Using multivariate statistical techniques to interpret patterns of flood plain sedimentation

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Abstract Interpretation of flood plain sedimentation often relies on qualitative evaluations. Quantitative analysis is often made difficult by large amounts of data generated through an array of physical and chemical measurements of sediment character. As such, analysis of sediment character is mostly focused on bivariate comparisons. This paper illustrates the utility of multivariate statistical techniques in the interpretation of flood plain sedimentation, which consider multiple factors simultaneously. Seventeen sediment characteristics were used to distinguish between groups of sediment samples collected from the lower Balonne flood plain in southwest Queensland, Australia. Sediment samples were analysed in a hierarchical manner according to a nested design of river, zone and geomorphic unit scales. The analyses demonstrated differences in sediment character at the river scale. Clear patterns in sediment character were noted at the zone and geomorphic units scales, although these were river-specific. Techniques used in this study can rapidly divide the flood plain into units based on similarities in sediment character, and can provide greater quantitative interpretations of flood plain sedimentation.

Keywords multivariate statistical analysis; flood plain; sediment character; lower Balonne flood plain; Australia

INTRODUCTION

Interpretations of flood plain depositional environments commonly use sediment data derived from horizontal and vertical sedimentary sequences (Amoros & Van Urk, 1989). Typically, these approaches generate large amounts of data which subsequently receive only limited quantitative analysis. In particular, analyses of sediment character tend to focus on bivariate comparisons of one sediment characteristic against depth, or on correlations between two factors that may display a causal relationship. In these types of analyses only two factors can be scrutinized at any one time and the volume of component information generated in this manner from a multi-factor data set can hinder interpretation of overall patterns and processes.

Multivariate statistical techniques provide an opportunity to simultaneously scrutinize multiple factors. These techniques are used extensively in community ecology and seek to reveal structure and pattern in multi-species data sets (Gauch, 1982). Analyses such as classification (cluster analysis), ordination and Analysis of Similarity are used to identify sites, samples or conditions that have similar community composition (Clarke & Warwick, 1994). Analyses such as Principal Axis Correlation (Belbin, 1993) and BIO-ENV (Clarke & Warwick, 1994) can then be used to identify factors associated with underlying compositional variation among sites, samples or conditions. These associations are not causal but rather, they provide an indication of the mechanisms that may be generating overall patterns and processes. This information can subsequently be used to generate hypotheses for further testing.

Multivariate techniques have rarely been applied in geomorphological contexts using flood plain data. The few exceptions to this are studies concerned with sediment source identification in fluvial environments (e.g. Walling *et al*., 1993). Another study by Brown (1985), employed cluster and principal components analysis of grain-size data only to identify changing processes of flood plain deposition over time. Multivariate analyses have the potential to identify units of similar sediment character within flood plain environments and to indicate the principal factors associated with each unit. Using quantitative data these techniques utilize a multiple suite of sediment variables, and compare each sample with every other sample. Hence, they provide a quantitative tool with which to summarize large amounts of data pertaining to patterns and processes within the flood plain environment. These techniques can also accommodate hierarchical philosophies of river system organization, which dictate that different patterns of sediment character may emerge at different scales. In this study we aim to apply multivariate statistical techniques to discriminate sedimentary patterns occurring at different scales within a large physically complex flood plain environment.

