Late Holocene dune accretion and episodes of persistent drought in the Great Plains of Northeastern Colorado

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Abstract

The Great Plains of the Mid West USA contain dunefields which display stratigraphic evidence of episodic sand drift throughout the Holocene and, in some cases, the Late Pleistocene. Widespread aeolian activity has been linked to persistent megadroughts caused by a weakening of the tropical moisture-laden circulation from the Gulf of Mexico and equatorial Pacific. Infrared stimulated luminescence (IRSL) dating has been applied to two exposures in the Fort Morgan dunefield of northeastern Colorado where radiocarbon-dated buried soils provide ages for land surface stability. IRSL ages show that sand drift occurred episodically during the Late Holocene at 4.85, 2.37, 1.06, 0.80, 0.6–0.53 and 0.37 ka.

1. Introduction

The aeolian-mantled landscapes of the Great Plains are particularly sensitive to climate change (Holliday, 1989; Muhs and Maat, 1993; Madole, 1994; Arbogast, 1996). Currently stabilised by prairie vegetation, aeolian dunefields and sand sheets cover large areas of Colorado, Nebraska, Wyoming, Kansas and Texas (Ahlbrandt and Fryberger, 1980; Holliday, 1985, 1989; Gaylord, 1990; Arbogast, 1996). Around 20% of eastern Colorado is blanketed by aeolian sands (Madole, 1994) which derive principally from the fluvial outwash plains of the South Platte river and its tributaries (Muhs et al., 1996). Four distinct Late Quaternary dunefields have been identified (Muhs et al., 1996): the Greeley and Sterling dunefields which lie north of the South Platte River; the Fort Morgan dunefield which comprises a series of dunefields lying to the south of the river; and the Wray dunefield which lies southeast of the Fort Morgan dunefield (Fig. 1). The Greeley, Fort Morgan and Wray dunefields are dominated by Holocene-age, simple and compound parabolic dunes which have been formed upon an older, Late Pleistocene sand sheet (27–11 ka) which outcrops as interdune surfaces (Muhs et al., 1996). Dune orientation studies have shown that the dominant sand-moving palaeowinds came from the northwest (Warren, 1976; Muhs, 1985; Muhs et al., 1996) which correspond to the dominant winter wind regimes today and this is also reflected in modern sand roses (Muhs et al., 1996; Fig. 1).

Stratigraphic evidence of episodic sand drift is exposed in sections cut into the Colorado dunefields, where sand units may be separated by at least two buried soils (Muhs, 1985; Forman and Maat, 1990; Madole, 1994, 1995; Muhs et al., 1996). Widespread mobilisation and deposition of aeolian sands during the Holocene has been correlated with episodes of prolonged drought and loss of plant cover rather than with increased sand supply (Muhs, 1985; Muhs and Maat, 1993; Madole, 1995). Tree rings, lacustrine salinity and wildfires provide proxy evidence for decadal-scale megadroughts during the last 2000 years (Millsbaugh and Whitlock, 1995; Woodhouse and Overpeck, 1998; Fritz et al., 2000). However, the history of dune mobilisation on the Great Plains suggests that the magnitude of medieval droughts may not have been as extreme as during the Middle Holocene (Dean et al., 1996; Smith et al., 1997). An understanding of the timing of sand drift on the Great Plains is therefore critical to gauging the severity, recurrence and extent of megadroughts during the Holocene (Forman et al., 2001).

