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Megadroughts and late Holocene dune activation at the eastern margin of the Great Plains, north-central Kansas, USA

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Optical and radiocarbon dating indicates that alluvium underlying dunes near Abilene was deposited at or before ~45 ka, and that the overlying dunes were active at ~1.1–0.5 ka. Geochemical data indicate that the Abilene dune sand is immature and was derived from the underlying Pleistocene alluvium, and not from Holocene age Smoky Hill River deposits. These findings suggest that dune activation was a response to increased aridity and local reduction in vegetation cover as opposed to changes in sediment availability from nearby rivers. The time interval of dune activation at Abilene overlaps Medieval Warm Period megadroughts, similar to the larger and more westerly dune fields on the Great Plains, including the Nebraska Sand Hills and the Great Bend Sand Prairie. The activation of smaller dune fields such as the Abilene dunes near the more humid eastern margin of the Great Plains shows the geographic extent and severity of paleodrought events. Unlike the Duncan dunes, another plains-marginal dune field, however, the Abilene dunes show no evidence for multiple drought events during the Holocene. This difference in dune activity, if it is not a result of sampling or preservation bias, indicates variations in the extent and severity of older drought events at the eastern margin of the Great Plains.

1. Introduction

Recent studies of dune activity in the central Great Plains have provided appreciable information on high-magnitude prehistoric drought events (Sridhar et al., 2006; Miao et al., 2007) that are termed 'megadroughts' to distinguish them from lower magnitude historic drought events. The impacts of these megadroughts, however, have not been adequately assessed beyond the region's larger dune fields. The ongoing study of small dune fields at the eastern margin of the Great Plains, of which this study is a part, is articulating the areal extent and impacts of such megadroughts. As geologic and geochronological data accumulate, an improved model of the impacts of large-scale, long-term periods of paleodroughts will emerge.

A small dune field near Abilene, Kansas is a conspicuously eastward-lying example among the numerous dune fields on the central Great Plains (Fig. 1), making it an important indicator of the geographical extent of prehistoric megadroughts in the interior of North America. This study presents the first numerical age data for the activation history of the Abilene dunes and then place that evidence within a larger framework of aeolian activity and paleoclimate change.

2. Previous studies

No detailed work has previously been carried out in the Abilene dunes, although several other dune fields on the Great Plains have been studied. Optical dating in the Nebraska Sand Hills and studies of adjacent loess deposits to the south and east have yielded an important chronological framework for aeolian activity and inferred drought (Fig. 1). Dune activity and continuous drought occurred in the Sand Hills between 9600 and 6500 years ago, and during events centered around 3800, 2500, and 700 years ago (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007). Furthermore, Forman et al. (2005) found evidence for much more frequent dune activation in the western Nebraska Sand Hills, identifying episodes around 3700, 670, 470, 240, 140, and 70 years ago. Similarly, the Wray dune field of southwestern Nebraska-northeastern Colorado (Fig. 1) was activated around 540, 420, and 70–80 years ago (Forman et al., 2005).

In the Great Bend Sand Prairie (Fig. 1) – the largest dune field in Kansas – radiocarbon dating of buried soils within the dunes and underlying alluvium indicates dune activation in episodes shortly

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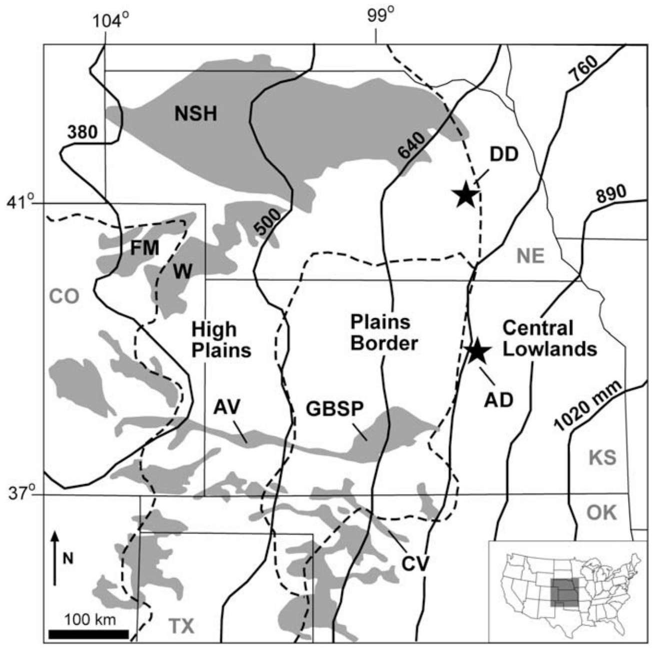

Fig. 1. Abilene dunes and other High Plains and Plains Border dune fields (shaded)(dune locations adapted from Muhs et al., 1999): AV, Arkansas Valley dunes (Forman et al., 2008); CV, Cimarron Valley dunes (Lepper and Scott, 2005); DD, Duncan dunes (Hanson et al., 2009); FM, Fort Morgan dune field (Clarke and Rendell, 2003); GBSP, Great Bend Sand Prairie (Arbogast and Johnson, 1998; Arbogast, 1996); NSH, Nebraska Sand Hills (Goble et al., 2004; Mason et al., 2004; Forman et al., 2005; Miao et al., 2007); W, Wray Dune field (Forman et al., 2005). Also identified are the Plains Border and High Plains Provinces of the Great Plains Physiographic Region. Isopleths indicate historic mean annual precipitation (mm).

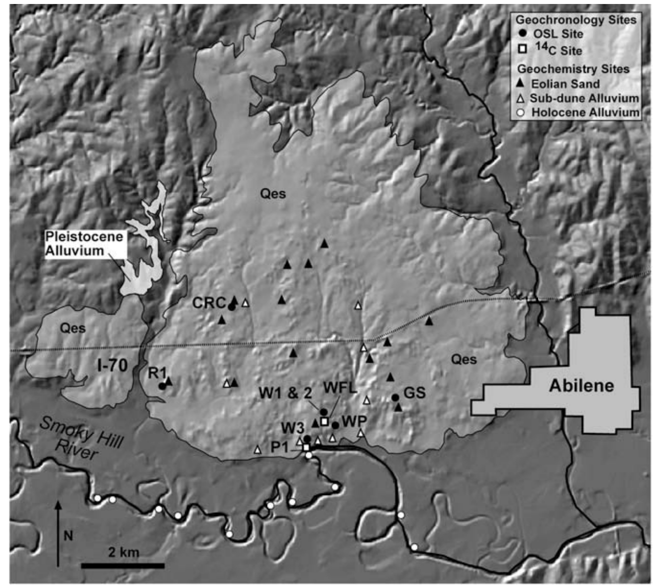

Fig. 2. Surficial geology around Abilene dunes, Kansas (McCauley and Johnson, submitted for publication) showing locations of geochronology and geochemistry sites. CRC, Cole Road Cut; GS, Garten Sites; Ph, Phelps Site; R1, Rodda Auger 1; W, Wilson 1, 2, 3, Wilson Pit (WP), and Wilson Feedlot (WFL) Sites. Qes, Aeolian sand. Pleistocene alluvium is found to the west of the Abilene dunes. Uplands surrounding dunes are primarily Permian bedrock units.

after 6700, 3700, 2300, 1400, 1100, 700, and 300 years ago (Arbogast, 1996; Arbogast and Johnson, 1998). Working farther west in dunes along the Arkansas River, Forman et al. (2008) used optical dating to document increased dune activity around 1490, 430, 380–320, 180, and 70 years ago. To the south in the Cimarron River valley of west-central Oklahoma and west-central Kansas, optical dating indicated dune activation around 900–700 years ago (Lepper and Scott, 2005) and between 800 and 300 years ago (Werner et al., submitted for publication).

