Hidden in the sands of time:  
geoarchaeology of sandstone landscapes  
in the Keep River region, Northern  
Territory, Australia  

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CHAPTER FIVE

Sediment Characterisation and Site Formation

*It is important to recognise that the sediment constitutes the site!*

– Farrand, 2001: 537.

5.1 Introduction

To geoarchaeologists the concept of formation processes means the search for processes of formation associated with the archaeological context (Stein, 2001). The depositional context is characterised through objective description of the sedimentary characteristics and formation processes. These processes include cultural and natural formation processes, which may be evident within the archaeological deposit itself and/or within deposits which reflect more regional influences. Deposit characterisation provides the basis for the interpretation of formation processes. Identification of both natural and cultural component begins with a consideration of sedimentation, which is a function of four factors (1) source, (2) transportation mechanism, (3) environment of deposition (comprises site-formation processes), and (4) post-depositional environment (Stein, 1985:5). Here, the physical and geochemical properties of escarpment bedrock and sediment samples from the rock-shelters, sand sheets and creeks are characterised and used to identify and understand the nature of these factors.

This study couples field observations with laboratory analyses to provide, first, the necessary basic description of the sediments and, second, an interpretation of the environment of sedimentation. Present understanding and empirical data on site formation processes in sandy deposits across northern Australia is limited; consequently the following sedimentary analyses are exploratory rather than comprehensive. The characterisation of bedrock and sand sheet sediments at the macro-scale (including petrography, grain size and morphology, sediment colour, etc.) provide a first-order indication of the composition (mineralogy) of the sandstone material. The geochemical analysis of sediments may indicate discrete groups that relate particular sediment sources or sinks, or to stratigraphic or taphonomic processes (Reynolds and
Catt, 1987). Phosphate minerals, for example, are particularly favourable for identification of inputs of human or animal wastes (Parnell et al., 2002).

Microscopic and micro-morphological analysis of sediments offers the potential for examination of cultural and non-cultural processes that might otherwise be undetected from field observations or bulk analyses (Courty et al., 1989; Davidson et al., 1992; Goldberg et al., 1994; Goldberg and Arpin, 1999; Matthews et al., 1997; Macphail et al., 1990). The necessarily small sample size means that these methods are only really effective when dealing with questions refined from larger-scale stratigraphic problems (French and Whitelaw, 1999). The appropriate resolution of individual depositional events and processes in the sandy sediments throughout northern Australia is poorly understood and hence poorly defined. Here, an attempt is made to reveal both the larger-scale stratigraphy and micro-stratigraphy of the sand sheets and rock shelters of the Keep River region. These studies can lead to an understanding of site-formation processes during human occupation, and eventually to a reconstruction of local and, in some cases, regional paleoclimates. Furthermore, sediment study is essential for intra-site correlation, independent of archaeological and chronological techniques.

The characterisation of the sediments in the Keep River region is aimed at answering the following questions:

- What do the characteristics of the bedrock, sand sheet, rock-shelter and creek sediments indicate about source and transport processes? Is it possible to correlate or differentiate sediment sources and sinks within and between (archaeological) site locations?
- What do the physical and geochemical characteristics of the sand sheet, rock-shelter and creek sediments indicate about post-depositional processes?
- Is there any distinct anthropogenic signature in any of the rock-shelter or sand sheet sediments?
- How might the above influence interpretations of the archaeological record?
5.2 Methodology

Six of the bedrock samples used for cosmogenic analyses (Chapter Four), were used to provide a compositional range of sandstone source material. In the absence of buried bedrock material, four rubble samples were retrieved from samples collected at the base of the excavation pits at Jinmium (original C1 trench), Gooururarmum (Goor-1 and 2) and Karlinga (Karl-1). Nearly 100 sediment samples were analysed in order to identify local chemical processes within the sand sheets. This included 4 of the samples used for cosmogenic isotope analysis (Chapter Four), 40 samples used for luminescence dating (Chapter Six), 8 samples from the original Jinmium trench, and ~ 50 selected samples (including pisolitic deposits) from other indicative sites.

Sediment sampling of the sand sheets surrounding Gooururarmum and Jinmium (Fig. 5.1), and Karlinga (Fig. 5.2) was undertaken over two separate field trips in 1999 and 2000 as part of the main archaeological field seasons. A key strategy was to compare rockshelter occupation deposits with occupation deposits on the adjacent sand plains. Two pits were excavated at Gooururarmum (KR31), one in the main rock shelter (Goor-2) and one ~ 25 m in front on the sand sheet (Goor-1) (Fig. 5.1). Archaeological pits were excavated at three separate sites in the Karlinga site area, one within the KR36 rock shelter (Karl-1), one within the elevated (~ 80 m) rock shelter (Karl-2), and another on the sand sheet adjacent to a small overhanging shelter (Karl-3). The elevated and sheltered location Karl-2 less directly relates to the sedimentary deposits of the sand sheets and was not used in this study.
Figure 5.1  (a) Location of sample sites around Jinmium, Goorurarmum and Sandy Creek Gorge, (contours from topographic maps) and (b) detailed map and contour survey of the Goorurarmum sand sheet and main rock shelter site (KR31). Areas shaded in brown, pink and blue represent bedrock, scree slope and swampland respectively.

In addition to the excavation pits, auger hole transects were cored across several of the sand sheets, 14 between Jinmium and Goorurarmum, 3 at Sandy Creek (Fig. 5.1), 14 cores at Karlinga (Fig. 5.2), and 4 at other sites in the Keep River region. This was presumed to provide a non-occupation sedimentary comparison to the archaeological sites. The absence of artefacts was confirmed from a selection sieved (using 2 mm sieve) auger samples in the field.