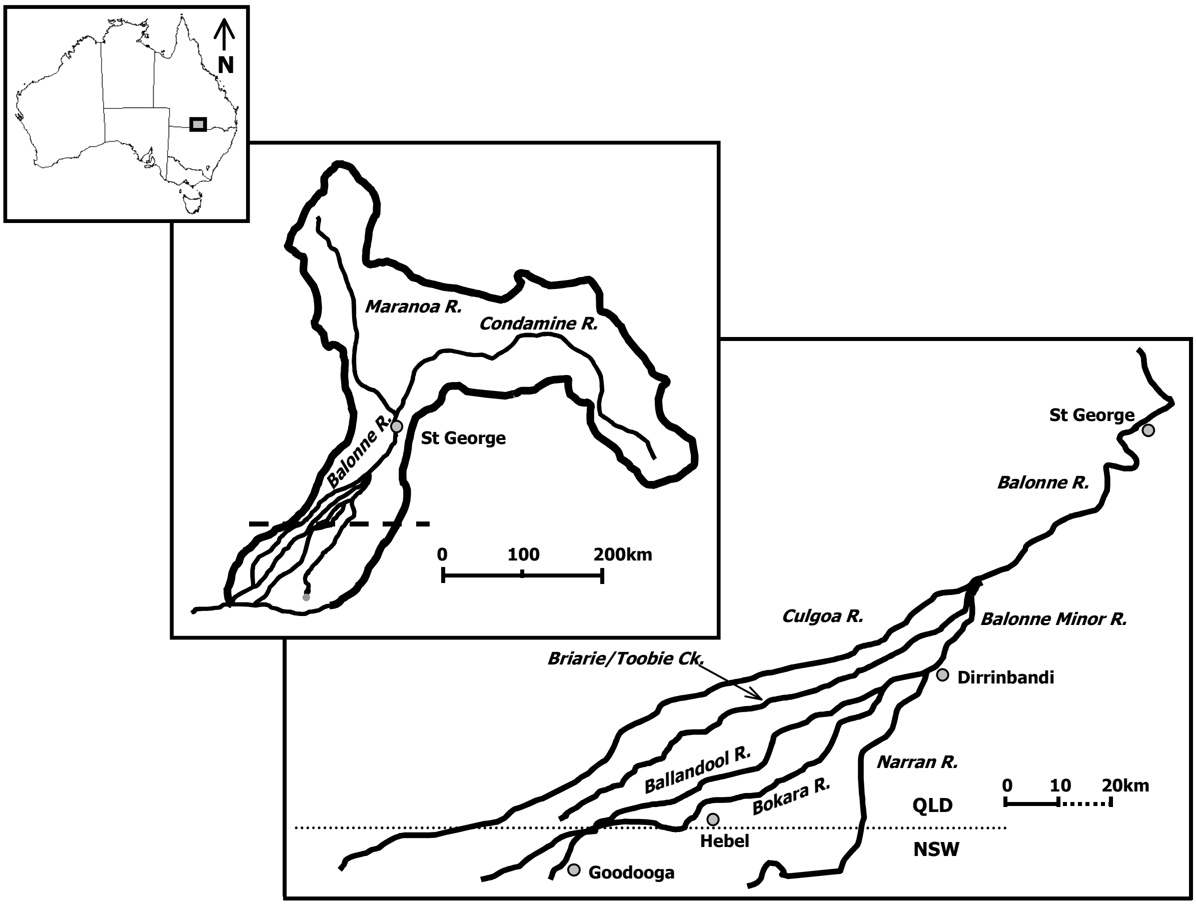

Fig. 1 The lower Balonne flood plain complex, Australia.

STUDY AREA

The lower Balonne flood plain complex, southern Queensland, Australia (Fig. 1) covers an area of 19 880 km^2 and is typical of Australia's inland flood plains (Thoms & Sheldon, 2000). The area is dominated by six main channels of which the Culgoa and Narran Rivers are the dominant flow channels, conveying 35 and 28% of the long-term mean annual flow at St George. The remaining four channels flow only during higher discharges. Channel gradients are low, ranging from 0.0002 to 0.0003 and channel capacities decline with distance downstream. As a result, extensive and regular inundation of the flood plain occurs during periods of high discharge, although this varies depending on subtle changes in channel and flood plain morphology. The lower Balonne flood plain is characteristic of a large low-angle alluvial fan, and contains three flood plain process zones (upper, mid and lower zones). These zones are similar to those noted by others in alluvial fan environments (cf. Blair & McPherson, 1994). The contemporary flood plain and its channel networks contain a complex suite of geomorphic features, which include; levee banks, scroll swales, scroll ridges, distributary channel networks, in-channel benches, palaeo-channels, oxbows and flat flood plains. These features create a complex yet subtle topography.

METHODS

Eighteen sediment cores, up to 2.0 m in length, were extracted from the study area according to a nested design comprising rivers (Briarie and Culgoa), flood plain process zones (upper, mid and lower) and geomorphic units (buried channel, bank, flat flood plain). The location of each scale in the study area was set *a priori* based on previous studies by Sims *et al*. (1999). Geomorphic units were selected because they

Table 1 Sediment variables measured in each core.

