Determination and interpretation of sediment provenance in a sedimentary sequence affected by post-depositional changes

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Abstract Post-depositional alteration of flood plain sedimentary deposits is a problem for the interpretation of environmental change. In particular, groundwater movement can alter the physical and chemical character of these deposits. This study considers the potential influence of post-depositional change on the geochemical character of sediments contained within the Narran flood plain, in semi-arid Australia, and the implications for interpreting environmental change. A series of 12 cores, ranging in length from 6 to 15 m, were collected from a number of different geomorphic regions across the flood plain. Stratigraphic analysis of the individual cores revealed extensive mottling and iron staining of sediments in all cores along with the presence of well developed carbonate nodules between 5 and 15 m below the surface. At this level of resolution it would appear that post-depositional processes have significantly influenced the geochemical character sediments within this flood plain deposit. However, a statistical comparison of the low and high solubility elements noted only small differences in the geochemistry of sediment within and between the different stratigraphic units of the individual cores. It appears that although the flood plain deposit has experienced post-depositional influences, as evident through the stratigraphic analysis, this has had little overall influence on sediment geochemistry. This highlights the importance of being scale aware when interpreting the environmental history of flood plain environments. In addition the study demonstrates the utility of integrating standard sedimentological and numerical techniques in unravelling environmental histories, possible post depositional processes and groundwater influences in flood plain depositional environments.

Key words flood plain deposits; post depositional processes; multivariate analyses; groundwater

INTRODUCTION

An understanding of sediment provenance can provide a rich source of information in sediment-based palaeo-environmental reconstruction. This is particularly so where catchments exhibit strong spatial patterns in the physical and chemical character of source materials. In these situations changes in the relative yields of sediment from different parts of the catchment can reveal much about changes in catchment runoff processes, climate, disturbance and land use.

Sediment sourcing through the matching of the geochemical signatures of sediment with that of different source areas within the catchment has been made more precise by the development of multiple source mixing models that allow the simultaneous inclusion several trace elements in models (Foster, 2000). The use of several elements increases confidence in matching geochemical signatures of sediments to those of source areas; however, any provenance estimates derived through the use of multiple source mixing models are potentially compromised where post-depositional processes have acted to alter sediment geochemical signatures. Post-depositional changes to geochemical signatures can occur where groundwater movement or infiltration of surface water through sediment profiles result in the removal or addition of soluble trace elements (Bauluz *et al.*, 2000), thus distorting the geochemical signature and preventing the accurate characterisation of sediment provenance.

In this study we report on the results of sediment provenance estimations for a 450 ka sediment record from a terminal flood plain lake system in a semi-arid region of eastern Australia. The record under investigation displays evidence of post-depositional chemical changes in the form of carbonate nodules and iron staining (Cossart, 2008). The degree to which these processes affected sediment geochemical signatures was determined through multivariate statistical comparison of signatures based on low and high solubility elements. Subsequent provenance estimations were based on the signatures of low solubility elements, and indicated strong temporal variation in dominant source areas which are hypothesised to reflect variation, at a range of temporal scales, in continental-scale rainfall patterns.

THE STUDY AREA

The Narran Lakes system is a dryland flood plain complex situated at the terminus of the Narran River, a distributary river of the Condamine Balonne River in SE Australia (Fig. 1). The climate in the region is semi-arid, with a mean annual rainfall of 480 mm (1938–2004), high inter-annual variability in rainfall (Cv = 238%) and mean annual evaporation in excess of 1.8 m. Two principal tributaries meet to form the Lower Balonne some 250 km upstream from the Narran Lakes: the Condamine River, which rises in the eastern highlands of southern Queensland, and the Maranoa, which rises in the Carnavon Range further west (Fig. 1). The climates of the two subcatchments differ in that the Condamine catchment, particularly in the east, is humid with relatively predictable rainfall, while the Maranoa catchment is more arid and is subject to less predictable rainfall (Thoms, 2003). The two catchments also contrast in their geology, with the Condamine catchment headwaters dominated by Tertiary volcanic rocks, while the Maranoa is dominated by Cretaceous sandstone.

