The formation process of a paleoindian open-air site in Central Brazil: integrating lithic analysis, radiocarbon and luminescence dating

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ABSTRACT

Lithic analysis, radiocarbon dating and luminescence dating are applied to a stratified open-air Paleoindian site in Central Brazil, lending some balance to a published record dominated by rock shelter sites. Most lithics are found in two discrete occupation layers. Lithics found outside these layers are attributed to post-depositional movement of small flake mainly upwards. Single-grain luminescence dating on quartz grains also suggest post-depositional movement. Both wind and bioturbation are suspected mechanisms. The luminescence analysis does not provide precise depositional dates in this situation but does support such dates suggested by radiocarbon.

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1. Introduction

Central Brazil has a rich Paleoindian record but most studied sites dating to the Pleistocene/Holocene transition are found in rockshelters (Kipnis, 1998; Prous and Fogaça, 1999; Schmitz, 1987). Only in sheltered sites has the Paleoindian record been well-dated, and also only in these sites has the transition between Paleoindian and subsequent technologies been described. Little is known about open-air occupations, although presumably they are important for understanding Paleoindian settlement and subsistence patterns. Schmitz (1980), for example, has suggested that populations aggregated in rockshelters during summer rainy seasons but dispersed to open-air locations along small rivers and creeks during dry seasons. Lack of detailed studies of open-air sites has prevented testing this hypothesis as well as a better understanding of Paleoindian territoriality. Although hundreds of open-air sites have been recorded, they rarely allow for clear stratigraphic sequences or good conditions for dating (Bueno, 2008; Kipnis, 1998; Prous and Fogaça, 1999; Rodet, 2006).

This paper provides a detailed analysis of the chronology and lithic technology of an extensively excavated Paleoindian open-air site near the city of Miracema do Tocantins, located in a paleo-dune field above the Tocantins River, at the northern outskirts of the Central Brazilian Plateau. Particular attention is paid to site formation processes in dune environments and the extent to which post-depositional sand movements and mixing might have affected the understanding of the occupation sequence and the detected changes in lithic technology.

2. Archaeological background: open-air sites and the early occupation of Central Brazilian Plateau

The Central Brazilian Plateau (CBP) is an uplifted region bordered by lowlands to the north (Amazonia), west/southwest (Chaco lowlands) and east (Atlantic seaboard) (Fig. 1). The main geologic features are flat, dry Mesozoic-aged sandstone plateaus, or chapadas, occasionally interrupted by pre-Cambrian mountain ranges (serras). Altitudes range from 200 to about 1000 m. A more rugged topography consisting of older limestone and quartzite mountains is found in the southeastern portion. Several large rivers, such as the Tocantins and the São Francisco, provide drainage, mostly to the north. Savannah-like cerrado vegetation...
dominates the landscape, though denser forests are found along rivers and canyons and on the moister slopes of the serras (Ab’Saber 1982, Ledru 1993, Oliveira and Marquis, 2002).

Hundreds of rockshelters are found along the steep slopes, or cuestas, of the chapadas, usually along small tributaries to the larger rivers. They are also found in limestone formations in the southeastern portion of the plateau (Araujo and Neves, 2010; Prous et al., 1998; Prous and Rodet, 2009). Paleoindian archaeological remains in the shelters date as early as 14–13.5 ka cal BP, but most sites date between 12.8 and 9.5 ka cal BP (Bueno, 2011; Dias, 2004; Prous and Fogaça, 1999; Kipnis, 1998; Oliveira and Viana, 1999/2000). Lithics are commonly characterized by formal, well-finished unifacial artifacts. The most distinctive are limaces, which are large, elongated flakes retouched into cutting/scraping tools with flat-convex transversal sections (Fig. 2). Expedient unifacial tools are also common. These assemblages are commonly referred to as Itaparica Tradition and, although they are defined mainly by these intensely retouched and curated unifacial tools, a few finely retouched stemmed bifacial points, and bifacially retouched flakes, are also found in most of these assemblages (Bueno, 2007a; Schmitz, 1987; Fogaça, 2001; Lourdeau, 2010).

Itaparica sites in the CBP sometimes form site aggregates such as in the Serranópolis, Peruaçu, Serra da Capivara and Lajeado/Miracema (middle Tocantins) areas (Schmitz et al., 2004; Fogaça, 2001; Rodet, 2006; Guidon, 1986; Bueno, 2007a). Whether these aggregates reflect settlement patterns of cyclic and recurrent occupations or are a matter of sample bias, is still an open question. What is indisputable is that late Pleistocene/early Holocene sites with similar formal and quantitative lithic characteristics are found over distances of more than 2000 km (Schmitz, 1981; Lourdeau, 2010; Bueno, 2011). These similarities are based on assemblage composition, raw material procurement

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behavior, and production process of formal artifacts, particularly the limace. There are also similarities in site location decisions and in local inter-site assemblage variability (Bueno, 2005/2006: p. 15). In the middle Tocantins, Peruaçu and Serranópolis regions there is also evidence of inter-regional variation in the chaine opératoire related to production of formal artifact types that may relate to cultural transmission mechanisms and histories (Bueno, 2005/2006, 2007b, Lourdeau, 2010). Subsistence patterns are also similar, with evidence of intensive exploitation of broad-spectrum resources based on medium- and small-size game and on intensive foraging for wild fruits and edible roots (Kipnis, 2003; Rosa, 2004).

