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

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CHAPTER SIX

Luminescence Dating and U-Series Dating of Sand Sheets and Archaeological Sites

*If there is one issue on which nearly all archaeologists can agree, it is the importance of chronology.* - Dean (1978): 223

6.1 Introduction

As previously outlined, the Keep River region was made known to the archaeological and public community through the controversy surrounding the luminescence dating of material from the excavations at the site of Jinmium. This chapter extends the luminescence dating in the Keep River region to other occupation deposits (rock-shelter sites and sand sheet sediments), and non-occupation deposits (creek bank profiles), and uses both thermoluminescence (TL) and optically stimulated luminescence (OSL) dating techniques. The luminescence ages are later combined with previous luminescence and radiocarbon ages (Chapter Seven) to provide a broad overview of the chronostratigraphy for this region, and an outline of some of the geomorphological processes which may occur within sandy sites, such as Jinmium.

6.2 Geoarchaeological Application of Luminescence Dating in the Keep River region

Luminescence dating techniques have found many applications in both archaeology (Roberts, 1997; Feathers, 1997a,b) and geomorphology (Duller, 1996; Stokes, 1999). Although mainly used as a dating tool, luminescence techniques are also being applied to specific studies of sedimentary processes, including bioturbation (Bateman et al., 2002), transport (Heimsath et al., 1999), and surface exposure dating (Habermann, et al., 2000). These applications illustrate how luminescence dating techniques may both provide chrononological context and understanding of geomorphological processes.
Dating of rock-shelter deposits may not be straightforward because sediments are commonly derived by various means and from various provenances. These transported sediment grains may not have been adequately bleached at the time of deposition, and the complexity of the stratigraphy can further complicate dose rate determinations (Feathers, 1997b). In the Keep River region, there is not only major discrepancy within the apparent age of some of the archaeological deposits but also between the archaeological sequences and the rock art. The original stratigraphy of the rock-shelter excavations (C1/II and III) (Fig. 6.1), shows the juxtaposition of 2.3 ky BP and 50 ky BP horizons, which contrasts with the Holocene age of sediments in the adjacent sand sheet excavation (C1/IV) (Fig. 6.2). These initial estimates were contradicted by subsequent elemental carbon and OSL age estimates (COOR numbers in Fig. 6.1) on large and small aliquots and single grains of sand (Spooner, 1998, Roberts et al., 1998a), although the reliability of these elemental carbon results also is uncertain (John Head, pers. comm., 2002). If the entire deposit is of Holocene age, as Roberts et al. (1998a) and others (Galbraith et al., 1999; Watchman et al., 2000) propose, and if the deposits reflect the age of the rock art (refer 7.4.2), then either the extant regional rock art sequence is much younger than is widely accepted, or the Aboriginal production of cupules and old paintings has left no signature in the excavated deposit.

In any case, all agree that the true luminescence history of the site is complex. Regardless of the physics of luminescence dating techniques, further research is needed to refine relationships between the visible rock art and the sedimentary and cultural deposits, especially since both young and old chronologies depend on some degree of taphonomic disturbance of the archaeological sediments. Consequently, the focus of this study is on the depositional processes that form the rationale for luminescence techniques. Duplicate excavation samples however, do allow for some comparison and estimate of reproducibility between OSL and TL dating and the implications this has for the application of the two techniques in these sorts of environments.
Figure 6.1 Stratigraphic sections of the north (C1/II and C1/III) and south (C1/III) faces of the Jinmium pit, adapted from Fullagar et al. (1996, Figs. 5 and 6). Crosses indicate TL ages (Fullagar et al., 1996), dots indicate single-grain OSL ages (Roberts et al., 1998a).

Figure 6.2 Stratigraphic section of the excavation pit C1/IV and auger hole 4 (A4) at Jinmium. Adapted from Fullagar et al. (1996, Fig. 7). Crosses indicate TL ages (Fullagar et al., 1996).
6.3 Luminescence Dating Theory

A comprehensive outline of TL dating techniques is given by Aitken (1985; 1989), and of optical dating by Aitken (1994). An account of the procedures and protocols for both TL and OSL dating of sediments is given by Mejdahl and Christiansen (1994) and Wintle (1998), and a recent review of luminescence models is given by McKeever and Chen (1998).

The general form of the luminescence equation is:

\[
\text{Age} = \frac{\text{Palaeodose}}{\text{Dose Rate}}
\]

Palaeodose (also known as equivalent dose, or archaeological dose) is the radiation dose needed to induce luminescence equal to that acquired subsequent to the most recent bleaching event, and includes a residual fraction of luminescence retained in a sedimentary sample after bleaching (Aitken, 1998). The dose rate (also known as the annual dose or radiation flux) is the rate at which radiation (measured from $^{232}$Th, $^{238}$U, and $^{40}$K) is absorbed by sediments. Uncertainties in the age therefore depend on the uncertainty in the palaeodose and the dose rate – including U-disequilibrium, mobility of U, Th and K isotopes, past water contents (Prescott and Fox, 1990; Olley et al., 1996).

In order to be comparable with previous studies on the Jinmium sediments (Fullagar et al., 1996; Spooner, 1998, Roberts et al., 1998a; Galbraith et al., 1999; Roberts et al., 1999; McCoy et al., 2000), this study makes use of both TL and OSL techniques to determine the luminescence age of sediments in the Keep River region. Despite lacking the interpretable structure of TL glow curves for thermal stability (Wintle, 1996), OSL dating is advantageous because it measures only the rapidly bleached signal (equivalent to the 325 °C peak used by TL), and so circumvents the need to assess the residual signal remaining at burial, giving greater accuracy and precision (< 5 %) for dating sunlight-exposed sediments than TL (Spooner, 1998). However, the use of the rapidly bleached signal implies that OSL is perhaps
less robust when used in disturbed sites. Both techniques are subject to the same uncertainties in the determination of the dose rate.

6.3.1 Determining Palaeodose

Critical to palaeodose determination is the uncertainty of whether there has been sufficient bleaching to remove all but the residual fraction by the time of deposition, which depends not only on the degree of illumination but also on the susceptibility of the sample to bleaching. While it is not clear whether the presence of impurities, such as organic or oxide coatings, hinders bleaching of quartz (Smith et al., 1997), it is only likely to be important if such impurities were obtained prior to transport (pre-depositional) (Roberts, 1991). Field observation indicates that most of the original oxide coating is removed by abrasion during transport, but upon burial a subsequent oxyhydroxide coating may form over time, and is evident from sediment characterisation (Fig. 5.15).

Despite the exposure of the sand sheets at Jinmium to full sunlight, incomplete bleaching was argued (Roberts et al., 1998a; Spooner, 1998) to account for the more ancient chronology presented by Fullagar et al. (1996). A recent study by McCoy et al. (2000) observed that the distribution of bright and dull quartz grains from the Jinmium excavation site does resemble that of a well reset site, rather than that of a poorly reset rock-shelter site. However, as Roberts et al. (1999) make clear, it is the anomalous palaeodose value that distinguishes unbleached grains, not the brightness sensitivity.

A more intrinsic problem in palaeodose determinations arises from the various possible depositional histories (refer 6.3), and potential mixing of younger and older sediments (Smith et al., 1997; Roberts et al., 1998b). As indicated by Roberts et al. (1999), older sediments may derive from in-situ disintegration of overlying bedrock or underlying saprolite (Fig. 6.3b), and neither would be distinguishable from partially bleached grains (Fig. 6.3d).
Using conventional multiple-grain TL methods, such mixing was thought to overestimate the average age of sediments in the Jinmium rock shelter (Spooner, 1998). This argument was supported by subsequent single-aliquot and single-grain OSL dating (Galbraith et al., 1999; Roberts, et al., 1999). Unfortunately, similar OSL analyses were not undertaken on samples from the adjacent sand sheet to indicate whether any of the features of the rock-shelter sediments were characteristic of the wider area.

Recent tests of single-grain OSL techniques are attempting to distinguish dose populations in natural deposits (Roberts, et al., 2000). These single-grain studies assume, as in standard multiple-aliquot studies (Olley et al., 1999), that the minimum palaeodose (or lowest 10% of values) gives the most reliable luminescence age of the sediment deposit because such grains...
are likely to have been bleached to the greatest extent (Roberts et al., 1999). However, studies have shown that young material may be incorporated into older sediments through bioturbation (Bateman et al., 2002), or intruded into older deposits through dessication cracks (Jon Olley, pers. comm., 2001), hence the minimum palaeodose may not always be stratigraphically accurate. Nevertheless, a recent study of burrow structures indicates that exhumation of material by bioturbation may not be significant, as the bulk of grains retain a significant palaeodose value corresponding to the depth and antiquity of the material exhumed (Bateman et al., 2002). Thus while single-grain dating improves the statistical distribution of palaeodose determinations, it does not identify the reason for the variability (McCoy et al., 2000), and an understanding of the geomorphological context remains critical to the reliability of dated sequences.

### 6.3.2 Determining Dose Rate

The dose rate is derived mainly from the decay of the lithogenic radionuclides uranium ($^{238}$U), thorium ($^{232}$Th), and potassium ($^{40}$K), and from cosmic rays, and is attenuated by water content of the sedimentary deposit (Olley et al., 1997). Cosmic rays contribute a small amount to the overall radiation flux level, and this only becomes significant when very low flux levels are in operation i.e. low K, Th and U values (Aitken, 1994). Estimates of dose rate cannot account for the long-term variations in the environment; thus a major uncertainty in dose rate comes from problems in the estimated measurement of both water content and in the disequilibrium in the U-Th decay series (Olley et al., 1996). Whilst water content does not directly contribute to the dose rate, its presence modifies the radiation flux level (Aitken, 1994). Thus radioactive disequilibrium may be significant where a site is wet or has been wet for any significant period (Prescott and Hutton, 1995). In the Keep River region, the land surface can be wet for 4 to 5 months of the year, during and after the wet season (Kinhill, 2001), although this may have been greater or less in the past. Although present uncertainties in dose rate calculations are unlikely to be above the 15 % threshold associated with luminescence dating (Roberts, 1996),
the error contribution from the dose rate becomes more significant as the precision in palaeodose determinations increases.

