The infilling of a terminal flood plain–wetland complex

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Abstract Flood plain–wetland complexes are mosaics of physical units and the sediments contained within these various units often display spatial and temporal complexity. This paper reconstructs the environmental history of a mosaic of geomorphic units within a large terminal flood plain–wetland complex in southeastern Australia in order to identify how the sediment character of the mosaic has changed through time. Sediment cores, up to 14 m in depth, were extracted from one flood plain and three lake units. Stratigraphy and multivariate analysis on these cores reveal a complex environmental history with sediment character highly variable in both time and space. All four geomorphic units—lake and flood plain—have undergone a convergent evolution from unique initial states. This study highlights how numerical methods, in association with standard sedimentological techniques, can assist in unravelling the environmental history of a temporally and spatially diverse landscape.

Key words complexity; convergence; sedimentation; stratigraphy

INTRODUCTION

Flood plain–wetland complexes located at the termini of river systems are three-dimensional sinks into which eroded and sorted sediments accumulate. Unlike other river flood–flood plains, they are not temporary storage areas of alluvium because they do not experience significant episodic working and/or removal of sediment during extreme events (Warner, 1994), or when certain threshold conditions are exceeded (cf. Nanson, 1986). The character of these alluvial stores is dependent upon the nature of the depositing environment, and the type of sediments and processes that govern their delivery to a site. At the landscape scale, flood plains consist of a suite of geomorphic units reflective of past and present geomorphic activities but few studies have investigated sedimentation in terminal flood plain settings. Thus terminal flood–flood plain deposits may display distinct spatial and temporal complexity that reflects broader regional conditions because of reduced local influences on reworking.

The purpose of this preliminary study is to identify spatial and temporal patterns in sedimentation geomorphic process operation in a terminal flood plain–wetland complex, the Narran Lakes, Australia. Four cores, ranging in depth from 6 to 14 m, were collected from one flood plain and three lake units in the northern part of the Narran Lakes. Each core was subject to both standard sedimentological and numerical techniques in order to elucidate changes in sediment properties through time. Although numerical methods have received limited use in geomorphology (Thoms *et al.*, 2006), they facilitate the identification of stratigraphic units and yield information as to the importance of various sediment properties in defining these units (Foster *et al.*, 2002). Spatial and temporal patterns obtained from these analyses will be used to ascertain the nature of natural and anthropogenically induced changes to the delivery of sediment to the Narran Lakes.

METHODS

Study area

The Narran Lakes flood plain–wetland complex is located in the northwest of the Murray Darling Basin in southeastern Australia. It is the terminal feature of the Narran River, the easternmost channel of the lower Condamine-Balonne distributary river network (Fig. 1(a)). Geologically, the Barwon-Darling Basin is a large inter-cratonic Cainozoic basin, which is infilling with alluvial sediments derived from the main East Australian Divide (Thoms *et al.*, 2004). However, the complex structural character of