The site of Miracema do Tocantins is located upon Pleistocene dune formations along the western margin of the Tocantins River, which flows north to Amazonia (Fig. 3). Several sites in these dunes were identified in the late 1990s during a CRM project when they were exposed during highway construction. The sites, buried more than 2 m deep, have been radiocarbon dated to the Pleistocene/Holocene transition. The dunes are currently stable with large flat tops covered by cerrado bushes. They provide ready access to the river plus broad vantage to the Serra do Lajeado to the southeast and to the transitional Amazonian vegetation to the north.

Dozens of lithic sites, typologically dating to the Paleoindian and Archaic periods, are found in the rolling hills between the eastern margin of the river and the serra escarpment (Bueno, 2007a). These sites are located on erosional surfaces and have no sub-surface remains. Several of them contain thousands of artifacts representing the entire lithic reduction process, but as palimpsests of several occupations, the sequence of technological change is difficult to disentangle. No organics are preserved for radiocarbon dating. Thus, a buried stratified site like Miracema do Tocantins, with opportunities for both radiocarbon and luminescence dating, has considerable value for understanding the early prehistory of this region.

Excavations have occurred at only five of the many sites recorded along these dunes. Miracema do Tocantins has received the most attention, with an excavated area of 68 m² from within a 500 × 200 m tract where most artifacts have been found. The excavation included both 52 m² of trenches and five blocks of horizontal exposure in the areas of highest artifact density (Fig. 4). A total of 10,873 lithic artifacts have been recovered, 60% of them from eight excavation units in the center of the site. Lithics appear in discrete concentrations, often with refitting possible within a concentration. The 2 × 2 m excavation units were dug in 10 cm arbitrary levels (Bueno, 2007a).

Deposits consist of fairly homogeneous sand. The top 30 cm consists of a dark brown organic soil horizon. Similar organic layers are found in some places as deep as 90 cm, suggesting ancient vegetated surfaces. Below the surface organic horizon is beige to brown sand, extending to 2.5 m and containing most of the archaeological remains. This sand grades into a yellow/orange sand that extends to the base of the excavation at 3.5 m. These dunes can occasionally reach a depth of 40 m, but excavation beyond 3.5 m was not safe due to unstable walls. Archaeological materials are rarely found below 3 m (Figs. 5 and 6). Roots extend as deep as 1.5 m.

Archaeological remains, mostly chipped lithics, fire-cracked rock and charcoal, are concentrated into two horizontal layers in the beige/brown sand, one at 90–120 cm and one at 170–220 cm.1 Scattered small lithic flakes (<1 cm) and charcoal are found outside these horizons. Charcoal was systematically collected from screening of 10 cm excavation layers, but two samples (Beta 148339 and Gif 11833) were collected in situ. Charcoal was wrapped in a...
aluminum foil and stored in plastic bags, all of the same size. The number of bags amounts to a proxy for the overall amount of charcoal collected from each layer.

The lithics from the two horizons differ markedly. The lower horizon is characterized by finished unifacial tools, abundant flakes from unifacial or bifacial reduction sequences, and small retouch flakes (defined as <1 cm). Raw material is mainly fine-grained sandstone and quartzite, with occasional good quality silex and quartz. No structural features have been found at this level.

The upper level assemblage is composed mainly of burned pebbles, with a few quartz and quartzite flakes and some formal tools. The only bifacial projectile point—a triangular, unstemmed variant made on quartz—was also found in this upper horizon. Also noteworthy is the presence of intact fire-cracked rock/charcoal features (“hearth”) in the upper level. Artifacts and charcoal in the lower layer were more dispersed. Stratigraphic sequences with similar variability in composition and technology are found at other nearby excavated dune sites.

Table 1 gives amounts of lithics and charcoal for each 10-cm level from the central excavated area (17 2 × 2 m units). Both have a continuous stratigraphic distribution with identifiable peaks at levels 90–120 cm (upper horizon) and levels 190–220 cm (lower horizon). The question posed is whether this represents continuous occupation or two discrete occupation periods blurred by post-depositional mixing? Bioturbation, often intense in the tropics, did not visually appear prominent in this sandy micro-environment; although it could account for the vertical displacement of the artifacts (Ahlbrandt et al., 1978). The presence of recognizable features in the upper horizon suggests this is not the case (Leigh, 2001), but as will be considered later, the presence of structure and the lack of any visible evidence may not preclude the possibility of extensive bioturbation.