Sediments included uniform red sands, mottled red and yellow sands, streaky red and grey sands, and pisolitic material, thus providing a range of moderate to intensively leached sites from a range of depths across the sand sheets. Where possible, samples were carefully taken to reflect obvious stratigraphic variations (in grain size or colour), which may correspond to changes in sedimentation. More easily accessible profiles of the sand sheet stratigraphy were obtained from two creek sections, one at Sandy Creek Gorge (Fig. 5.1) and another near the rock shelter KR99 (Fig. 5.2). These sites were chosen in order to provide the most extensive
and representative section within each creek. Digging vertical sections in steps, and removing slumped material revealed \textit{in situ} horizontal stratigraphic horizons (Fig. 5.3).

![Figure 5.2](image)

Figure 5.2  (a) Location of sample sites around Karlinga (contours from topographic map), and (b) detailed map and contour survey of the sand sheet and main rock-shelter site (KR36). Areas shaded in brown and pink represent bedrock and scree slope respectively.

\textit{In situ} sub-samples of sediment profiles were collected using Kubiena tins from two excavation pits, Goor-1 and Karl-3, and at the creek section near site KR99. Although only half the sample was successfully impregnated with the low-viscosity resin, it did provide enough material to prepare standard thin-sections and resin-mounted stubs. Significant expansion occurred in at least one sample (Goor-2-120 cm), thus the porosity present in the thin section will be partly artificial. Despite repeated attempts, the hydrophobic nature of the rock-shelter sediments (due to the high concentration of charcoal) prevented sampling of these sites. Details of sampling and thin section preparation are outlined in Appendix A3.2.
Descriptions of bedrock samples, sand sheet and rock-shelter sediments included petrography, grain size, and colour. Grain size variations were accurately obtained using two Long Bed Malvern Master Sizer, laser particle sizers, housed at James Cook University (JCU) and the University of Wollongong (UOW) (Appendix A3.4.1). Mineralogy was determined from petrographic observations, and using X-ray Diffraction (XRD) at UOW. Major element geochemistry was determined using X-Ray Fluorescence (XRF) at JCU. In order to present all aspects of the sedimentary micro-fabric, thin sections were observed at a range of scales, using the optical microscope, and electron microscopy. Detailed chemical mapping by SEM/EDXA provides elemental characterisation of single grains, surface coatings and interstitial material, which may also reflect sedimentary processes. SEM/EDXA analyses were undertaken at the Advanced Analytical Centre (AAC) at JCU, and details of the SEM/EDXA setup are outlined in Appendix A3.2.1.

Figure 5.3 Photograph of slumped material over the top of horizontal stratigraphic horizons at the site of KR99CP.
5.3 Results

Core diagrams including petrographic descriptions, grain size and artefact density with depth, and luminescence dating results (from Chapter Six) are given below for the initial Jinmium (C1/III) excavation (Fig. 5.4), the rock-shelter excavation at Goorurarmum (Fig. 5.5) and at Karlinga (Fig. 5.6), the sand sheet excavation at Goorurarmum (Fig. 5.7) and at Karlinga (Fig. 5.8), and for the creek profile near the site of KR99 (Fig. 5.9), and at Sandy Creek Gorge (Fig. 5.10). Core diagrams and sediment descriptions for all auger cores and excavation profiles are given in Appendix A3.1, for Goorurarmum and Jinmium (Fig. A3.2), Karlinga (Fig. A3.3) and Sandy Creek (Fig. A3.4). Results of grain size and major element analyses of bedrock and sedimentary material from each of the four main sites of Goorurarmum, Jinmium, Karlinga and Sandy Creek Gorge are outlined below. Full details and statistical analyses of grain size are given in Appendix 3.4.2 and 3.4.3 respectively, and for geochemistry in Appendix 3.5.2 and 3.5.3 respectively.

5.3.1 Sediment Macro-stratigraphy

5.3.1.1 Rock shelters

The original Jinmium (C1) rock-shelter excavation is summarized in Fig. 5.4 for comparison with the more recent excavation profiles described below. Original diagrams are depicted in Fig.s 6.1 and 6.2 and a full description is provided by Fullagar et al. (1996). The rock-shelter deposits are generally comprised of moderately sorted, medium-coarse (~ 400 µm), red-yellow (7.5YR 5/4) to dark brown (5YR 2.5/2) sands, with sandstone rubble increasing towards the base of the 1-2 m profiles. Charcoal (1–5%) and artefacts, present in the upper parts of the stratigraphy, were absent at the base of all the excavations.
Please see print copy for Figure 5.4
Please see print copy for Figure 5.5
Please see print copy for Figure 5.6
The Goorurarmum (Goor-2) rock shelter sediments comprise moderately sorted, med-fine (~ 201 µm), dark-reddish brown sands (5YR 3/3 to 2.5/2), with a relatively high percentage of charcoal (~ 5%) down to the base of the 30 cm deep profile (Fig. 5.5). These sediments lie on an indurated sandstone base of bedrock and/or rubble. No significant grain size change is observed. Artefact density decreases towards the base of the profile. The luminescence ages are discussed in Chapters Six (refer 6.6.2.3) and radiocarbon ages in Chapter Seven (refer 7.2.1).

The Karlinga (Karl-1) rockshelter sediments comprise well-sorted, dark brown (10YR 3/3 to 7.5 YR 3/4) med-fine sands (~ 260 µm), also with charcoal decreasing towards the base of the 30 - 40 cm profile (~ 5%) as evident from the colour change of the sands (Fig. 5.6). These sands infill and lie over a base of boulders and rubble material. Again the luminescence ages are discussed in Chapters Six (refer 6.6.2.3) and radiocarbon ages in Chapter Seven (refer 7.2.1).