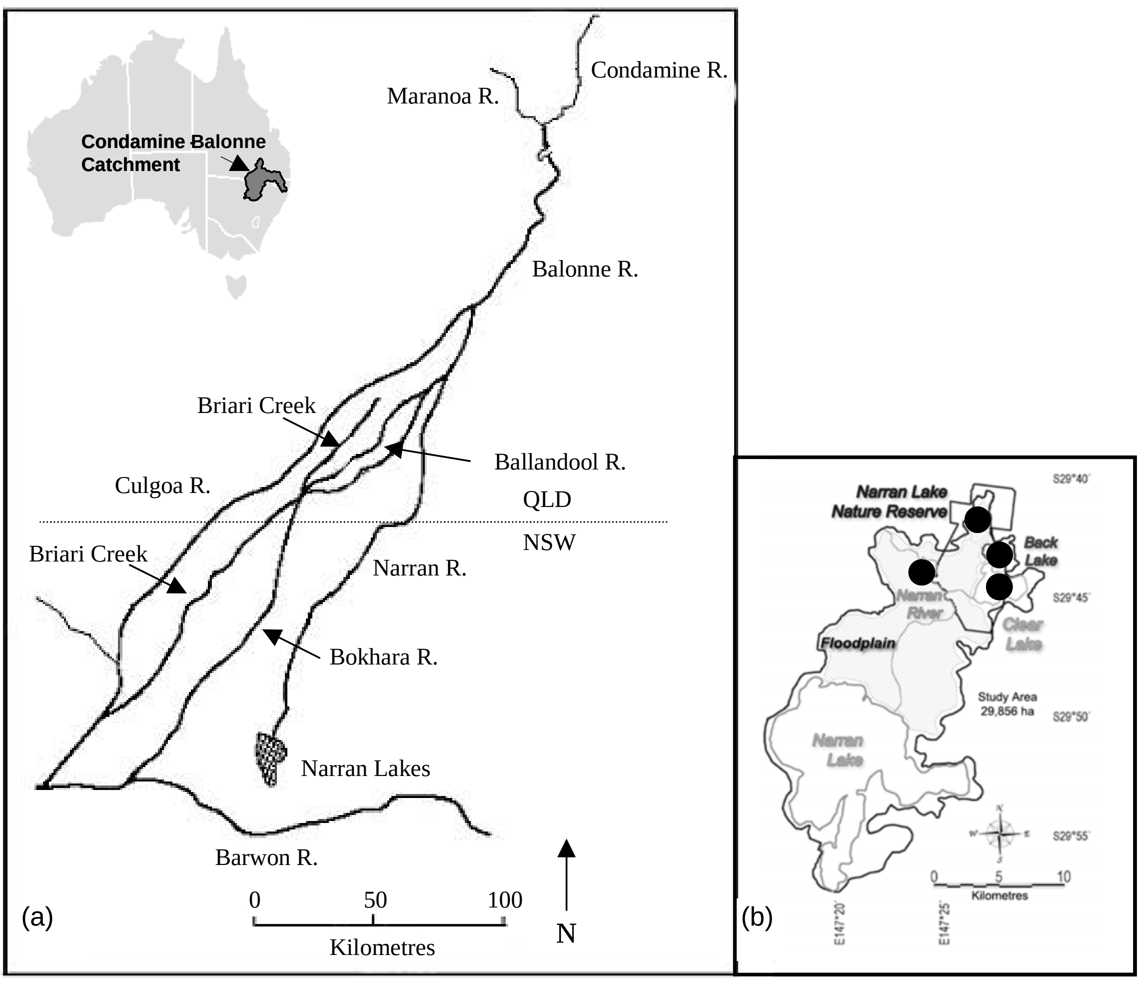

Fig. 1 The study area: (a) the flood plain of the Lower Balonne rgeion; and (b) Narran Lakes flood plain–wetland complex. Location of sediment cores is indicated.

the basin's basement rocks is reflected in a series of small regional basins nested nested within the larger regional inter-cratonic feature. The Narran Lakes terminal flood plain–wetland complex occupies one of these smaller regional depressions into which sediments from the Condamine Balonne catchment are depositing.

The Narran Lakes complex consists of a suite of geomorphic units including a flood plain (divided into two sections, southern and northern), four lakes (Narran Lake, Clear Lake, Back Lake and Long Arm), a delta and a complex channel network (Fig. 1(b)). These features create a complex yet subtle topography. This study focuses on the northern flood plain and the northern lakes (Clear Lake, Back Lake and Long Arm).

Sampling

Four sediment cores up to a depth of 14 m in length were extracted using a piston driven coring rig (Geoprobe Macro-Core Soil Sampler). The stratigraphy of each core was described using modified lithofacies classifications of Lewin (1996) and Miall (1985). Sediments were classified as mud, muddy sand (>50% Mud), sandy mud (<50% Mud) and sand. Specific inclusions such as lenses, gravel and carbonate nodules, organic matter, mottling, banding and basal contact, were also recorded. In addition, sediment colour was determined on dry samples using the Munsell Soil Colour Chart.