3. Radiocarbon dating

The radiocarbon dates point to three pulses of dune occupation (Table 2). The most recent (Gif 11833) refers to a ceramic horizon detected across the dunes area and beyond, and will not be considered here. All other dates were obtained from the excavations in the central area of the site, with the exception of one (Beta 148338) drawn from Locus 2 excavations on a lower flank. These dates are bimodal with one group clustering between 5950 and 6890 cal BP and the other between 10,270 and 12,400 cal BP. The absence of intermediate dates reinforces the perception of two discrete occupations. Can the lithic scatter between the clustered levels be explained then by post-depositional movement? We
evaluate this question with single-grain optically stimulated luminescence (OSL)\(^2\) and with in-depth lithic analysis.

4. Luminescence dating

While the vertical distribution of radiocarbon ages can give some confidence of stratigraphic integrity, radiocarbon addresses the age of the carbon, not the age of the deposit. (The radiocarbon ages could be out of order without any post-depositional mixing.) An advantage of OSL dating is the potential to directly assess sediment mixing, whether the grains themselves have moved. This is possible by computing the equivalent dose (\(D_e\)) of single grains, the distribution of which can be related to sediment mixing if other sources of variation are ruled out. A luminescence age is the quotient of equivalent dose, a measure of the absorbed dose accumulated through time, divided by the dose rate. We have performed single-grain dating on five samples collected in 2002.

Table 1

<table>
<thead>
<tr>
<th>Level (in cm)</th>
<th>Lithics</th>
<th>Charcoal</th>
<th>Level (in cm)</th>
<th>Lithics</th>
<th>Charcoal</th>
</tr>
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<tr>
<td>0–10</td>
<td>–</td>
<td>–</td>
<td>150–160</td>
<td>190</td>
<td>4</td>
</tr>
<tr>
<td>10–20</td>
<td>2</td>
<td>–</td>
<td>160–170</td>
<td>342</td>
<td>3</td>
</tr>
<tr>
<td>20–30</td>
<td>9</td>
<td>–</td>
<td>170–180</td>
<td>537</td>
<td>4</td>
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<tr>
<td>30–40</td>
<td>10</td>
<td>–</td>
<td>180–190</td>
<td>404</td>
<td>3</td>
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<tr>
<td>40–50</td>
<td>25</td>
<td>–</td>
<td>190–200</td>
<td>1326</td>
<td>4</td>
</tr>
<tr>
<td>50–60</td>
<td>25</td>
<td>–</td>
<td>200–210</td>
<td>865</td>
<td>6</td>
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<tr>
<td>60–70</td>
<td>42</td>
<td>–</td>
<td>210–220</td>
<td>788</td>
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<td>70–80</td>
<td>70</td>
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<td>220–230</td>
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<tr>
<td>80–90</td>
<td>109</td>
<td>2</td>
<td>230–240</td>
<td>60</td>
<td>2</td>
</tr>
<tr>
<td>90–100</td>
<td>134</td>
<td>5</td>
<td>240–250</td>
<td>33</td>
<td>1</td>
</tr>
<tr>
<td>100–110</td>
<td>134</td>
<td>6</td>
<td>250–260</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>110–120</td>
<td>133</td>
<td>3</td>
<td>260–270</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>120–130</td>
<td>103</td>
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<td>270–280</td>
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<td>130–140</td>
<td>113</td>
<td>–</td>
<td>280–290</td>
<td>9</td>
<td>–</td>
</tr>
<tr>
<td>140–150</td>
<td>118</td>
<td>2</td>
<td>3290–3300</td>
<td>6</td>
<td>–</td>
</tr>
</tbody>
</table>

4.1. Procedures

Procedures are similar to those followed at Lapa Vermelha in the southeastern part of the CBP (Feathers et al., 2010). Samples were collected in light-tight containers and removed in the laboratory under red light conditions for preparation. Quartz was isolated by...
applies a series of regeneration doses to calibrate the natural signal. The protocol employs only one aliquot (one grain in this case) and some of which are several meters apart, is small. The dose rate is, however, because the variation in radioactivity among the samples, the probability of more than one grain in a hole providing a signal would be low. Ds was measured using the single-aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) on a Risø TL-DA-15 reader equipped with a single-grain attachment containing a 532 nm laser for stimulation. The laser was set at 90% full power.