At Jinmium, as in most luminescence dating applications, it was assumed for simplicity that the dose rate had not changed over the period of burial (Fullagar et al., 1996). Evidence of large changes in water content and probable radioactive mobility throughout much of the Keep River region is manifested in the colouration and mottling of the sands by iron oxides and hydroxides (refer Chapter Five). Dissolution and re-precipitation of uranium and thorium in association with amorphous- and crystalline-iron and manganese oxides and hydroxides is typical of lateritic weathering environments (Short et al., 1989; von Gunten et al., 1999), and such element mobility may effect dose rate determinations. Studies at Allen’s Cave, Nullarbor Plain, have shown that sediment heterogeneity has the potential to induce significant differences in the dose rate of individual grains and hence age determinations (Olley et al., 1997). At Ngarrabullgan, Cape York, disparate multiple- aliquot OSL ages between closely spaced samples were considered to be a result of the mixing of sediments from an underlying mottled zone (either saprolite or an ancient palaeosol) and more recently bleached sediments (Roberts, 1997: 859). Regardless of any possible influence of the mottled zone on the dose rate, the age of occupation at Ngarrabullgan was revised from ~60 ky BP to 30 ky BP. Such results highlight the importance of understanding the relationships between pedogenic features, disequilibria and burial dose rates in semi-arid monsoonal sediments of northern Australia.

This study prefaces luminescence age calculations with a preliminary investigation of the potential correlation between the degree of mottling of the sediments and radioactive disequilibrium, using a combination of high-resolution gamma and alpha-particle spectrometry. For a more detailed study of post-depositional processes and the potential impact on luminescence dating refer to Roberts (1996). In conjunction with these U/Th studies, U-series dating of pisolitic material from Sandy Creek Gorge and the sand sheets at Jinmium is also undertaken.
The application of luminescence (TL and OSL) dating is used here to:

- Obtain age estimates and determine the chronostratigraphy for the sand sheets and creeks around Jinmium, Goorurarmum, Karlinga and Sandy Creek, and for the rock-shelter excavations at Goorurarmum and Karlinga.
- Investigate the effect of weathering and diagenesis on dose rate estimates
- Discuss the geoarchaeological implications of the above results.

6.4 Methodology

Both TL and OSL techniques were used for age determinations of sand sheet sediments and creek profiles (including auger samples and excavation profiles). The Jinmium rock-shelter site is even more exposed than that of either Goorurarmum or Karlinga, but the aspect of the Jinmium site is apparently insufficient (more probably due to sediment mixing rather than lack of solar exposure) to allow the TL signal to be completely reset (Roberts et al., 1998a; 1999). In any case, optical dating is preferred for the rock-shelter sites.

6.4.1 Field work

Luminescence samples were taken from the excavation pits only after all archaeological investigation and sampling had been completed. Sampled excavation pits include those from Goorurarmum (KR31) rock shelter (Goor-2) and sand sheet (Goor-1), and from the Karlinga rock shelter (Karl-1) and sand sheet (Karl-3). Luminescence samples were also taken from non occupation sites in the sand sheets (auger holes) and from the creek sections at Sandy Creek Gorge and near the rock shelter KR99.

Samples for TL and OSL dating were collected in separate tubing, the former in opaque polyethylene tubes and the latter in smaller steel tubes to minimise light penetration. Eight duplicate samples were taken for comparative TL and OSL analyses, two from each excavation profile at Goorurarmum and Karlinga, and four from the Sandy Creek Gorge profile. Details of
methodology used to take luminescence samples from auger holes and excavation pits are described in Appendix A3.1. Excavation profiles, creek profiles and core descriptions were done in situ, and collected samples were transported to UOW for analyses.

A total of 36 TL samples were collected around Karlinga, Goorurarmum, Jinmium and Sandy Creek Gorge in the 1999 and 2000 field trips, in order to discern the temporal and spatial variation in depositional age within and between each of the sites. Of the 36 samples collected, 33 were analysed. A total of 19 OSL samples were also collected but limitations with the OSL facilities at UOW constrained the total number of samples analysed to 15. Of the total 48 dated samples, 12 that had various degrees of mottling or red staining were specifically selected for dose rate measurements, and to help determine disequilibrium in the uranium and thorium decay series in relation to iron content, water table and depth. Pisolitic material from the base of the Sandy Creek Gorge profile (540 cm) and JG-1 auger (450 cm) was also obtained for U-series dating.

6.4.2 Laboratory work

TL analyses were undertaken by David Price at UOW, using the combined additive and regenerative method on the 90 – 125 μm quartz fraction as outlined in Nanson et al. (1991). Full details for TL determinations are given in Appendix A4.2. The following outlines the methods used for determination of palaeodose and dose rate in OSL dating, and full details are given in Appendix 4.3.

OSL determinations were also undertaken on the 90 - 125 μm quartz fraction, in order to be comparable with TL measurements and with previous studies (Fullagar et al., 1996; Spooner, 1998, Roberts et al., 1998a; Galbraith et al., 1999; Roberts et al., 1999; McCoy et al., 2000). Grain size analyses (Appendix 3.2.2) indicated that the 90 - 125 μm constituted about 10% of the dry mass. OSL sample processing was undertaken personally, under the direction of Dr. Jon Olley (C.S.I.R.O., Canberra) and Dr. Bert Roberts (UOW).
6.4.2.1 Palaeodose

The technique for palaeodose determinations derived from the studies of Galbraith et al., (1999), but followed the most recent and robust protocol of single-aliquot-regenerative-dose (SAR) outlined by Murray and Wintle (2000), and modified from Murray and Roberts (1998). Each of the 15 samples was split into three portions: one for grain size, another for palaeodose determinations (single- and multiple-aliquot), and the third for dose rate determinations.

Luminescence measurements were made at two laboratories (University of Wollongong, and CSIRO Land and Water in Canberra) using automated Risø TL/OSL (TL-DA-12) readers (Bøtter-Jensen and Duller, 1992). Samples were optically stimulated by a tungsten-halogen lamp filtered to between 420 and 550 nm using GG-420 filter in combination with an interference filter. Luminescence was detected by a Thorn-EMI 9235QA photomultiplier tube fitted with 2.5 mm of U-340 filter. Beta irradiations were delivered using calibrated $^{90}$Sr/$^{90}$Y sources (0.024 – 0.030 Gy s$^{-1}$). Riso software version 4.65 was used at both laboratories.

The sequence of protocols were made on most samples, comprised an IR check for feldspars (using 2 aliquots), a multiple-aliquot run (SARA, Mejdahl and Bøtter-Jensen, 1994) before and after sun bleaching (24 aliquots), a single-aliquot preheat plateau test (24 aliquots), two runs (24 aliquots) using a single-aliquot regenerative-dose (SAR, Murray and Roberts, 2000), and a double-regenerative test for 12 aliquots. The initial SARA run established a check of linearity and preliminary estimation of the true palaeodose, which allowed a single regenerative dose to be used in subsequent SAR determinations. A single regenerative dose may be unreliable if it is over 10 % of the true palaeodose (Folz and Mercier, 1999), or in the non-linear region of the OSL dose-response curve (Galbraith et al., 1999). A plot of palaeodose values from the SARA and SAR protocols indicates that there is good linear agreement ($r^2 = 0.92$) indicating that use of a single regenerative dose is reasonable. Where this was not the case (i.e. generally for palaeodose values over 20 Gy), multiple regenerative doses were applied which bracket the true palaeodose ($R_1 < N < R_2$) (refer Appendix A4.3.2).
6.4.2.2 Dose Rate Measurement

Twelve samples were selected for radionuclide analyses ($\alpha$, $^{232}$Th, $^{238}$U, and $^{40}$K). Three samples were taken from each of two profiles; the first was a 2.5 metre auger core taken from the Jinnmium sand sheets (JG-2), which grades from red sands to pisolitic red sands. The second profile was a 3.5 metre section taken from Sandy Creek Gorge that includes streaky red and grey horizons considered to be representative of a series of palaeosols. Another six samples, with various degrees of mottling or redness, were chosen for determination of dose rate and subsequent OSL determinations.

U-series dating was also undertaken on pisolitic material from the base of the above two profiles. Facilities for all U-series determinations were provided by ANSTO, with sample processing and chemistry based on methods outlined by Short et al. (1989) and Gilmore and Hemingway (1995). Measurement of isotopic concentrations of $^{236}$U and $^{238}$Th are made using high-resolution gamma spectroscopy (Canberra Industries GR5022 fitted with a NaI annulus) and alpha-particle spectrometry (EG & G Octete PC Alpha Spectrometer), with analytical uncertainties of 5 % based on counting statistics, variability in machine response and uncertainty in blank corrections. Details of chemical separations are outlined in Appendix A4.4. The results will be compared with thick-source alpha counting conducted for TL age determinations on similar deposits, at the University of Wollongong.