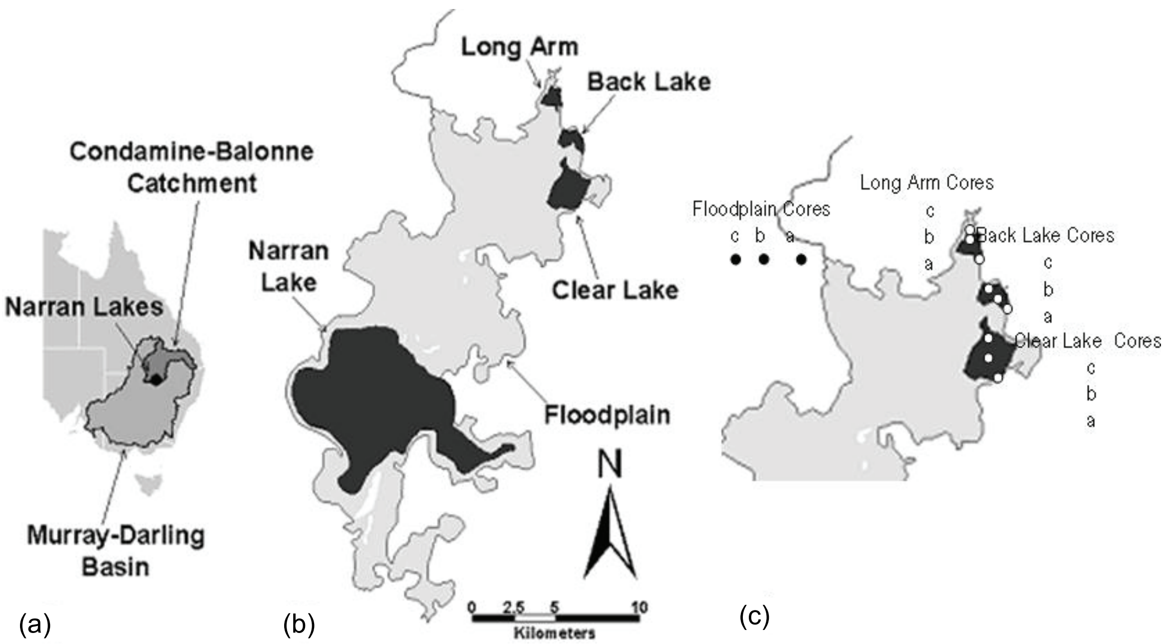

Fig. 1 The Narran Lakes system: (a) Location of the Lower Balonne region; (b) location of the Narran lakes system; (c) location of sediment cores within the Narran lakes.

The Narran Lakes system consists of a suite of geomorphic units including a flood plain (divided into the southern and northern sections), four lakes (Narran Lake, Clear Lake, Back Lake and Long Arm), a delta and a complex channel network (Fig. 1). 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).

METHODS

Three cores were taken from each of four geomorphic regions of the Narran Lake system: the flood plain, Clear Lake, Back Lake and Long Arm (Fig. 1). Coring was carried out in April/May 2005, during a period when the system was dry, using a piston driven coring rig (Geoprobe Macro-Core Soil Sampler). The cores were up to 14 m in length and were dated to a maximum of 450 ka using Optically Stimulated Luminescence (OSL) dating (Cossart, 2008). The stratigraphy of each core was described using a lithofacies classification scheme modified from Lewin (1996) and

Miall (1985). Lithofacies were based on texture, layering, basal contact, colour and presence of nodules and lenses, with the sediments being classified as either mud, sandy mud (<50% sand), muddy sand (>50% sand), or sand. Basal contacts were described as sharp or gradual with structural patterns such as laminating and cross-bedding noted. Specific characteristics such as lenses, nodules, carbonates, organic matter and mottling were recorded. Sediment colour was determined from dry samples using the Munsell Soil Colour Chart.

A total of 318 sediment samples were taken from the cores for geochemical analysis at depths determined on the basis of the lithofacies (Cossart, 2008). Samples were oven dried for 72 h at field temperature (~32ºC), disaggregated and dry sieved (<2000 μm) prior to analysis. Sediment geochemistry was determined for the <63 μm fraction only. This sediment fraction was selected because the majority of trace elements are bound to minerals of this size through absorption or direct incorporation into the lattice (Ernst, 1970). Fifteen geochemical variables were measured at the ALS Chemex laboratories using geochemical digestion – four acid (near total) – ICP Atomic Emission Spectrometry (ICPAES).

Table 1 Stable (relatively insoluble) and soluble elements determined for the geochemical analysis of the <63 μm fraction of sediments extracted from the Narran system.