Most of the aforementioned studies were conducted well to the west of the 98th meridian, but many smaller dune fields are found around the eastern margin of the Great Plains in central to eastern Kansas and Nebraska (Fig. 1). Optical dating of dunes near Duncan, Nebraska in the eastern Platte River valley (97.5°W) shows dunes were active 4300–3500 years ago and around 900–500 yrs ago (Hanson et al., 2009). These results correspond well with other records from the Nebraska Sand Hills (Miao et al., 2007) and the Great Bend Sand Prairie in Kansas (Arbogast, 1996; Arbogast and Johnson, 1998). With the exception of coastal dunes located along shorelines of the Great Lakes (e.g. Arbogast et al., 2002), the Duncan dunes are, in the current state of knowledge, the easternmost evidence for inland dune movement during the past ~1200 years.

3. Geographic and geologic setting

The Abilene dunes (~50 km^2) are on the northern edge of the Smoky Hill River Valley immediately east of the confluence of the Solomon River in Dickinson County, Kansas (Fig. 2). The region's surficial geology is dominated by Permian bedrock in the vicinity and to the east of the dunes, but Cretaceous bedrock cores the uplands ~10 km to the west of the study area. The dunes mantle two alluvial terraces along the Smoky Hill River floodplain which is ~351 masl to the south of the study site (Fig. 2). The lower terrace, designated T1, is found at an elevation of ~366 m and is located to the south of the dunes and directly adjacent to the Smoky Hill River floodplain, while the more extensive and higher T2 terrace tread is nearly completely covered by dunes and/or sand sheets (Fig. 2). Pleistocene alluvium mapped to the west of the dunes by McCauley and Johnson (submitted for publication) is interpreted to be the exposed sediments of T2 (Fig. 2). The Abilene dunes are relatively low-relief, with most having relief of <6 m, but some exceed 10 m in height. Aeolian sand sheets surround individual dunes and cover the majority of the Qes unit in Fig. 2. Specific dune forms are not identifiable in most cases, but some of the larger relief dunes have crescentic morphologies. The steepest slopes are most commonly found on the southeast end of the dunes, suggesting that the dune-forming paleowinds were from the northwest.

The Abilene dunes lie ~120 km to the northeast of the Great Bend Sand Prairie studied by Arbogast (1996) and Arbogast and Johnson (1998), and ~275 km south of the Duncan dunes (Hanson et al., 2009), making them independent test-cases of drought-related activation by virtue of their relative geographic isolation (Fig. 1). In addition, they lie within a relatively steep precipitation gradient where moisture decreases from west to east across the Plains (Fig. 1). Historic climate data from the past 100 years indicate that the Abilene dunes receive ~750 mm precipitation annually (High Plains Regional Climate Center, undated). This amount is much higher than the present day values for most of the dunes that have previously been studied on the central Great Plains, including the Nebraska Sand Hills (~380–640 mm/a) and the Great Bend Sand Prairie (~530–730 mm/a) (HPRCC, undated)(Fig. 1). The higher available moisture in the Abilene dunes makes them particularly important for the study of prehistoric droughts because they may have a higher threshold for movement, and therefore they may be singularly important indicators of paleodrought severity.

4. Methods

Age control for both dune and sub-dune sediments was acquired through both optical and radiocarbon dating. Twenty

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samples were analyzed using optical dating methods. These samples were collected from three artificial exposures and from six hand-augered holes as deep as 5.4 m in opaque sample tubes. Optical dating samples were retrieved from dune crests and the side slopes of dunes, rather than from blowouts, in order to determine when large-scale dune forms were active. Furthermore, samples were collected from at least 80 cm below the ground surface in order to minimize the likelihood that near-surface mixing by bioturbation would yield erroneous ages.

Optical dating was conducted at the University of Nebraska's Luminescence and Geochronology Laboratory, using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000). Samples were sieved to isolate 90–150 μm grains, treated with 1 N HCl to remove carbonates, and floated in 2.7 g/cm^3 sodium polytungstate to remove heavy minerals. The remaining sample was then treated with 48% hydrofluoric acid for ~75 min to remove feldspars and etch quartz grains, followed by a treatment in 47% HCl for ~30 min. The samples were then re-sieved to remove grains finer than 90 μm. Dose rate estimates were based on elemental concentrations of bulk sediments taken from an ~30 cm radius surrounding the optical dating sample. Bulk sediment samples were analyzed for concentrations of K, U, Th, and Rb using ICP-MS and ICP-AES. The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and the final dose rate values calculated following equations from Aitken (1998).

Optical dating analyses were carried out on a Risø model DA 20 TL/OSL reader equipped with blue and infrared diodes. A preheat plateau test showed no difference between aliquots run from 200 to 240 °C, therefore, a preheat temperature of 220 °C was chosen. Individual aliquots were rejected if their recycling ratios were ⩾ ±10%, or if they had measureable signals during exposure to infrared diodes. Aliquots were also rejected if their D_e values were >4σ from the mean D_e value, and final age estimates were calculated using a minimum of 20 accepted aliquots. Histograms of D_e distributions for all samples are available in a data repository. All optical ages are presented in calendar years before 2006, and age estimates and errors for younger samples (<1500 years ago) are rounded to the tenths, and the older samples to the hundredths.

Three samples were collected from total organic matter in buried A horizons and analyzed using radiocarbon dating. One sample taken from a soil buried in T1 alluvium was analyzed with the conventional radiocarbon dating method while two others, including one sample from T2 alluvium and one taken from a buried soil within a dune, were dated using the AMS method. All three age estimates were calibrated using Fairbanks et al. (2005) to enable a direct comparison with the optical ages.

In an effort to determine the source for aeolian sands, samples for trace-element (Ba, Rb, Sr, Ti, and Zr) analyses were collected from the dunes, Holocene age Smoky Hill River alluvium, and the sediment underlying the dunes. These analyses were carried out by X-ray fluorescence (XRF) on powdered sand samples using the pressed pellet technique at XRAL Laboratories in Lakefield, Canada. Three sediment cores were extracted with a trailer-mounted Giddings coring machine to better characterize site stratigraphy and sediment textures at the Wilson site (Fig. 2). Particle-size samples taken from these cores were pretreated with sodium hexametaphosphate and analyzed on a Malvern Mastersizer 2000E.

5. Results

5.1. Study sites

5.1.1. Cole Road Cut

The Cole Road Cut, the northeastern most study site, is located ~4 km north of the Smoky Hill River floodplain (Fig. 2). It exposes a ~2 m-thick section of a low-relief aeolian sand sheet lying ~30 m above the Smoky Hill River floodplain (Fig. 2). Soil development is limited to an A horizon and clay lamellae (Rawling, 2000) that occur from 35 to 200+ cm depth. An optical age estimate from a sample taken 130 cm below the ground surface yielded an age of 860 ± 70 years ago (Table 1: Fig. 3).

5.1.2. Garten sites

The three Garten sites are located ~1 km north of the Smoky Hill River, and 21–30 m above floodplain level, at the eastern edge of high-relief dunes (Fig. 2). Garten Augers 1 and 2 were taken ~35 m apart from near the crest (Auger 1) and on a side slope (Auger 2) of a large, high-relief dune (Fig. 2). Garten Augers 1 and 2 showed similar stratigraphy, but a buried A horizon was encountered at the base of Garten Auger 1, below 5.2 m depth (Fig. 3).