Variable type	Sediment variable	Acronym
Sediment texture	% sand	Sa
	% silt	Si
	% clay	Cl
	Median grain size	D_{50}
Sediment nutrients	Total organic carbon	TOC
	Total nitrogen	N
	Total phosphorus (by HNO_3 extraction)	TP
	Phosphorus (labile component, by $K_2S_2O_8$ extraction)	PK
Sediment geochemistry	Iron	Fe
	Aluminium	Al
	Magnesium	Mg
	Manganese	Mn
	Calcium	Ca
	Zinc	Zn
	Sodium	Na
	Potassium	K
	Salinity	Ec

were common to each zone and river. Subsamples of sediment were collected at 10-cm intervals along each core and their textural, nutrient and geochemistry character were determined (Table 1). The final data set, for use in the multivariate analysis, contained 156 samples (2 rivers × 3 process zones × 3 geomorphic units × variable numbers (n = 5–20) of subsamples from each core) and 17 sediment variables (Table 1).

Sediment data were analysed in a hierarchical manner using the PATN analysis package (Belbin, 1993). Sediment samples were partitioned into data sets corresponding to the nested river, zone and geomorphic unit scales. Thus, all flood plain data were used to elicit patterns in the two rivers, data from each river were used to elicit patterns in zones, and data from each zone were used to elicit patterns in geomorphic units. An association matrix was derived for each data set using the Gower similarity measure, recommended by Belbin (1993) for non-biological data. Sediment data were ordinated using Semi-Strong-Hybrid Multi-Dimensional Scaling. Each ordination was performed in three dimensions; however, only the axes representing the best separation of samples in multi-dimensional ordination space were selected for presentation. Stress levels for all ordinations were less than 0.2, indicating that the ordination solution was not random. The relationship between the different sediment variables and the position of samples in multi-dimensional space was determined using Principal Axis Correlation. Principal Axis Correlation (PCC) generates a correlation value for each sediment variable (R^2), with high values being indicative of a strong relationship between the sediment variable and the underlying compositional variation among samples. A Monte-Carlo permutation test was also performed and only the significant variables with an R^2 greater than 0.8 were considered to have the strongest associations with flood plain sediment character.

RESULTS AND DISCUSSION

River scale

Sediment samples from the Briarie and Culgoa Rivers do not show a distinct separation from each other in ordination space (Fig. 2). However, Culgoa River samples have a greater spread in ordination space in comparison to the Briarie Creek samples, which sit more closely together in the middle of the ordination plot (Fig. 2). This suggests that at a regional scale the Culgoa system has a more heterogeneous sediment character than the Briarie system. As such, associating the sediment variables and the position of sediment samples in ordination space was not useful at this scale because there was no clear separation.

Stream power and sediment source area controls are important factors influencing the character of sediment deposited in flood plain environments (Magilligan, 1992). Marriott (1996) noted that the texture of sediment deposited on flood plain surfaces during inundation events was related to the size of the flooding event. In particular, larger sediments are deposited during larger discharges that have commensurate stream powers (Thoms *et al*., 2000). In the lower Balonne the Culgoa flood plain experiences a greater range of inundation discharges than the Briarie system. The supply of sediment to the Culgoa flood plain may be more variable and result in a more diverse

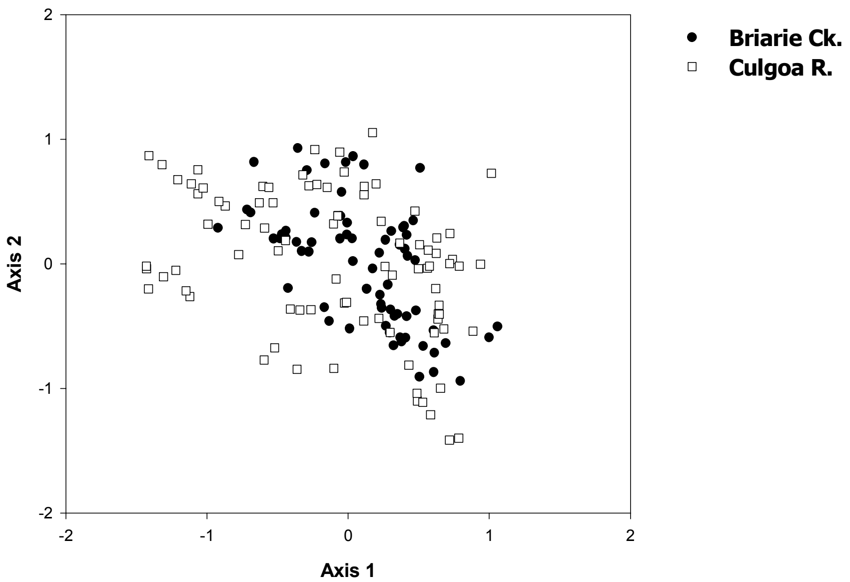

Fig. 2 River-scale ordination of Briarie Creek and Culgoa River.

sediment character when compared with Briarie Creek flood plain areas which are only inundated during larger infrequent events.