Dose rate was measured in the laboratory using thick source sieving, treatment with HCl and H2O2, etching for 40 min in 48% HF, and density separating using sodium polytungstate solution at 2.67 specific gravity. Dg was measured on two different grain-size fractions, 125–150 μm and 180–212 μm, but the ages reported here are based only on the larger size-fraction. The smaller size compromises single grain resolution to some degree because of the possibility of more than one grain fitting into the 300 μm diameter holes on the measuring disks. The smaller size was used on the expectation that the quartz would not be highly sensitive and that the probability of more than one grain in a hole providing a signal would be low. Ds was measured using the single-aliquot regeneration (SAR) protocol (Murray and Wintle, 2000) on a Risø TL-DA-15 reader equipped with a single-grain attachment containing a 532 nm laser for stimulation. The laser was set at 90% full power (50 mW/cm). Detection was through 7.5 mm of U340 ultraviolet filters. Exposures were for 0.8 s with the first 0.06 s used for analysis and the last 0.65–0.8 s for background. Preheats of 240 °C for 10 s after the natural and each regeneration dose and of 200 °C for 1 s after each test dose were employed. Other preheat combinations were not attempted, because this combination has proven satisfactory for other work done in Central Brazil (Feathers et al., 2010; Araujo et al., 2008). Test doses were about 3 Gy. The SAR protocol employs only one aliquot (one grain in this case) and applies a series of regeneration doses to calibrate the natural signal in terms of Ds. A series of identical test doses are used after each regeneration signal and the natural signal to correct for any sensitivity changes during the measurement sequence.

One advantage of doing single-grain dating is the opportunity to select only those grains whose luminescence properties conform to a set of quality standards. Grains were rejected for analysis if (1) the signal was small (the signal on the test dose less than three times the standard deviation of the background), (2) the ratio of sensitivity-corrected signals from two identical regeneration doses applied at the beginning and end of the SAR sequence was not between 0.8 and 1.2, (3) the sensitivity corrected signal on a zero dose was more than 10% of the natural signal, (4) the corrected natural signal did not intersect the growth curve created by the regeneration doses, and (5) application of an infrared exposure after two regeneration doses caused the sensitivity corrected signals to lie beyond one-sigma error of the curve created by the other regeneration doses (indicative of feldspar contamination). Ds distributions among grains were evaluated using central age and minimum age models (Galbraith et al., 1999) and the finite mixture model (Roberts et al., 2000).

Dose rate was measured in the laboratory using thick source alpha counting, flame photometry and beta counting. CaSO4 dosimeters were left at the sample locations but these were never retrieved. The laboratory measurements are probably sufficient, however, because the variation in radioactivity among the samples, some of which are several meters apart, is small. The dose rate is low for these samples, and consequently the cosmic dose rate forms a significant portion of the total dose rate. The cosmic dose rate was calculated following Prescott and Hutton (1988) assuming sediment density of 1.5 g/cm³ and that current depths have prevailed through most of the depositional time. The ages were also recalculated using half the current depth, which would assume a rather constant sedimentation through time.

4.2. Dose rate

The concentrations of the major radionuclides and beta dose rates are given in Table 4, which also includes the beta dose rate calculated in two ways. The beta dose rate derived directly from beta counting is systematically higher than the results calculated from alpha counting (assuming secular equilibrium) and flame photometry. The discrepancy, significant for three of the samples, may reflect some disequilibrium in the uranium decay chain. If fractionation between the parent 238U and daughter 234U has occurred, with the daughter becoming depleted, the higher dose rate from beta counting could be due to the strong beta emission from 234Pa, an intermediate decay product of 238U. Such fractionation is usually due to the solubility of some forms of U in water, the fractionation likely occurred in the source deposit rather than in the dune. Whatever the cause of the discrepancy, beta counting, as a direct measure, is considered more accurate and was used for the beta dose rate in age calculation for all samples. Moisture content was taken to be 6±4 percent (1σ), typical for sandy sediments (Brady, 1974) and encompassing current measured moisture (which ranged from 2 to 3 percent, but the samples were collected in the dry season). The difference in age due to differences in cosmic dose rate assuming different depositional modes (rapid versus prolonged) was not significant for any sample, but resulted in systematically lower ages assuming the prolonged mode, on the order of about 4%. This should not affect conclusions. Total dose rates are given in Table 5.

4.3. Equivalent dose

As a test of procedures, a dose recovery test was done on all samples from the 180–212 μm fraction. In this test, grains are first set to zero by exposure to the green laser for 1 s at 125 °C and then given a known dose. The SAR procedure is then applied to see if this

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Provenience information for each OSL collected sample.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lab number</td>
<td>Sample #</td>
</tr>
<tr>
<td>UW823 OSL 1</td>
<td>N1606 E1063</td>
</tr>
<tr>
<td>UW824 OSL 2</td>
<td>N1026 E1006</td>
</tr>
<tr>
<td>UW825 OSL 3</td>
<td>N1037 E1011</td>
</tr>
<tr>
<td>UW826 OSL 4</td>
<td>N1037 E1011</td>
</tr>
<tr>
<td>UW827 OSL 5</td>
<td>N1037 E1011</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Concentrations of the major radionuclides and beta dose rates.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>238U (ppm)</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------</td>
</tr>
<tr>
<td>UW823</td>
<td>0.65 ± 0.07</td>
</tr>
<tr>
<td>UW824</td>
<td>0.25 ± 0.05</td>
</tr>
<tr>
<td>UW825</td>
<td>0.53 ± 0.07</td>
</tr>
<tr>
<td>UW826</td>
<td>0.16 ± 0.07</td>
</tr>
<tr>
<td>UW827</td>
<td>0.38 ± 0.05</td>
</tr>
</tbody>
</table>