Stable elements	Soluble elements
Aluminium (μg/g)	Barium (μg/g)
Titanium (μg/g)	Calcium (μg/g)
Strontium (μg/g)	Copper (μg/g)
Lead (μg/g)	Iron (μg/g)
Cobalt (μg/g)	Potassium (μg/g)
	Magnesium (μg/g)
	Manganese (μg/g)
	Sodium (μg/g)
	Phosphorous (μg/g)

The influence of post-depositional processes on sediment geochemistry was determined by comparing resemblance matrices of sediment samples characterised by the concentrations of the five stable elements with resemblance matrices of the same samples characterised by sample concentrations of all 15 elements. Comparisons of matrices were made for each of the six stratigraphic units across samples grouped by the stratigraphic units determined by lithofacies analysis (Cossart, 2008). Matrices were generated using the *Gower metric* distance measure and compared using the RELATE procedure in PRIMER v.6. The resemblance matrices of each data set were compared using the Mantel test, which produces a Rho value that describes the significance of this relationship. A Rho value of 1 suggests that the two matrices are highly similar, while a value of 0 suggests that they are different (Clarke & Warwick, 1994).

Sediment provenance was subsequently investigated by reference to the geochemistry of the Narran sediments, principally in relation to titanium (Ti) and aluminium (Al). These elements were used because they are relatively stable or insoluble, and hence less prone to post-depositional movement, and because they characteristically differ in their relative concentration in the Condamine (where Ti/Al = 0.094) and Maranoa (where Ti/Al = 0.047) subcatchments.

RESULTS

Core stratigraphy

All cores except flood plain "a" and "b" are characterised by a basal unit with high sand and low organic content (sand unit) (Fig. 2). This unit is overlain in all but the flood plain "a" core by a unit containing several distinct upward fining sequences (cyclic unit) (Fig. 2). Finally, the surface

