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Stratigraphic evidence for late-Holocene aeolian sand mobilization and soil formation in south-central Kansas, U.S.A.

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Stratigraphic evidence and radiocarbon dating of sediments from the Great Bend Sand Prairie in Kansas indicates that significant deposits of aeolian sand have accumulated in the region during the late Holocene. Radiocarbon ages obtained from total humates in buried soils suggest that five periods of late-Holocene stability and soil formation are preserved in dune fields at approximately 2300, 1400, 1000, 700, 500 and 300 years B.P. Reactivation of aeolian sand in the past 1000 years has resulted in a variety of well defined, parabolic dunes. In general, events in the region correspond with established chronologies elsewhere on the Great Plains and in particular correlate well with dune fields in north-eastern Colorado. Overall, results indicate that the threshold of landscape stability on the Great Bend Sand Prairie can easily be crossed in the current climatic regime.

Keywords: Kansas; Holocene; sand dunes; aeolian; stability

Introduction

It is widely believed that increases in atmospheric CO_2 and other greenhouse gases could lead to significant global warming (Washington & Meehl, 1984; Hansen *et al.*, 1988). Climatic modelling (e.g. Hansen *et al.*, 1988; Schlesinger, 1989) indicates that the level of warming in the next few decades may reach the maximum levels achieved during the last few interglacials, especially if current levels of volcanism and insolation remain constant (Crowley & North, 1991). Although models suggest that warming will vary regionally, above-average levels of warming and aridity have been predicted, beginning this decade, for the already sub-humid and semi-arid Great Plains (Hansen *et al.*, 1988; Wetherald & Manabe, 1988).

Aeolian landscapes of the Great Plains are particularly sensitive to climate change. Large portions of the region are mantled by presently stabilized sand dune fields and sand sheets (e.g. Smith, 1940; Ahlbrandt *et al.*, 1983; Muhs, 1985; Holliday, 1989; Madole, 1994; Fig. 1). Periodic desertification and mobilization of sand sheets has been demonstrated during the late Quarternary when episodic drought reduced stabilizing vegetative cover (Madole, 1986, 1994, 1995; Holliday, 1989, Swinehart,

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1990). Dune formation apparently occurred during both cool, arid periods such as the late Wisconsin (e.g. Wright *et al.*, 1985; Forman & Maat, 1990) and warm, arid intervals like the middle Holocene (Ahlbrandt *et al.*, 1983; Holliday, 1989; Forman & Maat, 1990). The conditions under which these geomorphically sensitive areas would again destabilize, and the nature of the response, has been the focus of increased study in north-eastern Colorado (Muhs, 1985; 1991; Madole, 1986, 1994, 1995; Forman & Maat, 1990; Forman *et al.*, 1992; 1995; Muhs *et al.*, 1996), Wyoming (Gaylord, 1982; Stokes & Gaylord, 1993), Nebraska (Ahlbrandt & Fryberger, 1980; Ahlbrandt *et al.*, 1983; Swinehart, 1990; Ponte *et al.*, 1994), and Texas (Holliday, 1985, 1989).

Until recently, little information has emerged regarding the evolution of dune fields in Kansas, which occur mostly in the western half of the state along the Arkansas River. The largest sand sheet in the area is the Great Bend Sand Prairie, located in the south-central part of Kansas. This paper presents the results of detailed stratigraphic

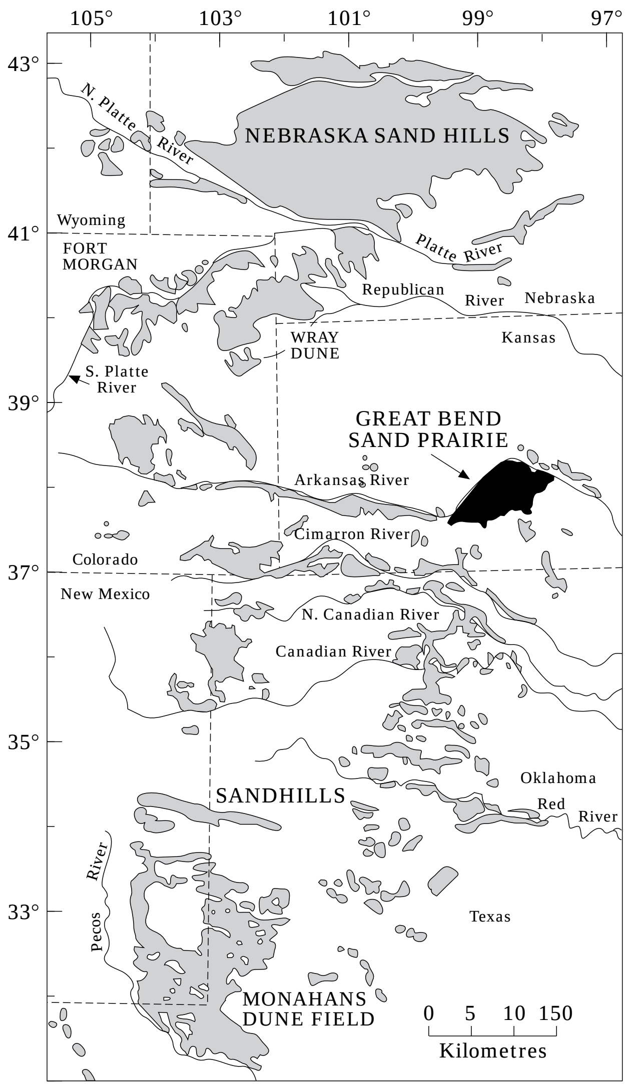

Figure 1. Location of the Great Bend Sand Prairie and other dune fields and sand sheets in the central Great Plains (modified from Muhs & Holliday, 1993).