Table 1
Equivalent dose, dose rate data, and optical age estimates for Abilene dunes.

Field site	OSL Sample #	UNL Lab #	Depth (m)	U (ppm)	Th (ppm)	K_2O (wt%)	In situ H_2O (%)[a]	Dose rate (Gy/ka)	D_e (Gy) ± 1 Std. Err.	Aliquots (n)[b]	Optical age ± 1σ
Cole Road Cut	OSL 1	UNL-1803	1.3	0.9	4.5	1.5	6.5	1.76 ± 0.12	1.52 ± 0.01	23/27	860 ± 70
Garten Auger 1	OSL 1	UNL-1806	1.6	0.8	3.5	1.8	1.6	2.01 ± 0.12	1.22 ± 0.05	24/27	610 ± 40
	OSL 2	UNL-1886	3.3	0.8	3.5	1.7	5.3	1.81 ± 0.13	1.38 ± 0.05	21/24	760 ± 70
	OSL 3	UNL-1807	5.4	0.8	3.9	1.8	4.3	1.90 ± 0.13	1.49 ± 0.03	23/27	780 ± 70
Garten Auger 2	OSL 1	UNL-1887	1.6	0.7	3.1	1.7	3.2	1.85 ± 0.12	1.33 ± 0.03	23/24	720 ± 60
	OSL 2	UNL-1888	3.3	1.3	5.7	1.6	10.5	1.89 ± 0.17	1.34 ± 0.04	22/24	710 ± 80
	OSL 3	UNL-1808	4.7	1.0	4.2	1.7	12.2	1.77 ± 0.19	21.15 ± 2.16	25/27	12,000 ± 1900
Garten Pit 1	OSL 1	UNL-1809	1.5	0.8	3.9	1.4	6.4	1.62 ± 0.11	1.22 ± 0.01	25/27	760 ± 60
	OSL 2	UNL-1889	4.5	1.0	4.3	1.6	14.1	1.69 ± 0.20	1.34 ± 0.02	23/24	790 ± 100
Rodda Auger 1	OSL 1	UNL-1804	1.5	0.8	3.4	1.6	1.7	1.87 ± 0.11	0.85 ± 0.02	24/27	460 ± 40
	OSL 2	UNL-1890	3.5	1.2	5.3	1.7	6.3	1.98 ± 0.14	1.26 ± 0.08	21/24	640 ± 70
	OSL 3	UNL-1805	5.3	1.3	6.4	1.7	3.9	2.14 ± 0.13	28.10 ± 1.59	21/24	13,100 ± 1200
Wilson Auger 1	OSL 1	UNL-1810	1.5	0.7	3.3	1.8	5.7	1.91 ± 0.14	1.36 ± 0.04	23/25	710 ± 60
	OSL 2	UNL-1891	3.3	0.8	3.4	1.8	10.2	1.80 ± 0.18	1.34 ± 0.04	22/23	750 ± 80
	OSL 3	UNL-1811	5.0	1.2	4.3	1.7	10.4	1.81 ± 0.17	79.77 ± 7.10	23/34	44000 ± 6000
Wilson Auger 2	OSL 1	UNL-1812	1.4	1.4	6.1	1.7	4.0	2.18 ± 0.13	>175	–	>80,000[c]
Wilson Auger 3	OSL 1	UNL-1892	1.3	0.7	3.1	1.3	5.5	1.51 ± 0.10	1.18 ± 0.03	20/20	780 ± 70
	OSL 2	UNL-1893	3.6	1.0	4.0	1.7	3.8	1.93 ± 0.12	84.79 ± 5.60	21/54	44,000 ± 4400
Wilson Pit	OSL 1	UNL-1894	1.2	0.7	3.3	1.5	2.2	1.77 ± 0.10	1.45 ± 0.05	20/24	820 ± 70
	OSL 2	UNL-1895	3.0	0.7	3.6	1.4	3.8	1.60 ± 0.10	1.70 ± 0.14	21/27	1060 ± 120

[a] Assumes 100% error in measurement.
[b] Accepted disks/all disks.
[c] Sample was too old to produce a meaningful age; this should be considered a minimum age estimate for the sample.

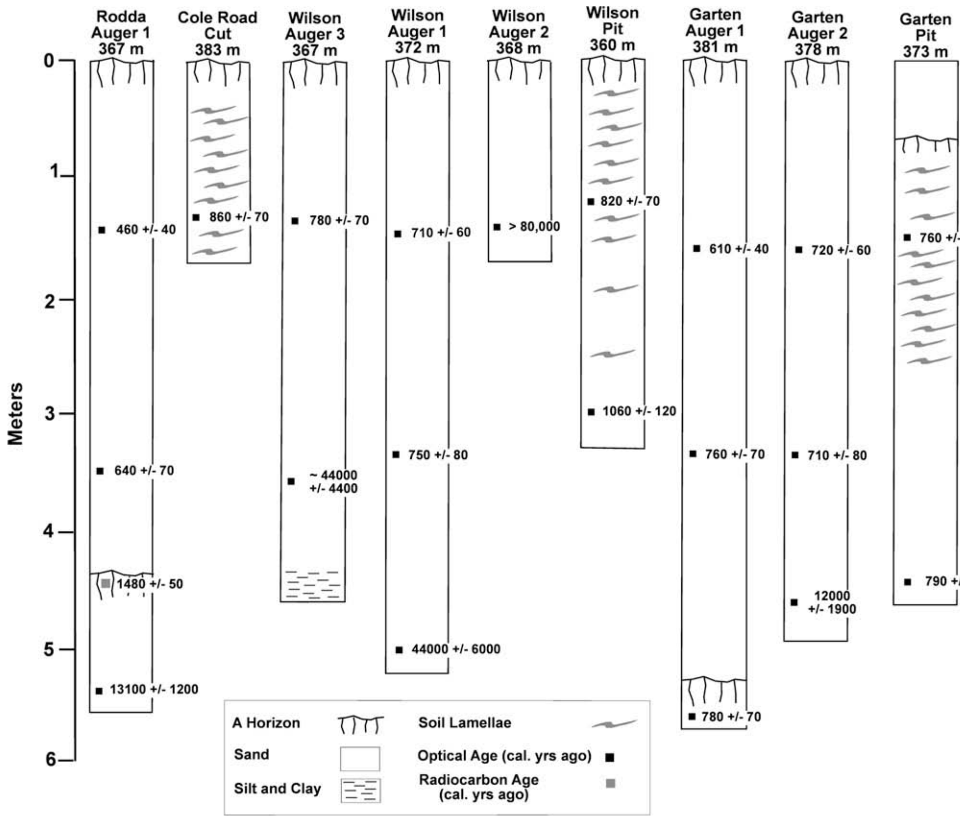

Fig. 3. Stratigraphy of dune sediments sampled from Abilene dunes. Optical and radiocarbon age estimates are shown with their 1σ errors. Auger and pit elevations are given in masl.

The Garten Pit site lies in a low-relief sand sheet ~220 m to the northeast of the aforementioned dune crest. In the Garten Pit, an A horizon, probably buried by late historic fill during pit operations, lies between 0.6 and 0.8 m depth. Underlying this A horizon are clay lamellae that start 0.2 m below the A horizon and extend from 0.8 to 2.5 m below the existing ground surface (Fig. 3).

A total of eight samples were collected for optical dating from the two Garten auger holes and the Garten Pit (Table 1; Figs. 2 and 3). Seven of these ages, derived from samples taken at depths of 1.5–5.4 m below the ground surface, ranged from 610 to 790 years ago. A sample taken at 5.4 m depth, below the buried soil at the base of Garten Auger 1, yielded an age estimate of 780 ± 70 (Fig. 3). One age estimate of 12,000 ± 1900 was derived from a sample taken at a depth of 4.7 m, near the base of Garten Auger 2 (Fig. 3). There is no indication of either dune truncation or soil development between the older and younger age estimates taken from Auger 2.