Table 5  | Dose rates (Gy/ka), corrected for moisture content. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample</td>
<td>Alpha dose rate</td>
</tr>
<tr>
<td>---------</td>
<td>-----------------</td>
</tr>
<tr>
<td>UW823</td>
<td>0.004 ± 0.002</td>
</tr>
<tr>
<td>UW824</td>
<td>0.003 ± 0.002</td>
</tr>
<tr>
<td>UW825</td>
<td>0.003 ± 0.002</td>
</tr>
<tr>
<td>UW826</td>
<td>0.003 ± 0.002</td>
</tr>
<tr>
<td>UW827</td>
<td>0.003 ± 0.002</td>
</tr>
</tbody>
</table>

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known dose can be obtained. The ratio of derived dose to administered dose \((n = 55)\) was \(1.01 \pm 0.04\) with an over-dispersion, \((\sigma_b^2)\) of \(179 \pm 0.3\%\). This magnitude of over-dispersion, a measure of spread that cannot be accounted for by differential precision, is the minimum that might be expected for a single-aged sample, due to variations in luminescence properties from grain to grain, machine scatter, or other variables intrinsic to the measurements or the grains. All extrinsic sources of \(\sigma_b^2\) — different depositional ages or differential dose rate — are controlled in dose recovery. Therefore \(\sigma_b^2\) values greater than about 15–20% in the \(D_e\) distributions of the natural samples can be attributed to these extrinsic factors.

Fig. 7 gives sample decay and growth curves. The sample distributions are summarized in Table 6. This gives the number of grains for which a \(D_e\) could be derived, the central tendency expressed as the central age model and \(\sigma_b\). The \(\sigma_b\) is high for all samples, meaning that extrinsic factors must be taken into account. (Minimum age model \(D_e\) values will be discussed later.) To look at the structure of the data, a finite mixture model was applied. This model separates grains into single-aged components based on the input of a given \(\sigma_b\) value and the assumption of a log normal distribution of each component. The model estimates the number of components, the weighted average of each component (using the central age model), and the proportion of grains assigned to each component. The model provides two statistics for estimating the most likely number of components, maximum log likelihood and Bayes information criterion. An \(\sigma_b\) of 20%, slightly higher than that obtained in dose recovery, was used to account for intrinsic factors. The number of components derived is then a function of only extrinsic factors. Using 15% increased the number of components by one for three of the five samples, adding an older component in all three cases. Using 25% decreased the number of components by one for one of the five samples, eliminating a younger component.

Table 7 gives for each sample the \(D_e\) value for each component as well as the proportion of grains assigned to each component, using 20% over-dispersion.

About 1800 grains of the 180–212 \(\mu\)m fraction for each sample were measured, but only 5% had acceptable signals, most others being rejected because of weak signal not distinguishable from background. Such a low value prompted use of the 125–150 \(\mu\)m grains to provide effective single-grain resolution. But Table 6 shows the \(D_e\) for the smaller fraction is systematically higher. Inspection of finite mixture results shows that this difference is due to a larger number of high \(D_e\) values in the smaller fraction, probably due to grains with high natural signals which would be rejected in true single grain analysis because of recycle failures or failure to intersect the growth curve. In the 2–3 grain aliquots of the 125–150 \(\mu\)m fraction, some of these might get coupled with another grain with measurable signal, allowing the value to pass the rejection criteria. This suggests that even very small aliquots might not provide accurate \(D_e\) information (Feathers and Tunnicliffe, 2011).

Wind-blown sediments are often considered ideal for luminescence dating. The high over-dispersion indicated in Table 6 therefore requires some explanation. One possible reason is differential dose rate. The \(D_e\) is measured on single grains but the dose rate used to determine age is the bulk value from the entire sample. The dose rate, in particular the beta dose rate, may vary at the scale of single grains depending on the distribution of radioactive sources relative to the individual grains. For sandy sediments, one likely candidate for dose rate heterogeneity is \(^{40}\)K from potassium feldspars, a strong beta emitter. A simulated model developed by Mayya et al. (2006) was applied to evaluate the potential, but could only explain a difference of 3–7% for the first two components, when they actually differ by 50–90%. Another

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Fig. 7. A) Decay curves for two quartz grains (disk#/grain#) from UW825. The one from 2/81 has been multiplied by 10 to enhance visibility. B) Growth curves for the same samples shown in A, squares are 2/81 and circles are 4/97. Open symbols are the natural signals and lines are saturating exponential fits. Lx is the luminescence signal from the regeneration dose, and Tx is the signal from the test dose. C) 1M-OSL curves from UW825 and UW826. Most grains appear dominated by the fast component as shown by the curves with the peak at less than 10% power, but a few, like 3/92, with a peak at greater than 10% power, appear dominated by the medium component.
possible candidate for dose rate heterogeneity is pedogenic carbonates, which tend to be low in radioactivity, but these are not present in the deposits.