6.5 Results

Section diagrams of all rock-shelter, sand sheet and creek excavations are presented in Chapter Five (section 6.3.1). A summary of TL age determinations for all auger cores and excavations is given in Table 6.1, and detailed in Appendix A4.2.1. OSL age determinations are similarly summarised in Table 6.2, and detailed in Appendix A4.3.3 and A4.4.2 respectively. An outline of how radial plots are constructed is given in Appendix A4.3.2. The chronostratigraphic results are presented in the discussion below.
### 6.5.1 Thermoluminescence (TL) dating

Table 6.1 Thermoluminescence (TL) age estimates, grouped according to location. All palaeodose estimates are calculated from the 375°C peak, except those marked with an asterix (*). The latter are derived from stepped plateaux (using the 325°C peak), hence the corresponding age determinations should be considered maximum values.

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Source</th>
<th>Sample Depth (cm)</th>
<th>Palaeodose (Grays)</th>
<th>Dose Rate (µGy/yr)</th>
<th>TL age (ky BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gr-1</td>
<td>Auger</td>
<td>90</td>
<td>2.0 ± 0.3</td>
<td>908 ± 29</td>
<td>2.2 ± 0.3</td>
</tr>
<tr>
<td>Goor-1</td>
<td>Excavation</td>
<td>95</td>
<td>23.7 ± 2.2</td>
<td>1220 ± 30</td>
<td>19.4 ± 1.9</td>
</tr>
<tr>
<td>Goor-1</td>
<td>Excavation</td>
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<td>5.9 ± 1.0</td>
<td>962 ± 28</td>
<td>6.1 ± 1.0</td>
</tr>
<tr>
<td>Gu-2</td>
<td>Auger</td>
<td>180</td>
<td>11.1 ± 0.9</td>
<td>1206 ± 31</td>
<td>9.2 ± 0.8</td>
</tr>
<tr>
<td>JG1</td>
<td>Auger</td>
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<td>22.4 ± 1.9</td>
<td>1428 ± 31</td>
<td>15.7 ± 1.4</td>
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<tr>
<td>JG2</td>
<td>Auger</td>
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<td>49.3 ± 4.3</td>
<td>1216 ± 28</td>
<td>40.5 ± 3.7</td>
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<td>JG2</td>
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<td>84.7 ± 6.1</td>
<td>1112 ± 29</td>
<td>76.1 ± 5.8</td>
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<td>JG4</td>
<td>Auger</td>
<td>420</td>
<td>40.7 ± 2.9</td>
<td>1053 ± 27</td>
<td>38.7 ± 2.9</td>
</tr>
<tr>
<td>JG4</td>
<td>Auger</td>
<td>590</td>
<td>93.2 ± 8.0</td>
<td>1275 ± 29</td>
<td>73.1 ± 6.5</td>
</tr>
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<td>9.1 ± 0.9</td>
<td>968 ± 30</td>
<td>9.4 ± 1.0</td>
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<tr>
<td>Ka-4</td>
<td>Auger</td>
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<td>6.3 ± 0.5</td>
<td>1075 ± 31</td>
<td>5.8 ± 0.5</td>
</tr>
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<td>Ka-4</td>
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<td>27.5 ± 2.8</td>
<td>1856 ± 34</td>
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<td>956 ± 28</td>
<td>4.4 ± 0.4</td>
</tr>
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<td>1034 ± 29</td>
<td>7.1 ± 0.6</td>
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<td>1055 ± 29</td>
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<td>1464 ± 25</td>
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</tr>
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<td>1291 ± 29</td>
<td>6.2 ± 0.5</td>
</tr>
<tr>
<td>Karl-3</td>
<td>Excavation</td>
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<td>13.4 ± 1.3</td>
<td>1206 ± 29</td>
<td>11.1 ± 1.1</td>
</tr>
<tr>
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<td>13.6 ± 1.1</td>
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<td>6.8 ± 0.6</td>
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<td>1338 ± 33</td>
<td>10.4 ± 1.3</td>
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<td>KR99CP</td>
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<td>6.8 ± 0.5</td>
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<td>SC1</td>
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<td>1130 ± 28</td>
<td>6.0 ± 0.5</td>
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<td>SC1</td>
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<td>1564 ± 29</td>
<td>9.0 ± 1.0</td>
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<td>1477 ± 27</td>
<td>7.2 ± 0.5</td>
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<td>Profile</td>
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<td>1333 ± 25</td>
<td>2.3 ± 0.5</td>
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<td>Profile</td>
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<td>3469 ± 65</td>
<td>3.8 ± 0.4</td>
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<tr>
<td>SCG</td>
<td>Profile</td>
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<td>22.7 ± 1.8*</td>
<td>3652 ± 58</td>
<td>6.2 ± 0.5</td>
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<td>1817 ± 55</td>
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<td>SCG</td>
<td>Profile</td>
<td>357</td>
<td>27.0 ± 2.1</td>
<td>3113 ± 66</td>
<td>8.7 ± 0.7</td>
</tr>
</tbody>
</table>
Chapter Six – Luminescence Dating

Jinmium

The sediments sampled between the major sites of Jinmium and Goorurarmum yield significantly older depositional ages than those sampled elsewhere in the Keep River region, with similar estimates of ~ 40 ky BP (W2969 and W2971) at about 400 cm depth (Table 6.1), and ~ 75 ky BP (W2972 and W2970) around 550 - 600 cm (Table 6.1). These results are in broad agreement with previous age determinations of the sand sheets around Jinmium (Fullagar et al., 1996).

Goorurarmum

TL determinations on sediment samples from the Goorurarmum catchment indicate the sand sheets are generally well bleached. The temperature plateau comparisons extend between 300 and 500°C, which indicate good TL resetting prior to final deposition (David Price, pers. comm., 2000). However, the TL ages of the two samples taken from the Goorurarmum (Goor-1) excavation are the inverse of their order of depth at 19.4 ± 1.9 ky BP at 95 cm (W3033) and 6.1 ± 1.0 ky BP at 155 cm (W3034) (Fig. 5.7). The older sample exhibited a truncated temperature plateau (Fig. 6.4 and Fig. 6.7), which indicates that this sediment was not completely reset at the time of deposition or contained older material. Additionally these samples displayed different secondary (laboratory generated) TL glow curve characteristics (Fig. 6.5), indicating a mixed provenance of quartz grains (Price, 1994b). These quartz grains may derive from different geographical sources or from different formation sequences in a single bedrock outcrop. The overall results indicate that the sand sheets around Goorurarmum have been accumulating for at least 10 ky BP.
Figure 6.4  Examples of the temperature plateau for Goor-1 samples taken at 95 cm (W3033) and 155 cm (W3034). Note the foreshortened temperature plateau in W3033, which is similar to those found in samples from the original Jinmium rock shelter excavation (Fullagar et al., 1996).

Figure 6.5  Examples of differing second glow curves for Goorurarmum (W3033 and W3034), indicating differing provenance of the sedimentary material.
Karlinga

TL determinations of the Karlinga sand sheet sediments indicate that they are generally well bleached, and as for Goorurarmum, the temperature plateaux extend between 300 and 500°C, which indicates the sediments are well-bleached prior to final deposition. The sample Ka-4 (W2793) taken near the edge of the Karlinga sand sheet (Fig. 5.2) at about 360 cm depth, had a relatively high water content (13 %) and radiation flux (~2000 µGy.yr⁻¹) compared to other samples from this site (refer Appendix A4.2.1). This probably reflects the position of the water table at the time of field sampling. The calculated age of the sample, using this high water content, is 14.8 ± 1.5 ky BP (Table 6.1).

Of the five samples taken from the Karlinga north excavation (Karl-3), two in the upper metre (Fig. 5.8) show an age reversal (3.8 ± 0.5 ky BP at 30 cm and 2.1 ± 0.2 ky BP at 60 cm), which may be attributed to bioturbation. The oldest age of 13.6 ± 1.1 ky BP in the deepest sample (Table 6.1) is consistent with above age estimate for the sand sheets around Karlinga.

North of this excavation site, two samples KN-2 (W2973) and KN-3 (W2974) exhibit quite different second glow-curve characteristics (e.g. Fig. 6.6), which is indicative of a sediment population(s) of differing provenance than other sediments around Karlinga (Price, 1994b). At the creek site east of Karlinga (KR99CP), the samples exhibit acceptable TL characteristics but fall into two age groups, the deeper of which have the more recent age. At 95 cm and 175 cm depth, the TL ages were 7.9 ± 0.7 ky BP (W3040) and 10.4 ± 1.3 ky BP (W3041) respectively (Fig. 5.9). At 225 cm and 320 cm the TL ages were 5.9 ± 0.5 ky BP (W3042) and 6.8 ± 0.5 ky BP (W3043) respectively (Fig. 5.9). Despite attempts to remove slumped material and sample from parallel horizons (Fig. 5.3), the results may represent a slumped or cross-channel sequence.
Figure 6.6 Examples of differing glow curves for auger samples KN-2 (W2973) and KN-3 (W2974), indicating a different provenance for sediments from these two sites.

**Sandy Creek**

With one exception (W2980), the samples from Sandy Creek transect exhibited stepped temperature plateaux characteristics (Fig. 6.7). This may indicate the samples have been insufficiently bleached or were re-exposed enough to minimise the entire TL energy spectrum between 300 and 500°C (Price, 1994a). These samples were analysed at both 325°C and 375°C, with the ages computed at the lower temperature more likely to represent the timing of the last period of sediment mobility, although according to David Price (pers. comm., 2000) this may still retain a percentage of previously acquired signal and therefore should be regarded as a maximum value. Samples taken nearest to Sandy Creek (SC1), at 55 cm and 200 cm, yielded identical ages of 3.6 ± 0.4 ky BP at 325°C (Table 6.1).