Zone scale

Given that there was variability in sediment character at the river scale, data for each river were analysed separately at the zone scale. In the Briarie Creek system, sediment samples from the upper, mid and lower zones form distinct groups in ordination space, although samples from the upper zone merge somewhat with samples from the mid and lower zones (Fig. 3(a)). Hence, the sediment character of the mid and lower flood plain zones are different from each other, while sediments from the upper zone are less distinctive. Different types of sediment variables were associated with each zone. Variables representing sediment nutrients were associated with the lower flood plain zone and variables representing sediment texture were associated with the mid zone (Fig. 3(b)). Geochemistry variables appear to be associated with the upper zone (Fig. 3(b)), yet this is complicated by a mixture of all three zones in this area of the ordination plot.

In the Culgoa system there is no distinct separation of the upper, mid and lower zones (Fig. 3(c)). Rather, there are two main groups of samples with similar sediment character that are individually comprised of samples from each zone type. This suggests that the sediment character of flood plain zones is less distinctive in the Culgoa than the Briarie system. Variables representing sediment geochemistry were associated with Group A and variables representing texture were associated with Group B (Fig. 3(d)).

Sediment character varies spatially in depositional environments. In the lower Balonne the spatial pattern of sediment character differs between the Briarie and Culgoa systems. The strong zonation pattern in Briarie Creek sediments resembles that reported for alluvial fan environments. Blair & McPherson (1994) demonstrated zonal