Regional drought driving widespread aeolian activity in the Great Plains has occurred as a result of enhanced westerly zonal circulation leading to an increased
residence of dry, Pacific-derived air east of the Rockies at the expense of cold, dry Arctic and warm, moist Gulf air masses (Muhs, 1985). At present, the climate of this region is controlled seasonally by the position of the polar front (Feiler et al., 1997). In winter, westerly, moisture-laden, Pacific-maritime airflow is intensified across the United States continental interior as the polar front expands and moves southwards. The rain shadow effect of the southern Rocky Mountains results in relatively dry air reaching the Great Plains (Whitlock and Bartlein, 1993; Whitlock et al., 1995) and strong prevailing NW winds (Forman et al., 2001). In summer, the dominant westerlies shift northwards as the polar front retreats and an influx of warm, moist air from the Gulf of Mexico brings agriculturally important rains for spring and summer crop growth. A weakening of this summer incursion causes drought in this semi-arid landscape, with a subsequent loss of vegetation cover and aeolian reactivation (McCauley et al., 1981). It is therefore clear that movement of the polar front has caused a weakening of the summer airflow regime during several periods in the past, although the driving mechanisms behind this climate change are a subject of continuing debate (Dean et al., 1996). A recent review of climate controls on North American aridity has suggested that the driving mechanisms for Great Plains drought conditions are La Niña-related cooler Pacific sea surface temperatures and a shift in the location of the Bermuda High Pressure System which weaken the northward moisture-laden air circulation from the Gulf of Mexico (Forman et al., 2001).

There is a clear need for an accurate chronology of Holocene sand mobilisation in order to further resolve the timing of megadroughts throughout the Holocene across this sensitive region, and to determine the relationship with climate change forcing (Dean et al., 1996). This paper presents the first results from a programme of luminescence dating of dune sands from the northeastern Colorado.

2. Chronology of aeolian activity

During this study, several locations were sampled for luminescence dating within the Fort Morgan dunefield (Fig. 1): Friehaufs Hill, Milliron Draw, Hillrose, Bijou Outlet (Madole, 1994, 1995) and Hudson (Forman and Maat, 1990). This paper presents new dates from Friehaufs Hill and Hillrose localities giving evidence of the timing of Late Holocene aeolian activity. Optical ages have been previously described by Madole (1995) from the Coors Mine and Milton Reservoir sections in the Fort Morgan dunefield. At Coors mine, the Pleistocene sand sheet deposits (termed the lower unit by Madole, 1995) gave quartz OSL ages of $16.5 \pm 5–6$ ka and $14.5 \pm 5–6$ ka. The sand sheet

![Fig. 1. Map of the study area showing dunefields, sand roses and palaeowind directions (after Muhs et al., 1996) and locations of sections mentioned in the text (after Madole, 1995).](image)
deposits are areally the most extensive aeolian sand unit in the region, extending several kilometers beyond younger sands, and capped by a well-developed surface soil (Muhs, 1985; Madole, 1995; Muhs et al., 1996; Forman et al., 2001). This soil has been correlated with soil development on the Kersey Terrace of the South Platte River which contains Clovis and Folsom palaeoindian artefacts, implying a cessation in aeolian activity before 12–11 ka. (Madole, 1995; Muhs et al., 1996). Radiocarbon and TL evidence from the Hudson locality shows that a period of aeolian activity 7.5–5.5 ka buried and truncated this soil (Forman et al., 1992, 2001). Forman et al. (2001) describe a composite lithostratigraphy for northeastern Colorado which suggests that the Middle to Late Holocene dune deposits contain up to four palaeosol horizons with palaeosol-type localities at Sterling, Milliron Draw and Friehaufs Hill. Calibrated radiocarbon dates from these locations (Madole, 1995) suggest soils developed around 6.4 ± 0.2, 3.0 ± 0.2, 1.2 ± 0.2 and 0.75 ± 0.1 ka (Forman et al., 2001) with intervening sand mobilisation. Quartz OSL dates for Middle Holocene parabolic dunes near Milton Reservoir and south of Hardin gave ages of 3.23 ± 0.25 and 6.94 ± 1.3 ka (Madole, 1995). Madole (1995, p. 170) argues on the basis of these dates that the sands are “interpreted as being the product of multiple aeolian events during the Middle Holocene time, the dates of which are not yet accurately known”. Thus it is clear that more absolute ages are needed to refine the chronostratigraphy of the Middle to Late Holocene sequence.

Eight samples of dune sand were taken from the Fort Morgan dune field for IRSL dating of the feldspar grains. Friehaufs Hill and Hillrose localities were chosen for IRSL dating in order to achieve a better resolution of the Middle to Late Holocene chronology at sites where two palaeosol horizons exist which have been radiocarbon dated (Madole, 1995; Fig. 2). Both sites are located within the same discrete dune field, northeast of the town of Brush and south of the South Platte River (Fig. 1). The Friehaufs Hill Section (40°18′00′′N, 103°31′60′′W; Madole, 1994; Figs. 1 and 2) above (NT02/17), in between (NT02/16) and below (NT02/15) the two buried soils. Radiocarbon ages of 910 ± 50 years BP (Beta-52719) and 1150 ± 70 years BP (Beta-59164) were, respectively, obtained for the weaker, upper and more developed, lower soil.