Taken at a further distance from Sandy Creek, the SC2 auger at 200 cm returned an age of 6.0 ± 0.5 ky BP using the 325°C peak and 7.6 ± 0.6 ky BP using the 375°C peak, indicating that any previous TL signal has been effectively minimised (David Price, pers. comm., 2000). The
sample taken the furthest away (~ 1 km) from Sandy Creek (SC3), exhibited a single
temperature plateau extending between 275°C and 500°C, indicating that the age of 7.2 ± 0.5
ky BP at 200 cm represents a reliable estimate of the depositional age (David Price, pers.
comm., 2000).

![Figure 6.7 Example of the stepped temperature plateau that is typical of the Sandy Creek sediments, this sample (W3044) was taken from Sandy Creek Gorge at 57 cm.](image-url)

Samples taken at Sandy Creek Gorge also reveal stepped plateau characteristics, with the exception of the sample taken from the lowest depth at 357 cm. Two samples, SCG-57 and SCG-214, were analysed only at 325°C, and returned an age of 2.3 ± 0.5 ky BP and 6.2 ± 0.5 ky BP respectively (Table 6.1). The sample taken at 126 cm returned an age of 3.0 ± 0.3 ky BP using the 325°C peak and 3.8 ± 0.4 ky BP using the 375°C peak. The samples taken at 321 cm returned an age of 9.2 ± 0.8 ky BP using the 325°C peak and 11.8 ± 1.0 ky BP using the 375°C peak. The sample taken at 357 cm exhibited acceptable TL characteristics and an apparently reliable TL age of 8.7 ± 0.7 ky BP (David Price, pers. comm., 2000). The age profile for this site is significantly less than was anticipated from the presence of the palaeosol horizons. Comparative dates are derived below from OSL dating and U-series ages of pisolites taken from the base of this sequence.
6.5.2 Optically Stimulated Luminescence (OSL) dating

Table 6.2 OSL age determinations, grouped according to location, and calculated using central age palaeodose and dose rate determined from thick-source alpha-counting (TSAC) and high-resolution gamma spectrometry for the two rock-shelter samples (*).

<table>
<thead>
<tr>
<th>Sample Code</th>
<th>Sample Depth (cm)</th>
<th>Palaeodose (Grays)</th>
<th>Dose Rate (uGy/yr)</th>
<th>OSL age (ky BP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goor-2</td>
<td>20</td>
<td>0.4 ± 0.01</td>
<td>760 ± 41*</td>
<td>0.53 ± 0.14</td>
</tr>
<tr>
<td>Goor-1</td>
<td>50</td>
<td>1.3 ± 0.03</td>
<td>1220 ± 30</td>
<td>1.1 ± 0.03</td>
</tr>
<tr>
<td>Goor-1</td>
<td>100</td>
<td>3.1 ± 0.05</td>
<td>1220 ± 30</td>
<td>2.5 ± 0.07</td>
</tr>
<tr>
<td>Goor-1</td>
<td>175</td>
<td>5.2 ± 0.08</td>
<td>1206 ± 31</td>
<td>4.3 ± 0.13</td>
</tr>
<tr>
<td>Goor-1</td>
<td>220</td>
<td>17.2 ± 0.23</td>
<td>1206 ± 31</td>
<td>14.3 ± 0.41</td>
</tr>
<tr>
<td>Karl-1</td>
<td>27</td>
<td>19.7 ± 0.27</td>
<td>1064± 75*</td>
<td>18.5 ± 1.38</td>
</tr>
<tr>
<td>Karl-3</td>
<td>90</td>
<td>3.4 ± 0.05</td>
<td>1378 ± 40</td>
<td>2.5 ± 0.08</td>
</tr>
<tr>
<td>Karl-3</td>
<td>150</td>
<td>11.4 ± 0.18</td>
<td>1249 ± 34</td>
<td>9.1 ± 0.29</td>
</tr>
<tr>
<td>Karl-3</td>
<td>210</td>
<td>24.2 ± 0.28</td>
<td>1252 ± 40</td>
<td>19.4 ± 0.64</td>
</tr>
<tr>
<td>Karl-3</td>
<td>240</td>
<td>23.4 ± 0.55</td>
<td>1297 ± 26</td>
<td>18.0 ± 0.56</td>
</tr>
<tr>
<td>KR99CP</td>
<td>95</td>
<td>14.4 ± 0.28</td>
<td>857 ± 28</td>
<td>16.9 ± 0.64</td>
</tr>
<tr>
<td>KR99CP</td>
<td>320</td>
<td>16.2 ± 0.32</td>
<td>1885 ± 42</td>
<td>8.6 ± 0.25</td>
</tr>
<tr>
<td>SCG</td>
<td>57</td>
<td>4.2 ± 0.06</td>
<td>1333 ± 25</td>
<td>3.1 ± 0.07</td>
</tr>
<tr>
<td>SCG</td>
<td>126</td>
<td>15.8 ± 0.22</td>
<td>3490 ± 65</td>
<td>4.5 ± 0.10</td>
</tr>
<tr>
<td>SCG</td>
<td>321</td>
<td>24.5 ± 0.30</td>
<td>1828 ± 55</td>
<td>13.4 ± 0.44</td>
</tr>
<tr>
<td>SCG</td>
<td>357</td>
<td>43.2 ± 0.59</td>
<td>3113 ± 66</td>
<td>13.9 ± 0.35</td>
</tr>
</tbody>
</table>

6.5.2.1 Palaeodose

Goorurarmum

Figure 6.8a shows the $T_r/T_a$ ratios obtained from samples from the Goorurarmum rock shelter (Goor-2) and sand sheet (Goor-1) excavation. Sensitivity changes are indicated by a slight increase in the $T_r/T_a$ ratio with preheat temperature, but the corresponding palaeodose estimates
are unchanged (Fig. 6.8b), indicating that the test dose OSL signal corrects sufficiently for changes in OSL sensitivity between the natural and regenerative dose cycles.

![Figure 6.8](image)

**Figure 6.8** (a) Test dose OSL (T_r/T_n) ratios and (b) palaeodose estimates obtained at preheat temperatures ranging from 160 – 300°C using an SAR protocol applied to 24 single aliquots of quartz from the Goorurarmum rock shelter, and from four different depths (50, 100, 150, 220 cm) of the Goorurarmum sand sheet excavation. The dashed line in (a) corresponds to a unit test dose OSL ratio (T_r/T_n = 1) that indicates no change in sensitivity between the natural and regenerative cycles. The dashed lines in (b) correspond to the average palaeodose for each sample.

The palaeodose estimates of the Goor-1 sand sheet excavation at 50, 100, 175 and 220 cm depths are in respective stratigraphic order of 0.4, 3.1, 5.2 and 17.2 Gy. The deepest sample at
220 cm gives a value over three times that at 150 cm, and despite the low dispersion shown using either MAA or SAR protocols, the possibility of some bedrock contamination cannot be ruled out.

Insufficient bleaching may be detected by scatter in $D_b$ results, shown on radial plots by the spread greater than accommodated with ± 2 band projected from y-axis. The low dispersion in the radial plots (Fig. 6.9) of the Goorurarmum rock shelter (Goor-2-20) sediments indicate they are surprisingly well bleached. Further confidence of laboratory protocol and palaeodose estimates was obtained from a double-regenerative test in which a known regenerative dose is repeated (on a 0.5 mm aliquot) to give a similar palaeodose estimate that is accommodated within +/- 2 sigma band projected from the y-axis (inset of Fig. 6.9).

Figure 6.9  Radial plot of palaeodose estimates for the Goorurarmum rock shelter at 20 cm depth. Inset shows palaeodose estimates for a double-regenerative test using a single regenerative dose of 0.4 Gy on 12 aliquots using a mask size of 0.5 mm.
Figure 6.10  Radial plots of palaeodose estimates for the Goorurarmum sand sheet samples at (a) 50, (b) 100, (c) 175 and (d) 220 cm. Inset shows palaeodose estimates for a double-regenerative test using a single regenerative dose of 1.5 Gy at 50 cm, 6.7 Gy at 175 cm and 17.5 Gy at 220 cm.
Samples from the sand sheet excavation show much greater dispersion in palaeodose estimates, which increase with depth (6.10a - d). The OSL palaeodose estimate of 3.1 ± 0.05 Gy at 100 cm is significantly less than the corresponding TL estimate of 23.7 ± 2.2 Gy. This large discrepancy can be explained if the sample was deposited as a result of a rapid depositional event allowing the OSL (325ºC) peak to be completely reset but not the TL (375ºC) peak.

A lesser difference is also evident between the TL (11.1 ± 0.9 Gy) and OSL (5.2 ± 0.08 Gy) palaeodose estimate for Goor-1 at 175 cm. The sample may comprise a mixed population of poorly bleached and well bleached quartz, accounting for the large scatter in palaeodose values evident from the radial plot (Fig. 6.10c). The scatter observed at 220 cm may be similarly explained, and is further supported by the outliers in the double-regenerative test (inset Fig. 6.10d). Thus the palaeodose estimate of 17.2 ± 0.23 Gy at 220 cm may be a slight overestimate and should therefore be taken as a maximum.