5.1.3. Phelps site

The Phelps site is a cutbank exposure on a meander of the Smoky Hill River adjacent to the south-central part of the dune field (Fig. 2). This site exposes the alluvial sand and gravel of the T1 fill, and exhibits a buried soil ~2.6 m below the terrace tread. A sample was collected within the interval 2.6–2.7 m and yielded a calendar age of 30,500 ± 700 yrs from bulk soil organic matter (Table 2). This numerical age provides a limit on the time of floodplain abandonment and channel entrenchment.

5.1.4. Rodda Auger

The Rodda site is located near the southwestern margin of the Abilene dunes on the crest of a high-relief dune (Fig. 2), ~1 km north of and ~13 m above the Smoky Hill River floodplain. Augering detected a surface A horizon and a buried A horizon at 4.3–4.6 m below the ground surface (Fig. 3). Optical age estimates were produced from hand-auger samples taken at 1.5 m (460 ± 40 years), 3.5 m (640 ± 70 years), and 5.3 m (13,100 ± 1200) in depth (Table 1; Fig. 3). An AMS radiocarbon age estimate taken from total organic matter from the buried soil at 4.3–4.6 m depth yielded a calendar age of 1480 ± 50 yrs BP (Table 2). This bulk soil age lies between the optical age estimate of 13,100 ± 1200 at a depth of 5.3 m and that of 640 ± 70 years ago from 3.5 m depth (Fig. 3).

5.1.5. Wilson sites

The three Wilson auger holes, the Wilson cores, the Wilson Pit and the Wilson Feedlot sites are located on the T2 tread within

Table 2
Radiocarbon age from soil organic matter in the Rodda Auger.

Field site	KU sample no.	Method	Laboratory no.	Depth (m)	Unit	$\delta^{13}C$ (‰)	Age ^{14}C Yr BP	Age Cal. Yr BP[a]
Rodda Dune	Rodda 1	AMS	OS-68474	4.4	Eolian sand	−22.9	1590 ± 30	1480 ± 50
Phelps	Phelps 1	Conventional	ISGS 5849	2.6	T1 alluvium	−22.8	25,400 ± 550	30,520 ± 700
Wilson Feedlot	Wilson 3-RC	AMS	OS-49604	0.5	T2 alluvium	−24.5	45,000 ± 520	48,930 ± 480

[a] Calendar age conversion using Fairbanks et al., 2005 (rounded to nearest decade).

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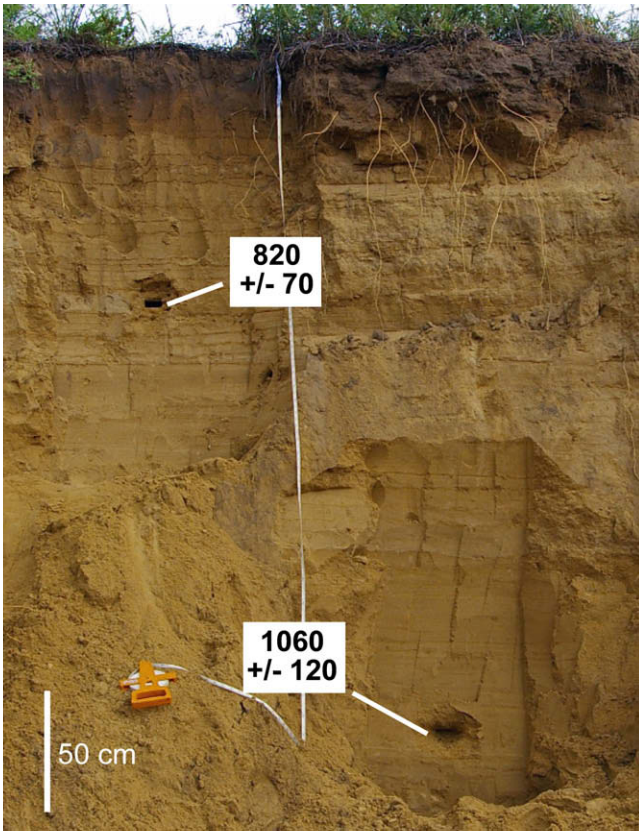

Fig. 4. Clay lamellae in aeolian sand at Wilson Pit (see Fig. 3). Excavations from optical age sample locations are shown with age estimates; upper and lower samples were taken from depths of 1.2 and 3.0 m, respectively.

1 km of the Smoky Hill River floodplain (Fig. 2). Wilson Augers 1 (372 masl) and 2 (368 masl) are about 17–21 m above the Smoky Hill River floodplain on a low-relief dune (Fig. 2). The Wilson Pit (360 masl) lies at the base of the dune, ~400 m to the southeast of Wilson Auger 1 (Fig. 2), and ~9 m above the Smoky Hill River floodplain. Wilson Auger 3 (~367 masl) is located >600 m to the southwest of Auger 1 and is >170 m from the Smoky Hill River floodplain (Fig. 2), and 16 m above the Smoky Hill River floodplain. The three hand-auger holes ranged from 1.6 to 5.2 m in depth. Silt and clay were encountered at depths of 4.5–4.6 m below the ground surface in Wilson Auger 3. The Wilson pit exposes ~3 m of exposed sediment, including clay lamellae (Figs. 3 and 4).

Continuous cores were taken from directly adjacent to Wilson Augers 1, 2, and 3 to better characterize the dune and sub-dune stratigraphy and identify the extent of aeolian deposits. Each of these cores was dominated by noncalcareous fine and medium sands that were laminated near the surface, but showed no bedding at depth (Fig. 5). Wilson Core 1 was 6.2 m in length and exhibited an A horizon developed in moderately well sorted fine sand with laminations that extend from 1.8 to 4.3 m depth. Moderately sorted fine and medium sands predominate from 4.3 to 6.1 m depth, and clay lamellae 1–4 mm in thickness were observed from 0.7 to 1.7 m below the ground surface. While the particle size trend in Core 1 shows little change with depth, both Core 2 and Core 3 show dramatic increases in silt content with depth (Fig. 5). In Core 2 the upper 2 m is predominantly moderately well sorted medium sand that overlies moderately sorted medium and fine sands. Laminations are found from 0.6 to 1.6 m depth. A silt increase is noted in the surface A horizon (Fig. 5), as well as below 2 m in depth (Fig. 5). Core 2 has clay lamellae as much as 5 mm thick in the interval between 0.4 and 2 m depth. Core 3 was 5.7 m deep, and revealed a buried A horizon from 0.6 to 1.0 m depth. Although located within ~15 m, this buried A horizon was not noted in Wilson Auger 3 (Fig. 3). The upper 3.2 m are moderately well