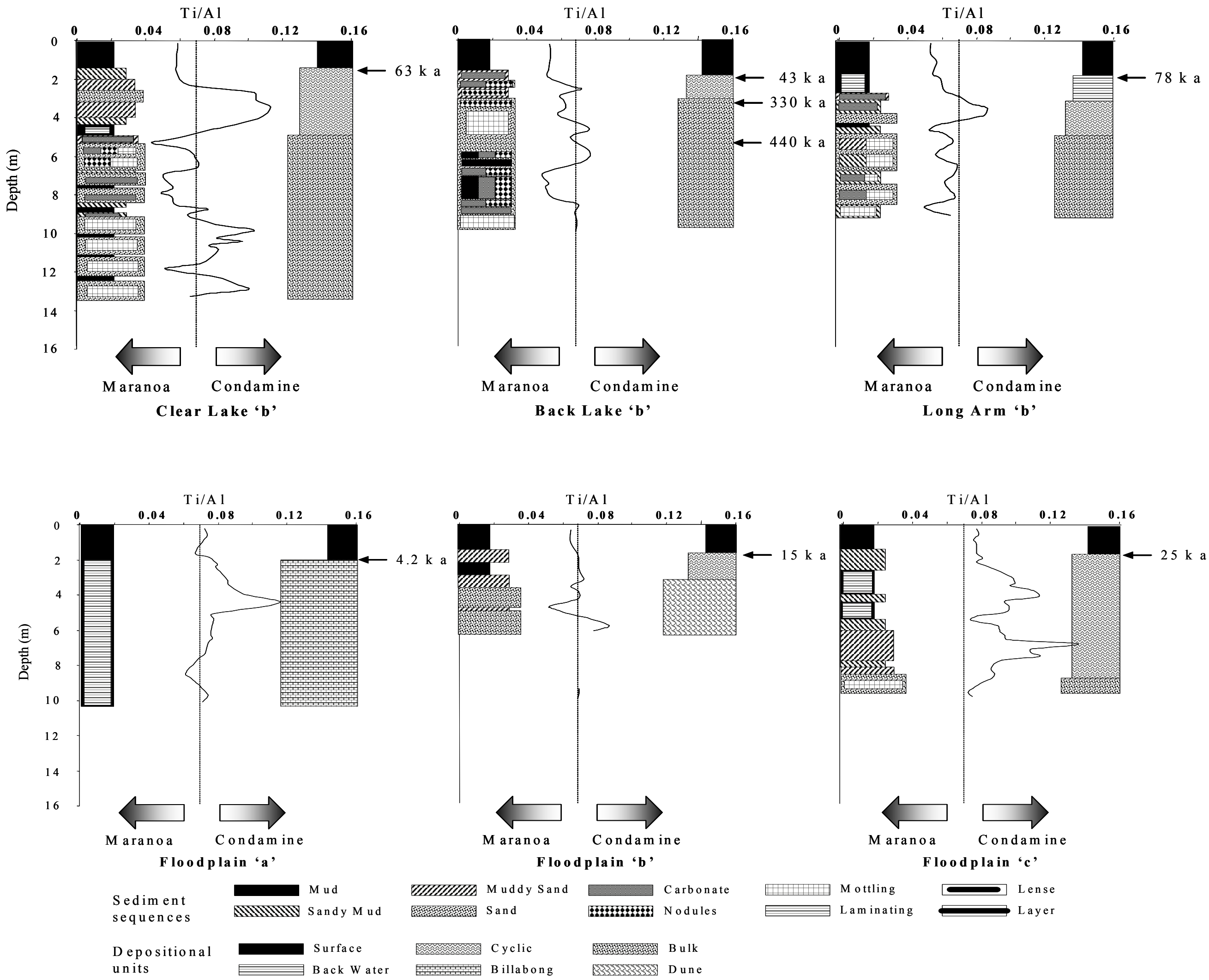

Fig. 2 Sedimentary sequences of the Narran Lakes cores. The stratigraphy and common depositional units of cores from the major geomorphic units are displayed along with the core profiles of Ti/Al ratios.

of all cores (surface unit) is characterised by uniform muddy sediment with high organic and low sand content and sharp basal contacts (Fig. 2). In addition to these three major units, which are found in most cores, three other distinct minor stratigraphic units were also identified in some cores; these are described as the backwater unit, the dune unit and the billabong unit. The backwater unit overlies the cyclic unit in the Long Arm cores and is characterised by laminations of fine sands in a greyish brown mud layer with high organic content (Fig. 2); the dune unit forms the basal unit in flood plain "b" and is characterised by well-rounded and sorted bleached sands (Fig. 2). The billabong unit forms the basal unit in flood plain "a" and is characterised by a greyish brown mud layer containing laminations of fine to medium sands, with moderate organic content throughout (Fig. 2).

Evidence of post-depositional changes

Post-depositional changes to the sediments are suggested by mottling or iron staining of sediments in sections of the sand and cyclic layers of the Clear Lake, Back Lake and Long Arm cores as well as in the dune unit of the flood plain "b" core. Similarly, carbonate nodules, ranging in size from 1 to 20 mm in diameter are present in the cyclic and sand units of the Clear Lake, Back Lake and Long Arm cores (Fig. 2).

Comparison of total and insoluble geochemistry of sediments

The resemblance matrices calculated from all 15 and just the five stable elements are statistically similar for the sand, cyclic, surface, billabong and backwater units, with Rho values for these comparisons ranging from 0.747 up to 0.875 (Table 2). In the case of the dune unit, matrices derived from the full set of 15 elements set and the stable subset of five elements showed greater dissimilarity, suggesting that post-depositional changes to sediment geochemistry may have been more substantial within this unit (Table 2).

When the major depositional units are nested within geomorphic regions the pattern is largely similar, although the difference between the stable element geochemistry and the full element geochemistry for the sand unit of the flood plain cores suggests post-depositional changes were more substantial in those sediments than in the sediments of the other major units and geomorphic regions (Table 3).

Table 2 Mantel test comparisons between resemblance matrices calculated using the full set of elements (n = 15) and the insoluble subset of elements (n = 5) for each depositional unit.

Depositional Unit	*Rho* statistic	*p* value
Surface	0.835	0.001
Cyclic	0.747	0.001
Sand	0.773	0.001
Backwater	0.875	0.001
Billabong	0.858	0.001
Dune	0.487	0.012

Table 3 Mantel test comparisons between resemblance matrices calculated using the full set of elements (n = 15) and the insoluble subset of elements (n = 5) for the major depositional units nested within geomorphic regions.

	Clear Lake:		Back Lake:		Long Arm:		Flood plain:	
	Rho statistic	*p* value	Rho statistic	*p* value	Rho statistic	*p* value	Rho statistic	*p* value
Surface	0.85	0.001	0.675	0.002	0.855	0.001	0.758	0.001
Cyclic	0.85	0.001	0.867	0.001	0.706	0.001	0.652	0.001
Sand	0.77	0.001	0.771	0.001	0.773	0.001	0.429	0.294

Sediment provenance

The Ti/Al ratios of Narran sediments range from 0.038 to 0.137. The average Ti/Al ratios for sediments from Clear Lake are fairly consistent across the three cores and fluctuate about 0.071, the value expected if contributions from each sub-catchment were equal (Fig. 2). In the case of the Back Lake and Long Arm sediments, there is also consistency across the cores; however, the Ti/Al ratios are slightly lower in these sediments than in Clear Lake, suggesting marginally greater inputs of Maranoa-sourced sediments in these sequences. There is greater variation in Ti/Al ratios among the flood plain cores. For the flood plain core "a", sediment Ti/Al ratios are mostly above 0.071, suggesting a dominance of Condamine-derived sediments. The dominance of Condamine-derived sediments is even greater in the flood plain "c" core where Ti/Al ratios are mostly greater than 0.08. In contrast, the Ti/Al ratios in the flood plain core "b" fluctuate about 0.071, suggesting that the contribution from Condamine and Maranoa source areas has been roughly equal.