investigations that were recently conducted on the Great Bend Sand Prairie (Fig. 2). The primary goal of the study was to reconstruct the late-Quarternary paleoenvironmental and geomorphic history, specifically the chronology of aeolian sand mobilization, in the region.

Study area and methods

The Great Bend Sand Prairie, approximately 4500 km^2 in size, is defined primarily by its inclusion within the 'great bend' of the Arkansas River (Figs 1 and 2). Major tributaries in the region are the North Fork Ninnescah River, which flows generally to the south-east, and Rattlesnake Creek, a north-easterly trending stream that bisects the study area (Fig. 2). The present climate is semi-arid to sub-humid and strongly continental, characterized by an extreme (–7·0–34·0°C) range in temperature. Mean annual precipitation is about 75 cm, but has ranged historically from 37 to 89 cm (Kansas Statistical Abstracts, 1990, p. 289). Generally, the region can be characterized as a high-energy environment (drift potential (DP) = 1090) with multi-directional winds. During the winter months prevailing winds are north-westerly (Fig. 3(a)), whereas they are southerly to south-westerly in summer (Fig. 3(b)). On an annual basis, summer winds are strongest, resulting in an overall north-easterly drift direction (Fig. 3(c); Muhs, unpub. data).

The late-Quarternary geology of the Great Bend Sand Prairie consists largely of two diachronous stratigraphic units: a near ubiquitous, poorly-sorted deposit of sand, silt and clay (a.k.a. silty sand) and aeolian sand (Rosner, 1988; Johnson, 1991). The silty sand is a late Wisconsin deposit that apparently accumulated in a series of playas and/

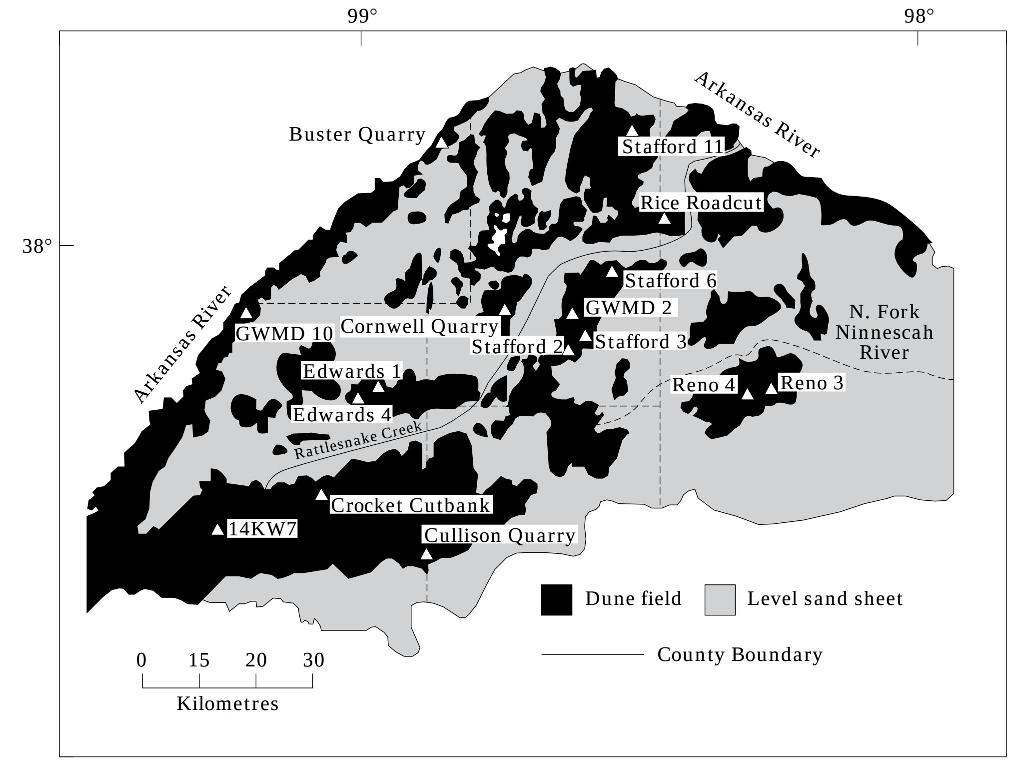

Figure 2. Major dune fields and study sites on the Great Bend Sand Prairie.