5.3.1.2 Sand Sheets

Sediments within the Goorurarmum ampitheatre comprise medium-fine (~ 160 µm), moderately sorted, unimodal sands with pebble and cobble material gradually increasing near the bedrock/rubble base. There is little or no stratigraphic differentiation throughout the sand sheet profile. In the Goorurarmum sand sheet excavation (Goor-1), the sediment colours range from red-brown sands (10YR 4/2 to 7.5YR 5/4) near the surface, to increasingly red (5YR 5/6) sands towards the bedrock/rubble base at about 2.4 metres depth (Fig. 5.7). The darker hue and colour near the surface probably results from recent burning. The luminescence ages are discussed in Chapters Six (refer 6.6.2.1) and radiocarbon ages in Chapter Seven (refer 7.2.1). A kilometre north, towards the coastal mudflats, the surface sediments from Gu-5 are a lighter brown (10YR 6/4) and at 2 m depth show deep red (10R 6/8) mottling.
Please see print copy for Figure 5.7
Please see print copy for Figure 5.8
West toward Jinmium, the sediments become less red and increasingly yellow with decreasing elevation. At the surface the sediments are orange-yellow (5YR 4/6 - 5/6), and at depth show varying degrees of red-yellow mottling (10R 4/6 and 7.5YR 6/8). Situated at a higher elevation (~15 m AHD), the sediments near Jinmium are typically lighter red (2.5YR 4/6) at the surface and become dark red at depth (10R 4/6), with pisolites developing at the base of the profile (Fig. A3.2), reflecting past fluctuations in the water table. The sediments around Jinmium (~380 µm) are slightly coarser and more angular than those at Goorurarmum. North of Jinmium and with decreasing relative level, the sediments again become light red to yellow (5YR 4/6) and are underlain at shallow depths (<2 m) by darker red sediments (10R 4/6) or pisolitic material.

Around the main Karlinga escarpment, the sediments are dominantly coarse (360 µm), poorly sorted, and ranging from medium brown sands (10YR 4/2) to slightly lighter sands at depth (10YR 7/2). In the Karlinga sand sheet excavation (Karl-3) the sediments are darker (7.5YR 3/2) at the surface, progressing through yellow-red and mottled yellow-orange sands (5YR 4/6) with red (2.5YR 3/6) pisolitic material at the base of the 2.5 m excavation pit (Fig. 5.8). Rubble layers, comprising (imbricated?) cobbles 5 - 10 cm thick, were encountered at depths of 1 m and 1.5 m (Fig. 5.8). Again, the luminescence ages are discussed in Chapters Six (refer 6.6.2.1) and radiocarbon ages in Chapter Seven (refer 7.2.1).

Traversing further south-east from the main Karlinga escarpment towards the Keep River, and with decreasing relative level, the sediments become more yellow-orange (10YR 5/8) and show a greater degree of slumping due to a higher water table at depth (Fig. A3.3). One auger hole, KN7, revealed a layer of red pisolitic sands at about 2 m depth indicating the presence of a fluctuating water table at some time in the past. At the lowest relative level, saturated brown sandy clay in KN8 reflected a swampland.
5.3.1.3 Creeks

It was observed after the 2000 wet season, that the sand deposits in the creeks which drained into the Karlinga and Goorurarmum sand sheets were significantly coarser than those of the respective sand sheets. Grain size analysis of a creek sample from each of these sites (~450 µm at Karlinga and ~320 µm at Goorurarmum) confirmed this observation, and indicates some process of preferential sorting and preservation within the sand sheets.

The sediments within the KR99 Creek Profile (Fig. 5.9) are similar to those found nearer to the main Karlinga site but are finer (~300 µm) with a significant clay fraction (<10 µm). These creek sediments progress down the profile from dark grey-brown (10YR 3/2) pebbly sands, through brown-white sands (5YR 5/4 - 8/1) and more abruptly into dark grey sands (5YR 5/1) with black streaks (7.5 YR N2). In addition to smaller lenses of coarser and dark brown sands, these changes possibly reflect changing energy levels in the adjacent creek at various times in the past. The luminescence ages are discussed in Chapters Six (refer 6.6.2.2).

The sediments adjacent to Sandy Creek comprise well-sorted, fine sands (~150 µm) with a subdominant clay fraction (<10 µm). The sediment colours range from fine yellow-brown sands (10YR to 7.5 YR 4/4) at the surface to more orange (10YR 5/6) about 2 m depth. Interestingly the water table was encountered progressively higher up the profile along the traverse from Sandy Creek towards the billabong near the auger core SC-3. In the nearby Sandy Creek Gorge, the creek section revealed strongly leached, highly differentiated lateritic soils and gleyed-podzolic soils with sinuous root mottles (Fig. 5.10) which are representative of one or more palaeosol horizons. The brown sandy sediments (7.5 YR 4/4) at the surface progressed downward into very well-sorted red clayey sands (2.5 YR 4/6) with small black pisolithes, into very well-sorted streaky red-grey (7.5 YR 3/8-6/6) clayey sand with dark red mottles (2.5 YR 3/6).
Figure 5.9 Profiles of the creek near the site of KR99. Luminescence dates are derived from Chapter Six.
Figure 5.10  Profiles of the creek at Sandy Creek Gorge. Luminescence dates are derived from Chapter Six.
At about 3 m depth in the Sandy Creek Gorge profile, a narrow band (~ 20 cm) of coarser sands was observed (Fig. 5.10). With increasing depth the sediments progressed from brown clayey-sands (7.5 YR 4/6) with degraded red pisolites to well-sorted mottled sandy-clay (7.5 YR 4/6, 10YR 3/2) with hard black pisolites (7.5 YR 3/2). The pisolitic material (5 - 8 mm diameter) increased in abundance to form a distinct horizon within the bed of Sandy Creek reflecting the presence of a fluctuating water table at some time in the past.

Also evident on the bank of Sandy Creek Gorge were two unconformable horizons of a hard, indurated silicate material (Fig. 5.11) at about 320 cm and 500 cm depth. These horizons were not observed in the section cut in the creek bank, indicating they are either an isolated outcrop or represent a later event. The luminescence ages are discussed in Chapters Six (refer 6.6.2.2).

Figure 5.11 An indurated silicate horizon situated adjacent to the main creek bank profile at Sandy Creek Gorge (refer text for further description).
5.3.2 Sediment Micromorphology

5.3.2.1 Bedrock

The sampled bedrock from the escarpments overlooking Jinmium, Goorurarmum and Karlinga generally comprises medium-grained quartz sandstone cemented with clay, and stained by limonite (Fig. 5.12a – f). Evidence of pressure-solution is evident from the interlocking of grains and occasional quartz overgrowths. Porosity is generally less than 10%.