Sediment sub samples were taken from each stratigraphic unit for textural and nutrient and geochemical analysis. Sediments were oven dried for 72 h at field temperature (~32°C), disaggregated and dry sieved (<2 mm) prior to analysis. Seven sediment variables were measured from each sub-sample (Table 1).

Table 1 The seven sediment characteristics used for multivariate analysis.

Variable type	Variable name	Abbreviation	Method
Texture	% Sand	*Sa*	125H Soil (ASTM, 2005)
	% Silt	*Si*	Hydrometer
	% Clay	*Cl*	
Nutrient	% Organic Matter	*OM*	Loss on ignition
	% Carbonate	*Ca*	
	pH	*pH*	1:5 Sediment water ratio
	Electrical conductivity	*EC*	

Data analysis

A suite of multivariate analyses was performed on the assembled data matrix (seven sediment variables and 96 samples) in the PATN statistical analysis package (Belbin, 1993). Initially, an association matrix was derived using the Gower distance measure—a range standardized measure recommended for non-biological data sets containing different units of measurements (Belbin, 1991). A one-way analysis of similarity (ANOSIM) was conducted on this association matrix to test similarity between *a priori* determined groups (geomorphic units and stratigraphic sequences), then the data were ordinated using Semi-Strong-Hybrid-Multidimensional-Scaling and expressed graphically. Stress levels for all ordinations were less than 0.2, indicating that the two-dimensional solutions were not random. A Principal Axis Correlation (PCC) was also conducted to identify relationships between sediment variables and their position in multivariate space. A Monte Carlo permutation test (Belbin, 1993) was also performed to test the significance of the correlation values. Variables with R^2 greater than 0.8 were considered to have a strong association with sediment character and those with R^2 between >0.5 and 0.79 were considered to have a moderate association with sediment character.

RESULTS

Four different stratigraphic sequences were observed between the cores (Fig. 2(a), (e), (i) and (m)). The upper profiles of the Clear Lake core (0–5 m) are characterized by an upward coarsening sequence followed by an upward fining sequence consisting of mud through to sandy mud (Fig. 2(a)) with abundant organic matter and sharp horizontal boundaries in the upper profile (Fig. 2(c)). An irregular sequence of sand and muddy sand with gravel and carbonate nodules is present in the middle (5–8.5 m) of the profile (Fig. 2(a) and (d)). The bottom section of the Clear Lake core (8.5–14 m) contains regular cyclic patterns of sand and mud (Fig. 2(a)) with higher levels of organic matter present in the mud layers and mottling in the sand (Fig. 2(c)). In contrast, the Back Lake sediment core is characterized by two upward fining sequences consisting of mud and muddy sand (Fig. 2(e)) with sharp horizontal boundaries and organic matter in the upper (0–3 m) profile (Fig. 2(g)). The middle (3–6 m) of the profile is dominated by sand with extensive mottling (Fig. 2(e)). The bottom section (6–9.5 m) is also sand dominated with mud lenses and gravel and carbonate nodules present (Fig. 2(e) and (h)). The Long Arm sediment core is characterized by four upward fining sequences ranging from mud through to sand with both sharp and gradational horizontal boundaries throughout the profile and mottling present in the bottom (5–10 m) sequence (Fig. 2(i)). Two stratigraphic sequences were identified in the flood–flood plain core (Fig. 2(m)). The upper (0–3 m) profile is characterized by mud and is similar to the uppermost section of the lake profiles, while the lower (3–6 m) profile is cyclic, changing repeatedly from sand to muddy sand with sharp boundaries throughout the profile.