Feldspars offer advantages for luminescence dating of Holocene sands because luminescence intensities are higher than for quartz (i.e. feldspar grains are brighter) and this allows very young samples to be dated. In addition, the dose rate contribution from within feldspar grains minimises uncertainties associated with past water content history and its effect on the external dose rate to the grains. The infra red stimulated luminescence (IRSL) single aliquot additive dose protocol (SAAD) has been previously applied to sand-sized potassium-rich feldspars from a range of aeolian contexts in which independent age control exists. Clarke (1994) describes dune sands which bracket the 7.7 ka Mazama tephra which give IRSL ages of 6.6 and 7.8 ka showing good agreement with the age control in an Oregon dune system. Similar good agreement has been found when SAAD IRSL ages have been compared with bracketing calibrated 14C dates from organic-rich palaeosols in aeolian and colluvial sands (Clarke and Kåykhö, 1997; Clarke et al., 1999, 2003).

However, some authors have found disagreement when comparing IRSL ages with independent age control suggesting that each site should be evaluated on an independent basis: Wallinga et al. (2001) found disagreement in fluvial sands when feldspar IRSL dates were compared with radiocarbon-dated macrophytes and van Heteren et al. (2000) found 10–20% age underestimations compared to radiocarbon dating for coastal sands. Age underestimations have been found in some feldspars which suffer from long-term loss of signal, known as anomalous fading (Spooner, 1994; Lamothe and Auclair, 1999; Huntley and Lamothe, 2001). Therefore, in addition to laboratory tests for the presence and rate of anomalous fading, comparison with independent age control is needed to assess the likely accuracy of the final IRSL age (Lian and Huntley, 2002).

3. Luminescence methodology

Sand samples were taken in the field by excavating clean exposures into the units with a spade. The freshly exposed face was then sampled by hammering lengths of
plastic drainpipe into the sand. In situ measurement of the gamma dose rate was undertaken using an NE Technology PSR8 ratemeter with a 2in diameter, thallium-doped sodium iodide detector. All preparation was undertaken in the laboratory under subdued orange lighting to prevent bleaching of the natural luminescence signal from the samples. Approximately 30g of each sample was removed for measurement of the field moisture content and, once dry, this fraction was ground in a ball mill to a mean diameter of less than 10μm for use in dosimetry measurements. The alpha dose to the sample was determined using a Daybreak 582 Thick Source Alpha Counter, and pairs counting was employed to ascertain uranium and thorium concentrations. The external beta dose was determined from 15g of the sample using an SURRC Thick Source Beta Counter with magnesium oxide as a background and a Shap granite standard (6.25 Gy ka⁻¹). The cosmic dose rate to the sample was calculated using the formula of Prescott and Hutton (1994). The internal beta dose from the decay of ⁴⁰K within feldspar grains was obtained from the K% concentration of individual grains. A total of 100 mg of the potassium-rich feldspar fraction was embedded in epoxy resin, polished to provide a cross section of the impregnated grains and carbon coated to provide a conductive surface for microanalysis. The chemical composition of individual grains was measured using a Cameca SX50 electron microprobe fitted with three wavelength dispersive spectrometers. The microprobe beam voltage operated at 15 kV and 20 nA. A beam diameter of 5μm was used for all analyses to counteract the migration of alkali elements under the electron beam. A minimum of 50 grains was analysed for each sample, chosen at random, and each grain was analysed for Na₂O, Al₂O₃, SiO₂, K₂O, CaO, MnO and FeO. Detection limits for each of the elements measured are 0.01 wt% per oxide.