The other principle extrinsic cause for over-dispersion is different-aged grains, either because only some of the grains were fully bleached at time of deposition or because post-depositional processes have mixed grains of different depositional age. If the distribution can be attributed to partial bleaching, the minimum age model for determining $D_e$ is appropriate. Before applying the model, a 20% $\sigma_i$ value was added in quadrature to the error terms for each $D_e$ value to account for expected intrinsic variation. The resulting minimum age $D_e$ values are shown in Table 6. The distributions for each sample are displayed as radial graphs in Fig. 8.

Distinguishing partial bleaching from post-depositional mixing is not straightforward. The observation that some traps in quartz bleach quicker than others is often used to identify partial bleaching. OSL, where the power of the laser is steadily increased during bleaching, is not straightforward. The observation that some traps in quartz can bleach quicker than others is often used to identify partial bleaching. For the 6 measured in the context of dose recovery, five produced "$D_e$" values within 2$\sigma$ of the administered dose, so there is no strong evidence slower components are causing signal build-up during the SAR sequence, which could result in younger ages.

### Table 6

<table>
<thead>
<tr>
<th>Sample</th>
<th>$N$</th>
<th>Central age $D_e$ (Gy)</th>
<th>$\sigma_i$ (%)</th>
<th>Central age $D_e$ (Gy) for 125–150 μm</th>
<th>Minimum age $D_e$ (Gy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW823</td>
<td>89</td>
<td>6.7 ± 0.3</td>
<td>39 ± 4</td>
<td>7.9 ± 0.3</td>
<td>4.3 ± 0.4</td>
</tr>
<tr>
<td>UW824</td>
<td>121</td>
<td>5.7 ± 0.2</td>
<td>38 ± 3</td>
<td>6.3 ± 0.2</td>
<td>3.8 ± 0.2</td>
</tr>
<tr>
<td>UW825</td>
<td>86</td>
<td>6.4 ± 0.4</td>
<td>50 ± 5</td>
<td>7.7 ± 0.4</td>
<td>3.6 ± 0.4</td>
</tr>
<tr>
<td>UW826</td>
<td>92</td>
<td>4.6 ± 0.2</td>
<td>44 ± 4</td>
<td>5.3 ± 0.2</td>
<td>2.8 ± 0.4</td>
</tr>
<tr>
<td>UW827</td>
<td>82</td>
<td>2.0 ± 0.2</td>
<td>66 ± 7</td>
<td>2.2 ± 0.2</td>
<td>0.9 ± 0.2</td>
</tr>
</tbody>
</table>

### 4.4. Ages

If the cause of high over-dispersion is neither dose rate heterogeneity nor partial bleaching, then post-depositional processes such as high over-dispersion and age refinement models. The most common component is in bold. In terms of stratigraphic expectations, UW823, UW824 and UW825 all relate to the lower lithic horizon, UW827 is younger than the upper lithic horizon, and UW826 lies between the two horizons. The age values are plotted with radiocarbon dates in Fig. 9. The central age and minimum age models produce dates that are in the correct stratigraphic order, within error terms. Neither the 1st or 2nd components do that. The most common component does but it does not distinguish between UW826 and the older samples nearly as well as either the central or minimum age models. This suggests the components are not describing discrete populations but rather continuous distributions that vary in their pattern from sample to sample, as the radial graphs show (Fig. 8). The central age dates are older than the radiocarbon dates and the minimum age dates are younger. Before offering an interpretation of these distributions, we first consider the lithic data.

### 5. Lithic technology, distribution and refitting

The central excavation area shows lithics concentrating in two modes. Fig. 10 gives the stratigraphic distribution of large lithic pieces (>2 cm) and smaller ones (<2 cm). Few large pieces are found in non-peak levels, but small pieces are scattered throughout, although still defining the same peaks. Almost half the small pieces come from between 190 and 220 cm depth. Another interesting feature is that for each peak the smaller pieces post-date the larger ones in one or two levels. This suggests smaller pieces are moving up.

Most small flakes between 190 and 220 cm are made of the highest quality raw material available in the region (fine-grained silicified sandstone and quartzite pebble cores, with occasional quartz and flint). They mainly relate to retouch and resharpening and are associated with final production stages of the formal bifacial and unifacial tools and the more sophisticated technology (Taparica style) that predominates in the lower horizon (Bueno, 2005, 2006, 2007a, b). In the upper horizon, stone quality is much more diverse and non-selective, with much less use of high quality material. Flaking on lower quality stone is more expedient with less standardized production sequences (Fig. 11). This relationship between macro- and micro-lithics supports the discreteness of the two occupations. Any post-depositional movement seems to involve mainly smaller flakes, and the direction seems to be movement up rather than movement down, because of the abrupt drop off in lithic concentration below 220 cm and because the fine-flaking materials associated with the lower horizon can be found scattered throughout the stratigraphy below 30–40 cm, but the lower quality material and expedient
technology associated with the upper horizon are not often found below that horizon. Unique raw materials, which are easy to identity, reinforce this appearance of movement up. For example, in unit N1031/E1011, some retouching flakes of fine red silicified sandstone found about 80–100 cm are clearly associated with a concentration of this material at 210 cm of the neighboring unit, N1032/E1011. Examples on other raw material types have also been noted. Some refitting also supports the integrity of the lower horizon, both within reduction sequences and among broken pieces. There are several examples that have been recorded, but

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no systematic study, which probably would have yielded many more, was done.