Numerical analyses of the sediment texture and nutrient properties both within and between the different cores were undertaken using a one-way ANOSIM. Between-core comparisons showed that there were no statistically significant differences between cores (Global $R < 0.5$, $p < 0.001$). However, within-core variations in sediment character were observed. Pairwise ANOSIM of within-core variation showed a difference between the surface and sub-surface sequences (Table 2) for each of the three lake cores, but not for the flood–flood plain core. Specific stratigraphic variations for Clear Lake showed that sequences (I) and (IV) are well separated ($R = 0.926$). However, the lower stratigraphic sequences in Clear Lake could not be meaningfully separated. For Back Lake, differences were observed between the upper and lower units of the profile (I and III, $R = 0.979$) and within the lower sequences (III and IV,

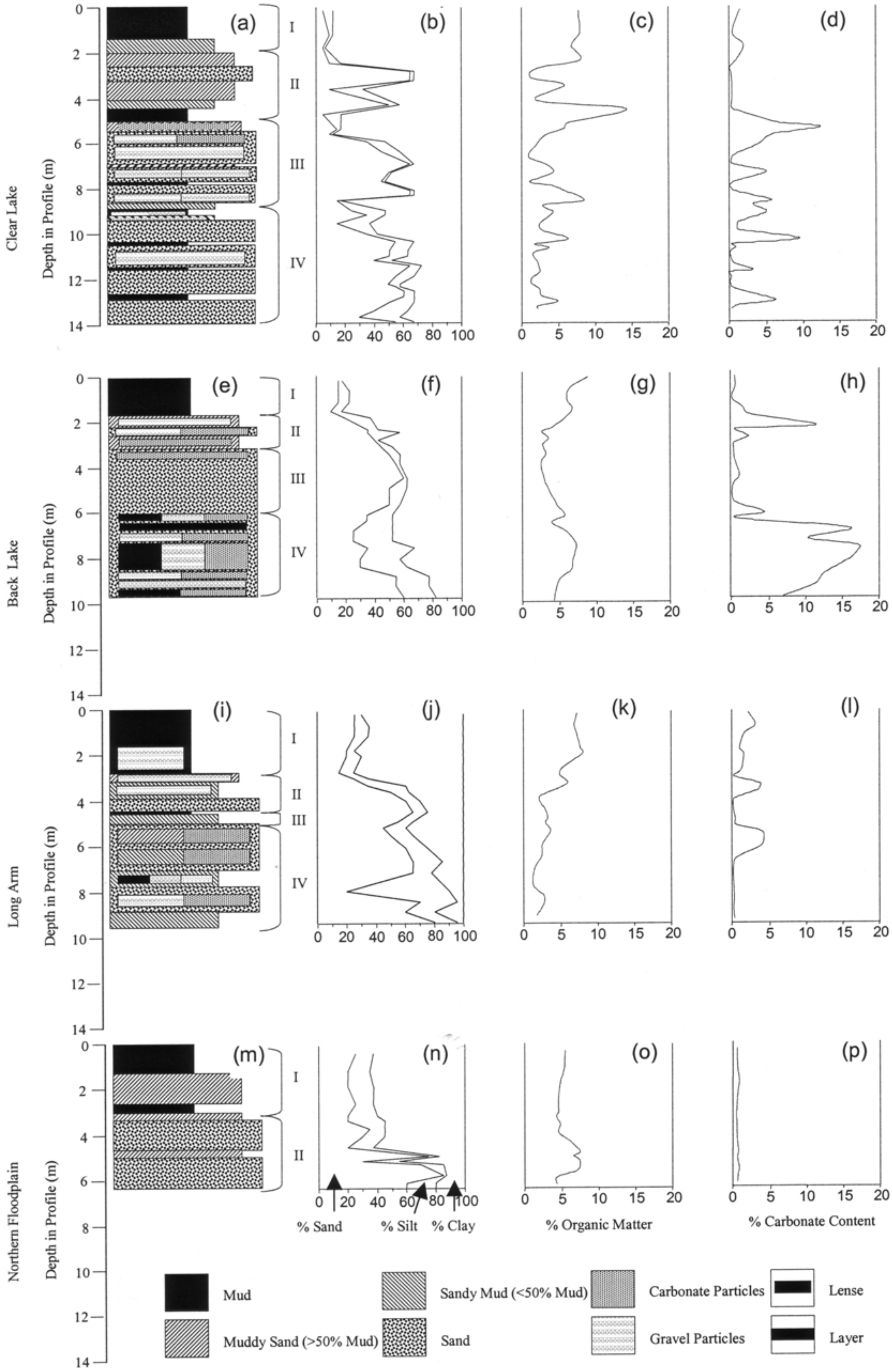

Fig. 2 Physical character of sediment cores—stratigraphy (sediment units), sediment texture (% sand, % silt and % clay), % organic matter, % carbonate content: (a)–(d) Clear Lake; (e)–(h) Back Lake; (i)–(l) Long Arm; and (m)–(p) the northern flood plain.