Stratigraphic variation in Ti/Al ratios, and hence sediment provenance, is also evident through the various cores. The records from Clear Lake are characterised by high Ti/Al ratios, and hence predominantly Condamine-derived sediment, in the bottom section of the sand unit (9–14 m), with low Ti/Al ratios, and hence predominantly Maranoa-derived sediment, in the upper section

(5–9 m). Through most of the cyclic unit of the Clear Lake records (5–2 m), the Ti/Al ratios are very high, suggesting a strong dominance of Condamine-derived sediments over this period. Ti/Al ratios subsequently decline at the top of the cyclic unit and remain consistently below 0.06 through the surface unit of Clear Lake.

Fluctuations in Ti/Al ratios are less pronounced in the Back Lake and Long Arm records. In the case of Back Lake, the Ti/Al ratios remain relatively close to 0.07 through the sand and cyclic units, suggesting roughly equal input of sediments from both subcatchments over this period, although values are consistently below 0.06 between around 8 m and 7 m, suggesting greater input of Maranoa sediments. As for Clear Lake, Ti/Al ratios are consistently below 0.06 throughout the Back Lake surface unit.

In Long Arm, relatively low Ti/Al ratios through the sand unit and the lower part of the cyclic unit suggest sediments were predominantly derived from the Maranoa over this period. A change in sediment provenance is evident in the upper portion of the cyclic unit in Long Arm, with an increased Ti/Al ratio from around 4.5 m to 3.5 m indicating a shift to predominantly Condamine-derived sediments during this time. This increase is short-lived, however, and the Ti/Al ratio subsequently declines through the backwater unit and remains consistently below 0.06 through the surface unit.

Each flood plain core has a different Ti/Al profile (Fig. 2). In flood plain core “a” the Ti/Al ratio is characterised by large peak at a depth of around 5 m, indicating that sediment inputs were strongly dominated by Condamine sources during this time. The Ti/Al ratios through the remainder of the core are mostly between 0.06 and 0.075, indicating that both subcatchments contributed a roughly equal proportion of sediment for most of the record. The Ti/Al profile in the flood plain “b” core is broadly similar, although it differs in that it lacks any substantial peak; thus, sediment inputs to this record appear to have been derived in roughly equal proportions from each subcatchment over the full record. A substantially different profile is evident in the flood plain “c” core. In this core, Ti/Al ratios increase from relatively low values in the basal sand unit to values of around 0.1 through most of the cyclic unit, suggesting a strong dominance of Condamine source inputs through the cyclic unit. As for most records, the Ti/Al ratios subsequently decline in the surface unit of the flood plain “c” core, indicating increased input of sediment from Maranoa sources under the most recent depositional regime.

DISCUSSION

Large volumes of sediment (414 559 071 tonnes) have accumulated in the Narran system over the last 440 ka; the rate of accumulation of sediments, however, has been low compared to other flood plain systems (cf. Walling *et al.*, 1997; Thoms, 2003). Sedimentation rates varied between 0.005–0.71 mm $year^{-1}$ for the various geomorphic units within the Narran system, with a progressive increase over time. During the period of “sand” deposition, beginning 440 ka years ago, sedimentation rates were 0.005 mm $year^{-1}$, this increased to an average of 0.008 mm $year^{-1}$during the period of “cyclic” deposition between 330 and 78 ka. Finally, the “surface” depositional unit, 78 ka to present, was deposited at rates ranging from 0.053 to 0.71 mm $year^{-1}$ for the different regions of the Narran system. In general, rates of sedimentation on the flood plain were greater than the lakes (mean of 0.012 mm $year^{-1}$). The rates across the flood plain also appear to decrease with distance from the river channel. For example, the surface unit at the core “a” site was deposited at a rate of around 0.71 mm $year^{-1}$ compared to a rate of 0.07 mm $year^{-1}$ at the core “c” site. Overall the rates of sediment accumulation are 156 times lower than those reported for the Lower Balonne flood plain immediately upstream of the Narran system (Thoms *et al.*, 2007). This disparity suggests that the low rates of sediment accumulation in the Narran System result from inefficient delivery of sediment from upstream rather than low yields from source areas and that this inefficient sediment transport is an important factor contributing to the stability and persistence of Narran in the landscape (Cossart, 2008).

