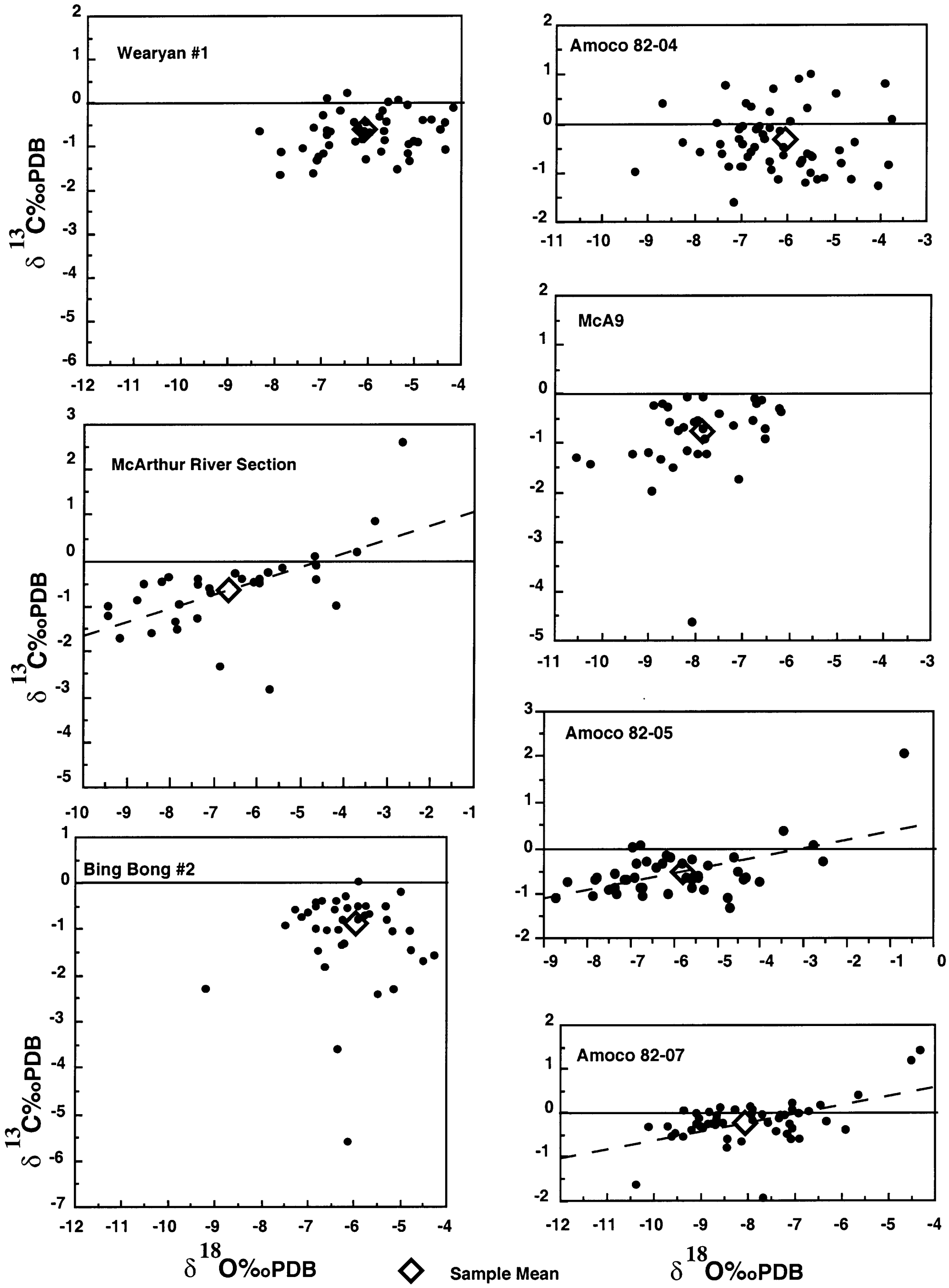

Fig. 5. $\delta^{13}C_{carb}$ vs. $\delta^{18}O_{carb}$ cross-plots for data from McArthur Basin drill core. Note that most values cluster relatively tightly around $\delta^{13}C_{carb}$ values close to −0.5‰. Most altered values lie well beyond two standard deviations from the main clusters of points. 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.

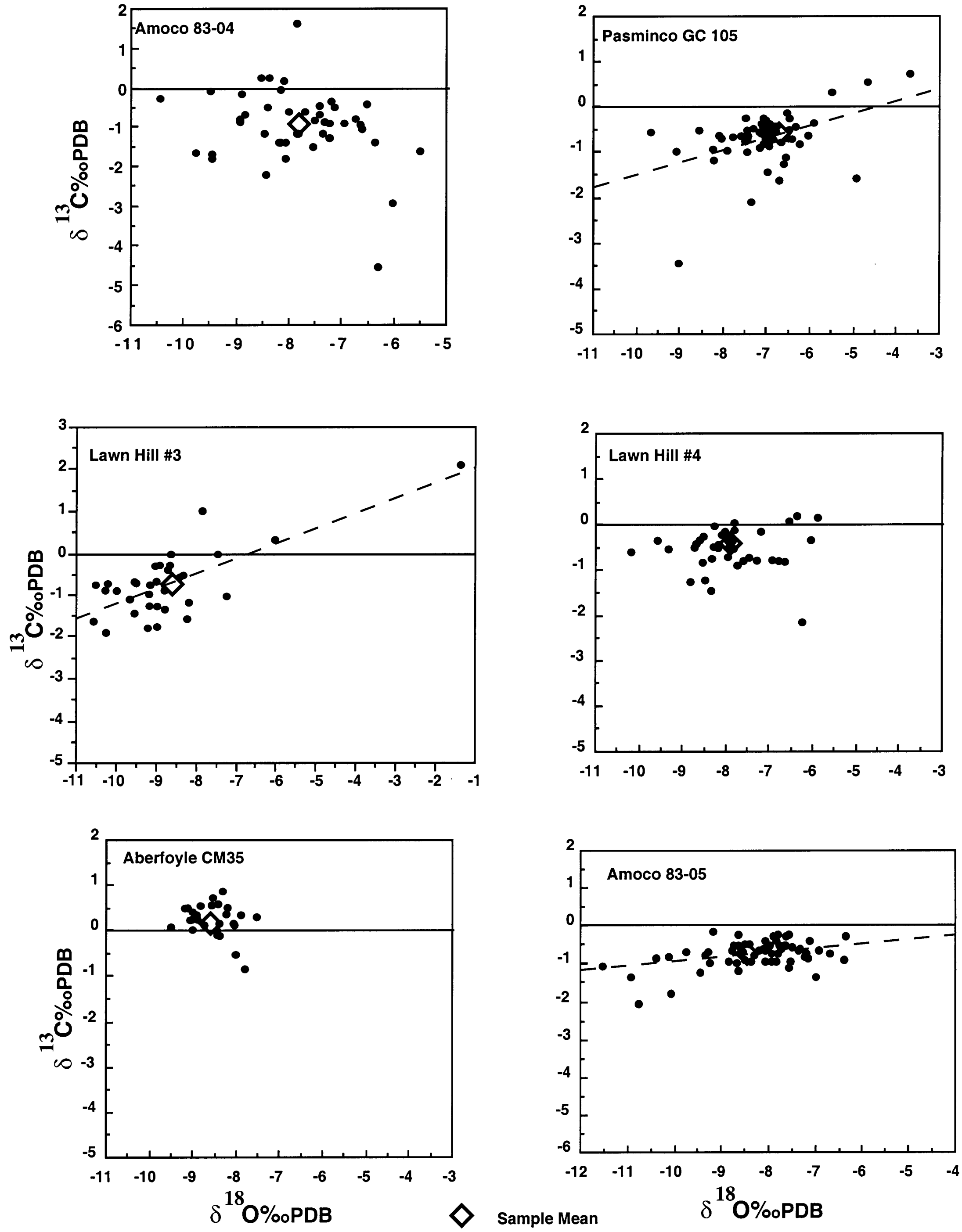

Fig. 6. $\delta^{13}C_{carb}$ vs. $\delta^{18}O_{carb}$ cross-plots for data from Mount Isa Basin drill cores. Note that most $\delta^{13}C_{carb}$ values cluster relatively tightly close to −0.5‰. Some covariance is apparent in the Pasminco GC105, Lawn Hill 3 and Amoco 82-05 drill cores, suggesting 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.

$\delta^{18}O_{carb}$ 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 $\delta^{13}C_{carb}/\delta^{18}O_{carb}$ cross-plots provide useful information, the best indication of alteration in the $\delta^{13}C_{carb}$ data comes from the presence of anomalous outlying values. Where single $\delta^{13}C_{carb}$ 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 $\delta^{18}O_{carb}$ 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 basinal 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 volcanoclastics associated with the Masterton Sandstone and the Gold