Figure 5.12a – f  Thin section of escarpment bedrock sampled from (a and b) Goorurarmum, (c - e) Karlinga and (f) Jinmium (scale bar = 250 µm).
Moderately-sorted, sub-rounded to sub-angular quartz grains range from 0.2 - 0.4 mm in diameter. Monocrystalline, non-undulose quartz is dominant, with lesser amounts (< 10 %) of polycrystalline quartz and vein quartz (possibly from conglomerates). Thin banding evident in hand specimens is comprised either of alternating fine and medium grained laminae and/or high concentrations of heavy minerals, mainly iron oxides (e.g. Fig. 5.12). Minor amounts of lithics include tourmaline, chlorite, zircon, sphene and epidote.

5.3.2.2 Sand Sheets

Sediments from the Goorurarmum excavation comprise medium to fine, sub-rounded, moderately-sorted quartz. Thin section reveals the quartz comprises both monocrystalline and larger clasts of polycrystalline quartz (Fig. 5.13). Iron-staining generally occurs around the boundaries of the quartz grains, and also as overgrowths in some quartz grains. Although minimal, there is indication of an increase in the fine clays with depth, and illuviation of clays in the voids and around quartz grains. Porosity is about 40 %, and there is no obvious evidence of compaction or bedding. Apart from the much greater porosity and an absence of lithics, the sediments are very similar to the bedrock sampled in this area.

Sediments from the Karlinga excavation are obviously coarser in thin section than those from Goorurarmum, but are of a similar composition and porosity. Compared to the bedrock samples from this area, the sediments from this locality showed the greatest similarity with the escarpment bedrock directly north of the site (COS-K4), rather than with bedrock overlooking the main Karlinga site (COS-K1 and K2). The strong dark red colour in matrix exemplified in the buried sediments at Karlinga (Fig. 5.14), show the incorporation of iron oxides with clay in these horizons. This may indicate the process of rubefaction (reddening).
Figure 5.13 Thin section of Goorurarmum (Goor-1) sand sheet sediments, taken at 75 cm, 120 cm, and 175 cm respectively (scale bar = 100 µm).
Figure 5.14  Thin section of the Karlinga (Karl-3) sand sheet sediments, taken at 100 cm and 240 cm respectively (scale bar = 100 µm). Inset shows limonite staining in sediment matrix, which may indicate the process of rubefaction (reddening).

SEM analyses of sand sheet sediments

SEM/EDRXA analyses also indicate that Fe₂O₃, present as iron oxides and oxyhydroxides (limonite), is intimately mixed with Al₂O₃ as phyllosilicate clay minerals. Together these are present as grain cutans, infilling grain fractures, diffuse impregnations of the groundmass, and on the walls of root channels. The composition of the clay minerals is kaolinite and illite,
determined from presence of $\text{Al}_2\text{O}_3$, $\text{SiO}_2$ and $\text{K}_2\text{O}$ in EDRXA traces and bulk XRD analyses. The cutans are not present in surface sands appear to form post-depositionally (Fig. 5.15).

![Image of quartz grains](image)

**Figure 5.15** Post depositional formation of iron-clay cutans as evidenced from the contrasting images of quartz grains (a) before burial, and (b) after burial. Inset of (b) shows a cross-section of a quartz grain highlighting the $\text{Fe}_2\text{O}_3$- and $\text{Al}_2\text{O}_3$- rich cutan.

With continued burial, some of the quartz grains show increasing evidence of deterioration (Fig. 5.16). There is little or no presence of pitting or etching that would be indicative of aeolian weathering. Rather features such as grain angularity and adhering particles are more typical of *in situ* weathering. The few etched grains observed indicate some sediment populations probably derive from dissolution of bedrock material, and have subsequently acquired iron-enriched clay cutans through burial diagenesis.

![Image of quartz grain deterioration](image)

**Figure 5.16** General observation of deterioration of quartz grains from with depth in sand sheet profiles.
Fig. 5.17 shows examples of the more angular grains that are present within some of the sands from the various rock-shelter and sand sheet excavations. No clear evidence of fracturing was discernable on these grains to clearly distinguish them as possible flaked material (microliths) amongst the general population of moderate to poorly sorted sands in the sand sheets throughout the Keep River region. However, a more thorough study distinguishing such microlithic flakes is presently being undertaken by George Susino (in prep.). The presence of cutans on these angular grains indicates that they have probably undergone a similar period of burial as other grains with which they are associated.

Figure 5.17 Example of shard-like grains sampled from the Karlinga (Karl-3) and Goorurarmum (Goor-1) excavations.

SEM analyses of pisolites

The iron-rich concretions observed at the base of one site near Jinmium (JG4) and at Sandy Creek Gorge consist of goethite, quartz and kaolinite. In thin section, the pisolites at the Jinmium site (Fig. 5.18) are homogeneous. In contrast, the pisolites from Sandy Creek Gorge (Fig. 5.19) comprise up to 15 bands of iron-rich material that probably reflect periodic change in physicochemical conditions during formation. The unrounded shape and poorly sorted matrix of the pisolites at Sandy Creek Gorge indicate they are probably in situ.
Figure 5.18  Cross section of pisolitic material taken from the base of the profile (450 cm) of auger JG4, near Jinmium. The sample has a thin crust and a matrix of poorly sorted quartz and clay.

Figure 5.19  Cross section of pisolitic material taken from the base of the profile (540 cm) of Sandy Creek Gorge. The sample has a thick crust, and a matrix of poorly sorted quartz and clay minerals.

5.3.2.3 Creeks

Impregnated samples were not taken from the main profile of Sandy Creek Gorge, but a thin section was made of the adjacent indurated horizon (Fig. 5.20). Thin section reveals very fine grained, iron-stained quartz surrounding larger degraded clasts, comprised of lithics including iron oxides, chlorite and zircon (Fig. 5.20). Despite extensive investigation, the nearest identification was with what has been termed ‘creek rock’ in parts of North Queensland (Bob Henderson, pers. comm., 2001).
Figure 5.20 Magnification (x 50) of indurated silicate material adjacent to Sandy Creek Gorge profile, showing the fine grained, iron-stained quartz surrounding larger degraded opaline-like clasts (scale bar = 100 µm).