**Karlinga**

Compared to the Goorurarmum rock shelter, the Karlinga rock-shelter samples show significantly greater scatter, as evident in the dispersion shown in double-regeneration plot (inset of Fig. 6.11) indicating they are less well bleached. The Karlinga rock-shelter sediments may derive from local bedrock material that has not been fully bleached at deposition. In addition, the rock shelter sediment show little temperature sensitivity but have a significantly lower $T_r/T_n$ ratio (0.74 ± 0.053) (Fig. 6.12) than those from the Goorurarmum (Goor-2) rock shelter (0.97 ± 0.073). This low sensitivity probably indicates the rapidly bleached traps (325ºC) are saturated but the slowly bleached traps (375ºC) are empty, and are sensitised by exposure on the OSL machine (Jon Olley, pers. comm., 2001). A partial analysis of the Karlinga rock-shelter sample by TL provided a palaeodose estimate of 40.25 Gy (D. Price, pers. comm., 2002), which is evidently much higher than the OSL palaeodose estimate and most likely indicates that these rock-shelter sediments have seen very little exposure to light. A minimum palaeodose of around 14 Gy may be a more accurate indicator of the depositional age.
of the sediments at 27 cm depth, although this value is not much less than the central palaeodose estimate of 19.7 ± 0.27 Gy.

Figure 6.11 Radial plot of palaeodose estimates for the Karlinga (Karl-1) rock shelter. Circles represent estimated palaeodose values using a single regenerative value (D₂ = R₁), and the diamonds estimated palaeodose values using bracketed regenerative values (R₁ < De < R₂) for the SAR protocol. Inset shows palaeodose estimates for a double-regenerative test using a single regenerative dose of 18 Gy on 12 aliquots using a mask size of 0.5 mm.

With the exception of the deepest samples at 210 cm and 240 cm, the samples from the Karlinga sand sheet excavation (Karl-3) also show little OSL sensitivity with temperature, and have an average Tₛ/Tₐ ratio less than 1.0 (Fig. 6.12). All of the samples from the Karl-3 excavation show a significant amount of dispersion that increases with depth, as evident from the increasing standard error (Table 6.2). These samples probably comprise a mixed population of well-bleached and poorly bleached quartz. The palaeodose estimates of the Karl-3 samples at 90, 150, 210 and 240 cm depths are also in respective stratigraphic order of 3.4, 11.4, 24.2 and 23.4 Gy. No bedrock material was encountered during sampling but the water table was reached on the lowest sample at 240 cm.
Figure 6.12  As for 6.10, for samples from the Karlinga rock shelter (Karl-1 at 27 cm) and Karlinga sand sheet excavation (Karl-3) from depths of 90, 150, 210 and 240 cm.
Figure 6.13  Radial plot of palaeodose estimates for the Karlinga (Karl-3) sand sheet excavation at (a) 90, (b) 150, (c) 210 and (d) 240 cm. Circles represent estimated palaeodose values using a single regenerative value ($D_e = R_1$), and the diamonds estimated palaeodose values using bracketed regenerative values ($R_1 < D_e < R_2$) for the SAR protocol. Inset shows palaeodose estimates for a double-regenerative test for a regenerative dose of 25 Gy at 210 cm and 40 Gy at 240 cm.
Karlinga Creek

The Karlinga Creek samples show increasing sensitivity (T/\text{T}_b\text{ ratio}) with preheat temperature, but there is negligible thermal transfer in the corresponding palaeodose estimates (refer Appendix A4.3.3). As in the sand sheet, the dispersion in palaeodose estimates indicates the sediments probably comprise a mixed population of well-bleached and poorly bleached grains. The estimated palaeodose of 14.4 ± 0.3 Gy and 16.2 ± 0.3 Gy at 95 cm and 320 cm respectively, are both greater than the corresponding palaeodose values of 6.8 ± 0.6 Gy and 12.9 ± 1.0 Gy estimated from TL dating.

Figure 6.14 Radial plot of palaeodose estimates for the Karlinga Creek site (KR99CP) at (a) 95 cm and (b) 320 cm.
Sandy Creek

All the Sandy Creek Gorge samples show a sensitivity change with temperature (Fig. 6.15a), but again the average palaeodose at the corresponding range of temperatures (160 to 300°C) implies negligible thermal transfer (Fig. 6.15b). The palaeodose estimates for samples at 57, 126, 310 and 357 cm increase respectively from 4.2, 15.8, 24.5 to 43.2 Gy. The deepest sample at 357 cm shows the greatest degree of dispersion using either MAA and SAR protocols (refer Appendix A4.3.3). This dispersion, also shown in the radial plot diagrams (Fig. 6.16), indicates the probable presence of incompletely bleached grains in this alluvial sample. As such, the estimated palaeodose value should be considered a maximum.
Figure 6.16  As for Figure 6.13 for samples from Sandy Creek Gorge at (a) 57, (b) 126, (c) 321 and (d) 357 cm. A regenerative dose of 4.7 Gy at 57 cm, 24.4 Gy at 321 cm and 40 Gy at 357 cm was used for double-regenerative tests (shown inset).
6.5.2.2 Dose Rate

Comparisons of $^{238}\text{U}$ and $^{228}\text{Th}$ data calculated by high-resolution gamma spectroscopy (HRGS) and alpha-particle spectrometry (APS) indicate the former values are 2 to 6 times higher for $^{238}\text{U}$ and approximately 0.6 times less for $^{228}\text{Th}$ (Table A6.3). The reason for this is unknown but may be attributed to differences in U and Th chemistry (Andrew Jenkinson, pers. comm., 2002), or may reflect problems in the radiochemistry methods, or the analytical programs used to calculate the individual radionuclide concentrations (Bert Roberts, pers. comm., 2002).

More significantly, the estimated values for U, Th and K obtained by HRGS and APS provide dose rates that are 30 – 50 % of that estimated from thick-source alpha counting (TSAC). Although the absolute numbers may be imprecise, the radionuclide ratios should be reliable and can be used to provide some estimate of disequilibria. Thus dose rates estimated from TSAC where available are used for age calculations (Table 6.2) and use of TSAC results is justified by the secular equilibrium which generally prevails in the U-series (mean $^{238}\text{U}/^{226}\text{Ra}$ is $1.1 \pm 0.39$ and $^{210}\text{Pb}/^{226}\text{Ra}$ is $0.9 \pm 0.22$) and Th-series (mean $^{228}\text{Th}/^{228}\text{Ra}$ ratio is $0.9 \pm 0.19$). By mainly using TSAC, the only variable in comparisons of TL and OSL techniques is the palaeodose, which in any case is the most likely source of any major age discrepancy.

Dose rate calculations were individually assessed, for the samples where TSAC was not undertaken. For the Karlinga sand sheet samples at 90, 150 and 210 cm, dose rates were calculated from the average value of that estimated from bracketing sample depths – i.e the dose rate for Karl-3 at 90 cm is the average of the dose rate estimated by TSAC at 60 cm and 120 cm depth. If instead the HRGS results were used, the calculated ages for these three samples would be almost double that estimated using the bracketed dose rate values, and also inconsistent with the chronostratigraphy determined by TL dating. For the Goorurarmum sand sheet sample (Goor-1 at 220 cm), the 100% error in U, Th and K concentrations estimated from HRGS would render any subsequent age calculations meaningless. The average dose rate of $1.13 \pm 0.312$ Gy/ka is used in preference, and is estimated from TSAC for the shallower depths from the same Goorurarmum site.
The mean dose rate for all samples calculated using TSAC, excluding the Sandy Creek Gorge samples, is $1.3 \pm 0.29 \text{ Gy.ky}^{-1}$. The mottled sediments from Sandy Creek Gorge have a higher dose rate of $3.0 \pm 0.83 \text{ Gy.ky}^{-1}$, which reflects the higher U, Th and K concentrations in these samples. The 12 samples selected for HRGS and APS, which include the highly mottled sediments from Sandy Creek Gorge, show no apparent correlation between the degree of mottling and relative disequilibria in either the U-series or Th-decay series. Rather virtually all the samples indicate relative secular equilibrium, although the excess of $^{234}\text{U}$ over $^{230}\text{Th}$ and $^{228}\text{Th}$ over $^{232}\text{Th}$ does indicate some post-depositional migration and precipitation of $^{234}\text{U}$ and $^{228}\text{Th}$ with amorphous iron oxides and oxyhydroxides.

For the two rock-shelter samples, Karl-1 (27 cm) and Goor-2 (20 cm), the dose rates were estimated from HRGS, acknowledging some degree of uncertainty with the results. Whilst the K concentrations values do not significantly affect the total dose rate, the low $^{40}\text{K}$ values in other samples measured by HRGS compared to the equivalent K concentration estimated by flame photometry (for TL determinations) indicate that U and Th concentrations may also be underestimated. The radionuclide ratios indicate secular equilibrium in the U-series for both samples. However, in the Karl-1 sample possible disequilibrium and redistribution of Ra in the Th-series is indicated from a low $^{228}\text{Th}/^{228}\text{Ra}$ ratio (0.41), which may result in an underestimate of the dose rate and an overestimate of the luminescence age. Thus the total dose rates estimated for Karl-1 ($1.06 \pm 0.075 \text{ Gy/ka}$) and Goor-2 ($0.67 \pm 0.169 \text{ Gy/ka}$) may be too low, and the age for these sites may be overestimated and should be taken as a maximum and with a maximum 15% error.
6.5.3 Comparison of OSL and TL results

As indicated above, similar palaeodose estimates were obtained from OSL determinations, using MAA and SAR protocols ($R^2 = 0.92$), for values less than about 20 Gy. The correlation between OSL and TL palaeodose determinations is poor. As indicated above (refer 6.5.2.1), the large disparity between the palaeodose estimate of 19.4 Gy by TL and 3.1 Gy by OSL for Goor-1 at 100 cm depth probably reflects the effect of a depositional event associated with limited sunlight exposure which reset the rapidly bleached 325°C TL peak but not the more robust 375°C TL peak (resulting in a foreshortened plateau) (Fig. 6.4). Thus excluding Goor-1-100 cm and Karl-3-90 cm (whose TL value is an approximate calculation), OSL palaeodose estimates are approximately 20% greater than the corresponding TL estimate. For SCG-357, the OSL palaeodose estimate (~43 Gy) is almost double that of the corresponding TL estimate (~27 Gy). The OSL signal is more readily bleached during transport and deposition hence the greater TL age over the OSL age is unusual and not easily explained.