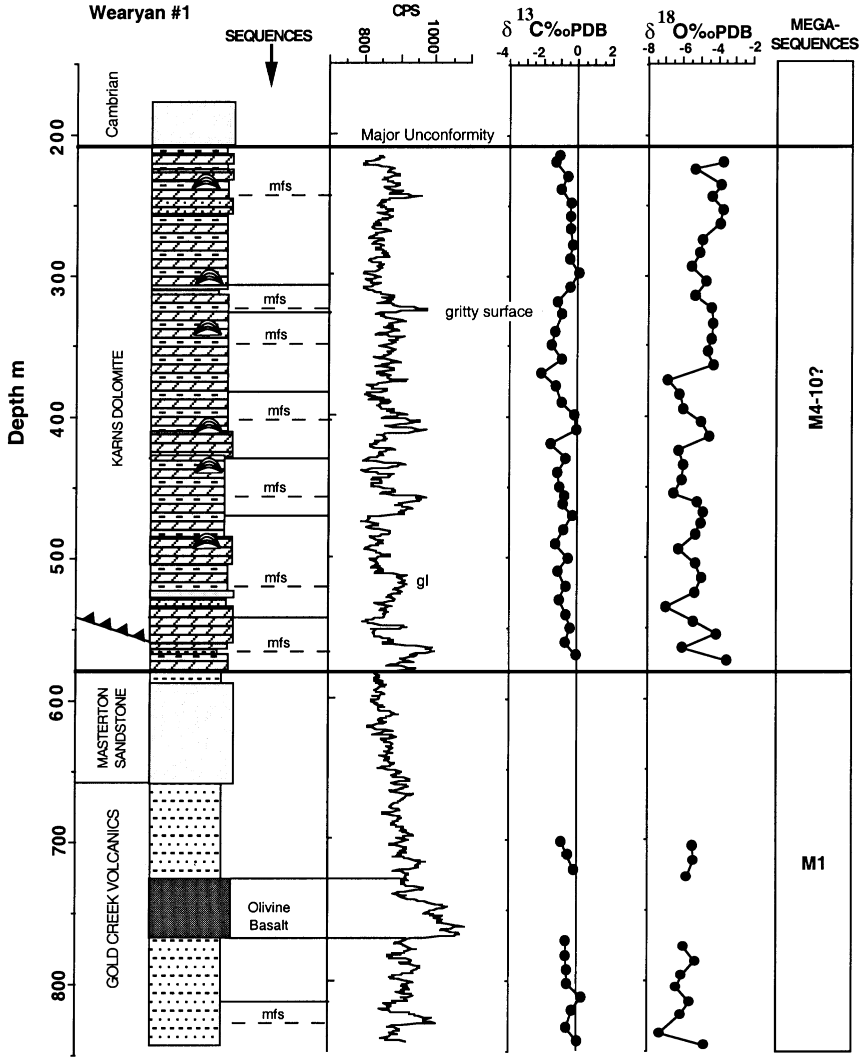

Fig. 7. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Wearyan 1 drill hole from the Wearyan Shelf area of the McArthur Basin, northern Australia. Note the complexity of the gamma log, which suggests major time breaks within the condensed/abbreviated section. For key, see Fig. 10.

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 evaporitic 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 $\delta^{13}C_{carb}$ curve is almost monotonic within the Karns Dolomite (Fig. 7) with values ranging from a minimum of −2.0 to 0‰. The $\delta^{18}O_{carb}$

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 $\delta^{18}O_{carb}$ (Fig. 5) shows that the values cluster tightly around the mean, implying that the carbon was not altered by later events. A small number of samples from dolomitic sandstones in the Gold Creek Volcanics produce $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ vales 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 backstep 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).

$\delta^{18}O_{carb}$ data from the formation (Table 1, Fig. 8) are relatively consistent (−9.3‰ to −3.8‰) within the lower two sequences but are much more varied in the overlying thinner sequences. $\delta^{13}C_{carb}$ signatures (−1.6‰ to +1.0‰) are much more consistent (Table 1) than associated $\delta^{18}O_{carb}$ values. $\delta^{13}C_{carb}$ values tend to increase upward throughout the formation from close to −1.2‰ at the bottom of the drill core towards +1.0‰ near the top of the formation, with only a small inflection at the sequence boundary separating M3 and M4. Overall, the positive upward shift in $\delta^{13}C_{carb}$ values throughout M3 and M4 coincides with a general increase in the evidence for evaporitic conditions within the larger sequence framework, presumably as water depths decreased.

An erosion surface/sequence boundary at the top of the Mallapunyah Formation marks a major interval of erosion and nondeposition upon which the Nathan Group was deposited (M8–M10). An inflection in the gamma-log curve near the base of the Smythe Sandstone indicates the start of a new basin phase (M8). Above the inflection, the gamma count initially increases, indicating an increase in accommodation, but then gradually

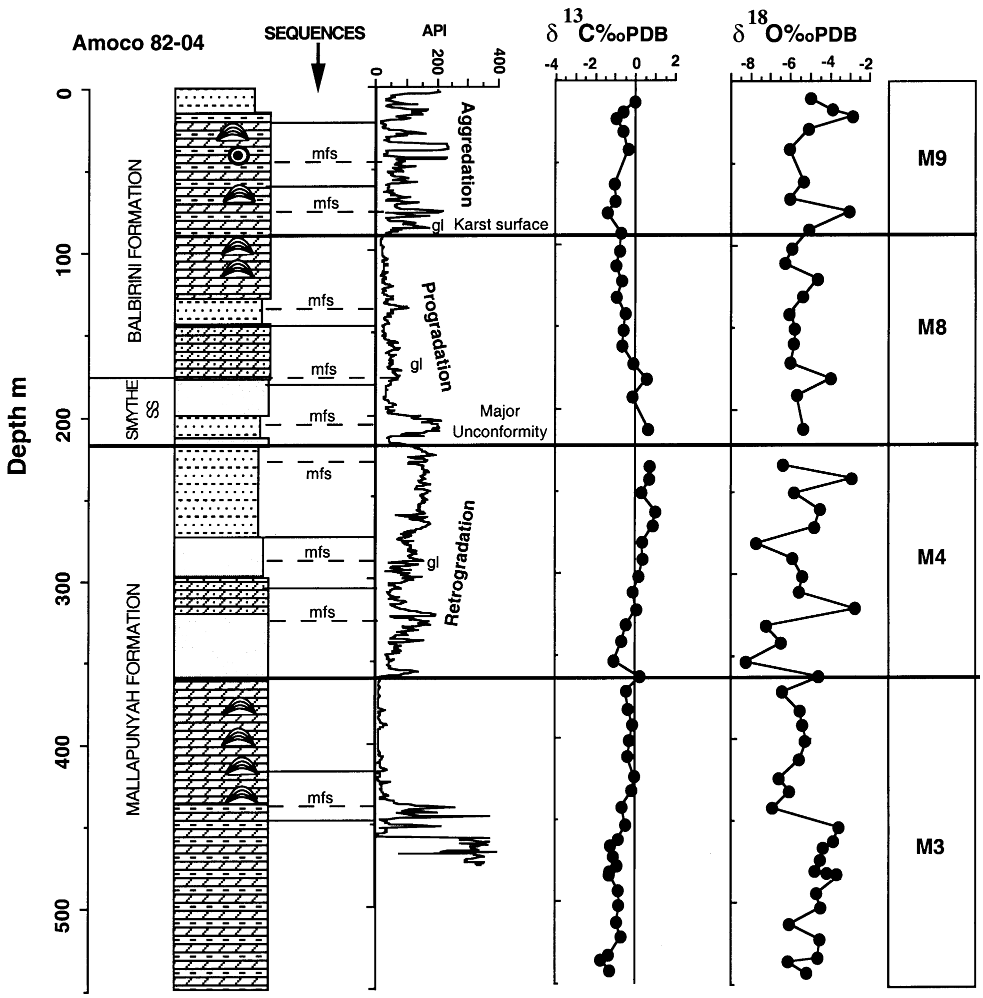

Fig. 8. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Amoco 82-04 drill hole from the McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

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 dololutites. 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 megasequence boundary, dololutites are more abundant, 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 sporadically throughout. Although Jackson et al. (1987) suggested a continental sabkha origin for the Balbirini Formation, because of the common evaporitic textures, gamma-log and facies analysis suggest a more open tidal or peritidal origin in a broad platform setting for large parts of the formation.

$\delta^{13}C_{carb}$ values within the Nathan Group begin with moderately heavy values of around +0.6‰ at the base, declining to ca. −1.0‰ at the karst surface within the Balbirini Formation that defines the M8–M9 boundary, and increasing again to near 0.0‰ at the top of the core (Table 1, Fig. 8). $\delta^{18}O_{carb}$ 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 section 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 parasequences consist of a generally shallowing upward cycle of basal intraclasts and oolitic dolostones, locally showing evidence of desiccation in the form of both halite and gypsum casts, followed by domal, columnar and then laminar stromatolites. 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 parasequences 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 widespread deposition of sulphate evaporites (Walker et al., 1977; Jackson et al., 1987).

The Amelia Dolomite was deposited in a shallow 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 environment. Within the Tatoola Sandstone, the transgressive systems tract consists of very fine to fine-grained, flaggy sandstone, which, as indicated by the reversal of the gamma log, grades to medium to 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 Tooganinie Formation. A combination of structures 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