Sediments from the KR99 creek section reveal an increase in lithics, and degree of sorting, and a slight decrease (~ 10 %) in porosity down the profile. The sediments generally consist of medium to coarse, sub-rounded, moderate to poorly sorted mono-crystalline quartz; the coarse clasts generally comprising polycrystalline quartz with occasional inclusions. The obvious change in colour in the field section at about 3 m depth is also obvious in thin section where there is a distinct increase in iron staining around the quartz (Fig. 5.21).
Figure 5.21 Thin section of KR99CP sediments, taken at 95 cm, 180 cm, 255 cm and 340 cm respectively (scale bar = 100 µm).
5.3.3 Sediment Geochemistry

Mineralogical analyses indicate the sand sheet sediments are dominated by quartz, with lesser amounts of kaolinite and minor accessory minerals. The mineralogy of sediments elsewhere in the Keep River region is similar, with the addition of micaceous (muscovite) and hydrated clay minerals (illite, smectite, montmorillonite) in the cracking clay soils. The average bedrock and sediment geochemistry is given in Table 5.1. Statistical analyses are given in Appendix A3.5.3.

5.3.3.1 Bedrock and Rubble Geochemistry

The dominance of quartz in all the bedrock samples is indicated by the high percentage of SiO₂ (95 wt. %), with minor amounts of clay and organics indicated by low concentration of Al₂O₃ (2.0 wt. %), and LOI (1.5 wt. %). The greatest geochemical variation is shown in the relative percent of Fe₂O₃ (0.08 to 1.6 wt. %), with the higher concentrations reflecting the redness of the bedrock sample. The overall geochemistry of the rubble samples is more like that of the sand sheet sediments than the escarpment bedrock samples, although the degree of difference between the bedrock and all other sediment samples is not significant except perhaps at Jinmium. At this site the bedrock geochemistry is distinguished by higher relative concentrations of SiO₂, Al₂O₃, Fe₂O₃ and P₂O₅ (refer Appendix 3.5.3). The similar sediment mineralogy and geochemistry of the escarpment bedrock and sand sheet samples supports the microscopic evidence that the sediments have not undergone any significant transport.
Table 5.1 Summary (mean and standard deviation, SD) of sediment geochemistry for each location, and for all combined sediment samples compared to bedrock (in bold). Results indicate the very similar geochemistry of all samples.

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<th>Location</th>
<th>SiO2</th>
<th>TiO2</th>
<th>Al2O3</th>
<th>Fe2O3</th>
<th>MgO</th>
<th>CaO</th>
<th>Na2O</th>
<th>K2O</th>
<th>P2O5</th>
<th>LOI</th>
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5.3.3.2 Rock-shelter Geochemistry

There is no significant difference in grain size between the rock shelters and the adjacent sand sheets, except at Karlinga where the rock-shelter (~ 260 µm) sediments are finer grained than the adjacent sand sheet (~360 µm). This is marginally reflected in the higher relative concentration of SiO$_2$ and lower relative concentration of Al$_2$O$_3$ in the sand sheet sediments.

Within the three rock shelters of Jinmium (CI/III), Goorurarmum (Goor-2) and Karlinga (Kar-1), the relative concentrations of P$_2$O$_5$ and LOI are significantly higher than the adjacent sand sheets (Table 5.1). However, the correlation between P$_2$O$_5$ and LOI is not significant, possibly indicating the presence of P$_2$O$_5$ with both organic and inorganic components. Organic phosphatic additions could be derived from either human or animal activity. The Goor-2 rock-shelter sediments are also distinguished by lower relative concentrations of SiO$_2$ and higher concentrations of CaO. The high CaO content is probably sourced from gypsum salts (refer Fig. 5.23). The Jinmium rock shelter has lower relative concentrations of Al$_2$O$_3$ and Fe$_2$O$_3$ than the adjacent sand sheets, possibly reflecting low clay content. There is no correlation of any of these distinguishing elements (SiO$_2$, Al$_2$O$_3$, CaO, P$_2$O$_5$, and LOI) with artefact distribution in any of the shelters, but this may partly be an effect of the low number of geochemical analyses compared to artefact analyses.

5.3.3.3 Sand sheet Geochemistry

The three main modal sizes in the sand sheet sediments are coarse sands (250 - 500 µm), med-fine sand (125 - 180 µm) and clay (< 10 µm). Depth profiles of the sediment grain size and geochemistry in the sand sheets and rock shelters (Appendix Figs. 3.7 – 3.10) show that, in general, the mean modal size follows the trend of SiO$_2$ (as quartz), and the < 60 µm fraction and more especially the < 10 µm fraction follows the trend of Al$_2$O$_3$, K$_2$O and Fe$_2$O$_3$ (as oxyhydroxides), and the organic (LOI) content generally mirrors that of SiO$_2$. 
Mineralogical analyses indicate the sand sheet sediments are dominated by quartz, with lesser amounts of kaolinite and minor accessory minerals. Statistical analyses indicate that there is a much greater difference between the four sites of Goorurarmum, Jinmium, Karlinga and Sandy Creek Gorge than there is within the sites. This difference is manifest in the difference in grain size (Appendix 3.4.3) and to a lesser extent in the geochemistry (Appendix 3.5.3). The sediments around Karlinga are generally coarser and the relative concentration of SiO₂ higher, whilst the sediments surrounding Jinmium are distinguished by slightly higher relative concentrations of Al₂O₃ and Fe₂O₃, and those at Goorurarmum by higher relative concentrations of CaO, P₂O₅, and to a minor extent organic (LOI) content.