![Comparison of TL and OSL palaeodose estimates](image)

Figure 6.17 Comparison of TL and OSL palaeodose estimates. Samples should plot along the equilibrium line if there is a good correspondence between the two methods.
A poor correlation between TL and OSL palaeodose estimates may result where inadvertently bleaching by the laboratory illumination induces a stepped TL plateau, and only the 325°C TL peak is used for age calculations. Otherwise the 325°C TL and OSL palaeodoses should be similar although not exactly the same because of a contribution to the former from the underlying 375°C TL peak. The palaeodose value calculated using the 375°C TL peak of all samples with stepped-plateau is also approximately 20% greater than that calculated at 325°C. The step or depression of the plateaux may be attributed to partial exposure during transport in the field, releasing electrons trapped at lower energy (325°C) levels but insufficient to release those stored at deeper (375°C) levels (Price, 1994a). Alternatively, the use of yellow light (500 nm) filters in the TL laboratory may be removing a proportion of the 325°C signal (Spooner and Prescott, 1986; Smith, 1988; Spooner, et al., 1988) as demonstrated by Roberts (1997) (Fig. 6.18).

Please see print copy for Figure 6.18

Figure 6.18 Palaeodose ‘plateau test’ for aliquots of sample KTL167 processed under red (filled triangle) and yellow (open circle) light from Roberts (1997: 854, his figure 9(b)). Note the “double” or stepped plateau and partial erasure of 325°C peak under yellow illumination, compared to the full plateau under red illumination.

It might be questioned why only some samples prepared under yellow lights show significant loss of the 325°C TL signal, and why some samples without stepped TL plateau (e.g. SC3) still produce a lower palaeodose estimate than the corresponding OSL palaeodose estimate. It is
possible that yellow lights are affecting all samples and that the 20% difference between TL and OSL estimates is simply more apparent in samples of older age (Fig. 6.17). Two tests were conducted to see if there is a significant loss of the 325°C TL/OSL signal due to the use of yellow lights in the laboratory, or due to something inherent in the sample.

The first test involved a TL test on two samples, one with a stepped plateau (SCG-321) and one without (Goor-1-220). After being given a known dose of 100 Gy, three aliquots of each sample were exposed to red and another three to yellow light for 3 hours. If the yellow laboratory illumination had no effect, the TL glow curves for the ‘red light’ sample should be the same as the corresponding ‘yellow light’ sample. The results indicate that the 325°C peaks are diminished in both samples after 3 hours exposure to yellow light (Fig. 6.19). However, because the 375°C peak is dominant in both samples to start, the diminution in the 325°C peak is only slight. Consequently the age estimated from the 375°C peak should be fairly reliable. Further tests may be able to separate these overlapping peaks and accurately estimate the effect of yellow light exposure on each.

Figure 6.19 Comparative glow curves for two samples (a) Goor-1 at 220 cm and (b) SCG at 321 cm, exposed to red (red curve) and yellow light (yellow curve) for 3 hours. The latter sample has an initial stepped TL plateau. After 3 hours exposure to yellow illumination
the 325°C peak is diminished relative to the sample exposed under red illumination. Refer text for details.

The second test involved exposing aliquots of the same two samples to yellow light for different lengths of time to see if the OSL signal is proportionately diminished. This test assumes that the decline in the 325°C TL peak and OSL signal result from emptying of the same electron source traps (Aitken, 1998). After being bleached to the background count rate (using blue LEDs) and then given a known beta-dose of 20 Gy, three aliquots of each sample were exposed to yellow light for 1, 10, 100, 1000 and 10,000 seconds respectively (Fig. 6.20). Another three aliquots of each sample were exposed to red light for 10,000 seconds (~ 3 hrs) as a control (Fig. 6.20). The exposure times assumed a rapid decline (e.g. exponential) in the OSL signal with yellow light exposure. The SAR protocol (Murray and Wintle, 2000; Murray and Roberts, 1998) was used to calculate the doses.

The results show that whilst exposures of less than 1000 seconds to yellow light have no discernable effect, a 20–25% loss of the 325°C TL peak is measurable at 10,000 seconds (Fig. 6.20). This is longer than the estimated maximum exposure time of one hour for samples...
prepared and dated in the TL laboratory (David Price, pers. comm., 2003) (although this was unknown before the experiment) but some loss of the 325°C TL peak may be expected to occur within this time. Again, a more reliable estimate of age may be calculated from the 375°C peak (provided the sample was well bleached at the time of deposition) or from the OSL samples, which were prepared under red light. Agreement between these paired ages would confirm that the sample had been sufficiently bleached at the time of burial.

In summary, the results of the above tests indicate that prolonged exposure (~ 3 hrs) of samples to yellow illumination in the laboratory can result in a significant loss of the 325°C TL peak, which may induce a stepped-plateau in some samples. The stepped-plateau present in several of the Sandy Creek and Sandy Creek Gorge samples indicate that they have either been partially exposed in the field, or subject to prolonged exposure in the TL laboratory. It is unknown why only the samples from the one locality of Sandy Creek Gorge show these stepped plateaux. The majority of samples in the Keep River region have a dominant 375°C TL peak, which means that the adverse effects of yellow illumination and corresponding age determinations based on this peak are minimised. Thus the discrepancy between the OSL and TL age determinations (almost all of which are calculated from the 375°C TL peak) may only be partially explained by yellow light exposure. Additional discrepancy may be due to contamination of younger age grains, which may be masked in TL analyses by the large number of grains comprised in each aliquot. Hence, OSL age calculations which are based on small aliquots (10 - 20 grains) arguably provide a more reliable indication of the depositional age and dispersion of a population(s) of grains.
6.5.4 U-series dating of pisolites

Uranium series analysis of the pisolites from one of the auger holes near Jinmium gives an estimated age > 350 ky BP at 420 - 450 cm. This means that the pisolites come from an open system, which results in an excess of $^{230}$Th, and cannot be dated (Fig. 6.21). It is noted that the raw concentration of thorium (8.90 ± 0.260 ppm) is approximately twice that of the pisolites taken from Sandy Creek Gorge, and the uranium (0.996 ± 0.039 ppm) concentration is approximately one-sixth the value, indicating quite different groundwater influences.

The pisolites taken from Sandy Creek Gorge at about 550 cm depth give an estimated age of 45 ky BP ± 20 - 15 ky BP (Fig. 6.21). This age is significantly more than expected from the luminescence dating of the underlying sediments, which give an age of 9 ky BP from TL determinations or 13 ky BP from OSL determinations at about 360 cm depth. The pisolites from this site are considered to be in situ (refer 5.2.2.2). From the chronological evidence alone, at least one diastem in the sequence is assumed (Fig. 5.10).

![Isochron plot of U-series dating of pisolitic material from Jinmium and Sandy Creek Gorge, indicating an open and closed system for the former and latter sites respectively.](image.png)
6.5.5 Age-depth Curves

Age determinations from past and present TL, OSL and U-series dating are combined to provide age-depth curves for individual sites (Fig. 6.22), and collated for the Keep River region as a whole (Fig. 6.23). In theory, age-depth curves can allow calculation of the rates of accumulation of various components of the deposit (e.g. sediment, stone artefacts, shell) which when compared may provide some insight into the history of human occupation and the of the site environment and its surroundings (Hughes and Djohadze, 1980).

Figure 6.22 Age-depth curve for the sand sheets at Karlinga (Karl-3), Goorurarmum (Goor-1), Jinmium (Auger 4 and 5, from Fullagar et al., 1996), and for Sandy Creek Gorge. A line of best fit for all data shows a progressive increase in sedimentation from about 30 ka.

Age-depth curves of sand sheet and creek profiles from this study show relatively similar trends for each site (Fig. 6.22), allowing a general sedimentation rate to be calculated. Whilst the inflection point or curve-fitting is in effect subjective, the overall trend indicates that the sedimentation rate increases progressively from about 120 - 150 mm.ka\(^{-1}\) during the early Pleistocene to about 200 mm.ka\(^{-1}\) during the Holocene. The rates are slightly less if the creek sediments are excluded, but the overall increase in sedimentation is still valid. The Jinmium
sand sheet has the lowest overall sedimentation rate (~100 mm.ka\(^{-1}\)), whilst Sandy Creek Gorge has the highest overall sedimentation rate (~250 mm.ka\(^{-1}\)) and probably reflects the difference in alluvial transport and deposition of these sediments.

Figure 6.23 shows an age-depth curve of all luminescence ages (and the U-series age on the pisolites) determined from this and previous studies in the Keep River region. It is apparent that the regional trend follows that shown at the individual site level (Fig. 6.22) with a progressive increase in sedimentation rate from less than 100 mm.ka\(^{-1}\) in the early Pleistocene to over 200 mm.ka\(^{-1}\) during the Holocene. If only Holocene ages are considered, the age-depth curve reveals a constant sedimentation rate of ~250 mm.ka\(^{-1}\). The results however reveal a great degree of spread, and any local or short-term geochronological discontinuities may not be revealed by this general extraction of the data.