Table 2 Summary of One-way ANOSIM pairwise test on geomorphic units and stratigraphic units.

Geomorphic units	Stratigraphic units	*R* statistic	*p* value
Clear Lake	A,B	0.187	0.133
	A,C	0.495	0.005
	A,D	0.926	0.002
	B,C	0.106	0.129
	B,D	0.483	0.001
	C,D	0.202	0.016
Back Lake	A,B	0.136	0.306
	A,C	0.979	0.036
	A,D	0.829	0.018
	B,C	0.204	0.056
	B,D	0.490	0.002
	C,D	0.505	0.005
Long Arm	A,B	0.854	0.003
	A,C	0.987	0.028
	A,D	0.858	0.001
	B,C	–0.143	0.600
	B,D	0.108	0.226
	C,D	–0.116	0.600

Number of permutations: 999 (random sample from a large number).
R statistic: >0.75, groups well separated; >0.50, groups overlapping but a clear difference; <0.25, groups not separable.

R = 0.505) (Fig. 3(a)). Stratigraphic units from Long Arm showed a clear separations between the surface and lower sequences only (I and III, R = 0.987) (Fig. 3(a)). But no other separations were evident. Finally, the flood–flood plain sequences showed no separation of groups (Global R = 0.164, p = 0.089).

Ordination of stratigraphic sequences graphically represented the separation within cores. As previously mentioned, the surface sequences (I) differed from the bottom sequences (III and IV) in all of the lake cores (Fig. 3(a), (c) and (e)). However, clear overlap was evident in each of the lower sequences in each lake as well as for the two sequences in the flood–flood plain core (Fig. 3(a), (c), (e) and (g)).

Principal Axis Correlation highlighted clay and sand as the dominant variables associated with stratigraphic sequences and their position in ordination space. The upper sequences of the lake profiles were strongly associated with clay and, to a lesser extent, organic matter, with the lower sequences being associated with sand and carbonate nodules (Fig. 3(b), (d) and (f)). The upper stratigraphic unit of the flood plain was associated with clay and pH, and the lower unit with sand and organic matter (Fig. 3(h)).

DISCUSSION

The contemporary Narran Lakes are composed of a series of lakes and flood plains dissected by an extensive distributary channel network. Clear Lake, Back Lake, Long Arm and the flood plain are regularly inundated by floodwaters from the Narran River. In fact, most of the northern portion of the Narran Lakes is inundated on average once