Iron minerals, evident from the red and yellow colour of many of the sediments, generally occur below the level of detection by XRD (2 %), thus no mineralogical distinction could be made between the mottles and sediment matrix. The exception is in the deep red sands between Jinmium and Goorurarmum where relative percentages of hematite and goethite are above 5 %. The positive association of Fe₂O₃ with Al₂O₃ (r = 0.77) and K₂O (r = 0.53) indicates iron oxide and oxyhydroxide minerals are closely associated with clay minerals, and confirms microscopic observations of illuviation of clays in the voids and around quartz grains. In general, shallow yellow sediments (< 2 m) are observed at lower depositional levels whereas deep red sediments were measured to the limit of the auger depth (6 m), and are observed at slightly higher relative levels.
5.3.3.4 Creek Geochemistry

The sediments at Sandy Creek Gorge have a significantly higher relative concentration of \( \text{Al}_2\text{O}_3 \) and \( \text{K}_2\text{O} \) and smaller grain size. The relative enrichment of potassium in the Sandy Creek sediments reflects the preferential removal of other cations and silica, and illitisation of sediments, and is clearly shown in a triplot of \( \text{Al}_2\text{O}_3-\text{Na}_2\text{O+CaO-K}_2\text{O} \) (Fig. 5.22). This trend is typical of many clayey palaeosols that are predominantly illitic in composition, and which contain large root traces of the kind formed under forests (Retallack, 1990). A depth profile of grain size and geochemistry at Sandy Creek Gorge (Fig. 5.10) indicates at least three horizons, distinguished by the marked change in \( \text{SiO}_2 \) and \( \text{Al}_2\text{O}_3 \), with the \( \text{SiO}_2 \)-enriched middle horizon corresponding to the coarse sandy horizon observed in the field at about 3 m depth.

Please see print copy for Figure 5.22
5.4 Discussion

The following discussion considers how the characteristics of sandy deposits in the Keep River region reflect source and transport processes, depositional environment, and post-depositional processes, and how these may have influenced the formation and preservation of archaeological deposits.

5.4.1 Depositional Processes – Source and Transport Processes

In the Arnhem Land plateau, Roberts (1991) argued that although the geological rate of weathering and erosion has been constant over the Quaternary period, fluctuations in hydrological activity have changed the dominance of particular sediment sources. In the Keep River region, not only has the rate of escarpment denudation been relatively constant (Chapter Four), but petrographic evidence indicates that the source and sedimentary processes have not significantly altered during the period of sand sheet formation in any of the site catchments of Jinmium, Goorurarmum, and Karlinga. However, the rate of depositional processes may have been more erratic.

The distribution and mixing of the three modal sizes namely coarse sand (\(\sim 360 \mu m\)), med-fine sand (\(\sim 180 \mu m\)) and clay (< 10 \(\mu m\)), reflects the influence of the escarpments and rivers as sources and/or as agents of sedimentary processes. Nearer the escarpments, the dominantly unimodal (Fig. 5.23), moderately sorted and sub-rounded quartz sediments reflect a single major source and/or local transport process. Towards the major rivers and creeks the sediments are multi-modal (Fig. 5.23) and well-rounded reflecting the contribution and transport of material from more than one source, although these sources have not changed through time. Essentially the depositional environment becomes less endogenous with increasing distance from the escarpments.
Figure 5.23  Grain size map, indicating typical grain size distribution for the different depositional sand sheet and mud flat environments.
Walsh (2000: 384) observes that sediment populations of 360 µm, 250 µm and 60-70 µm are observed in other parts of north-east Kimberley, and argues that all three modes are indicative of widespread aridity. It is questionable whether grain size can be used as a proxy for climate. In any case, the similarity of the 360 µm and 250 µm modes in the Keep River region most likely reflects a common type of sandstone source as exists throughout the rest of the Kimberley region. The 60 - 70 µm fraction noted elsewhere in the north-east Kimberley apparently represents aeolian dust (McTainsh, 1989), derived from the Quaternary Dust Path which originated in Central Australia and passed off the Kimberley coast into the Indian Ocean (Bowler, 1976). The virtual absence of the 60 - 70 µm mode within the Keep River sand sheets might indicate that this region lies outside this dust path. More likely, the absence of this mode reflects a similar absence in the local sandstone source and/or selective reworking and transport of silt from the sand sheets in the upper catchments onto the black soil plains via river systems. It is possible that ants and termites are also a contributor to selective reworking as some species prefer silt and clay size material to sand when re-arranging soil particles (Lobry de Brun and Conacher, 1990). The mud in the estuaries that form the black soil plains is derived from the shelf as a result of the high energy tidal range that operates in northern Australia (Woodroffe et al., 1989; Chappell and Woodroffe, 1997).

The moderately poor sorting observed in each of the sand sheet sediments probably reflects the degree of sorting in the bedrock source more than any particular transport process. As found previously (Aldrick and Moody, 1977), the similar petrology and geochemistry of the sand sheet and bedrock sediments limits determination of a specific source at any particular site. Rather the similar geochemistry of the bedrock and sediment samples supports microscopic observations that the sand sheet sediments are locally derived and have not undergone significant transport. Coarser sands may be concentrated in small creeks and fans debouching onto the sand sheets due to lower competence of flow. The unconsolidated sands are closely packed, and the absence of well sorted, layered deposits and poor differentiation along slope indicates the sand sheet sediments are most likely transported mainly by sheet flow rather than by major flood events (Courty et al., 1989, Coventry et al., 1988). The surface of the sand
sheets are protected by a lag, a few grains thick, of the coarsest particles that can be easily shifted by wind or water.

High water tables, seasonal saturation and/or bioturbation may further inhibit the formation or preservation of any obvious lamination in any of the sand sheet sediments. There is evidence from root and burrow traces that some mechanical disturbance does occur in the uppermost sediments, but ferruginisation of these remnant traces indicates this disturbance is essentially limited to the upper metre. Consideration of biogenic processes on archaeological site formation is given in Chapter Seven (see also Ward and Larcombe, in press).