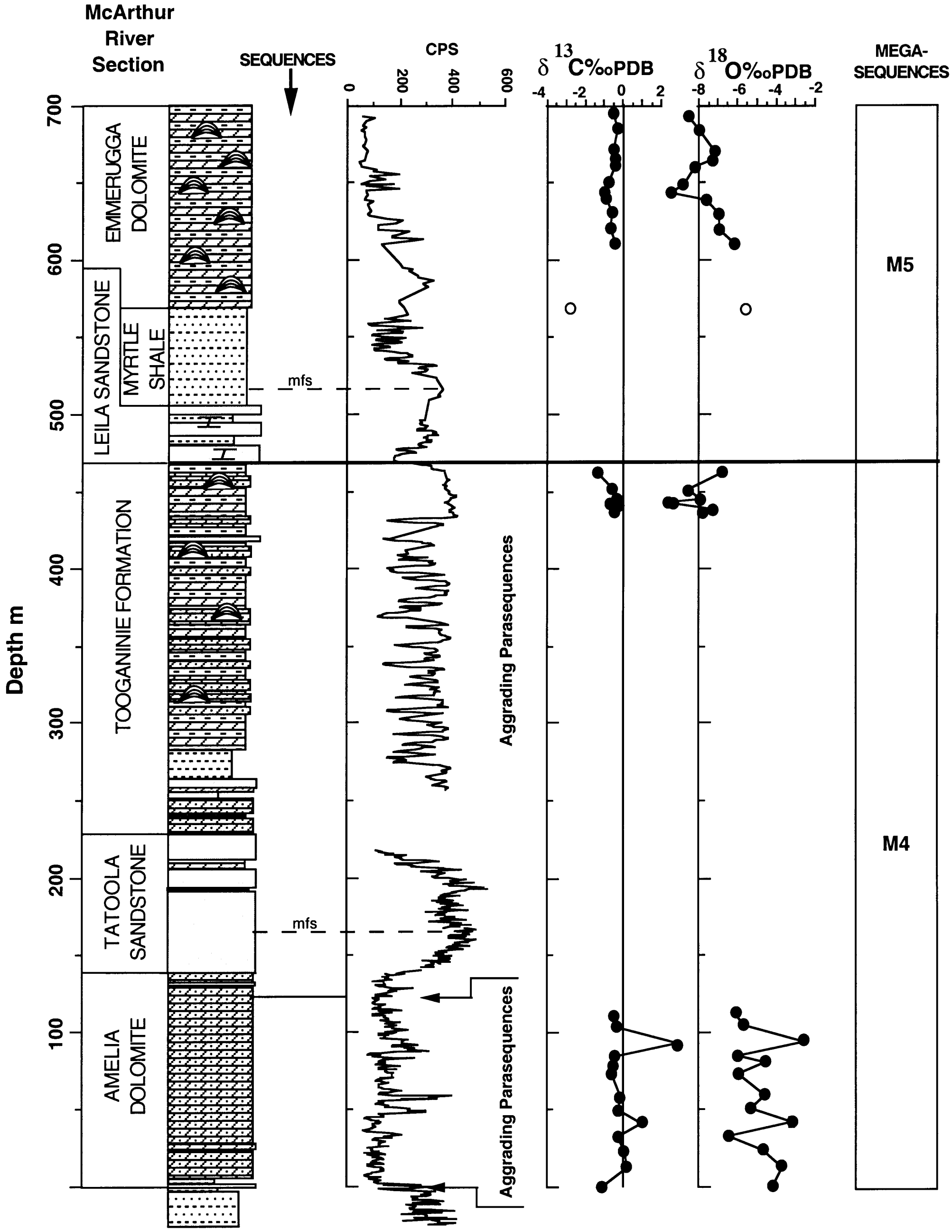

Fig. 9. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the composite McArthur River section of the Batten Subgroup in the southern Batten Trough area of the McArthur Basin, northern Australia. For key, see Fig. 10.

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 Tooganinie Formation was deposited in a shallow marine, often evaporitic, platform setting with sediments being deposited in subtidal to peritidal environments.

The Leila Sandstone, Myrtle Shale and Emmerugga Dolomite form a large-scale depositional sequence at the base of M5. The Leila 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 Leila 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 Tooganinie 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 dololutite 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

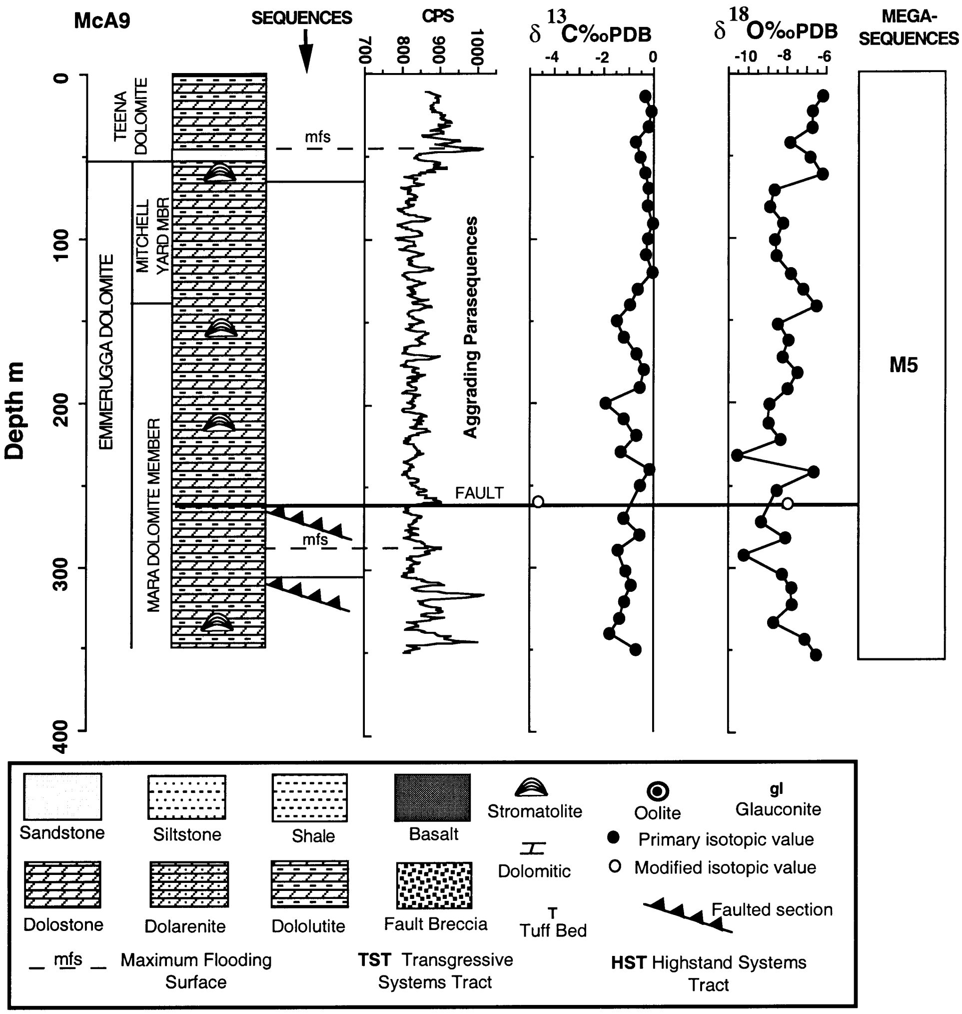

Fig. 10. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the McA9 drill hole from the lower McArthur Group, McArthur Basin, northern Australia.

backstepping facies indicated by the increasing gamma log intensity, however, suggests increasing water depth.

$\delta^{13}C_{carb}$ 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 evaporitic 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. $\delta^{18}O_{carb}$ values are much more varied (Table 1), as expected. As in previous cores, there is a decrease in the $\delta^{18}O_{carb}$ 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-

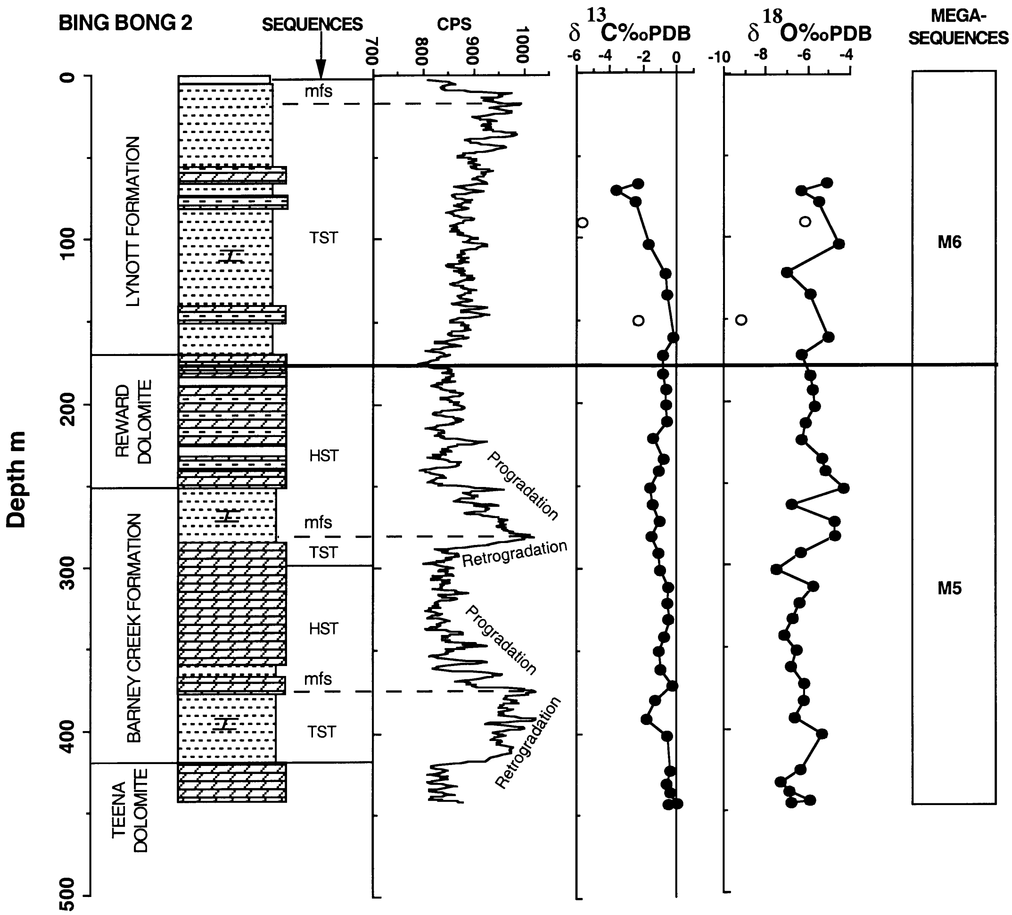

Fig. 11. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Bing Bong 2 drill hole from the middle McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

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 siltstone 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).

$\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ curve crosses sequence boundaries without interruption. The $\delta^{18}O_{carb}$ 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).