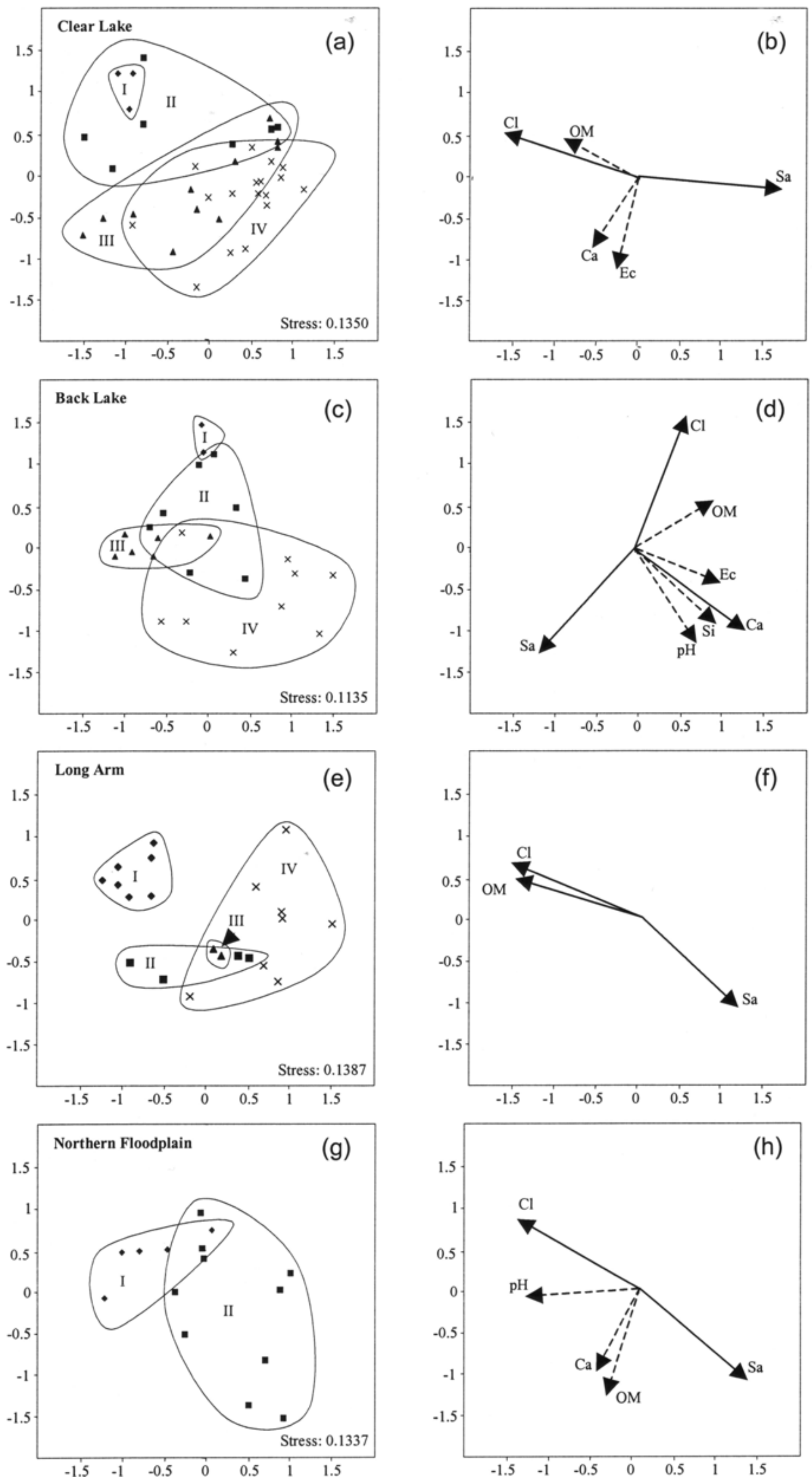

Fig. 3 Ordination and PCC results of the Narran Lakes sediments: (a) and (b) Clear Lake; (c) and (d) Back Lake; (e) and (f) Long Arm; and (g) and (h) the northern flood plain. Symbols highlight stratigraphic sequences within each core. Solid line indicates those sediment properties with $R^2 < 0.8$; broken line indicates those sediment properties with $R^2 = 0.5–0.79$. Descriptions of individual vector labels used in the PCC are given in Table 1.

every two years. Contemporary modern flows in the Narran River are very low energy, transporting mostly fine silts and clays. Consequently, the surface material in each of the four cores is of similar origin and character. The dominance of clay-size sediment differentiates the surface sediment layers from those found at depth in each of the four cores investigated (Fig. 3). Given the close proximity of the four cores and their similarity in geological setting (i.e. down thrust basin), it should come as no surprise that the four cores exhibit a great deal of overlap in sediment characteristics. In fact, there are no statistically significant differences in the sediment properties of the four cores when taken as a whole. However, the stratigraphy of the individual cores suggests there to be a great deal of spatial and temporal variability in the sedimentation of the Narran Lakes. This is reflected in the clear differences between sediments within individual cores and stratigraphic sequences between cores.