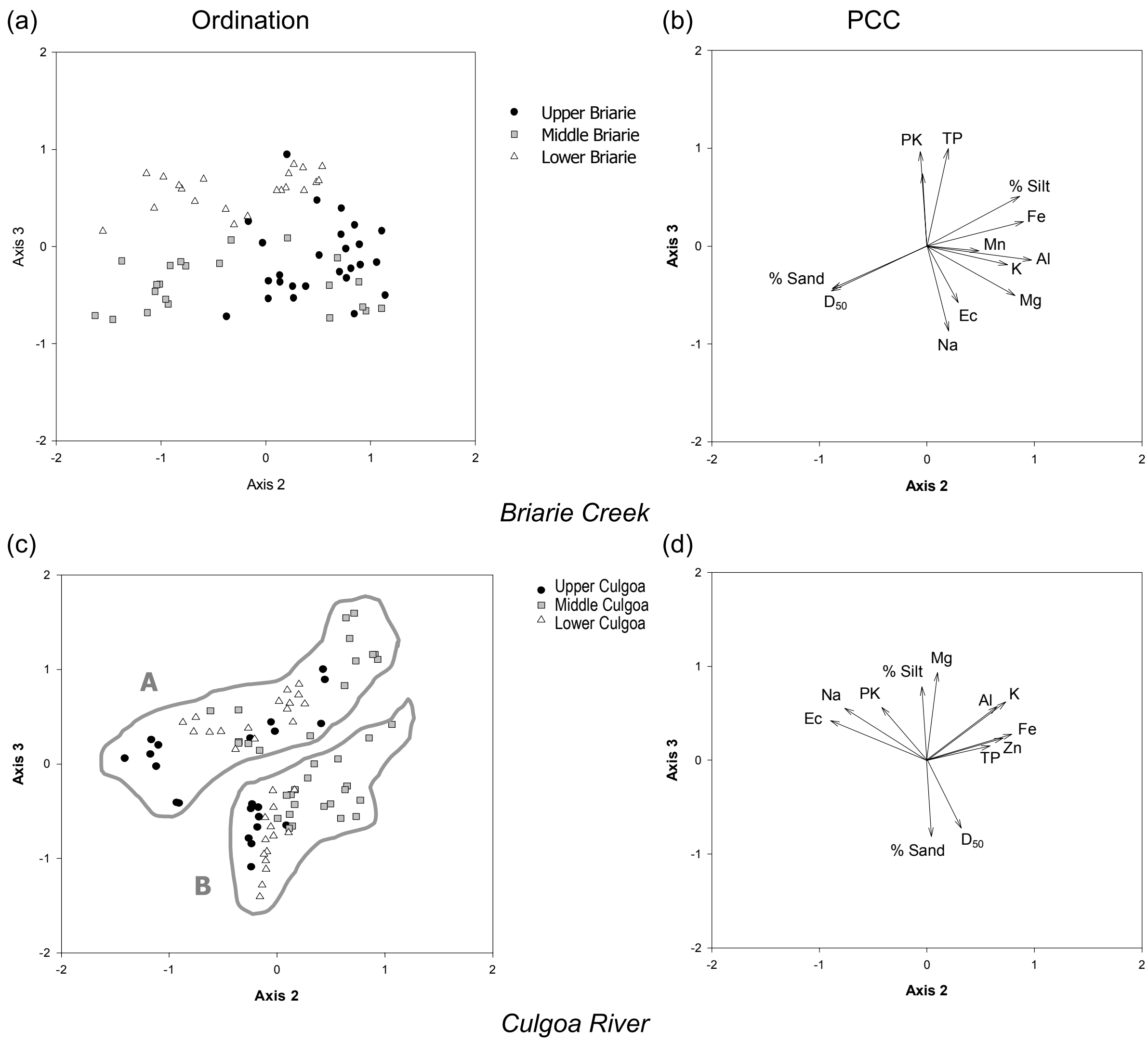

Fig. 3 Zone-scale ordination and PCC of Briarie Creek ((a) and (b)) and Culgoa River ((c) and, (d)). Symbols highlight zones within each river; Groups represented by A and B in diagram (c) are discussed in the text. Refer to Table 1 for explanation of vector labels used in the PCC ((b) and (d)).

patterns along alluvial fans based on textural differences only. Coarse, poorly sorted sediments dominate upper fan zones, while finer well-sorted sediments are more prevalent in lower zones. The present study demonstrates that zonation can occur in flood plain environments (Fig. 3(a)), and that different types of sediment variables are related to this zonation (Fig. 3(b)). This zonation may have been less apparent with the use of bivariate comparisons, as all samples and sediment variables are not incorporated simultaneously.

The lack of clear zonation in the Culgoa contrasts with that found in the Briarie system. Clear groups of samples with similar sediment character were formed in the Culgoa, although they do not correspond with flood plain zones. The influence separating Group A from Group B is presently unknown, however, it may be the result of processes occurring at a different scale (Fig. 3(c)). Knowledge of the structure and functioning of multi-channel flood plain systems like the lower Balonne is limited in comparison to single channel systems. However, a recent study on Cooper Creek, a large Australian anabranching river system, revealed marked spatial variation in morphology among individual channels (Nanson & Knighton, 1996). The contrasting zone-related patterns of sediment character observed in the Briarie and Culgoa systems suggest that like Cooper Creek, individual channels of the lower Balonne may differ in structure and function. Further, these differences in flood plain structure and function may be scale dependent and hence, may manifest different patterns of sediment character at different scales. Multivariate analysis at the zone scale confirmed the *a priori* allocation of Briarie zones but highlighted a more complex pattern of sediment character within the Culgoa system.

Geomorphic unit scale

Given the differences of sediment character among zones, patterns at the geomorphic unit scale were examined in each zone type. In the Briarie system, samples from each of the three geomorphic units form groups in ordination space for all zones, yet these groups have a tendency to overlap (Fig. 4). In the upper zone, the bank, buried channel and flat flood plain samples merge together but some samples do not fall into distinct groups associated with these geomorphic units (Fig. 4(a)). In the mid zone, the bank and buried channel samples merge together but the sediment character of the flat flood plain is distinctive (Fig. 4(c)). In the lower zone, the buried channel and flat flood plain samples merge together but the sediment character of the bank is distinctive (Fig. 4(e)). Hence, some geomorphic units have a distinct sediment character, but the degree of distinctiveness varies among zones.