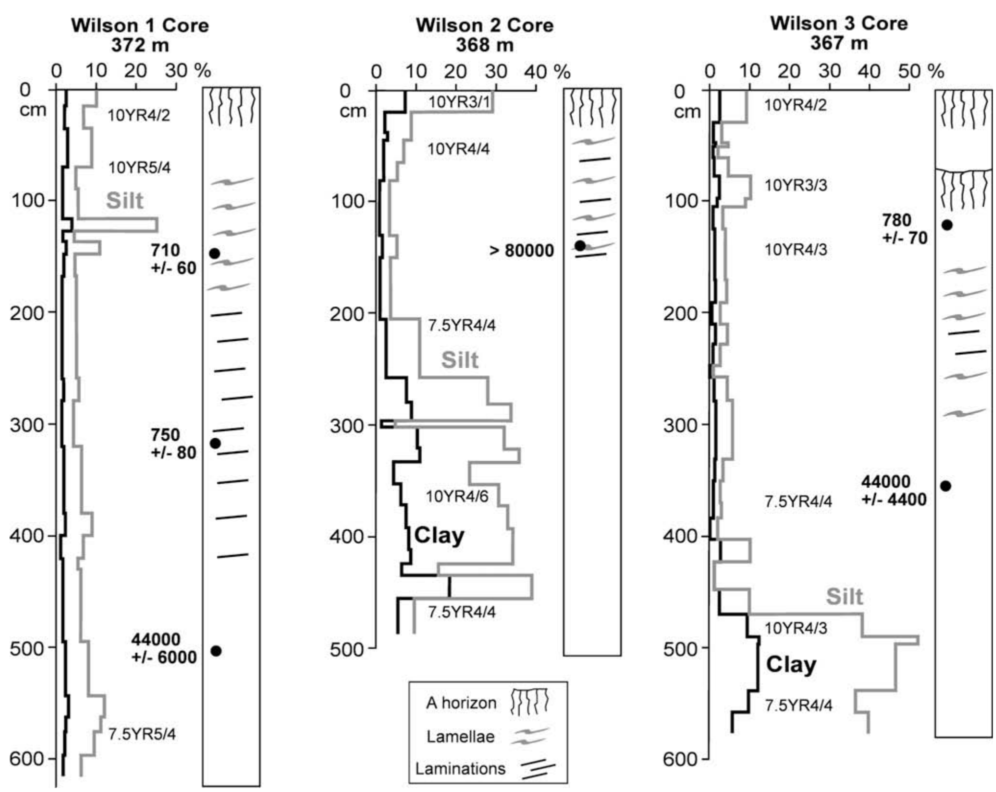

Fig. 5. Particle size trends and stratigraphy for Wilson Cores 1, 2, and 3 (Fig. 1). Elevations are given in masl. Depths of lamellae and/or laminations roughly correspond to aeolian sand that overlies Pleistocene alluvial sediments. Munsell colors are shown at significant changes in color. Optical ages shown are from Augers taken in close proximity to these cores (Fig. 3).

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sorted fine sands, overlying moderately sorted fine and medium sand from 3.2 to 4.6 m, and moderately sorted fine and very fine sand and silt from 4.6 to 6.2 m (Fig. 5). Clay lamellae appear between 1.5 and 2.9 m, and sedimentary laminae exist from 2.2 to 2.5 m (Fig. 5).

The lower portions of each of these cores show redder hues (e.g. 7.5YR 4/4 vs. 10YR 4/4) compared to the upper portions of these deposits (Fig. 5). In Cores 2 and 3 these redder colors correspond to the increased silt and clay contents that occur below 2 and 3.8 m, respectively (Fig. 5). In Core 1, redder colors are found below 5.7 m, but do not correspond to a change in sediment texture. In each of these cores, the redder sediments lack evidence indicating extensive soil development such as clay skins or any significant development of soil structure. We interpret the upper laminated, moderately well sorted fine and medium sands in each of these cores as aeolian sands, and the lower sandy and silty sediments as alluvial deposits. These alluvial sediments are most likely the Pleistocene alluvium that is mapped to the west of our study sites (McCauley and Johnson, submitted for publication; Fig. 2). This interpretation is supported by the similar elevations for the dunes (∼360–385 masl) and the Pleistocene alluvium that is found immediately to the west of our study sites (371–381 masl).

Three optical ages and one radiocarbon age obtained from subdune alluvium at the Wilson sites indicate that the alluvium underlying the dunes was deposited over 40,000 years ago (Figs. 3 and 5). The stratigraphically-lowest optical age estimate from Wilson Auger 1 is 44,000 ± 6000 (5.0 m) years ago (Fig. 3). One age estimate from near the base of Wilson Auger 2 was too old to produce a meaningful age estimate using the optical dating methods employed here, and is assigned a minimum age of 80,000 years ago on the basis of the highest regenerative dose below the saturation limit for the sample. The lowest age estimate from Wilson Auger 3 was taken from 0.85 m above the silt and clay encountered at the base of this hole and yielded an age estimate of 47,000 ± 4400 (3.6 m) years ago. A radiocarbon age for a sample collected from a soil exposed within the high-terrace (T2) alluvial fill at the Wilson Feedlot produced a calendar age of 48,930 ± 480 yrs ago (Table 2). This age is consistent with the lowermost optical ages taken from Wilson Augers 1 and 3 (Fig. 3), indicating an age for the upper alluvium in the high terrace of ∼45 ka or older. The older sediments found in the Wilson Augers were taken at elevations of 367–364 masl or ∼16–13 m above the present floodplain.

Five optical dating samples taken from aeolian sediments in the Wilson hand-auger holes and the Wilson Pit ranged from 1060 to 710 years ago (Table 1; Fig. 3). The two upper age estimates from Wilson Auger 1 are 750 ± 80 (3.3 m) and 710 ± 60 (1.5 m) years ago. Two ages derived from the Wilson Pit were 1060 ± 120 years ago at a depth of 3.0 m and 820 ± 70 years ago at a depth of 1.2 m (Figs. 3 and 4). The upper sample was taken from within the horizon containing dense clay lamellae, but the lower age was taken just below the base of readily identifiable lamellae (Fig. 4). The upper age estimate from Wilson Auger 3 is 780 ± 70 (1.3 m) years ago. Neither a buried soil nor a truncation surface was identified between the older alluvium and the younger aeolian ages from Wilson Auger 1 or 3.

6. Discussion

6.1. Dune source area and mineralogical maturity

In addition to reconstructing the history of aeolian sand deposition in the Abilene dunes, a goal of this study was to identify the source sediment for the dune sand. Potential dune source sediments are: (1) Pleistocene alluvium lying both adjacent to and directly underneath the dunes and (2) Holocene alluvium from the Smoky Hill River floodplain, which borders the dune field immediately to the south (Fig. 2). In this context, several studies of Great Plains dune fields (Muhs et al., 1996, 1997a,b; Arbogast and Muhs, 2000; Muhs and Holliday, 2001; Muhs, 2004) employed trace-element analysis to determine both the source areas for aeolian sands and their mineralogical maturity. For example, Muhs et al. (1996) determined that the source area of the Wray and Fort Morgan dune fields in northeastern Colorado has been the South Platte River, rather than the underlying Ogallala Formation as previously assumed. Similarly, Arbogast and Muhs (2000) argued that the Arkansas River is the likely source for dunes within the Great Bend Sand Prairie. These conclusions were based on the fact that concentrations of Ba, Rb, Sr, Ti, and Zr can be measured with high precision by X-ray fluorescence spectrometry. As outlined by Muhs et al. (1996), Ba and Rb substitute for K and are thus found in K-feldspar and biotite. Ba is usually enriched in early-formed K-bearing minerals because of its higher charge, whereas Rb tends to be enriched in later-formed K-bearing minerals due to its larger ionic radius. Sr substitutes for Ca and is found mostly in plagioclase, although it also occurs in some K-bearing minerals. Ti fundamentally occurs in ilmenite, and Zr is almost always found in zircon.