The Ti/Al profiles from the lake and flood plain cores suggest that the relative contribution of Condamine and Maranoa derived sediment to the Narran system has varied over the last 440 ka years and that the relative contribution of sediment from each source area has also varied spatially across the various geomorphic regions. Overall, and particularly over the last 78 ka years, the lakes have received relatively more sediment from the Maranoa subcatchment. In contrast, the flood plain, particularly more distant from the river channel, has received relatively more sediment from the Condamine sub-catchment. It is possible that this pattern reflects the need for synchronous high flows from both subcatchments to occur for sediments to be deposited on the more distal parts of the flood plain.

Variation in sediment provenance within the different geomorphic units may reflect climatic influences on the supply of sediment to Narran system. Sediments of the sand unit, which accumulated between 440 to 330 ka, fluctuated between the Condamine and Maranoa catchment and were indicative of a relatively high-energy environment. This period is representative of humid climatic conditions that existed for much of the Pleistocene in the Murray Darling Basin (Nanson *et al.*, 1988). Sediments that accumulated between 330 to 78 ka – the cyclic unit – were predominantly from the Condamine catchment with limited contributions from the Maranoa. This reduction in provenance variability contrasts to the variability in fluvial energy of this unit. The regular fining upward sequences of the cyclic unit correspond to the regular wet and dry oscillations that have been reported for much of SE Australia (cf. Rust & Nanson, 1988). Thus, variation in transporting energy was only associated with the eastern, Condamine, region of the catchment. Since 78 ka there has been a marked reduction in fluvial energy and an overall increase in the predominance of Maranoa-derived sediment accumulating in the Narran Lakes. However, sediments accumulating on the flood plain are mainly from the Condamine catchment. The differential sediment provenance between the lakes and flood plain is similar to that reported by Rayburg & Thoms (2008), who showed that sediments in rarely flooded areas were predominantly derived from the Condamine sub-catchment while sediments in frequently flooded areas were predominantly derived from the Maranoa sub-catchment.

The observed patterns in sediment provenance within Narran are consistent with those recorded by Brennan (2001), who demonstrated that finer sediments accumulating on the Lower Balonne flood plain originate in the Maranoa catchment whereas coarser sediments originate in the Condamine. The underlying geology of the Maranoa catchment (sandstone bedrock) and the presence of sands within the active Maranoa River channel (Galloway, 1974) might suggest that coarser material would be derived from the Maranoa catchment; however, Brennan (2001) hypothesised that the observed converse pattern was due to lower discharges, stream power and potential sediment transport energy in the Maranoa sub-catchment and the higher stream energy and transport capacity in the Condamine catchment.

Much of the information gained from this study has relied on the capacity to match geochemical signatures within the Narran system to those from upstream catchments. Initial analysis of the stratigraphy of the Narran cores suggested substantial post-depositional changes had occurred within the sediments, as indicated by extensive mottling and iron staining of the sediments and the presence of carbonates nodules. The movement of sub-surface water has been reported to significantly alter the chemical composition of the sediments (Bauluz *et al.*, 2000). However, a comparison of different suites of geochemical signatures demonstrates there to be no statistical difference in the collective of soluble and non soluble elements of the Narran sedimentary deposit. Whilst the actual processes creating this situation remain unclear, it appears that post-depositional processes may have had little effect on the sediment geochemistry of the Narran cores thereby allowing sediment provenance investigations to proceed.

CONCLUSIONS

Sedimentation within the Narran system has displayed a complex response to catchment and climatic influences. There has been a gradual reduction in the energy contributing to the supply and deposition of material within the basin. There have also been substantial fluctuations in sediment provenance over time as well as spatial variation in the relative contributions from each sub-catchment to the sediment accumulating within the various geomorphic regions. During the most recent depositional regime, represented by the "surface" unit that is present in all cores, a relatively constant pattern has evolved whereby the sediments deposited in the lakes are derived predominantly from the Maranoa sub-catchment, while those deposited on the flood plain, particularly those areas more distant from the main river channel, contain a greater proportion of material from the Condamine sub-catchment.

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