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

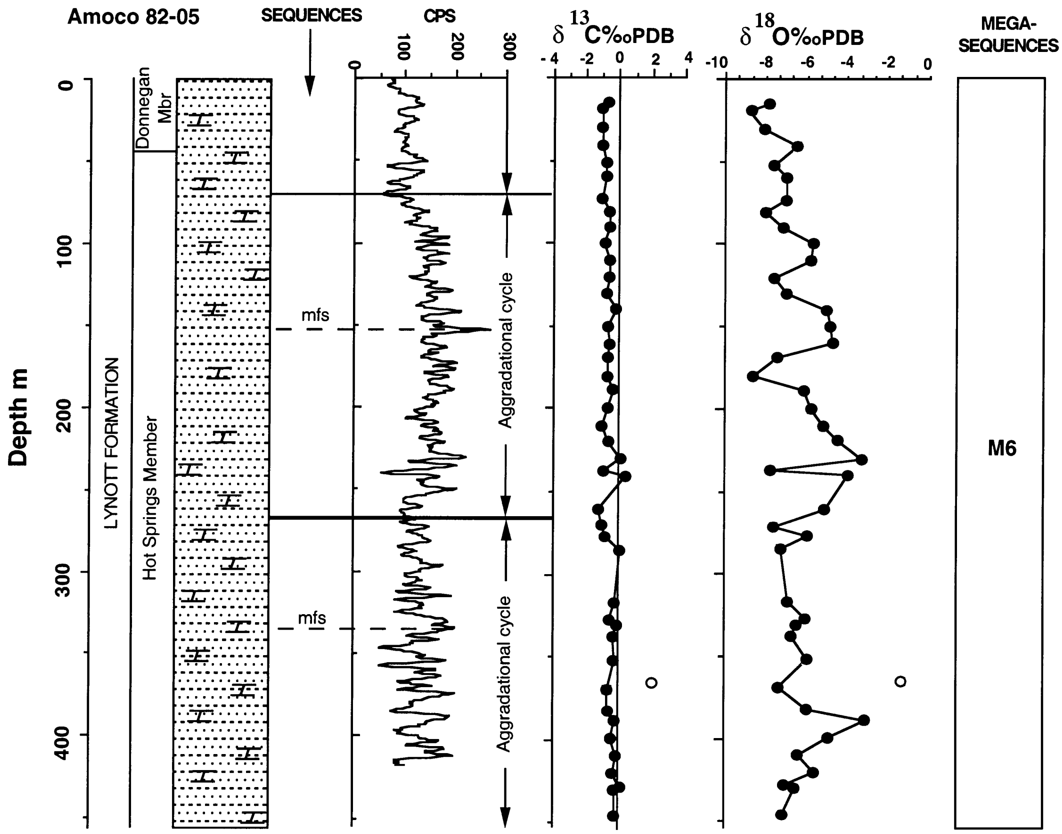

Fig. 12. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Amoco 82-05 drill hole from the middle McArthur Group, McArthur Basin, northern Australia. For key, see Fig. 10.

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 Formation 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 somewhat cleaner dololutites in the highstand (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.

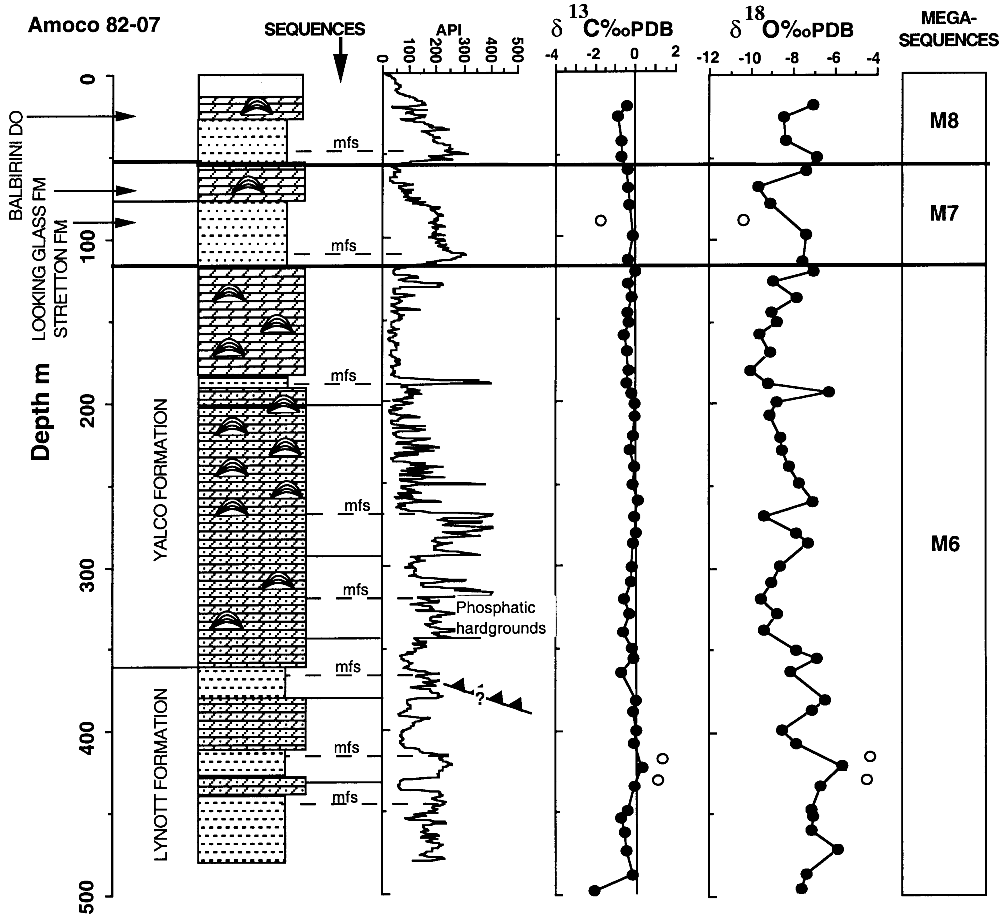

Fig. 13. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Amoco 82-07 drill hole from the upper McArthur and Nathan Groups, McArthur Basin, northern Australia. For key, see Fig. 10.

The $\delta^{13}C_{carb}$ 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 $\delta^{18}O_{carb}$ values, suggesting early diagenetic alteration. The $\delta^{13}C_{carb}$ curve for megasequences M6–M8 is thus quite flat. Throughout the drill core, $\delta^{18}O_{carb}$ values are more erratic than $\delta^{13}C_{carb}$ 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 megasequences 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 continental tholeiitic volcanics intercalated with clastics and minor carbonates. The overlying megasequences, 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 dominated by rocks of fluvial origin. Overall, the architecture 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 basinal 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 formations: the Fish River Formation, Walford Dolomite, Mount Les Siltstone and Doomadgee Formation (Fig. 3). The succession along the Murphy Inlier is highly condensed with pronounced 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 generally 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 phosphatic hardgrounds are present in the Walford Dolomite. Because of the nature of the depositional 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 sandstone, 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-

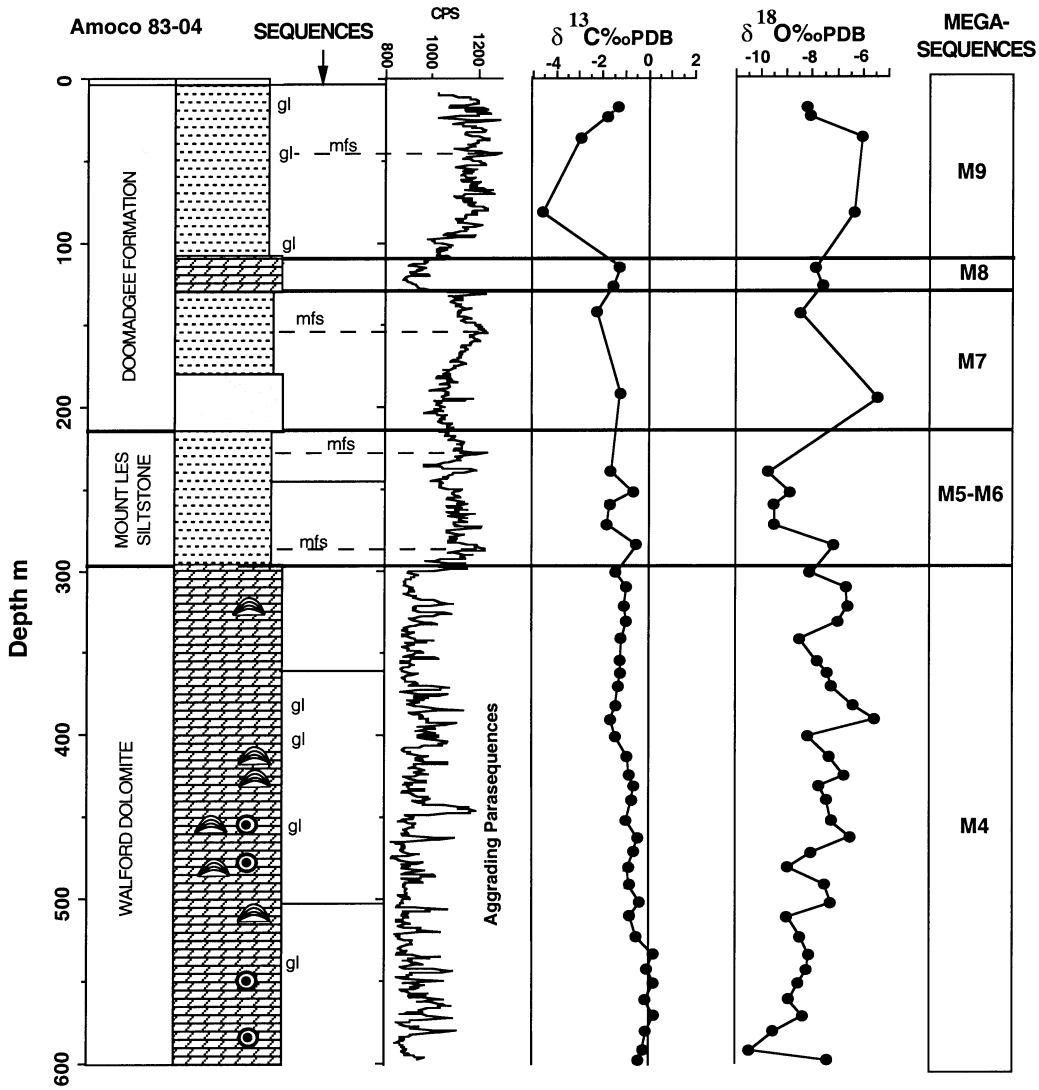

Fig. 14. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Amoco 83-04 drill hole from the Fickling Group adjacent to the Murphy Inlier, Mount Isa Basin, northern Australia. For key, see Fig. 10.