Different types of variables were associated with the position of geomorphic units in ordination space, but again, these associations differ between zones. In the upper zone the variables % silt, N, Al , Fe and Mn were associated with the flat flood plain and buried channel geomorphic units and the variables Ca, Na and % sand were associated with the bank geomorphic unit (Fig. 4(b)). The association between sediment variables and geomorphic units is clearer in the mid and lower zones, because separation of the geomorphic units was better defined. In the mid zone, geochemical variables and one textural variable were associated with the flat flood plain geomorphic unit and textural variables were associated with the buried channel geomorphic unit (Fig. 4(d)). In the lower zone, a combination of mainly textural and nutrient variables were associated with the bank geomorphic unit while mainly geochemical variables were associated with the buried channel and flat flood plain units (Fig. 4(f)).

In the Culgoa system, the bank, buried channel and flat flood plain geomorphic units form distinct groups in ordination space (Fig. 5(a), (c), (e)), indicating that sediment character is distinctive among geomorphic units. This pattern occurs over all three flood plain zones and is in contrast to patterns observed in the Briarie system (Fig. 4). Moreover, there is a consistent association between sediment variables and the three geomorphic units in each of the flood plain zones. Sediment variables representing texture were associated with the bank geomorphic unit (Fig. 5(b), (d), (f)) while geochemical and nutrient variables were associated with the buried channel geomorphic unit. Likewise, Na, Ca and Ec were consistently associated with flat flood plain sediment samples across all zones.