The remaining sample (i.e. not used in dosimetry measurements) was sieved and the 180–212μm grain size chosen for mineralogical separation and used in luminescence measurements. This fraction was treated with 0.0032 M hydrochloric acid and 30% hydrogen peroxide to remove carbonates and organic matter. Potassium-rich feldspars were then separated from the polymineral sands using solutions of the heavy-liquid sodium polytungstate. Quartz and heavy minerals were separated from the lighter feldspars using a density of 2.62 g cm⁻³ and the potassium feldspars were subsequently separated from the sodium and plagioclase feldspars using a density of 2.58 g cm⁻³. The sands of the Fort Morgan dunefield are feldspar-rich and geochemically identical to South Platte river sediments (Muhs, 2001).

Fig. 2. Stratigraphic logs of the sections showing location of samples and IRSL ages.
Thus, there is abundant feldspar available for IRSL measurements. Subsamples of approximately 10 mg of the potassium feldspars were mounted onto 1 cm diameter aluminium discs for use in luminescence measurements.

Luminescence measurements were undertaken in an automated Risø TL-OSL Reader mounted with an integral $^{90}$Sr-$^{90}$Y beta source. Stimulation was achieved using an array of 31 TEMT484 infrared diodes with a peak emission wavelength of 880 ± 80 nm delivering a power of 40 mW cm$^{-2}$ to the sample. The detection system consisted of an EMI9635QA photomultiplier tube filtered with a combination of Schott BG39 and Corning 7-59 colour glass filters. The ED was determined on 12 of these aliquots using the SAAD protocol, employing infrared stimulation for 0.5 s at 50°C and a preheat of 220°C for 10 min. Use of this preheat regime has been demonstrated to remove both the thermally unstable component associated with the 290 nm recombination centre and charge transferred to longer wavelength centres (Clarke and Rendell, 1997). Tests for anomalous fading were undertaken following the procedure outlined in Clarke et al. (2003), which is similar to the method b approach of Huntley and Lamothe (2001).

4. Results and discussion

Mean equivalent dose determinations for each aliquot of the samples are shown in Table 1. All of the samples appear to have been well bleached at deposition (according to the criteria of Clarke, 1996), and are therefore expected to give an accurate age for burial and accretion of the dune forms. Attenuated dose-rate contributions and calculated IRSL ages are also shown in Table 1. Microprobe analysis of the feldspar separates shows that they are dominated by high potassium feldspars (Table 2). Of the 505 grains analysed only 10 grains were found to have higher concentrations of sodium than potassium, with eight albites and two plagioclase grains. No evidence for anomalous fading was found during laboratory tests with these samples.

Table 1 shows the IRSL ages from both Friehaufs Hill and Hillrose localities. These can be compared with the independent age control provided by calibrated radiocarbon dates on intervening palaeosols (Table 3). The presence of two soils at these sites provides a well-constrained intercalated, regional sand horizon of known age to test the accuracy of the IRSL procedure.

The conventional radiocarbon dates (Madole, 1994, 1995; Fig. 2) have been calibrated (Table 3) using the revised (Stuiver et al., 1998) CALIB4.1 program of Stuiver and Reimer (1993). The upper soil at Friehaufs gives three possible intercepts with the INTCAL98 calibration curve (Stuiver et al., 1998), whilst the upper soil at Hillrose gives five possible intercepts. The older, well-developed soil at both sites gave a single intercept with the INTCAL98 curve.

Although no fading was exhibited by these samples, it has been recently suggested that all sand-sized feldspars from North America are affected to varying extents by anomalous fading, resulting in “ubiquitous” IRSL age underestimation (Huntley and Lamothe, 2001). Huntley and Lamothe (2001) produce a fading map (p. 110; their Fig. 5) which implies that feldspars derived from NE Colorado could be expected to show a fading rate between 4% and 7% per decade of time since the applied radiation dose. Table 3 shows the effect on the IRSL age of applying a fading rate of 5% per decade to the samples from Friehaufs Hill and Hillrose, following the correction procedure of Huntley and Lamothe (2001). This fading rate was essentially an arbitrary choice in order to explore the implications of correction for these samples. Using this fading correction increases the IRSL age by 22–31% and the likely accuracy of these corrected dates are best illustrated for samples NT02/12 and NT02/10 at Friehaufs Hill and NT/02/16 at Hillrose which have bracketing independent age control. The calibrated radiocarbon dates from both sites imply that the intervening sand invasion from the South Platte river occurred some time between 1000 and 800 years ago.