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

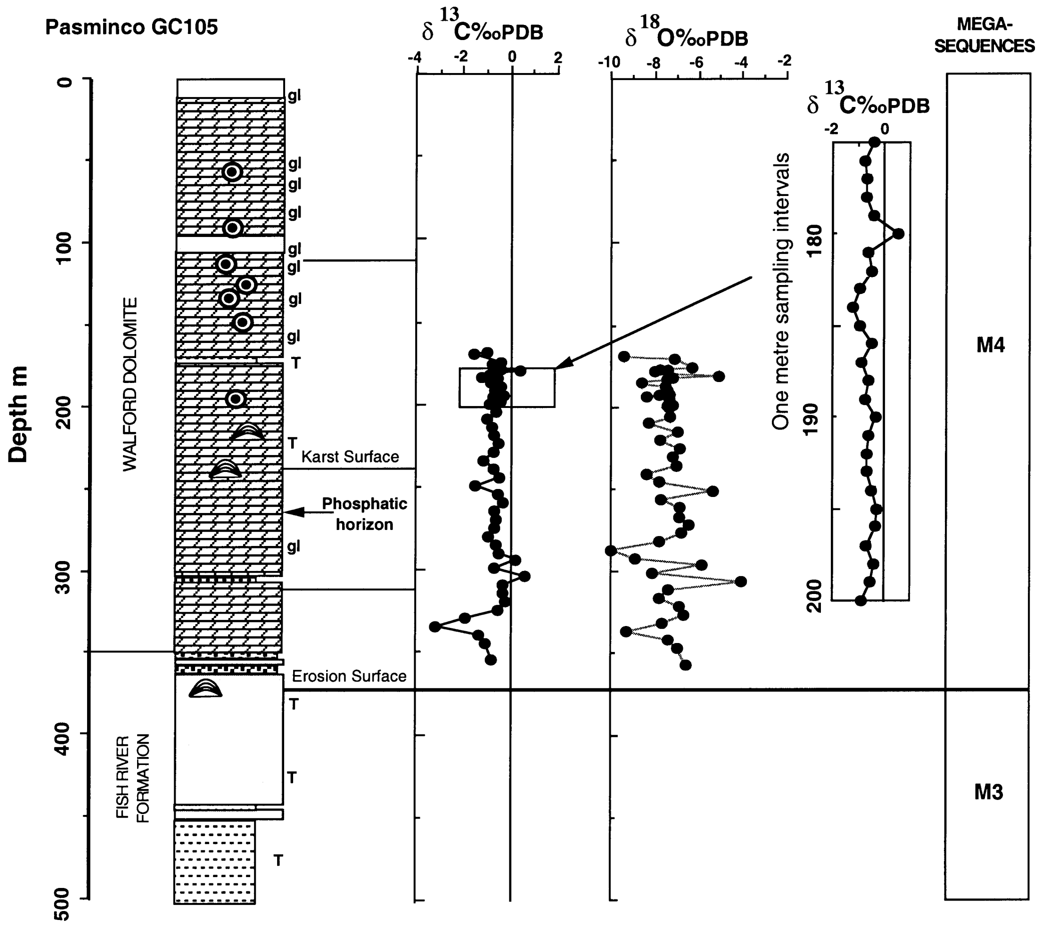

Fig. 15. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Pasmico GC105 drill hole from the Fickling Group adjacent to the Murphy Inlier, Mount Isa Basin, northern Australia. For key, see Fig. 10.

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 then 0.5% throughout the Doomadgee 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 $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ (Fig. 6). $\delta^{18}O_{carb}$ values show a greater variance than $\delta^{13}C_{carb}$ (Table 1). Extreme $\delta^{18}O_{carb}$ values range from −10.4‰ to −5.5‰ due to the increased potential for diagenetic alteration in the more permeable clastic units higher in the section. $\delta^{18}O_{carb}$ values from the Mount Les Siltstone are the most negative (−8.92±1.05‰), whereas $\delta^{18}O_{carb}$ values for the Doomadgee Formation (−7.53±0.89‰) are slightly heavier than the mean $\delta^{18}O_{carb}$ values for carbonate units (−7.75±1.02‰).

The $\delta^{13}C_{carb}$ values range from −4.6‰ to 1.6‰, with most values confined to a narrow range between −2.0 and 0.0‰ (Table 1). The least variable $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ values show an oscillatory decrease upward through the Walford Dolomite from around 0‰ at the base to close to −2‰ 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 onlapping the major sequence boundaries 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 predominantly 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 transgressive 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 dolomitic. The basal Gunpowder Creek Formation was deposited in a shallow marine shoreface clastic

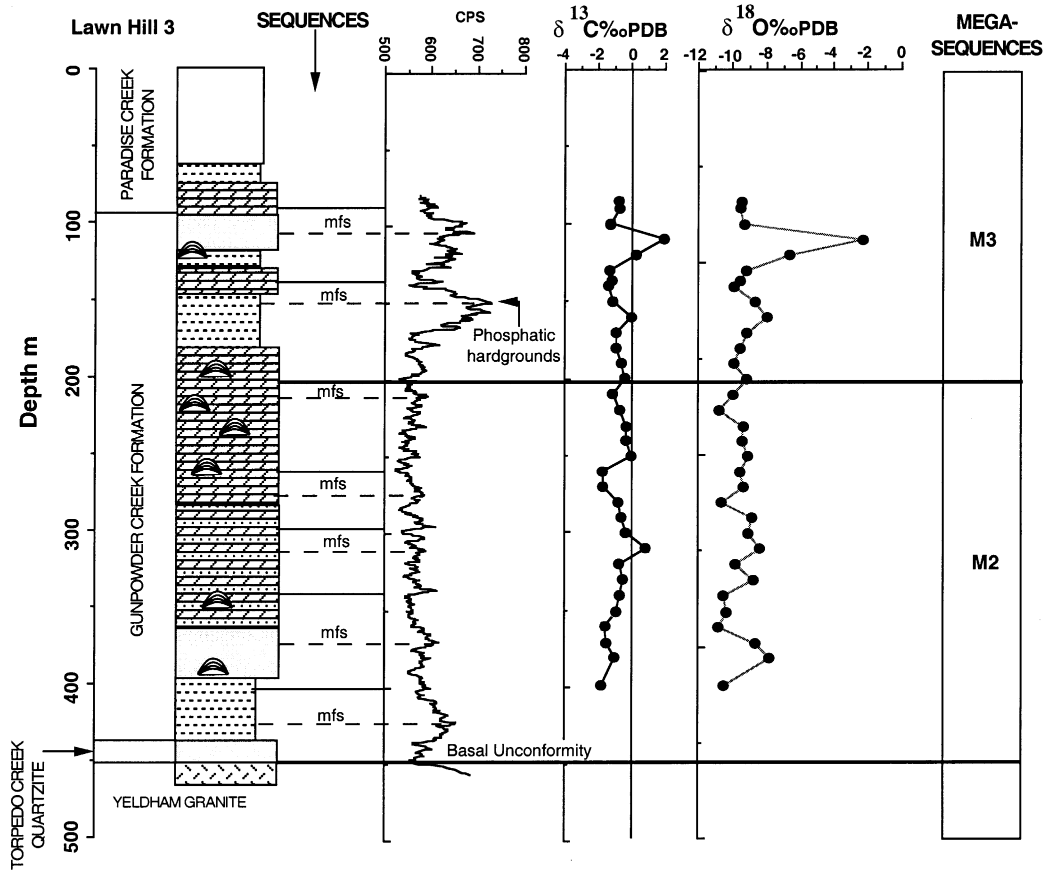

Fig. 16. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Lawn Hill 3 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

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 aggrada-

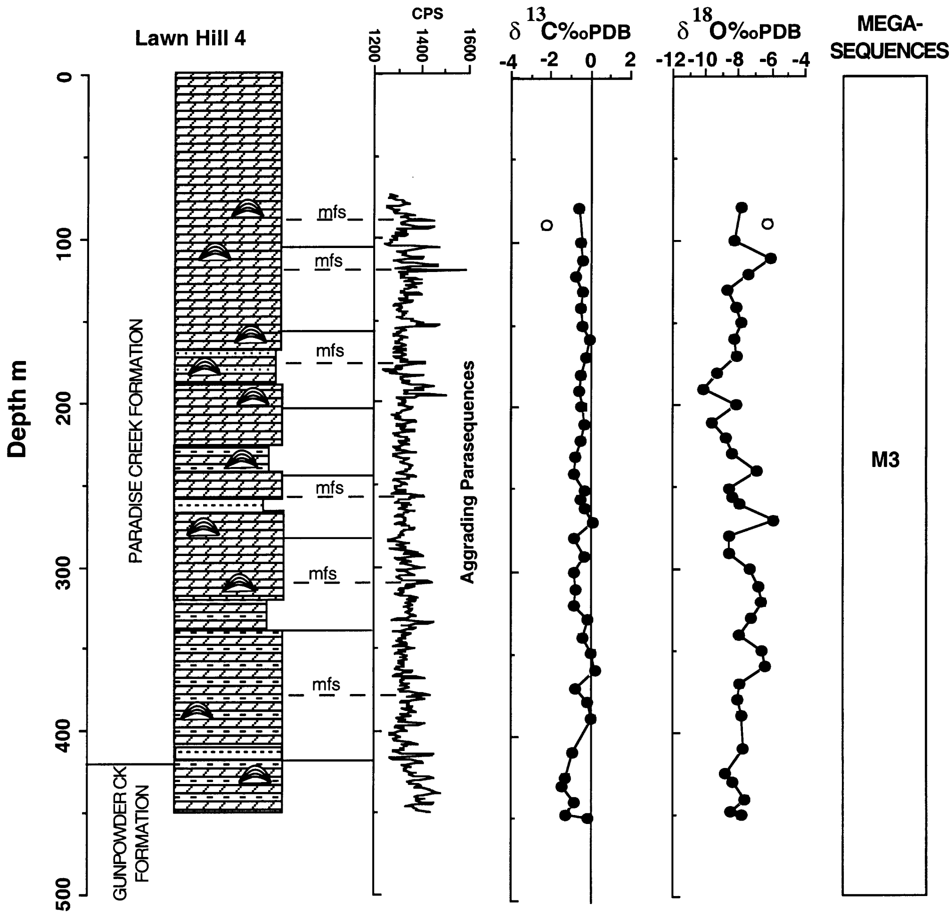

Fig. 17. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Lawn Hill 4 drill hole from the lower McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key, see Fig. 10.

tional stacking patterns and facies distribution visible in the gamma log and core (Fig. 17) suggest that the Paradise Creek Formation was deposited in a ramp setting (cf. Dunster, 1996; Sami et al., 1997). Lithofacies indicate tidal and peritidal conditions.