5.4.2 Environment of Deposition (Site Formation)

Typically, the sand sheet and rock-shelter stratigraphy comprise loose charcoal-enriched surface sands, overlying slightly more compact sands, which themselves overlie rubble and/or a bedrock base. The Jinmium archaeological deposit, according to Roberts (pers. comm., 2002), is constrained in a ‘basin’ of crumbling saprolite. However, the distinction needs to be made between saprolite as in situ decomposed bedrock and incorporated bedrock material that is broken down within a sedimentary profile. It is not possible from the close geochemical similarity of bedrock and loose sand to positively distinguish saprolite or buried rubble in the sand sheets. However, the observed exfoliation of modern surfaces (Fig. 5.24) indicates that much of the rubble in the Jinmium deposit, including the ‘sandstone pavement’ depicted in Fullagar et al. (1996), probably derives from previously exfoliated material rather than underlying saprolite (see also Bednarik, 2002: 1215). Robbins et al. (2000: 1090) describe a similar scenario of rock breakdown and burial in the White Paintings rock shelter, in the northwest Kalahari Desert, during a period of increased moisture and rock breakdown at the shelter.
Chapter Five – Sediment Characterisation

The precipitation of gypsum (CaSO₄.2H₂O), particularly within and around the rock shelters, is seen to increase the breakdown of sandstone (Fig. 5.25) and exacerbate the exfoliation of rock-art. This is supported by the higher concentration of CaO in the rock-shelter sediments. Thin sections of the escarpment bedrock confirm the breakdown of the escarpment sandstone through the removal of intergranular cement, as described by Young and Young (1992).

Figure 5.24 Throughout the Keep River region, large slabs of bedrock can be observed in the process of mass exfoliation; this example has a petroglyph on the surface. The frequency of mass exfoliation of these sandstone surfaces may provide some indication of the age of the engraving.
5.4.3 Post-Depositional (Diagenetic) Processes

5.4.3.1 Sediment Colour

Sandy sediments across northern Australia often appear homogenous, with the only changes in the form of colour (e.g. Jones and Johnson, 1985; Allen and Barton, 1989; O’Connor, 1999). Dark hues may partly result from organic matter. Pigmentation of sediments (or lack thereof) is often due to the nature of iron oxide and hydroxide minerals, and may be characteristic of the sedimentary environment (Table 5.2). The red and yellow sediments observed in the Keep River region (Fig. 5.24) are common throughout northern Australia (Coventry and Williams, 1984), and result from different degrees of leaching and deposition of iron and silica. A strong relationship may develop between morphological features of the soils (including mottling, gleying, and clay content) and the depth and duration of profile saturation (Coventry and Williams, 1984).
Good drainage and aeration of the sand sheet sediments at higher relative levels and lower water table levels is evident from the hematite-rich deep red (10R 4/6 or 2.5 YR 3/6) and reddish brown (7.5YR 5/4) colours found typically around Jinmium and Goorurarmum. At lower relative levels and higher water tables such as typically found around the Karlinga area, the poor drainage results in reduction and leaching of iron minerals to give the goethite-rich yellow (7.5YR 6/8) and orange-yellow (5YR 4/6) colours (Table 5.2). Although hematite may be less abundant than goethite, it is in fact the hematite content that usually determines the redness of a soil (Schwertmann, 1993).

Table 5.2 Pigmentation of sediments is due mainly to the nature and grain size of iron oxide and hydroxide minerals, and may provide information on the pedoenvironment (from Schwertmann, 1993: 54).

Please see print copy for Table 5.2
Care must be taken to show whether sediment reddening is inherited from the parent rock or has been acquired post-depositionally, particularly as it may influence the properties of the sediment for luminescence dating. Whilst field observations indicate that some degree of redness is retained through transportation, the comparison of ‘fresh’ and buried quartz grains at high magnification (Fig. 5.15) corroborates the post-depositional accretion of iron-rich clay coatings, and Roberts (1997: 862) corresponding evaluation of the Jinmium sediments. The association of iron with aluminosilicate minerals as fine clay coatings or within pore spaces indicates that clay coatings are a co-requisite for iron staining (Sullivan and Koppi, 1998). The deposition of clay itself is favoured by the weathering of ash (high in K) (Courty et al., 1989), which is abundant from the frequent bushfires in the Keep River region.

As previously indicated (refer 2.3.2), one of the concerns expressed in relation to the Jinmium site was that the TL ages of > 100 ka were not supported by the weathering colours of the sandy soils (Roberts et al., 1998a). Rubefaction reflects the intensity as much as the duration of such pedogenic development and, as such, is not useful as an indicator of soil development and proxy chronosequence. The timespan necessary to obtain a homogenous rubefied (red) layer is on the order of a few hundred to a few thousand years depending on the environment (Schwertmann, 1993). Interpretations based on hue of sediments may therefore only be useful for comparison of palaeosols with a common burial history (Retallack, 1997). Correspondingly, the absence of post-depositional red staining of the sand in the Jinmium rock-shelter (C1) trench compared to that developed in the supposedly coeval sand aprons (Roberts, 1997: 863) is not necessarily evidence for any inconsistency in the luminescence ages. Rather the colour differences between the rock shelter and adjacent sand sheets might indicate slightly divergent post-depositional histories.
Figure 5.24 Examples of the coloured sands found throughout the Keep River region, including the red sands around Jinmium (JG-1) and yellow sands overlying a red pisolitic horizon around Karlinga (KN-7).
According to Fullagar et al. (1996), the sand sheet sediments surrounding the Jinmium rock shelter show a colour change from yellow-grey to a deep weathered red at about 60 cm depth. Red soils occurring in an area where only yellow-brown soils are presently forming can usually be recognised as palaeosols (Schwertmann, 1993), providing some credence to the 100 ky BP luminescence ages obtained from the base (~ 5 m) of this sand sheet profile. In contrast, the sediments within the Jinmium rock shelter show a high degree of mottling including yellow-grey (7.5YR 4/4), red-yellow (7.5YR 5/4), and light yellow-red sand (5YR 5/3) respectively in the horizons overlying the sandstone rubble base. This discolouration probably results from incomplete weathering and poor drainage of the rock-shelter rubble and sandy sediments, and may be complicated by the hydrophobic nature of the charcoal-enriched sandy sediments.