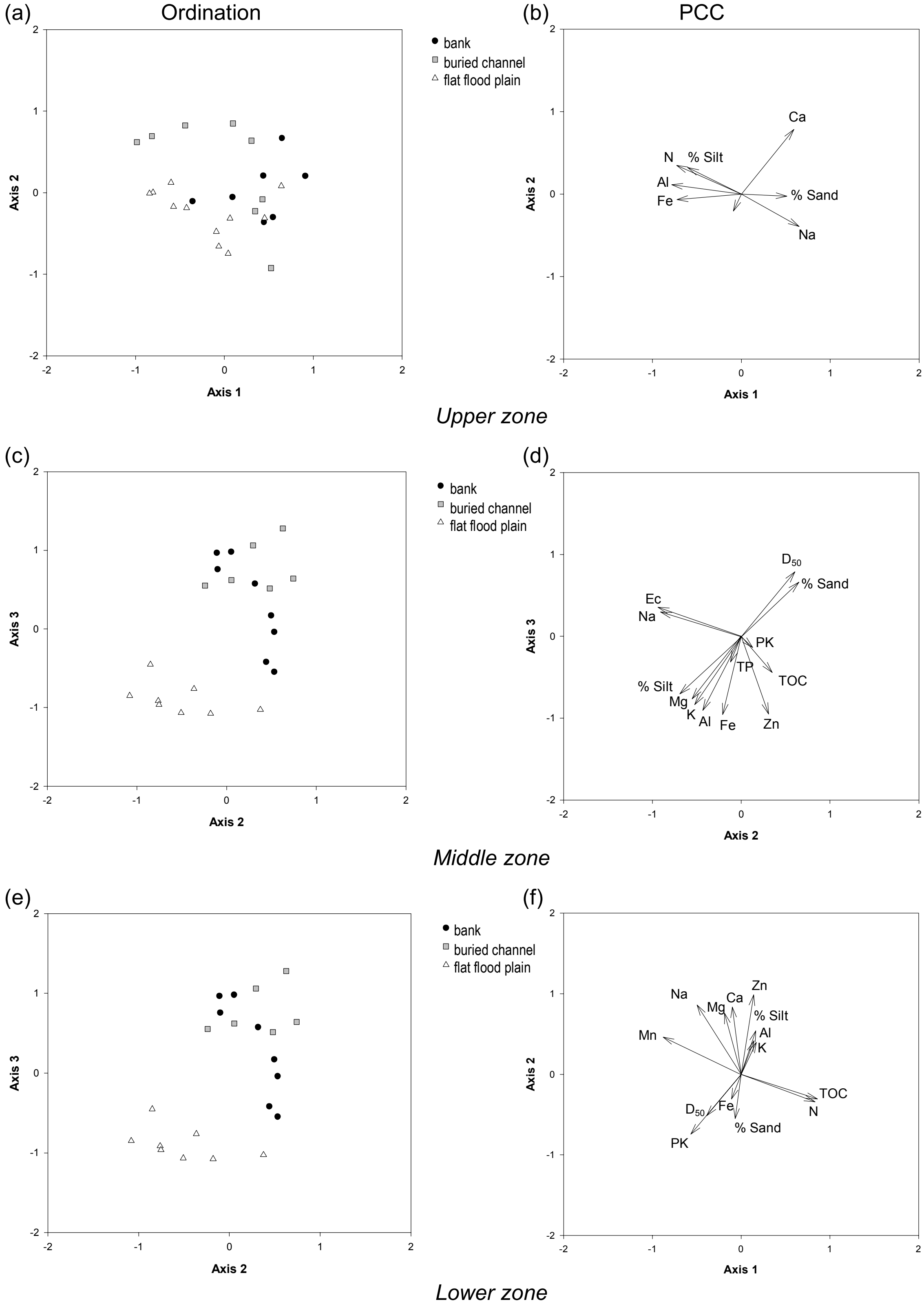

Fig. 4 Geomorphic unit-scale ordination and PCC of Briarie Creek; upper zone ((a) and (b)), middle zone ((c) and (d)) and lower zone ((e) and (f)). Symbols highlight geomorphic units within each zone. Refer to Table 1 for explanation of the vector labels used in the PCC ((b), (d) and (f)).