Table 1
Attenuated dosimetry data, equivalent dose and IRSL ages for the samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Internal beta dose rate (Gy/ka)</th>
<th>External alpha dose rate (Gy/ka)</th>
<th>External beta dose rate (Gy/year)</th>
<th>Gamma and cosmic dose rate (Gy/ka)</th>
<th>Total dose rate (Gy/ka)</th>
<th>Equivalent dose (Gy)</th>
<th>IRSL age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT02/09</td>
<td>0.67 ± 0.09</td>
<td>0.40 ± 0.21</td>
<td>2.78 ± 0.20</td>
<td>1.66 ± 0.19</td>
<td>5.54 ± 0.36</td>
<td>3.30 ± 0.52</td>
<td>595 ± 100</td>
</tr>
<tr>
<td>NT02/10</td>
<td>0.72 ± 0.07</td>
<td>0.39 ± 0.18</td>
<td>2.57 ± 0.17</td>
<td>1.54 ± 0.17</td>
<td>5.21 ± 0.31</td>
<td>5.56 ± 0.58</td>
<td>1065 ± 125</td>
</tr>
<tr>
<td>NT02/11</td>
<td>0.71 ± 0.08</td>
<td>0.41 ± 0.21</td>
<td>2.68 ± 0.24</td>
<td>1.64 ± 0.19</td>
<td>5.43 ± 0.38</td>
<td>12.85 ± 0.71</td>
<td>2370 ± 210</td>
</tr>
<tr>
<td>NT02/12</td>
<td>0.70 ± 0.08</td>
<td>0.37 ± 0.19</td>
<td>2.61 ± 0.52</td>
<td>1.56 ± 0.17</td>
<td>5.22 ± 0.58</td>
<td>4.22 ± 0.27</td>
<td>805 ± 105</td>
</tr>
<tr>
<td>NT02/14</td>
<td>0.71 ± 0.09</td>
<td>0.25 ± 0.13</td>
<td>2.73 ± 0.19</td>
<td>1.47 ± 0.16</td>
<td>5.16 ± 0.29</td>
<td>2.77 ± 0.59</td>
<td>535 ± 115</td>
</tr>
<tr>
<td>NT02/15</td>
<td>0.71 ± 0.08</td>
<td>0.20 ± 0.10</td>
<td>2.57 ± 0.18</td>
<td>1.35 ± 0.15</td>
<td>4.83 ± 0.26</td>
<td>23.43 ± 0.95</td>
<td>4850 ± 325</td>
</tr>
<tr>
<td>NT02/16</td>
<td>0.71 ± 0.08</td>
<td>0.24 ± 0.12</td>
<td>2.50 ± 0.20</td>
<td>1.40 ± 0.15</td>
<td>4.85 ± 0.28</td>
<td>5.14 ± 0.35</td>
<td>1060 ± 95</td>
</tr>
<tr>
<td>NT02/17</td>
<td>0.70 ± 0.08</td>
<td>0.25 ± 0.13</td>
<td>2.57 ± 0.22</td>
<td>1.48 ± 0.16</td>
<td>4.99 ± 0.31</td>
<td>1.83 ± 0.22</td>
<td>370 ± 50</td>
</tr>
</tbody>
</table>
Table 2
Mean chemical composition of the potassium feldspar separates from each sample, where $n =$ number of grains analysed