Figure 6.23 Age-depth curve combining all present and previously published (Fullagar et al., 1996) luminescence and U-series ages from the Keep River region. A line of best fit is drawn for the original Jinmium (C1) excavation and another for all other data (refer text for explanation).
The other obvious trend is the digression from the main curve of the original TL ages determined from the C1/I and C1/III excavation at Jinmium, which indicates they have been deposited at a significantly lower sedimentation rate and by a different process than sediments elsewhere in the region, or that something is aberrant in the luminescence ages themselves. This is equally applicable of the sediment trend shown from the Karlinga rock shelter (15 mm.ka\(^{-1}\)), although this was calculated from only a single OSL age. These results are discussed further below and in Chapter Seven.

6.6 Discussion

The following discussion presents a broad overview and diagrammatic summary of the chronostratigraphy of the rock shelters, sand sheets and creek profiles in the Keep River region as determined from past (Fullagar et al., 1996; Roberts, 1998a) and present results of TL and OSL dating.

6.6.1 Sedimentation Rates and Processes

The collective age/depth curve indicates that the sedimentation rate throughout the Keep River region has increased progressively from 100 mm.ka\(^{-1}\) during the late Pleistocene up to 250 mm.ka\(^{-1}\) during the Holocene. The range of accumulation rates at the individual site scale is similar to those determined from the collective age/depth curve. The difference in accumulation rates between individual sites largely reflects the depositional environment, such that higher accumulation rates (250 mm.ka\(^{-1}\)) are observed in higher energy river and creek sites, and lower accumulation rates (100 mm.ka\(^{-1}\)) are observed on the lower energy sand sheet sites. It is likely that sedimentation rates are likely to differ again for individual units (if these can be distinguished) within each site. The sedimentation rate of the excavation sequences on the sand sheets which comprise occupation records is similar to those which do not, hence the increase in sedimentation in the Holocene most likely results from natural processes, such as enhanced monsoonal activity in this part of northern Australia (Hubbard, 1995; Nott and Price,
1994) and/or the post-glacial marine transgression (Woodroffe, 1993). It is not possible to
discern from the available ages if rate of sedimentation changed significantly over the late
Holocene or in the past 200 years since European occupation. At Nauwalabila, in Arnhem
Land, Hope et al. (1995) also noted a progressive increase in sediment accumulation over 60
ka, and tentatively argued for an apparent cessation of sedimentation over the past 2 ka. High
resolution dating is needed to confirm whether the long-term increase in sedimentation reflects
a more regional trend.

There is an indication from the luminescence data that episodic rapid deposition of individual
or isolated units does occur. As indicated above, the discrepancy in the OSL (~ 3 Gy) and TL
(~ 19 Gy) palaeodose estimates from a sample from the Goorurarmum sand sheet (Goor-1) at
100 cm may reflect a rapid depositional event such as localised mass wasting of escarpment
bedrock, or dump of sediment during a storm. The event age may be indicated by the OSL age
of ~2.5 ky BP. Foreshortened plateaux were also noted in the original Jinmium rock shelter
and upper part of the nearby sand sheet (Auger 4) (Fullagar et al., 1996). These foreshortened
plateaux were considered to result from partial re-exposure following deposition (Fullagar et
al., 1996: 768). Alternatively, it is possible that these sediments also represent a similar rapid
depositional event to that at Goorurarmum.

Thus accumulation rates for smaller excavated areas may be higher than those calculated for an
entire site, with deposition beginning and ending over discrete periods (e.g. Stein et al., 2002)
and also over discrete areas. Thus the calculated accumulation rates do not always represent
continuous human occupation characterised by gradual accumulation of material, but rather
short-duration occupations that were repeated infrequently in the same area (Stein et al., 2002).
Accordingly, where there are enough data points to allow it, estimations of archaeological
accumulation rates should be calculated from the duration of accumulation between any two
points in time rather than from the total period of accumulation (e.g. Stein et al., 2002; Ward
and Larcombe, 2003).
6.6.2 Chronostratigraphy

6.6.2.1 Chronostratigraphy of the Sand Sheets

The chronology and first evidence of stone, seed and ochre in each of the sand sheet profiles which contain evidence of occupation is summarised in Fig. 6.24. The following discussion concentrates on the chronostratigraphy. Further analysis of the rate of artefact accumulation and sediment accumulation for each of the archaeological excavation sites is given in Chapter Seven (refer 7.3.3).

Figure 6.24 Ages and archaeological evidence from the three sand sheet excavations with occupation records in the Keep River region, including Karlinga (Karl-3), Goorurarmum (Goor-1) (this study) and Jinmium (Auger 4) (Fullagar et al., 1996).

In the Karlinga sand sheet excavation (Karl-3), the lowermost luminescence age of 13.6 ky BP (TL) or 18 ky BP (OSL) represents a minimum age for the beginning of sand sheet formation as there was no contact made with the underlying bedrock. Assuming that the respective OSL ages of 19.4 ky BP and 18 ky BP at 210 cm and 240 cm provide the more representative
estimate of depositional age than the TL age (refer 6.5.3), then there is either a major change and/or hiatus in sedimentation sometime between 18 ky BP and 9 ky BP. There is also a less distinct change or hiatus in sedimentation between 6 ky BP and 3 ky BP. There is no significant change in the stratigraphy to represent a sedimentary hiatus, although the presence of two cobbles layers between each of these two possible chronological ‘hiccups’ may be significant boundary markers (e.g. Robbins et al., 2000). These cobbles layers were not found in adjacent profiles, so are unlikely to represent a lag deposit, and may represent an anthropogenic feature. The peaks in artefact (stone tool) density occur above and below these cobbles layers, around 2.5 ky BP and 10 ky BP (Fig. 5.8).

The sand sheet excavation at Goorurarmum (Goor-1) effectively abuts the escarpment, and contact is made with an underlying bedrock horizon at about 2.5 m, which is dated to 14.3 ky ± 0.4 ky BP (Fig. 6.21). It is possible that the base of the Goorurarmum excavation represents an LGM surface. Between 14 ky BP and 6 ky BP there is either an increase in sedimentation or there is a chronological hiatus that is not evident from the stratigraphy. However, a TL age of 9.2 ± 0.1 ky BP at 180 cm in an adjacent auger (Gu-2) effectively fills this chronological gap, and highlights the discontiguous nature of sedimentation on the sand sheets. The inversion between the OSL age of 4.3 ± 0.1 ky BP at 180 cm and the TL age of 6.1 ± 0.1 ky BP at 155 cm may indicate some secondary mixing of the sediment profile. Either way the results indicate a slightly faster rate of sedimentation than the Karlinga or Jinmium sand sheets, with up to 180 cm deposited over 6 ka (Fig. 6.21). The indication of a rapid depositional event at 100 cm or around 2.5 ka (refer 6.6.1) may have exacerbated this process. The peak in artefact density occurs in upper 50 cm or around 1 ky BP (Fig. 5.7).

The chronology obtained from the Jinmium sand sheet excavation and adjacent auger hole (Auger 4) (from Fullagar et al., 1996) indicates a relatively constant rate of sedimentation from about 10.5 ky BP. Fullagar et al. (1996) note that stone artefacts are found throughout the deposit, but no peak is documented. Between Jinmium and Goorurarmum, luminescence dating indicates that the sand sheets are older than 76 ky BP (Fig. 6.25), the basal age limited to the 6
m length of auger. The results from this study lend support to the luminescence chronology determined by Fullagar et al. (1996) for the sand sheet sediments near the Jinmium site, which provided an age of 103 ± 14 ky BP at 5 m depth (Fig. 6.25). Thus the most recent phase of sand sheet accumulation in the Keep River region may be of the equivalent age (but not depth, Fig. 7.6) to those in Arnhem Land, which began to develop at 220 - 230 ky BP and 100 - 120 ky BP: these ages coinciding with the start of the last penultimate and last interglacials respectively (Roberts, 1991).

The Jinmium and Goorurarmum catchments are at a similar or slightly lower relative level as the Karlinga catchment and only a few kilometres further inland. Hence it may be presumed that sequences older than 20 ky BP do exist around Karlinga but were not sampled or dated in this study (Fig. 6.26). Alternatively it is possible that the palaeosurface over which these sand sheets have accumulated at Karlinga occurs at a higher relative level, so that only the more recent (Holocene) period of sedimentation is preserved and is preserved differentially. In contrast, the older (early Pleistocene) sediments around Jinmium represent a topographic low. Compared to the redder sands near Jinmium, the more leached sands at Karlinga (refer 5.4.3.1) also indicate that the water table, and hence a less permeable barrier, occurs at a higher relative level at this site.

The implication is that in the absence of any obvious regional chronological hiatuses, the spatial range of the chronostratigraphy is essentially limited by the relative level of the present surface and underlying palaeosurface topography (refer 4.5.2). There is a greater representation of Holocene age sediments in all of the sand sheet excavations. The collective ages hint at a possible continuity, albeit spatially variable, between Pleistocene and Holocene levels. Such dynamic spatial (not temporal) distribution of sedimentation is likely to impress upon the preservation of archaeological deposits.
Please see print copy for Figure 6.25
Figure 6.26  Chronostratigraphy of the Karlinga to Karlinga North transect.
6.6.2.2 Chronostratigraphy of Karlinga Creek and Sandy Creek

The calculated luminescence ages at the Karlinga creek site (KR99CP) (Fig. 5.9) imply there is an age inversion of the sediments. An age inversion might occur if well-bleached sediments were deposited at night (Bert Roberts, pers. comm., 2002), and although this may occur occasionally for one or two facies it is unlikely for an entire stratigraphic sequence. Alternatively, inverted luminescence ages might partly be explained by water contents and dose rate calculations (Feathers and Bush, 2000). Neither the TL (Tables 6.1) and OSL (Table 6.2) palaeodose values, nor the dose rate values indicate a significant inversion. The best conclusion from these data is that ages of all four samples are similar, and reflect a mixed population of presumably water-laid and partially-bleached sediments. The combined palaeodose (mean value 12.6 ± 3.27 Gy) and dose rate (mean value 1.6 ± 0.52 Gy.yr\(^{-1}\)) values give a mean depositional age of 7.7 ± 3.16 ky BP. The sedimentary characteristics of this creek site are indicative of infilling of a small alluvial swamp (refer 5.4.3.2), which from the luminescence ages, may have occurred sometime after ~ 10 ky BP.