Results from trace-element analyses reveal the most likely source for the aeolian sands contained within the Abilene dune field. A scatterplot of Rb vs Sr (Fig. 6a) indicates that the dune geochemistry is most closely associated with the alluvium that underlies the dunes, whereas the Holocene alluvium found along the modern Smoky Hill River and its floodplain are a separate, distinct population. Similar diagnostic patterns are visible in plots of Ba/Sr vs Rb/Sr (Fig. 6b) and Ti/Zr vs Rb/Sr (Fig. 6c). A Kuskal–Wallis test at $\alpha = 0.05$ demonstrates that the trace-element compositions of dunes and of the underlying alluvium are essentially the same, whereas the aeolian deposits and Holocene alluvium from the Smoky Hill River are significantly different. These results suggest that the adjacent and underlying Pleistocene alluvium was the dominant source for aeolian sands in the Abilene dune field. Importantly, geochemistry data suggests that dune activation in this setting resulted directly from vegetation reductions due to aridity, rather than from changes in sediment availability from the local floodplain.

Trace-element analysis also provides an indirect measure of the mineralogical maturity of the dune field. According to Blatt et al. (1972), mineralogically mature sandstones and sandy sediments are those characterized by an abundance of quartz relative to feldspars. This dichotomy can occur either because the source sediments for a particular dune field are low in feldspar, or because of long-term processes acting on sediment that has a high feldspar content. Given that feldspar is generally resistant to chemical weathering over relatively short time periods, K-feldspar depletion is most likely the result of mechanical weathering through repeated ballistic impacts during long-term aeolian activity (Dutta et al., 1993).

The mineralogical maturity of an aeolian sand depends upon: (1) the mineralogical composition it inherits from source sediments (*inherited maturity*, in our terminology) and (2) subsequent changes in its bulk mineralogy produced by abrasion during progressive stages of aeolian transport (*acquired maturity*). Acquired maturity is important in cases of extensive aeolian transport because repeated ballistic impacts gradually remove feldspars and carbonates by attrition. The mineralogical maturity of dunes in the Great Plains has been attributed to both inherited and acquired maturity. For instance, the relatively mature sands in the Nebraska Sand Hills (Muhs et al., 1997a) and the Monahans dune field in Texas (Muhs and Holliday, 2001) are attributed to mechanical weathering and ballistic impacts that occurred during long-term aeolian transportation (Muhs, 2004). In the northern part of the Southern High Plains, however, the Muleshoe dune field is derived

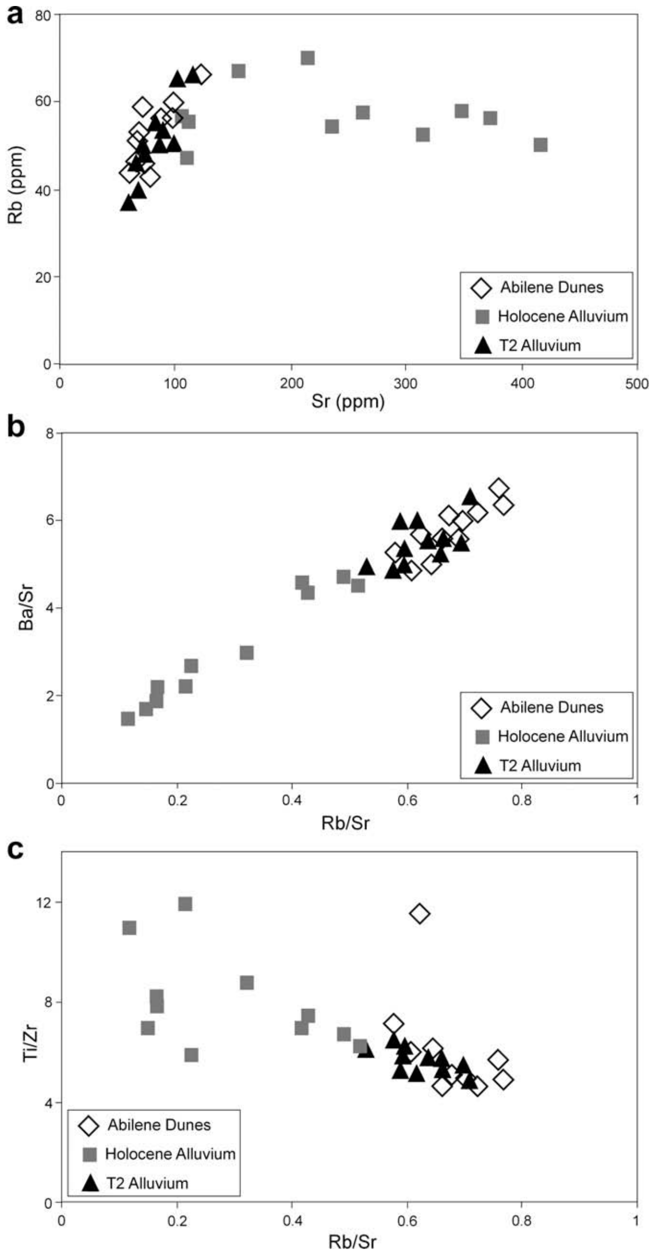

Fig. 6. Trace-element scatter plots from sand samples. (a) Plots of Rb vs Sr from the Abilene dunes (diamonds), alluvium underlying the dunes (triangles), and Holocene sediments from the Smoky Hill River (grey squares). (b) Plots of Ba/Sr vs Rb/Sr from the Abilene dunes, sub-dune alluvium, and the Holocene Smoky Hill River alluivum. (c) Plots of Ti/Zr vs Rb/Sr from the Abilene dunes, sub-dune alluvium, and the Holocene Smoky Hill River alluvium.