$\delta^{13}C_{carb}$ values are all within a narrow range throughout the cores (Figs. 16 and 17, Table 1). Variations in the values are somewhat greater in M2 and the lower part of M3 where carbonates are not as massive and contain some thin clastic intervals. The more massive carbonates of the Paradise Creek Formation produce an almost monotonic $\delta^{13}C_{carb}$ curve. There is little evidence of covariance between $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ (Fig. 6). $\delta^{18}O_{carb}$ values are somewhat more varied (Figs. 16 and 17). It is perhaps significant that $\delta^{18}O_{carb}$ values become lighter at the top of some of the larger depositional cycles, suggesting diagenetic modification that may have been broadly contemporaneous with exposure on the sequence boundary.

8.2.2. Amoco 83-05 and Aberfoyle CM35 drill holes

Amoco 83-05 and Aberfoyle CM35 drill holes (Fig. 1) penetrate 582 and 349 m, respectively, of a possible 2000 m of the Lady Loretta Formation (Fig. 18). Gamma-log data suggest that the Amoco 83-05 drill hole cored sedimentary units

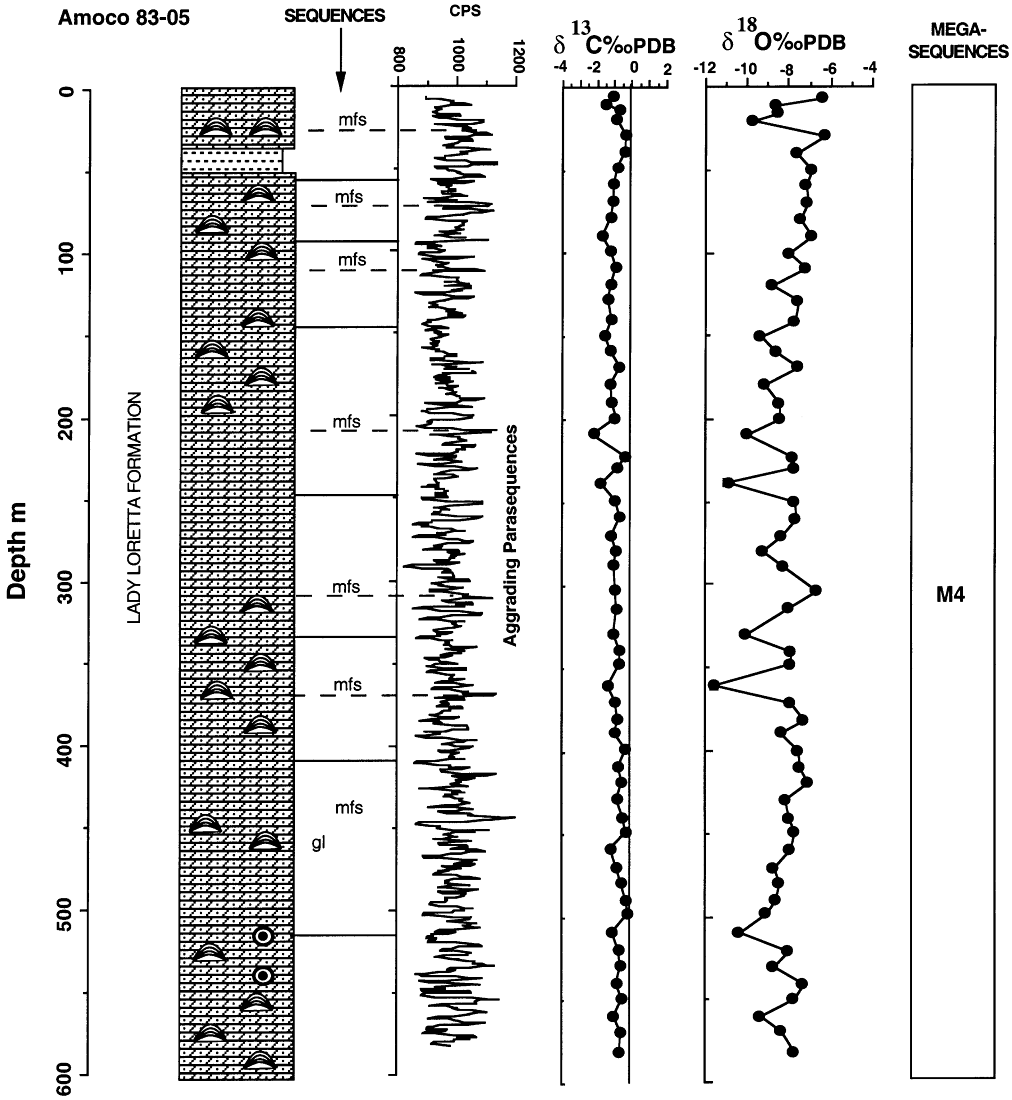

Fig. 18. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Amoco 83-05 drill hole from the middle McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. For key see Fig. 10.

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-

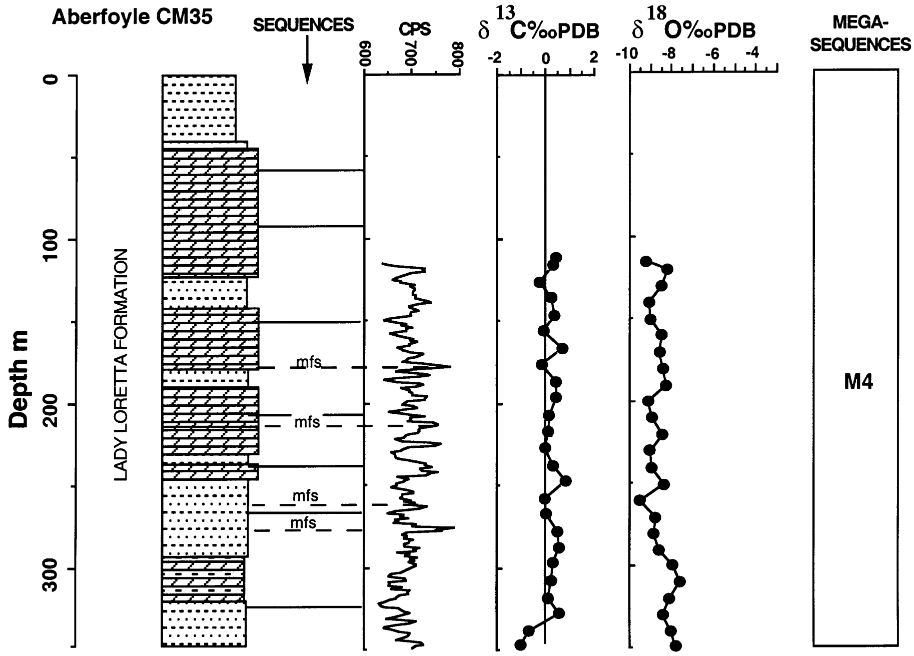

Fig. 19. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ stratigraphy of the Aberfoyle CM35 drill hole from the middle McNamara Group in the Lawn Hill area of the Mount Isa Basin, northern Australia. Test sampling at 1 and 5 m intervals was carried out on this core. For key, see Fig. 10.

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).

$\delta^{13}C_{carb}$ values are relatively consistent throughout the cored section of the formation (Fig. 18, Table 1). The $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ curve is thus consistent with the unvarying facies, suggesting that the primary signature is unaltered. The $\delta^{18}O_{carb}$ 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 $\delta^{13}C_{carb}$ signatures.

Stable isotope data from the McArthur and Mount Isa Basins therefore provide, for the first time, a comprehensive $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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 $\delta^{18}O_{carb}$ values appear to have been much more sensitive to the passage of meteoric waters than the $\delta^{13}C_{carb}$ values. $\delta^{18}O_{carb}$ values average −7.3‰ for all data from both basins. The results confirm earlier speculation (cf. Des Marais et al., 1992) that $\delta^{13}C_{carb}$ 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 $\delta^{13}C_{carb}$ 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.

Acknowledgements

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References

Aigner, T., Schauer, M., Junghans, W.D., Reinhardt, L., 1995. Outcrop gamma-ray logging and its applications: examples from the German Triassic. Sediment. Geol. 100, 47–61.

Andrews, S., 1996. Stratigraphy and depositional setting of the Upper McNamara Group, Lawn Hill region. In: Baker, T., Rotherham, J.F., Richmond, J.M., Mark, G., Williams, P.J. (Eds.), New Developments in Metallogenic Research: The McArthur Mount Isa Cloncurry Minerals Province. MIC '96. Extended Conference Abstracts. EGRU Contribution 55. James Cook University of North Queensland, 5–9.

Bradshaw, B., Lindsay, J.F., Krassay, A., Wells, A.T., press. Attenuated basin-margin sequence stratigraphy of the Isa Superbasin: The Fickling Group Southern Murphy Inlier. Aust. J. Earth Sci.

Brand, U., Veizer, J., 1980. Chemical diagenesis of multicomponent carbonate system — 1. Trace elements. J. Sediment. Petrol. 50, 1219–1250.