One further observation about the lithic assemblages from dune sites provides additional information about the sedimentary process at the site. None of the lithics, no matter from what depth, exhibit any patina. This is in contrast to other open air sites located outside the dune fields, on hardened older ground. It suggests rapid burial, which might also preserve the integrity of the horizons.

In sum, study of the lithics supports the discreteness of the horizons, although the distribution of tiny flakes does indicate some post-depositional upward movement of small (and light) material.

### Table 8
Ages derived from the central age model, the minimum age model and the first two components of the finite mixture model. The component containing the most grains is in bold.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Age (ka) central age model</th>
<th>Age (ka) minimum age model</th>
<th>Age (ka) 1st component</th>
<th>Age (ka) 2nd component</th>
</tr>
</thead>
<tbody>
<tr>
<td>UW823</td>
<td>13.3 ± 1.5</td>
<td>8.5 ± 1.2</td>
<td>6.4 ± 1.3</td>
<td>16.3 ± 1.9</td>
</tr>
<tr>
<td>UW824</td>
<td>13.5 ± 1.6</td>
<td>9.0 ± 1.1</td>
<td>11.7 ± 1.4</td>
<td>23.0 ± 4.0</td>
</tr>
<tr>
<td>UW825</td>
<td>13.7 ± 1.6</td>
<td>7.7 ± 1.1</td>
<td>4.1 ± 0.8</td>
<td>13.0 ± 1.5</td>
</tr>
<tr>
<td>UW826</td>
<td>9.7 ± 1.2</td>
<td>5.9 ± 1.0</td>
<td>6.1 ± 1.3</td>
<td>10.4 ± 1.4</td>
</tr>
<tr>
<td>UW827</td>
<td>4.2 ± 0.6</td>
<td>2.0 ± 0.4</td>
<td>3.0 ± 0.4</td>
<td>9.6 ± 1.3</td>
</tr>
</tbody>
</table>

Fig. 9. Comparison of radiocarbon and luminescence dates, the latter using dates calculated from the central age model, the minimum age model and the first two components of the finite mixture model. Samples are listed in stratigraphic order rather than depth, because the samples came from different areas where stratigraphic changes occurred at different depths.

6. Dune formation processes and the archaeological record at Miracema

Analysis of lithic distribution seems to show that small flakes from the lower occupational level, representing curated technology, have moved considerably, mostly upward where they have
become mixed with the more expedient technology of the upper occupation level. Quartz sand grains have also become mixed, according to the luminescence analysis. Quartz sand has likely migrated upward as well, but the mechanism is not clear. Excavations were not designed to deal with formation processes at this scale, so specific field data for evaluating the cause of this upward movement are lacking.

Archaeological literature, although not concerned with movement of sand grains in particular, has considered the effect of post-depositional processes on the archaeological record (e.g., Cahen and Moeyersons, 1977; Wood and Johnson, 1978; Schiffer, 1987). In regards to unconsolidated sandy sediments, archaeologists have noted the fluidity of such deposits, by processes such as erosion, deflation, and pedoturbation, and how this has affected the content and spatial arrangement of artifacts (e.g., Moeyersons, 1978). But, “despite the implications of wind action on archaeological sites in an unconsolidated matrix, it appears that little research has been done on the subject” (Lancaster, 1986: p. 359). Most available studies are concerned with downslope (e.g., Rick, 1976) or downward (e.g., Courtin and Villa, 1982; Buck et al., 2002; Mayor, 2002) movements.

A few exceptions are worth mentioning in the context of the Miracema evidence. In an experimental study of lithic dispersion in an active dune environment, Lancaster (1986) found “stones of different morphology may be affected at different rates and different circumstances—smaller chips were found upwind and had further to go to leave the quadrat” (p. 362). One should have expected “more small stuff in the flaking areas than was evident from the size of the chips remaining and wind distribution tends to a more even distribution than originally has been deposited in desert areas.” These comments are relevant to the Miracema evidence, which shows a more even distribution of small debitage than of larger, heavier items.

Rowlett and Robbins (1982) note that only about 10% of the materials move outside the original depositional area. The other 90% remain in the immediate vicinity. They further note, in similarity with Miracema, that only about 30% of the moving small materials descends. The rest ascends. Their figure (p78) shows a similar distribution as Fig. 10 in this paper.