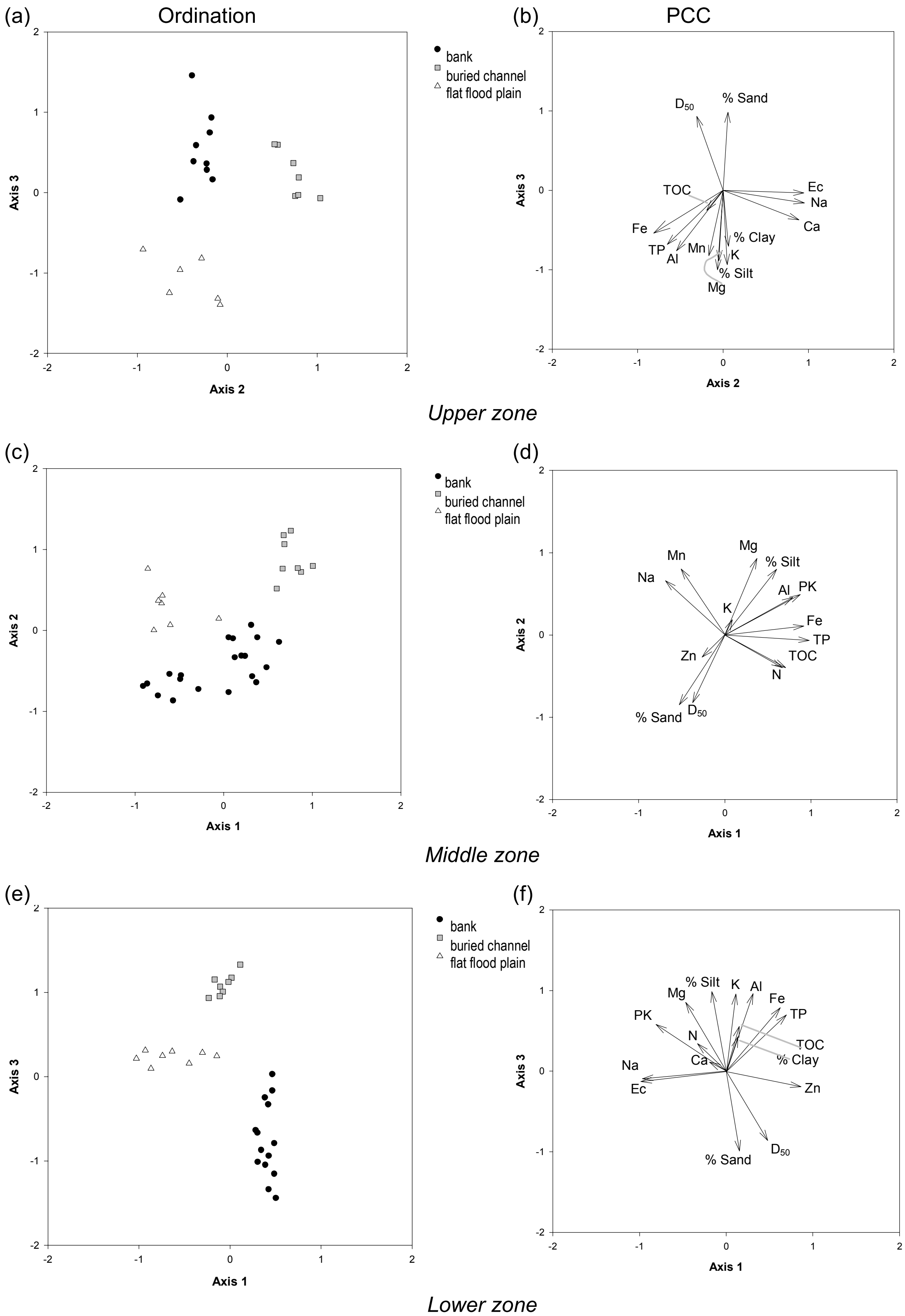

Fig. 5 Geomorphic unit-scale ordination and PCC of Culgoa River; upper zone ((a) and (b)), middle zone ((c) and (d)) and lower zone ((e) and (f)). Symbols highlight geomorphic units within each zone. Refer to Table 1 for explanation of the vector labels used in the PCC ((b), (d) and (f)).

Differences in sediment composition between flood plain landforms have been demonstrated at a geomorphic unit scale (Anderson *et al*., 1996). In particular, differences in sediment texture have been associated with variations in stream energy across flood plain surfaces (e.g. Marriott, 1996). For example, the model of James (1985) demonstrated decreases in flow turbulence with distance from the main river channel, resulting in near channel deposits being coarser than those in distal flood plain areas. At the time scale of a flood event, both Walling *et al*. (1997) and Thoms *et al*. (2000) have provided evidence that sediment textural and nutrient character differ between areas close to the river channel and those at more distal locations on the flood plain. Thoms *et al*. (2000) suggested this to be primarily a result of variations in energy and sediment supply conditions. The geochemical, nutrient and textural character of sediments from the individual geomorphic units are more distinctive in the Culgoa than they are in the Briarie system. Like the model of James (1985), such patterns of flood plain sedimentation may relate to differences in energy conditions and flow regime between the two systems investigated here. Multivariate analyses at multiple scales suggests that the hydrological conditions that form patterns of sediment character at different scales across the Culgoa flood plain are different to those that form patterns of sediment character across the Briarie flood plain.

CONCLUSIONS

Australia's large lowland river flood plains are typically characterized by complex landform assemblages. Clear patterns in sediment character were observed for the various landform features of the lower Balonne; however, these occurred at different scales in the Briarie and Culgoa. In the Briarie, there were clear patterns at the zone scale (Fig. 3) while in the Culgoa clear patterns emerged at the geomorphic unit scale (Fig. 5). The differences observed in the operation of scale among the rivers may be related to variations in energy conditions, flow regimes and sediment supply. In the lower Balonne, the Culgoa system experiences greater flow variability than the Briarie system and patterns of sediment character manifest at the geomorphic unit scale. In contrast, the Briarie flood plain is only inundated at relatively higher flood magnitudes and experiences a smaller range of sediment transporting flows. Thus, patterns of sediment character manifest longitudinally at the zone scale rather than across the flood plain or at a geomorphic scale. Overall, these patterns equate to a longitudinal or zone-scale influence of sediment transport and energy conditions in the Briarie system, and a lateral or geomorphic unit-scale influence in the Culgoa system.

The multivariate approach used in this paper differs somewhat from the majority of traditional sedimentation studies and offers several advantages. First, a large number of sediment variables can be analysed simultaneously, in a relatively short time frame. Using all variables together bypasses the necessity for a large number of individual analyses that compare one variable with another. Second, the incorporation of all variables facilitates greater interrogation of data, and provides increased scope to generate hypotheses. Third, multivariate analyses allow the use of an entire data set to elicit patterns and infer process in a quantitative rather than a qualitative manner. Fourth, multivariate analyses allow the investigation of scale dependant relationships within a large data set, and facilitate multi-scalar sequences of analyses where results from higher scales are incorporated into the interpretation of patterns at smaller scales. For example, the Culgoa River had a greater heterogeneity of sediment character than the Briarie Creek, which suggested it may be useful to examine both rivers individually at the zone scale. The ability to examine many sediment characteristics simultaneously make multivariate statistical techniques an extremely powerful interpretative tool that can be used to complement traditional approaches to the examination of flood plain sedimentation.

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