Brasier, M.D., Rozanov, A.Yu., Zhuravlev, A.Yu., Corfield, R.M., Derry, L.A., 1994. A carbon isotope reference scale for the Lower Cambrian succession in Siberia: report of IGCP Project 303. Geol. Mag. 131, 767–783.

Brasier, M.D., Shields, G., Kuleshov, V.N., Zhegallo, E.A., 1996. Integrated chemo- and biostratigraphic calibration of early animal evolution: Neoproterozoic to early Cambrian, southwest Mongolia. Geol. Mag. 133, 445–485.

Brasier, M.D., Lindsay, J.F., 1998. A billion years of environmental stability and the emergence of eukaryotes: New data from Northern Australia. Geology 26, 555–558.

Brasier, M.D., Lindsay, J.F., in press. Did a crustal revolution trigger the 'Cambrian explosion'? In: Riding, R., Zhuravlev, A.Y. (Eds.), Ecology of the Cambrian Radiation. Columbia University Press, New York.

Broecker, W.S., 1970. A boundary condition on the evolution of atmospheric oxygen. J. Geophys. Res. 75, 3553–3557.

Brown, M.C., Claxton, C.W., Plumb, K.A., 1969. The Proterozoic Barney Creek Formation and Some Associated Units of the McArthur Group Northern Territory, Bureau of Mineral Resources, Australia Record 1969/145.

Buick, R., Des Marais, D.J., Knoll, A.H., 1995. Stable isotope compositions of carbonates from the Mesoproterozoic

Bangemall Group, northwestern Australia. Chem. Geol. 123, 153–171.

Calver, C.R., Lindsay, J.F., 1998. Ediacarian sequence and isotope stratigraphy of the Officer Basin, South Australia. Aust. J. Earth Sci. 45, 513–532.

Chamberlain, A.K., 1984. Surface gamma-ray logs: a correlation tool for frontier areas. Am. Assoc. Petrol. Geol. Bull. 68, 1040–1043.

Crick, I.H., Boreham, C.J., Cook, I.C., Powell, T.G., 1988. Petroleum geology and geochemistry of the Middle Proterozoic McArthur Basin, northern Australia II: Assessment of source rock potential. Am. Assoc. Petrol. Geol. Bull. 72, 1495–1514.

Derry, L.A., Kaufman, A.J., Jacobsen, S.B., 1992. Sedimentary cycling and environmental change in the late Proterozoic, evidence from stable and radiogenic isotopes. Geochim. Cosmochim. Acta 56, 1317–1329.

Derry, L.A., Brasier, M.D., Corfield, R.M., Rozanov, A.Yu., Zhuravlev, A.Yu., 1994. Sr and C isotopes in Lower Cambrian carbonates from the Siberian Platform: A paleoenvironmental record during the 'Cambrian explosion'. Earth Planet. Sci. Lett. 128, 671–681.

Des Marais, D.J., Strauss, H., Summons, R.E., Hayes, J.M., 1992. Carbon isotope evidence for the stepwise oxidation of the Proterozoic environment. Nature 59, 605–609.

Domagala, J., McConachie, B., Bradshaw, B., Krassay, A., 1997. Upper Riversleigh Siltstone–Termite Range Formation, Sections and Correlations. Aust. Geol. Survey Organisation, Record 1997/12.

Dorrins, D.K., Womer, M.B., 1983. McArthur River. Part A: Results of 1982 Field Program (Amoco). Northern Territory Geological Survey, Unpublished Report PR 83/036. 115 pp.

Dorrins, D.K., Humphreville, R.G., Womer, M.B., 1983. Lawn Hill Area, Queensland, Field Program Results, 1983 (Amoco). Queensland Geological Survey, Unpublished Report CR 12489. 73 pp.

Dunster, J.N., 1996. Sedimentology of the Lady Loretta Formation — a comparison of the regional setting to that of the Lady Loretta orebody. In: Baker, T., Rotherham, J.F., Richmond, J.M., Mark, G., Williams, P.J. (Eds.), MIC '96. Extended Conference Abstracts. EGRU Contribution 55. James Cook University of North Queensland, 47–50.

Fairchild, I.J., Marshall, J.D., Bertrand-Sarfati, J., 1990. Stratigraphic shifts in carbon Isotopes from Proterozoic stromatolitic carbonates (Mauritania): Influences of primary mineralogy and diagenesis. Am. J. Sci. 290, 46–79.

Green, O.R., 1993. The Use and Application of Stains and Dyes in Geological Techniques. The Institute of Science Technology, Official Publication 28, 2–26.

Gurnis, M., 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. Nature 322, 695–699.

Haines, P.W., Pietsch, B.A., Rawlings, D.J., Madigan, T.L., 1993. 1:250,000 Geological Map Series Explanatory Notes. Mount Young SE53-15. Northern Territory Geological Survey, Australia.

Hayes, J.M., 1983. Geochemical evidence bearing on the origin of aerobiosis, a speculative hypothesis. In: Schopf, J.W. (Ed.), Earth's Earliest Biosphere: Its Origin and Evolution. Princeton University Press, Princeton, NJ, pp. 291–301.

Hutton, L.J., 1983. Stratigraphic drilling report — GSQ Lawn Hill 1–4. Queensland Gov. Mining J. 84, 228–240.

Idnurm, M., Giddings, J.W., 1995. Palaeoproterozoic–Neoproterozoic North America–Australia link: new evidence from paleomagnetism. Geology 23, 149–152.

Idnurm, M., Giddings, J.W., Plumb, K.A., 1995. Apparent polar wander and reversal stratigraphy of the Paleo-Mesoproterozoic southeastern McArthur Basin, Australia. Precamb. Res. 71, 1–41.

Jackson, M.J., Muir, M.D., Plumb, K.A., 1987. Geology of the southern McArthur Basin, Northern Territory. Bulletin 220. Bureau of Mineral Resources, Australia.

Karhu, J.A., Holland, H.D., 1996. Carbon isotopes and the rise of atmospheric oxygen. Geology 24, 867–870.

Kaufman, A.J., Knoll, A.H., Awramik, S.M., 1992. Biostratigraphic and chemostratigraphic correlation of Neoproterozoic sedimentary successions: Upper Tindir Group. northwestern Canada, as a test case. Geology 20, 181–185.

Kaufman, A.J., Knoll, A.H., 1995. Neoproterozoic variations in the C-isotope composition of seawater: stratigraphic and biochemical implications. Precamb. Res. 73, 27–49.

Klein, C., Beukes, N.J., Holland, H.D., Kasting, J.F., Kump, L.R., Lowe, D.R., 1992. Proterozoic atmospheres and oceans. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere — A Multidisciplinary Study. Cambridge University Press, Cambridge, pp. 137–174.

Knoll, A.H., Walter, M.R., 1992. Latest Proterozoic stratigraphy and Earth history. Nature 356, 673–678.

Knoll, A.H., Grotzinger, J.P., Kaufman, A.J., Kolosov, P.N., 1995a. Integrated approaches to terminal Proterozoic stratigraphy: an example from the Olenek Uplift, northeastern Siberia. Precamb. Res. 73, 251–270.

Knoll, A.H., Kaufman, A.J., Semikhatov, M.A., 1995b. The carbon-isotope composition of Proterozoic carbonates: Riphean succession from northwestern Siberia (Anabar Massif, Turukhansk Uplift). Am. J. Sci. 295, 823–850.

Krassay, A., Bradshaw, B., McConachie, B., Domagala, J., Jackson, M.J., 1997. Stratigraphy of the Upper McNamara Group, Lawn Hill region: Shady Bore Quartzite to Middle Riversleigh Siltstone, Australian Geological Survey Organisation, Record 1997/12.

Le Messurier, P., Williams, B.T., Blake, D.H., 1990. Tennant Creek Inlier — Regional geology and mineralisation. In: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. The Australian Institute of Mining and Metallurgy Monographs 14, 829–838.

Lindsay, J.F., 1987. Sequence stratigraphy and depositional controls in Late Proterozoic–Early Cambrian sediments of Amadeus Basin, central Australia. Am. Assoc. Petrol. Geol. Bull. 71, 1387–1403.

Lindsay, J.F., Korsch, R.J., Wilford, J.R., 1987. Timing the breakup of a Proterozoic supercontinent: Evidence from Australian intracratonic basins. Geology 15, 1061–1064.

Lindsay, J.F., Korsch, R.J., 1989. Interplay of tectonics and sea-level changes in basin evolution: an example from the intracratonic Amadeus Basin, central Australia. Basin Res. 2, 3–25.

Lindsay, J.F., Kennard, J.M., Southgate, P.N., 1993. Application of sequence stratigraphy in an intracratonic setting Amadeus Basin central Australia. In: Posamentier, H.W., Summerhayes, C.P., Haq, B.U., Allen, G.P. (Eds.), Sequence Stratigraphy and Facies Associations. IAS Special Publication 18, 605–631.

Lindsay, J.F., Leven, J.F., 1996. Evolution of a Neoproterozoic to Palaeozoic Intracratonic Setting, Officer Basin, South Australia. Basin Res. 8, 403–424.

Lindsay, J.F., Brasier, M.D., Dorjnamjaa, D., Kruse, P., Goldring, R., Wood, R.A., 1996. Facies and sequence controls on the appearance of the Cambrian biota in southwestern Mongolia: implications for Precambrian–Cambrian boundary. Geol. Mag. 133, 417–428.

Lindsay, J.F., Wells, A.T., 1997. The Fickling Group and the Palaeoproterozoic basin margin, Mount Isa Basin, North Queensland. Australian Geological Survey Organisation, Record 1997/12.

Lindsay, J.F., 1998. The Broadmere Structure: a Window into Palaeoproterozoic Mineralisation McArthur Basin Northern Australia, Australian Geological Survey Organisation Record 98/38.

Lodwick, W.R., Lindsay, J.F., 1990. Southern Georgina Basin: a new perspective. Aust. Petrol. Explor. Assoc. J. 30, 137–148.

Logan, G.A., Hayes, J.M., Hieshima, G.B., Summons, R.E., 1995. Terminal Proterozoic reorganisation of biogeochemical cycles. Nature 376, 53–56.