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO$_2$ (%)</th>
<th>Al$_2$O$_3$ (%)</th>
<th>CaO (%)</th>
<th>MnO (%)</th>
<th>FeO (%)</th>
<th>Na$_2$O (%)</th>
<th>K$_2$O (%)</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NT02/09</td>
<td>64.94 ± 0.68</td>
<td>17.91 ± 0.20</td>
<td>0.02 ± 0.07</td>
<td>0.00 ± 0.01</td>
<td>0.05 ± 0.05</td>
<td>0.91 ± 1.06</td>
<td>15.99 ± 1.62</td>
<td>57</td>
</tr>
<tr>
<td>NT02/10</td>
<td>64.37 ± 0.53</td>
<td>17.76 ± 0.26</td>
<td>0.03 ± 0.12</td>
<td>0.00 ± 0.00</td>
<td>0.09 ± 0.30</td>
<td>0.78 ± 0.67</td>
<td>16.02 ± 1.06</td>
<td>50</td>
</tr>
<tr>
<td>NT02/11</td>
<td>64.24 ± 0.51</td>
<td>17.75 ± 0.20</td>
<td>0.03 ± 0.07</td>
<td>0.00 ± 0.00</td>
<td>0.04 ± 0.04</td>
<td>0.95 ± 0.93</td>
<td>15.70 ± 1.42</td>
<td>59</td>
</tr>
<tr>
<td>NT02/12</td>
<td>63.98 ± 0.58</td>
<td>17.66 ± 0.17</td>
<td>0.01 ± 0.03</td>
<td>0.00 ± 0.01</td>
<td>0.04 ± 0.05</td>
<td>0.95 ± 1.02</td>
<td>15.57 ± 1.57</td>
<td>53</td>
</tr>
<tr>
<td>NT02/14</td>
<td>64.18 ± 0.58</td>
<td>17.64 ± 0.22</td>
<td>0.02 ± 0.08</td>
<td>0.00 ± 0.00</td>
<td>0.04 ± 0.04</td>
<td>0.92 ± 0.98</td>
<td>15.83 ± 1.52</td>
<td>57</td>
</tr>
<tr>
<td>NT02/15</td>
<td>63.92 ± 0.39</td>
<td>17.64 ± 0.21</td>
<td>0.03 ± 0.10</td>
<td>0.00 ± 0.00</td>
<td>0.06 ± 0.06</td>
<td>0.83 ± 0.73</td>
<td>15.83 ± 1.24</td>
<td>52</td>
</tr>
<tr>
<td>NT02/16</td>
<td>64.63 ± 0.48</td>
<td>17.91 ± 0.16</td>
<td>0.03 ± 0.12</td>
<td>0.00 ± 0.00</td>
<td>0.04 ± 0.04</td>
<td>0.99 ± 0.88</td>
<td>15.87 ± 1.39</td>
<td>60</td>
</tr>
<tr>
<td>NT02/17</td>
<td>64.21 ± 0.53</td>
<td>17.72 ± 0.20</td>
<td>0.03 ± 0.06</td>
<td>0.00 ± 0.01</td>
<td>0.04 ± 0.04</td>
<td>1.07 ± 0.94</td>
<td>15.50 ± 1.43</td>
<td>58</td>
</tr>
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</table>

Table 3
Comparison of IRSL ages (uncorrected) with the ages obtained by applying a 5% decade fading correction

<table>
<thead>
<tr>
<th>Site</th>
<th>Radiocarbon age range [2σ max cal age (cal age intercepts) 2σ min cal age]</th>
<th>Sample</th>
<th>Uncorrected IRSL age</th>
<th>Fading corrected IRSL age</th>
<th>% age increase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Friehaufs Hill</td>
<td></td>
<td>NT02/14</td>
<td>535 ± 115</td>
<td>655 ± 140</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NT02/09</td>
<td>595 ± 100</td>
<td>730 ± 125</td>
<td>22.7</td>
</tr>
<tr>
<td></td>
<td>913 (758, 751, 742) 677</td>
<td>NT02/12</td>
<td>805 ± 105</td>
<td>1000 ± 130</td>
<td>24.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NT02/10</td>
<td>1065 ± 125</td>
<td>1335 ± 160</td>
<td>25.4</td>
</tr>
<tr>
<td></td>
<td>1476 (1292) 1090</td>
<td>NT02/11</td>
<td>2370 ± 210</td>
<td>3040 ± 270</td>
<td>28.3</td>
</tr>
<tr>
<td>Hillrose</td>
<td></td>
<td>NT02/17</td>
<td>370 ± 50</td>
<td>450 ± 60</td>
<td>21.6</td>
</tr>
<tr>
<td></td>
<td>931 (879,871,822,814,792) 705</td>
<td>NT02/16</td>
<td>1060 ± 95</td>
<td>1325 ± 120</td>
<td>25.0</td>
</tr>
<tr>
<td></td>
<td>1260 (1058) 930</td>
<td>NT02/15</td>
<td>4850 ± 325</td>
<td>6350 ± 425</td>
<td>30.9</td>
</tr>
</tbody>
</table>