The hydrophobic character of charcoal-enriched sediments may be related to organic compounds (e.g. waxes) associated with organic material rather than the charcoal itself (Ross Coventry, pers. comm., 2002). Little is known about the fluid dynamics of hydrophobic sandy sediments, but water is probably concentrated along preferential pathways, such as root burrows at the sediment/bedrock/rubble interface, rather than through the sediment as a whole (Peter Ridd, pers. comm., 2002). Where water is concentrated for longer periods, it will not only enhance sandstone decomposition but may also result in greater attenuation of dose rates and potentially influence luminescence age determinations (e.g. Goldberg, 2002). The hydrodynamic and sedimentary environment, and luminescence dating thereof, is likely to be more predictable with increasing distance from the escarpments and rock-shelters.

5.4.3.2 Mottles and Concretions

The site of KR99CP is positioned at the head of a large creek, and it is possible that the creek previously drained into a small alluvial swamp. The mottled greyish, brownish and yellowish colours revealed by the creek sediments at Karlinga (KR99CP, Fig. 5.9) are indicative of the incomplete decay of organic matter that probably accumulated in waterlogged (swamp) conditions. The relatively abrupt change from dark (7.5 YR N2) to lighter (5YR 5/4 - 8/1)
coloured sands is certainly indicative of a long-standing water table. Whilst such waterlogging may have allowed the carbonaceous palaeosol to develop, periodic drying of the swamp sediments (possibly through seepage) may have minimized peat accumulation (Rapp and Hill, 1998: 35). Subsequent sand deposition probably filled out the swamp (refer 6.6.2.2 for chronology), reducing its extent to the present creek that runs alongside the cliff. Periods of alternating high energy and low sedimentation are indicated by short but successive intervals of coarse sands in the creek profile (Fig. 5.9). The fact that the stratified organic layers are preserved in the earlier creek sediments indicates that initial bioturbation may have been reduced at this site (possibly as a result of rapid sedimentation), and/or that bioturbation is presently concentrated in the upper metre.

The reddish-grey streaked (10YR 3/2 - 10R 7/1) or pseudogley horizons observed in the Sandy Creek Gorge profile also indicate that previous hydrological changes have allowed temporary waterlogging of these sediments and localised iron movement due to changing redox conditions (Courty et al., 1989). The sinuous root mottles which extend up to a metre deep, along with the presence of in situ ferric nodules and concretions, may indicate the former existence of a dry rainforest or vine thicket community that once existed along Sandy Creek (Fig. 5.25). If it were wooded grassland, as exists presently, the root mottles would be expected to be less than 2 mm in diameter and much shallower (Retallack, 1997). Palaeobotanical studies indicate that rainforest trees (Atchison, 2000) and vine thicket communities (Jon Luly, pers. comm., 2002) were more extensive in some parts of the Keep River region (see 7.1.2 for further discussion). Atchison (2000) also indicates that present monsoon rainforest patches are small and isolated on dolomite outcrops – although not all dolomite outcrops have monsoon rainforest. The indurated silicified horizon at Sandy Creek Gorge may therefore represent a degraded detrital dolomite outcrop upon which an isolated rainforest community once existed. Groundwater may have effected the process of dedolomitisation and replacement of carbonate by silica (Folk, 1968).
Figure 5.25 Hypothetical interpretation of the present sedimentary features observed at Sandy Creek Gorge. A soil horizon(s) formed (a) initially under an ancient rainforest or vine thicket community undergoes (b) post-depositional burial gley of organic matter, dehydration of ferric oxyhydroxides, compaction and illitisation of smectite clay (modified from Retallack, 1990).

The occurrence of sand sheets over laterite and ferruginous nodules is not unusual (Newsome, 2000) and, throughout the Keep River region, ferruginous mottles and pisoliths are found in association with red and yellow sands. Caution is however advised in the use of such concretions as palaeoenvironmental indicators (Young et al., 1987; Nanson et al., 1991), particularly as such ferruginous weathering may be ongoing in the present climate. Indeed, the apparent continuity between the pisolitic and overlying ferruginised deposits indicates that time rather than climate has had a greater effect on stratigraphic differentiation of sandy sediments in the Keep River region. The time factor is the subject of the following chapter.
5.5 Conclusions

The analyses of bedrock, rock shelter and sand sheet material indicates that basic sediment characterisation is not especially useful in differentiating depositional facies and processes, or distinguishing cultural and natural deposits in these unconsolidated sandy sediments. This essentially reflects the similarity of the quartz sandstone bedrock and quartz-rich sand sheets, and the fact that aboriginal people didn’t significantly alter their environment. Thus despite earlier criticisms (refer 2.4.1), the stratigraphy of these sandy sediments may be better defined from the geochronology (Chapter Six).

Poorly-sorted, medium to coarse sand sheet sediments, are derived locally through mass wasting, salt weathering and granular disintegration of local escarpment bedrock. Post-depositional processes in the sand sheets include the loss or gain of organic matter, silicate clay minerals and iron oxides, changes in sediment colour, and the development of mottles or concretions. The pigmentation of the sediments reflects topographic and groundwater levels, rather than the degree of maturation or stratification of the sand sheet sediments. Palaeosol horizons in two creek profiles are distinguished by sediment mottling and illitisation, and potentially mark significant palaeoenvironmental and palaeoclimatic changes during the Quaternary (refer 6.6.2).

Microscopic analyses of rock-shelter and sand sheet sediments do not reveal any distinct anthropogenic signatures, such as laminated sediments, organic residues, or ash from fires. Attempts to obtain comparative micro-morphological (thin section) analyses of the charcoal-enriched rock shelter sediments were unsuccessful, due to their hydrophobic nature. The present work may, however, provide a useful foundation on which to do more detailed geological or archaeological studies related to specific field problems or site formation studies in the Keep River region.