The infilling of sediment to Clear Lake has occurred in three distinct phases: surface sediments are unique in character and are dominated by fine clay-size sediments; the middle phase exhibits irregular sediment deposition patterns; and the lower phase is characterized by regular episodic fining upwards sequences. The lowest portion of the Clear Lake core exhibits four cyclic periods of deposition, suggesting a periodic change in the hydraulic environment from high energy (sand deposition) to low energy (deposition of fines). The chaotic nature of the sediments mid-core illustrates a much more irregular and unsettled period of sediment supply to Clear Lake. Finally, in the uppermost section of the core, a shift to a dominance of fine sediments likely reflects a shift towards conditions similar to those seen today with low energy flows bringing in fine silts and clays during regular flooding. In contrast, the flood–flood plain core shows well-bleached sand-sized sediments at depth, which likely result from aeolian processes. The surface sequence, on the other hand, is upward fining suggesting vertical accretion of sediment resulting from overbank flows from the Narran River. The character of the surface sequence is similar to that of other flood–flood plain sediments in the lower Balonne complex (Thoms *et al.*, 2006).

The infilling of Back Lake and Long Arm has differed to that of Clear Lake and the flood plain. Regular upward fining sequences suggest that the supply of sediment has been episodic through time. This could be the result of two factors: the migration of the river channel away from the lakes resulting in a decrease in energy, or alternatively, a change in sediment supply up river possibly resulting from climatic fluctuations. Mottling of sediments within the all of the lake profiles suggests that post-depositional processes resulting from groundwater interactions have also influenced the character of the sediments. It is hypothesized that the observed gravel and carbonate nodules are the result of this groundwater interaction.

Flood plains are complex depositional features in the riverine landscape. Variations in flood–flood plain morphology and sedimentation have been reported in many studies (e.g. Brown, 2002; Benedetti, 2003). Despite the acknowledgement of the temporal and spatial complexity of flood plains, the majority of flood–flood plain studies have tended to focus on riverine flood plains and not those located in terminal systems—flood plains that have not yet been placed into a category (cf. Nanson & Croke, 1992). Sedimentation in the former generally reflects the episodic nature of larger-scale energy and sediment supply conditions. However, sedimentation within the Narran Lakes highlights distinct interactions between fluvial, aeolian and hydrological processes—both surface water and groundwater. These processes have been responsible for a convergence of physical form in the Narran Lakes. Convergence refers to a situation when different processes and causes produce similar effects—often referred to as equifinality (Chorley, 1962). Each of the four geomorphic units studied have, through a series of different environment process trajectories, converged to form a contemporary flood–flood plain surface and three flood–flood plain lakes. In addition, numerical analyses further highlight the similarities of sediment proprieties in the uppermost sediment sequences.

Multivariate statistical techniques provide extremely powerful methods of analysis and interpretation that can be used to complement traditional stratigraphic examinations of flood–flood plain sedimentation. Although it differs from the traditional approach to flood–flood plain sedimentation studies, it offers several advantages (Thoms *et al.*, 2006). First, a range of sediment variables can be analysed simultaneously, which bypasses the necessity for a large number of individual analyses that compare one variable against another. Second, consideration of a range of variables facilitates greater interrogation of data, and provides increased scope to generate hypotheses. For example, even though PCC associations are not causal, they highlight factors that could be investigated in mechanistic studies of flood–flood plain sedimentation. Third, multivariate analyses elicit patterns and infer processes in a quantitative rather than a qualitative manner. Combined, the two methods both convey a different resolution of information on flood–flood plain sedimentary environments and it is recommended that both should be used for a fuller understanding of flood–flood plain depositional environments.

CONCLUSION

Four geomorphic units—three lakes and a flood plain—have undergone convergent evolution from vastly different initial states. Further, the path each unit has undergone to arrive at its present state (fluvial depositional environments) has been markedly different and highly variable through time. Thus, there has been a complex response to environmental change in the Narran Lakes. The interaction of fluvial (surface and subsurface) and aeolian processes has combined to form this rich sedimentology. The use of standard sedimentological and numerical techniques has facilitated the interpretation of the sedimentology of each of the four cores illustrating the value of this approach in the reconstruction of the environmental history.

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