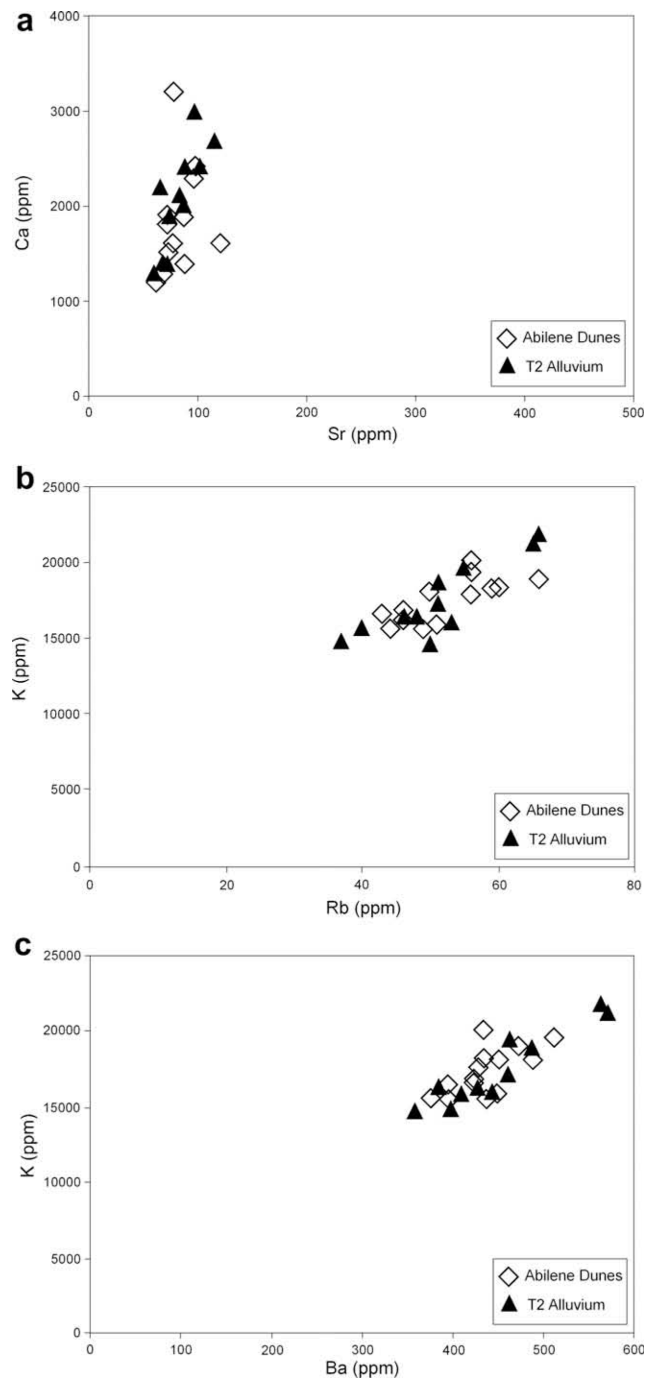

Fig. 7. Assessment of mineralogical maturity of Abilene dune field. (a) Plot of Ca vs Sr from the Abilene dunes (diamonds) and alluvium (triangles) from under the dunes. (b) Plots of K vs Rb and K vs. Ba from Abilene dunes and alluvium from under the dunes.

from the feldspar-poor Blackwater Draw Formation (Muhs and Holliday, 2001), and therefore, these dunes have an inherited maturity. In contrast to the Nebraska Sand Hills and some dune sands on the Southern High Plains, dunes in northeastern Colorado (Muhs et al., 1996) and the Great Bend Sand Prairie of Kansas (Arbogast and Muhs, 2000) have higher feldspar contents and can be considered to be comparatively immature, almost certainly because dunes in these areas have had a limited activation history.

The mineralogical maturity of a sand is reflected in its chemical composition. Plots of Ca vs. Sr (Fig. 7a), K vs. Rb and K vs. Ba (Fig. 7b) from the Abilene dunes indicate little evidence of feldspar depletion in the aeolian sands compared to the underlying Pleistocene source sediments. These data suggest that the Abilene dune sands are relatively immature. Consequently, these geochemical data, in conjunction with the geochronological data, support the conclusion that the Abilene dunes have not been activated for extensive periods during the Holocene. Furthermore, it is clear that the aeolian sands did not move far from their source sediments. In contrast, Arbogast and Muhs (2000) demonstrated that aeolian sands in the Great Bend Sand Prairie moved tens of kilometers southeastward and downwind from the Arkansas River, the likeliest sediment source because there is a subtle gradient in feldspar depletion from northwest to southeast across the dune field.

6.2. Soil development and formation of clay lamellae

Surface and buried soils encountered in the upper portions of profiles and cores indicated soils were limited to the development of A horizons and clay lamellae that are found within 0.2–0.5 m below an overlying A horizon (Figs. 3–5). Clay lamellae appear in the Cole Road Cut, and in the Garten and Wilson cores and borrow pits, including both sand sheet and higher-relief dunes. Although lamellae were not identified in the auger holes from either high- or low-relief dunes, they were identified in each of the three cores taken from the Wilson Sites, and from each of the three exposure sites. It is assumed that clay lamellae were not identified in Augers because of the disruptive nature of hand augering (Hanson et al., 2009), and that the artificial exposures and cores provide the best information on soil development in the field area.

Most authors attribute clay lamellae to either primary depositional banding or to pedogenic alteration (Rawling, 2000). The lamellae encountered in this study are attributed to clay illuviation on the basis of their consistent occurrence below A horizons and their marked decrease in frequency with depth (Figs. 3–5). The optical age chronology indicates that clay lamellae can form by illuviation within ~700 yrs of subaerial exposure in this portion of the central Great Plains. Holliday and Rawling (2006) reached a similar conclusion in the Muleshoe Dunes in Texas where lamellae were not observed in sediment deposited in the 19th or 20th centuries, but a few, thin, and discontinuous lamellae were found in sediments deposited between 200 and 1000 years ago.

6.3. Abilene dune chronology

Most optical age estimates from dune sands clustered into one relatively young group, and the remaining age estimates indicate much older periods of sedimentation. Fifteen of the 20 age estimates indicate that dune activity occurred between ~1060 and 460 years ago (Figs. 3 and 8). With the exception of the single age estimate from Wilson Auger 2, each of the surface sediments sampled indicated that dunes in the region were active within the past ~1100 years. A radiocarbon age estimate of 1480 ± 50 years BP from buried soil bulk organic matter in Rodda Auger 1 (Fig. 3) supports the relatively young age estimates for the overlying optical ages. Although radiocarbon ages derived from bulk soil organic matter are prone to contamination by younger or modern carbon (Martin and Johnson, 1995; Wang et al., 1996), it is unlikely that this radiocarbon age was adversely affected by younger carbon due to its burial depth of ~4.6–4.3 m.

Age inversions were not identified in the majority of these estimates, but in Garten Auger 1 an age estimate of 780 ± 70 years ago was found below a buried soil that underlies an age estimate of 760 ± 70 years ago (Fig. 3). These two ages clearly overlap within their 1σ errors, and given the presence of an intervening buried A horizon, there should be an age difference of ⩾100 years between them, or the expected length of time for an A horizon to develop in this setting. Although this problem could be related to the resolution of the optical dating technique, other factors such as bioturbation could be affecting one or more of these age estimates. Specifically, sample UNL-1807 (Table 1) was taken from ~10 cm below the overlying buried A horizon (Fig. 3), and sands from this depth in a profile can produce young age estimates due to bioturbation (Bateman et al., 2003; Feathers, 2003; Rawling et al., 2008). Based on the data available these cases cannot be adequately assessed, but the uncertain implications of this single age have little bearing on the conclusions drawn from the age data as a whole.

Age estimates taken from the sand sheets in the Abilene dunes are similar to, or perhaps slightly older than, age estimates taken from the higher-relief dunes (Table 1; Fig. 3). The three oldest age estimates in the past ~1500 years were obtained from sand

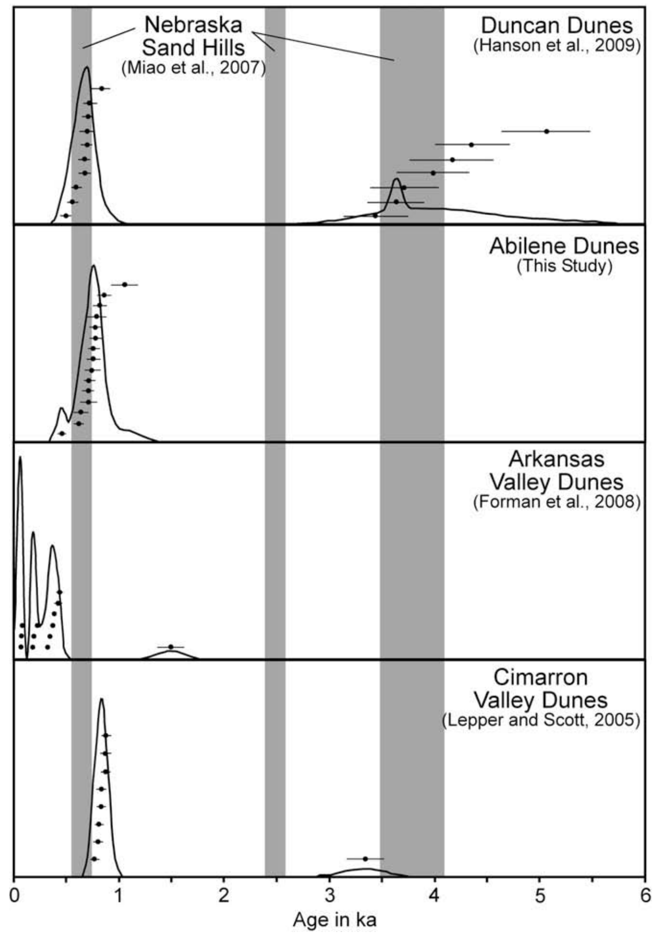

Fig. 8. Probability plots showing optical age estimates for dune activation from near eastern edge of High Plains and Plains Border, including records from Abilene dune field, Duncan dunes (Hanson et al., 2009), and Cimarron Valley dunes (Lepper and Scott, 2005); see Fig. 1 for locations. Vertical gray bars are megadrought events identified from the Nebraska Sand Hills and adjacent loess deposits by Miao et al. (2007). A dune activity record for the Arkansas Valley Dunes (Forman et al., 2008) is also shown; this record shows a comparative dune activation history of western Great Plains. Vertical scales for probability plots are in arbitrary units.