Table 3 shows that the uncorrected IRSL ages agree well with this interpretation at both sites, whereas the fading-corrected IRSL ages appear too old. Sample NT02/16 overestimates the true age of the deposit at Hillrose. The situation at Friehaufs Hill is not as clear cut; correcting the age of sample NT02/10 also appears rather old although the corrected IRSL age and the underlying soil radiocarbon age are essentially indistinguishable within their respective error terms. However, the uncorrected ages agree much better with the findings of Upper Republican artefacts, with a known occupation of 1.0–0.7 ka, at the surface of the lower soil—the corrected ages overestimate this period. Given the clear age overestimation at Hillrose and the lack of fading in our samples, we believe the uncorrected IRSL provides the more accurate ages for deposition and burial of these aeolian sands because anomalous fading appears to be insignificant within the geological time associated with dune development at these sites. From this study we conclude that it is unwise to assume ubiquitous fading, as suggested by Huntley and Lamothe (2001), but instead it is important to treat each geological setting independently, and to perform rigorous tests to assess each location on its merits.

The uncorrected IRSL ages for the sands underlying the lower palaeosol, of 4850 ± 325 years and 2370 ± 210 years along with the optical dates from parabolic dune sands at Milton Reservoir and Hardin (Madole, 1995), suggest episodic Middle to Late Holocene mobilisation. Elsewhere in the Great Plains, widespread dune accretion occurred at Chaco dunefield, New Mexico between 6.5 and 2.8 ka (Wells et al., 1990), sand deposition occurred in the Ferris dunefield, Wyoming at 4160 ± 670 and 4040 ± 770 years (optical dates of Stokes and Gaylord, 1993) and dune development at 2370 ± 210 years agrees with episodes of sand accretion at the Great Bend Sand Prairie, Kansas (Arbogast, 1996; Arbogast and Johnson, 1998) and the Nebraska Sand Hills (Stokes and Swinehart, 1997). The episode of dune reactivation constrained by the buried soils at Friehaufs Hill and Hillrose suggests a sand drift episode 1065 to 800 years ago. Again this coincides with the timing of sand drift at the Great Bend Sand Prairie (Arbogast, 1996; Arbogast and Johnson, 1998). Concordant IRSL ages at Hillrose and Friehaufs may imply a notable drought interval at 1060–1065 years ago.

The most recent period of dune accretion at Friehaufs Hill is IRSL dated between 595 ± 100 and 535 ± 115 years ago with 5.9 m of sand deposition during this time testifying to significant aeolian mobilisation. Sand was deposited at Hillrose 370 ± 50 years ago. Dune reactivation is known to have occurred in the Wray dunefield...
(Muhs et al., 1997; Fig. 1), the Nebraska Sand Hills (Ahlbrandt et al., 1983; Muhs et al., 1997; Stokes and Swinehart, 1997), the Southern High Plains (Holliday, 1997) and the Great Bend Sand Prairie (Arbogast, 1996; Arbogast and Johnson, 1998) during this time. Further dating studies are needed to refine these periods before firm conclusions can be made about the duration and periodicity of megadrought intervals. However, from this IRSL dating study it is clear that activation of the Colorado dunefields was synchronous with other evidence of widespread aeolian mobilisation across the Great Plains region.

5. Conclusions

IRSL ages for potassium feldspar sands agree well with independent age control provided by radiocarbon dating of soil humus. Significant aeolian mobilisation has occurred during the Late Holocene in the Fort Morgan dunefield with episodes dated at 4.85, 2.37, 1.06, 0.8, 0.6–0.53 and 0.37 ka. Sands were mobile, perhaps in response to increased supply from the South Platte River (Muhs et al., 1996), at times of sustained drought which appear to be driven by a change in regional climate. More dates are needed to resolve the timing of Late Holocene megadroughts in this sensitive region.

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