In Sandy Creek Gorge, the age of the pisolithic palaeosol which forms the creek bed is estimated from U-series dating to be about 45 ky BP (Fig. 6.27). Similar ages were found for pisolithic deposits in Arnhem Land (Roberts, 1991), whilst slightly older ages of 66 ± 12 ky BP were obtained from pisolites in the Gilbert River, northern Australia (Nanson et al., 1991). According to Nanson et al. (1991), the induration of such ferricrete accumulations cannot occur during periods of sediment deposition, hence their presence provides a chronological marker of stratigraphic discontinuity. In the chronostratigraphic sections between Jinmium and Gooruramum (Fig. 6.25) and between Karlinga and Karlinga North (Fig. 6.26) the pisolithic deposits, wherever documented, are tentatively marked at 40 ky BP. However, not all pisolithic deposits are necessarily in situ and further dating is required before any regional interpretations can be made.
Figure 6.27 Chronostratigraphy of Sandy Creek Gorge and Sandy Creek transect. It should be noted that the TL age estimates are mainly derived from stepped plateaux and therefore represent maximum values.

At Sandy Creek Gorge, the pisolitic palaeosol is overlain by alluvial sediments dated by OSL from about 14 ky BP (Fig. 6.27). At shallower depths of 200 cm, comparative OSL ages of 6 – 8 ka are obtained for sand deposits at Sandy Creek Gorge and alongside Sandy Creek (Fig. 6.27). The majority of these show stepped TL plateaux (hence partial bleaching) which may signify the rapid deposition of these sediments. Stepped plateaux have also been observed in marine sediments from the Shoalhaven River by Price et al. (1999), which were to result from a rapid depositional event, such as a major storm or a tsunami.

The rapid deposition of the Sandy Creek sediments, may perhaps be compared with the infilling of Magela Creek in Arnhem Land at about 8 ky BP. Infilling of the Magela Creek occurred with sand supplied by gullyng of nearby sand aprons in association with the enhanced
monsoonal activity to the region during the post-glacial marine transgression (Roberts, 1991). Evidence of enhanced alluvial activity between 12 and 6 – 5 ka is also indicated from dated overbank deposits at Cabbage Creek, just south of Kununurra (Wende et al., 1997). Thus the proposed infilling of the Karlinga Creek site, alongside the rapid deposition of the sediments around Sandy Creek, may be indicative of a more regional event.

It is possible that as these smaller floodplain creeks became infilled, alluvial activity may have been concentrated in the main Keep River, just as it was in the main Magela Creek in Arnhem Land (Nanson et al., 1993: 298). This may have resulted in preferential preservation of some Pleistocene sequences, and follows Gregory’s (1998) conclusion that the major aspect of archaeological preservation in the Ord-Victoria region is fluvial. The further implication is that at the regional scale continuous archaeological sequences may be preserved near major rivers, but at the site specific scale archaeological sequences may be better preserved away from major rivers. Consequently, just as the ecology in the Keep River region retains both continuity and change (Atchison, 2000), so to does the geoarchaeology (refer 2.3).

6.6.2.3  Chronostratigraphy of Rock-shelter Excavations

OSL determinations indicate that the rock-shelter sediments at Goorurarmum are well bleached and have accumulated over much less time (0.5 ± 0.14 ky BP) than those at Karlinga (18.5 ± 1.4 ky BP). Given the large boulders protecting the opening of the Karlinga rock shelter, the poorer bleaching characteristics are not unexpected. However, the significantly old age at Karlinga at such a shallow depth of 27 cm is surprising. The quartz grains in the Karlinga rock shelter have a consistently low regeneration ratio (T_r/T_n >> 1) (refer 6.5.2.1), and are analogous to the weakly luminescent (‘dim’) grains in the Jinmium rock-shelter previously described by Roberts et al. (1999: 392). These weakly luminescent grains are probably derived from the slow disintegration of the overlying and surrounding bedrock and as such will not provide a reliable age estimate or sedimentation rate of these rock-shelter sediments using either TL or OSL dating techniques. Moreover the 18.5 ky BP age is inconsistent with the much younger
radiocarbon estimates of charcoal samples from the same sediments (refer 7.2.1), and also with other luminescence and radiocarbon ages for rock-shelter excavations undertaken in the Keep River region (Fig. 6.28 and Fig. 7.7). The divergence of luminescence dates on the age-depth curve (Fig. 6.23) further support the view that the sediments in both the Karlinga and Jinmium (C1) rock-shelter excavation probably include material from the overlying bedrock.

Please see print copy for Figure 6.28

Figure 6.28  Ages and archaeological evidence from five rock-shelter excavations from past and present research in the Keep River region, including Karlinga (Karl-1), Goorurarmum (Goor-2) (this study), Punipunil (PP1), Granilpi (G1) (Atchison, 2000, Atchison et al., in prep.), and Jinmium (C1) (Fullagar et al., 1996; Roberts et al., 1998; Atchison et al., in prep.). The OSL ages for the Jinmium profile represent central age estimates from single-grain dating (from Roberts et al., 1998).
Roberts et al. (1998) argue that the true age of the Jinnium rock-shelter sediments should be bracketed by the minimum and central age estimates of 1.9 to 6.9 ky BP from single-grain OSL analyses. Thus, disregarding the 18.5 ky BP estimate for the Karlinga rock shelter, the rock shelters in the Keep River region are all late Holocene in age (Fig. 6.28). The earliest preservation of archaeobotanical (Atchison, 2000; Atchison et al., in prep.) and stone artefact records (Fullagar et al., 1996) is also around 4 ka. The OSL age of the sediments in the Goorurarmum and Karlinga rock shelters are younger than that indicated from presence of points (Fig. 6.28), indicating that representative sediments from the period of point production have been reworked or lost, or that the points themselves have been moved or reworked. The seed and stone artefact chronology for Granilpi and Jinnium are considered to generally support the young sediment chronology provided by the OSL and radiocarbon dates (Atchison, 2000; Atchison et al., in prep.), despite any apparent disturbance or contamination (Roberts et al., 1998).

The luminescence ages of the surrounding sand sheets sediments correspond with the main regional trend and validate the Pleistocene age of the surrounding sand sheet sediments. So both the Jinnium and Karlinga rock-shelters comprise sediments and associated cultural sequences that are much younger than those outside the rock shelter. The presence of older and deeper deposits outside rock shelters has also been noted in Kakadu (Allen and Barton, 1989), and north Queensland (Morwood, 1981; Morwood et al., 1995). Thus, contrary to the view that enclosed rock-shelters offer greater potential for older sequences (Lourandos and David, 1998), better preservation of older sequences may actually be found in more open sites. However, the antiquity of the rock art record is not necessarily predicated by either the luminescence age of the rock shelter or the adjacent sand sheet sediments (refer also Bednarik, 2002). Further discussion of the stone-artefact and rock art record is given in Chapter Seven (refer 7.3).
6.7 Conclusions

Useful age determinations are gained from both TL and OSL analyses of rock-shelters and sand sheets of the main archaeological sites of Goorurarmum, Jinmium and Karlinga and also from the non-archaeological site of Sandy Creek Gorge. Whilst OSL ages are considered more reliable estimates of depositional age, TL plateaux and glow curves are useful for discerning depositional processes - normal TL plateaux indicate well-bleached sediment, foreshortened TL plateaux may indicate episodic rapid deposition (e.g. mass wasting), stepped TL plateaux may indicate partial bleaching (e.g. storm event) or partial re-exposure, and differing glow curves within or between sequences may indicate differing provenance of source sediments (refer also Price, 1994b). Attempts to obtain a more accurate assessment of radionuclide mobility and dose-rate by high-resolution techniques have been problematic. Radionuclide ratios indicate secular equilibrium in the uranium- and thorium-series decay chains, and justify using TSAC results for age calculations.

Whilst a young age (~ 500 yrs) for the Goorurarmum rock shelter is acceptable, the Pleistocene age (~ 18 ky BP) of the Karlinga rock shelter is less certain. The sedimentary record in the Keep River region is temporally and spatially discontiguous. The sand sheets around Jinmium and Goorurarmum have possibly been accumulating since the last interglacial (~100 ky BP), whereas only the last glacial (~ 20 ky BP) is represented in the sand sheets around Karlinga (although the latter have not been dated to the bedrock base). Sedimentation rate has progressively increased from 100 mm.ka⁻¹ during the Pleistocene to 200 mm.ka⁻¹ during the Holocene, in both unoccupied and unoccupied sediment sequences indicating this increase is probably due to environmental rather than anthropogenic processes. The geomorphic relationship between the rock shelters and adjacent sand sheets remains to be accurately determined, as does the age relationship between these sedimentary records and the rock art.