The geological literature is also concerned with post-depositional change in sand dunes (e.g., Pye and Tsoar, 1990), but little information is available about movement of individual grains, largely because no tool, before single-grain luminescence analysis, has been available to assess it. Current discussion incorporates luminescence. Telfer (2011) studied the migration and reworking of longitudinal dunes in the Kalahari, using OSL dating in part to interpret his findings, although not at a single-grain level and only to show evidence of reworking, not individual grain movement. He suggests there are two modes of sediment deposition, one that results in dune progradation and one that simply reworks the upper most sands. Chronometric ages may reflect reworking, not original deposition. Others (e.g., Maxwell and Haynes, 2001) have also noted evidence of extensive reworking in upper layers and...
Radiocarbon calibration is as in Table 2, except for Jiboia, which is calibrated with the INTCAL09 curve (Reimer et al., 2009). Wright et al. (2011) argued that precise dates for aeolian activity are difficult to obtain “because sediments move and settle on various temporal scales of days, months or years (p: 14).”

Bateman et al. (2007) considered the effect of bioturbation on determining accurate depositional ages for aeolian sediments in four case studies from Florida and Texas. Both multi-grain and single-grain OSL were employed to complement independent age evidence from radiocarbon and artifact typology. They conclude that presence or lack of structure in the deposits is no indication of the extent of bioturbation, as their case studies show that lack of structure does not necessarily indicate bioturbation and that presence of structure does not necessarily preclude extensive bioturbation. They also showed that OSL dates in the correct stratigraphic order do not necessarily mean accurate depositional ages can be obtained. For a structureless deposit, such as that at Miracema, one case study showed extensive post-depositional particle movement, while another one showed some movement but not extensive. In the latter case, something similar to a minimum age model was employed to derive the depositional ages in order to exclude older grains that had moved upward.

The occupation levels at Miracema consist of several discrete clusters of lithic materials and charcoal arranged horizontally. The distribution of the small debitage laterally and upward from these clusters suggest post-depositional movement. The equivalent dose distributions also suggest post-depositional movement. Presumably sand grains would move up with the lithics, but is there movement in other directions and what are the mechanisms? The finite mixture analysis of equivalent dose, if translated into age, shows both younger and older components, neither of which provide correct stratigraphic order. Which if any of the components for any sample can represent the depositional age? If sand particles have moved predominately upward, as the small lithics have, this might suggest that the minimum age model (unlike the youngest component which varies widely for every sample) may represent the depositional age, since older grains have been moved upward. Table 7 shows that for four of the five samples, UW824 being the exception, the majority of the grains are much older than the minimum age, up to 90% for UW825. This would indicate extensive localized reworking. A possible mechanism is wind, the reworking by which is amply documented in the geological literature. But for this to explain the $D_e$ distributions and the minimum age model as the appropriate model for depositional age, the extensive reworking would have to occur without exposing the sediment to light. Night wind is a possibility but hard to envision as the main reworking agent. Alternatively, maybe the minimum age model represents the age of reworking, not a depositional age. The depositional age then is older, but by how much? The central age model would make the depositional ages much older than the radiocarbon dates.

If not entirely wind, then bioturbation as a mechanism for reworking must be considered. There is no direct evidence of bioturbation, aside from some root extensions, but mixing evident in structureless sand bodies has been attributed to bioturbation in other places (e.g., Bateman et al., 2007).

A plausible explanation might be that both wind and bioturbation have reworked the Miracema deposits, exposing some grains to light but not all grains. Wind alone does not seem to account for all of the mixing because of the possibility of sunlight exposure, and the minimum age model may just represent those grains that were exposed. Wind, over a short distance, might also be expected to affect the sediments more or less uniformly, but the finite mixture model suggests more complicated structure. UW823, UW824 and UW825 should all be close to the same age, but the $D_e$ distribution structure of UW825 differs significantly from the other two, while UW823 and UW824 differ substantially from each other in the proportional amount of grains in either component (Table 7, Fig. 8). Localized bioturbation therefore seems a likely compliment, moving grains but without necessarily any solar exposure.

If reworking has exposed some grains to light, then the minimum age model, as mentioned, will date the reworking, not the original deposition, and will therefore underestimate the age of occupation. The lithic data suggests that post-depositional movement has mainly been up, so sand grains have probably mainly moved up as well, including some without resetting. Any sample will thus have a component of older grains, not all of which may have been exposed. This would make the central age model an over-estimate. It is likely, therefore, that the true age of deposition will lie between...
7. Conclusions

The stratigraphic distribution of lithic remains at Miracema do Tocantins shows two distinct cultural layers which are radiocarbon dated around 6–7 and 10.5–12.5 ka cal BP. Internal technological coherence and refitting provide confidence in the integrity of the two layers, but dispersion of small lithic debris throughout the stratigraphy as well as the OSL data suggest some post-depositional mixing. Larger lithic pieces do not appear to have moved significantly. The migration of lithic debris seems on technological grounds to be mainly upward. It is more difficult to understand the OSL 

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