sheet deposits in the Wilson Pit (1060 ± 120 and 820 ± 70) and at the Cole Road Cut (860 ± 70). The youngest dune ages were obtained from high-relief dunes at the Rodda Auger 1 (640 ± 70 and 460 ± 40) and the Garten Auger 1 (620 ± 50) sites. Even though the sample size is limited and some of these age estimates overlap within 2σ, the apparent trend could be explained by differences in landscape position. For instance, this difference could be attributed to greater moisture stress in the higher-relief dunes, resulting either in decreased stability or in increased reactivation rates in these dunes.

6.4. Regional comparisons of late Holocene dune activation histories

Most dune records from the central Great Plains show that the last significant period of dune activation occurred between ~1000 and 600 years ago. The majority of the Abilene dune ages overlap within 1σ of the megadrought event identified by Miao et al. (2007) for the Nebraska Sand Hills and adjacent loess deposits (Fig. 8). Likewise, Arbogast (1996) demonstrated that dunes in the Great Bend Sand Prairie were activated shortly after 1400, 1100, 700, and 300 years ago. At least two of the events identified by Arbogast (1996) overlap with ages derived from the Abilene dunes, which were last active from 1060 to 460 years ago. The

Cimarron Valley dunes in western Oklahoma were last active between 870 and 770 years ago (Lepper and Scott, 2005), and the majority of the Abilene age estimates, overlap within 1σ errors of ages taken from the Duncan dunes in eastern Nebraska (Figs. 1 and 8). Overall, these comparisons bolster the assertion that many of the dunes on the central Great Plains were activated by increased aridity during the Mediaeval Warm Period (Daniels and Knox, 2005). Importantly, dune records from the eastern margin of the Great Plains show similar reactivation histories (Fig. 1). The Abilene, Cimarron Valley (Lepper and Scott, 2005), and Duncan (Hanson et al., 2009) dunes all show the last period of dune activation occurred between ~1.2 and 0.5 ka.

Although most dunes in the region were activated 1200–600 years ago, evidence for younger and more frequent dune activity within the past ~500 years is found in some dune fields located to the west of the modern 500 mm isopleth (Fig. 1). The Arkansas Valley dunes are particularly relevant in comparison to the Abilene record because of their relatively close proximity (Fig. 1). The Arkansas Valley dunes show increased aeolian activity occurred at ~1490, 430, 380–320, and 70 years ago (Fig. 8; Forman et al., 2008). Similar young ages are found in several other dune fields. Forman et al. (2005) found evidence for much more frequent dune activation in the western part of the Nebraska Sand Hills, identifying episodes around 3700, 670, 470, 240, 140, and 70 years ago. The Wray dune field of southwestern Nebraska-northeastern Colorado (Fig. 1) was activated around 540, 420, and 70–80 years ago (Forman et al., 2005). IRSL age estimates from the Fort Morgan dune field indicate it was active at 4.85, 2.37, 1.06, 0.8, 0.6–0.53, and 0.37 ka (Clarke and Rendell, 2003). The overall poor correspondence between these records and those from the Abilene and other western High Plains dunes (Fig. 8) may be attributed to differences in climate and/or landscape resilience from the more humid east to the more arid west (Fig. 1). Indeed, most sites showing frequent aeolian activity within the past ~500 years are located near or to the west of the 500 mm isopleth (Fig. 1). More dune sites with age control from the Great Plains will enable scientists to better assess the causes for these differences in chronologies.

In contrast to the majority of dune records from the central Great Plains (Fig. 8), the data from the Abilene dunes indicate only one significant period of activity during the Holocene, rather than multiple middle- to late-Holocene episodes of dune reactivation. For example, Arbogast and Johnson (1998) found dune deposition after 6700 years ago and after 3700 years ago in the Great Bend Sand Prairie (Fig. 1). Additionally, the Nebraska Sand Hills show periods of continuous drought from 9600 to 6500 years ago and later dune activation events centered on 3800, 2500, and 700 years ago (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007); the Duncan dunes were also active between 4300 and 3500 and between 900 and 500 years ago. The Abilene dunes show no evidence for significant dune activation prior to 1100 years ago. The basal age estimates from Wilson Augers 1, 2, and 3 are interpreted as alluvial deposits, and with the exception of Wilson Auger 2, aeolian sand with ages of 800–700 years directly overlies these older deposits. Optical age estimates taken from Garten Auger 2 and Rodda Auger 1 indicate that the sediments at the base of these profiles were deposited at ~12.0 and 13.1 ka, respectively. In both cases these older sediments were fine to medium sands similar to the overlying aeolian deposits, but both samples were taken from soil Augers, and therefore sedimentary features that would be necessary to indicate a particular depositional environment were not observable. However, the luminescence signals from these two older samples show significantly more spread than is common for aeolian sediments. Based on this evidence, it is likely that these deposits are not aeolian, or that these sediments were not transported appreciable distances from their source. Given the available data, it is not possible to distinguish between these two possible scenarios.

The lack of evidence for reactivation of the Abilene dunes at other times in the Holocene suggests a potential sampling or preservation bias, significant differences in climate, and/or differential resilience of dune field geoecosystems to droughts. The limited number of optical ages taken from the Abilene dunes does not allow us to assess the validity of these different hypotheses, but additional dune dating on the Great Plains will aide us in better understanding differences in activation histories of Great Plains dune fields.

7. Conclusions

Geochemical data indicate that the Abilene dunes in east-central Kansas resulted from the deflation of Pleistocene alluvial fill from at least one terrace level above the Smoky Hill River. The sand in these dunes is mineralogically immature and did not travel far from its source. Geochemical data rule out Holocene aged Smoky Hill River deposits as a sand source, further suggesting that the dunes originated because of increased aridity and a local reduction in vegetative cover, rather than from changes in sediment availability alone. Optical dating reveals that the Abilene dunes were active between 1100 and 500 years ago, an interval overlapping dune activation in more arid portions of the Great Plains, such as the Nebraska Sand Hills and the Great Bend Sand Prairie. By combining the activation record from the Abilene dunes with those retrieved from other, smaller dune fields along the eastern margin of the Great Plains (Cimarron Valley and Duncan dunes), it can be concluded that that Mediaeval Warm Period megadroughts, associated mostly with the Nebraska Sand Hills, also impacted areas far eastward on the plains. In contrast to other records from the region, the Abilene dunes show no evidence for multiple drought events during the Holocene. This difference in dune activity may indicate variability in the extent and severity of older drought events at the eastern margin of the Great Plains. Future studies will work toward delineating the geographical extent of megadrought impacts even farther eastward onto the Central Lowlands.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.aeolia.2009.10.002.

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