Logan, R.G., Williams, N., 1984. Sedimentary controls on the hydrothermal system that formed the HYC deposit at McArthur River, Northern Territory, Geosciences in the Development of Natural Resources Seventh Australian geological Convention Sydney, 1984. Geological Society of Australia, Abstracts 12, 339.

Lowe, D.R., 1992. In: Schopf, J.W., Klein, C. (Eds.), Major events in the geological development of the Precambrian Earth. The Proterozoic Biosphere — A Multidisciplinary Study. Cambridge University Press, Cambridge, pp. 67–75.

McConachie, B.A., Barlow, M.G., Dunster, J.N., Meaney, R.A., Schaap, A.D., 1993. The Mount Isa Basin — definition, structure and petroleum geology. Aust. Petrol. Explor. Assoc. J. 33, 237–257.

Marshall, J.D., 1993. Climatic and oceanographic signals from the carbonate rock record and their preservation. Geol. Mag. 129, 143–160.

Mount, J.F., Signor, P.W., 1992. Faunas and facies — fact and artifact: paleoenvironmental controls on the distribution of Early Cambrian faunas. In: Lipps, J.H., Signor, P.W. (Eds.), Origin and Early Evolution of the Metazoa. Plenum, New York, pp. 27–51.

Muir, M.D., 1979. A sabkha model for deposition of part of the Proterozoic McArthur Group of the Northern Territory. Bureau of Mineral Resources. J. Aust. Geol. Geophys. 4, 149–162.

Myers, K.J., 1989. The origin of the Lower Jurassic Cleveland Ironstone Formation of north-east England: evidence from portable gamma-ray spectrometry, Geological Society of London Special Publication 46, 221–228.

Myers, K.J., Bristow, C.S., 1989. Detailed sedimentology and gamma-ray log characteristics of a Namurian deltaic succession; II gamma-ray logging, Geological Society of London Special Publication 41, 81–88.

Needham, R.S., De Ross, G.J., 1990. Pine Creek Inlier — Regional geology and mineralisation. Geology of the Mineral Deposits of Australia and Papua New Guinea. In: Hughes, F.E. (Ed.), The Australian Institute of Mining and Metallurgy Monographs 14, 727–737.

O'Dea, M.G., Lister, G.S., MacCready, T., Betts, P.G., Oliver, N.H.S., Pound, K.S., Huang, W., Valenta, R.K., 1997. Geodynamic evolution of the Proterozoic Mount Isa terrain. In: Burg, J.P., Ford, M. (Eds.), Orogeny Through Time. Geological Society Special Publication 121, 99–122.

Page, R.W., Williams, I.S., 1988. Age of the Barramundi Orogeny in northern Australia by means of ion microprobe and conventional U–Pb zircon studies. Precamb. Res. 40–41, 21–36.

Page, R.W., 1997. Geological constraints provided by U–Pb zircon dating of basin phases in the Lawn Hill and McArthur Basins, Australian Geological Survey Organisation Record 1997/12.

Page, R.W., Sweet, I.P., 1998. Geochronology of basin phases in the western Mount Isa Inlier, and correlation with the McArthur Basin. Aust. J. Earth Sci. 45, 219–232.

Pelechaty, S.M., Kaufman, A.J., Grotzinger, J.P., 1996. Evaluation of $\delta^{13}C$ chemostratigraphy for intrabasinal correlation: Vendian strata of northeast Siberia. Geol. Soc. Am. Bull. 108, 992–1003.

Pietsch, B.A., Rawlings, D.J., Creaser, P.M., Kruse, P.D., Ahmad, M., Ferenci, P.A., Findhammer, T.L.R., 1991. 1:250,000 Geological Map Series Explanatory Notes. Bauhinia Downs SE53-3. Northern Territory Geological Survey, Australia.

Plumb, K.A., Ahmad, M., Wygralak, A.S., 1990. Mid-Proterozoic basins of the northern Australian craton — regional geology and mineralisation. In: Hughes, F.E. (Ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. Australasian Institute of Mining and Metallurgy, Melbourne, pp. 881–902.

Plumb, K.A., 1991. New Precambrian time scale. Episodes 14, 139–140.

Powell, T.G., Jackson, M.A., Sweet, I.P., Crick, I.H., Boreham, C.J., Summons, R.E., 1987. Petroleum geology and geochemistry, middle Proterozoic McArthur Basin, Bureau of Mineral Resources Geology and Geophysics, Australia Record 1987/48. 286 pp.

Pysklywec, R.N., Mitrovica, J.X., 1998. Mantle flow mechanisms for the large scale subsidence of continental interiors. Geology 26, 687–690.

Sami, T., Southgate, P., James, N., Jackson, J., 1997. An integrated sequence stratigraphic and sedimentological model for the evolution of the Lower McNamara succession, Australian Geological Survey Organisation, Record 1997/12.

Schidlowski, M., Hayes, J.M., Kaplan, I.R., 1983. Isotopic inferences of ancient biochemistries: Carbon sulfur hydrogen and nitrogen. In: Schopf, J.W. (Ed.), Earth's Earliest Biosphere: Its origin and Evolution. Princeton University Press, Princeton, NJ, pp. 149–186.

Schopf, J.W., 1992. Evolution of the Proterozoic biosphere: benchmarks, tempo and mode. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere — A Multidisciplinary Study. Cambridge University Press, Cambridge, pp. 583–600.

Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere — A Multidisciplinary Study 1992. Cambridge University Press, Cambridge.

Sloss, L.L., 1963. Sequences in the cratonic interior of North America. Geol. Soc. Am. 74, 93–114.

Sloss, L.L., Speed, R.C., 1974. Relationships of cratonic and continental margin tectonic episodes. In: Dickinson, W.R. (Ed.), Tectonics and Sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication 22, 98–119.

Southgate, P.N., Bradshaw, B., Domagala, J., Jackson, M.J., Lindsay, J.F., Idnurm, M., Krassay, A., McConachie, B., Page, R., Sami, T., Scott, D., press. Unravelling the stratigraphic architecture of Palaeoproterozoic basins northern Australia. Aust. J. Earth Sci.

Strauss, H., Des Marais, D.J., Summons, R.E., Hayes, J.M., 1992. The carbon-isotopic record. In: Schopf, J.W., Klein, C. (Eds.), The Proterozoic Biosphere: A Multidisciplinary Study. Cambridge University Press, New York, pp. 117–128.

Strauss, H., Vidual, G., Moczydlowska, M., Paczesna, J., 1997. Carbon isotope geochemistry and palaeontology of Neoproterozoic to early Cambrian siliciclastic successions in the East European Platform, Poland. Geol. Mag. 134, 1–16.

Summons, R.E., Powell, T.G., Boreham, C.J., 1988. Petroleum geology and geochemistry of the Middle Proterozoic McArthur Basin, northern Australia: III. Composition of extractable hydrocarbons. Geochim. Cosmochim. Acta 52, 1747–1763.

Summons, R.E., Walter, M.R., 1990. Molecular fossils and microfossils of prokaryotes and protists from Proterozoic sediments. Am. J. Sci. 290A, 212–244.

Vail, P.R., Mitchum Jr., R.M., Thompson, S., 1977a. Seismic stratigraphy and global changes of sea level. Part 3. Relative changes of sea level from coastal onlap. Part 4. Global cycles of relative changes of sea level, AAPG Memoir 26, 63–97.

Vail, P.R., Mitchum Jr., R.M., Thompson, S., 1977b. Seismic stratigraphy and global changes of sea level, part 4, global cycles of relative changes of sea level. In: Payton, C.E. (Ed.), Seismic Stratigraphy — Applications to Hydrocarbon Exploration: AAPG Memoir 26, 83–97.

Vail, P.R., 1987. Seismic stratigraphy interpretation using sequence stratigraphy. Part 1: Seismic stratigraphy interpretation procedure. In: Bally, A.W. (Ed.), Atlas of Seismic Stratigraphy, AAPG Studies in Geology 27 1, 1–10.

Van Wagoner, J.C., Mitchum Jr., R.M., Posamentier, H.W., Vail, P.R., 1987. Seismic Stratigraphy interpretation using sequence stratigraphy. Part 2: key definition of sequence stratigraphy. In: Bally, A.W. (Ed.), Atlas of seismic stratigraphy, AAPG Studies in Geology, 27, 11–14.

Van Wagoner, J.C., Mitchum Jr., R.M., Campion, K.M., Rahmanian, V.D., 1991. Siliciclastic sequence stratigraphy in well logs, cores, and outcrops: Concepts for high-resolution correlation of time and facies, AAPG Methods in Exploration Series 7, 53 pp.

Veizer, J., 1983. Chemical diagenesis of carbonates: theory and application of trace element techniques. In: Arthur, M.A.Anderson, T.F., Kaplan, I.R., Veizer, J., Land, L.S. (Eds.), Stable Isotopes in Sedimentary Geology, Society of Economic Paleontologists and Mineralogists Short Course 10, Tulsa 3-1-3-100, 3–100.

Veizer, J., Plumb, K.A., Clayton, R.N., Hinton, R.W., Grotzinger, J.P., 1992. Geochemistry of Precambrian carbonates: V. Late Proterozoic seawater. Geochim. Cosmochim. Acta 56, 2487–2501.

Walker, R.N., Muir, M.D., Diver, W.L., Williams, N., Wilkins, N., 1977. Evidence of major sulphate evaporite deposits in the Proterozoic McArthur Group, Northern Territory, Australia. Nature 265, 526–529.

Wyborn, L.A.I., 1988. Petrology, geochemistry and origin of major Australian 1880–1840 Ma felsic volcanic suite: A model for intracontinental felsic magma generation. Precamb. Res. 40–41, 37–60.

Xiao, S., Knoll, A.H., Kaufman, A.J., Yin, L., Zhang, Y., 1997. Neoproterozoic fossils in Mesoproterozoic rocks? Chemostratigraphic resolution of a biostratigraphic conundrum from the North China Platform. Precamb. Res. 84, 197–220.