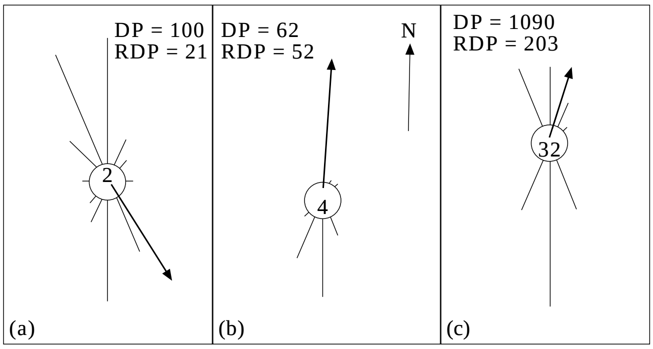

Figure 3. (a) February sand rose diagram (complex) for Hutchinson. Winds are multi-directional, with the prevailing wind from the north-west and a south-easterly resultant drift direction (RDD; modified from Muhs, unpub. data). Drift potential (DP; measured in vector units) is a measure of relative sand-moving capability of wind, whereas the RDP is the resultant drift potential. The reduction factor, which is the number by which the vector-unit total of each sand rose arm was divided so the longest arm would plot at < 50 mm (Fryberger & Dean, 1979) is 2. (b) July sand rose diagram (wide unimodal) for Hutchinson. Winds are dominantly southerly with a north to north-easterly RDD. (c) Annual summary of sand rose diagrams (complex) for Hutchinson (modified from Muhs, unpub. data).

or low-energy fluvial systems (Arbogast, 1995). Although the silty sand occasionally is found at the surface, it is usually mantled by variable thickness of aeolian sand that form a number of dune fields, including a variety of parabolic forms.

Although summary statistics on the morphometry of dunes have not been calculated, the orientation of most parabolic limbs empirically is south-west to north-east (Fig. 4). Given the north-easterly drift direction that results in the region due to

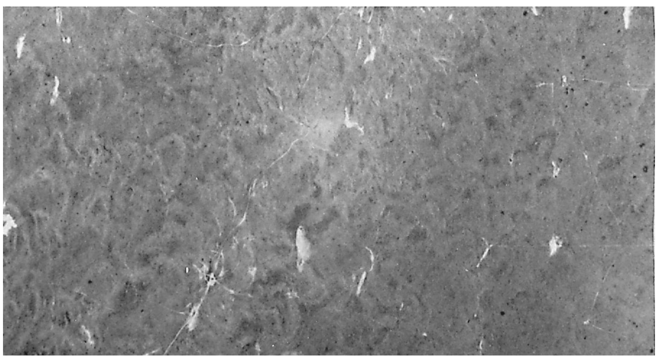

Figure 4. Aerial photograph of a parabolic dune field in secs 9, 10, T.27S., R.20W. Dune arms point to the south-west, indicating that prevailing winds were south-westerly. Bright spots are blowouts, where sand is locally active. Thin, bright lines are cattle trails. Distance across the photograph is approximately 3·2 km.

the relative strength of summer winds (Fig. 3(c)), it is concluded that most dune movement occurs during the summer.

Stratigraphic information presented in this report was obtained from 16 localities distributed throughout the Great Bend Sand Prairie (Figs 2 and 4). Nine sites were described by backhoe trenching, whereas the remainder are cut bank, quarry or roadcut exposures. Each site is situated in a parabolic, compound parabolic, or compound sub-parabolic dune field. The chronology of aeolian sand mobilization and stability in dune fields is reconstructed from radiocarbon ages obtained from the total humate fraction of bulk samples ($\geq$ 4 kg) collected from the upper and/or lower 5 cm of buried A horizons. Radiocarbon ages from the lower parts of buried A horizons provided the closest minimum-limiting ages for the parent aeolian sand, whereas those from the upper parts of buried A horizons estimate the closest maximum-limiting ages for overlying aeolian sand. During preparation, rootlets and other detrital plant material were removed by flotation, the sand fraction was separated by decantation, and HCl treatment was performed to eliminate carbonates. Samples were subsequently oven-dried, pulverized, and submitted to the University of Texas (Austin) for age determination. All ages were calculated at 2σ, corrected for isotopic ($\delta^{13}C$) fractionation (Stuiver & Polach, 1977), and calibrated to the tree-ring curve (Stuiver & Reimer, 1993) to provide conservative estimates. Resultant $\delta^{13}C$ values reflect a warm/semi-arid climate (Krishnamurthy *et al.*, 1982; Nordt *et al.*, 1994), much as the present one, in which C_4 plants such as blue grama (*Bouteloua gracilis*) and buffalo (*Buchloe dactyloides*) grass thrived (Table 1).

Late-Holocene aeolian sand mobilization

Radiocarbon ages obtained from buried soils at 16 localities on the Great Bend Sand Prairie indicate that parabolic dune fields in simple, compound, and complex forms are generally late-Holocene landforms with significant, but episodic, aeolian sand accumulation in the past 1000 years. At 11 sites, the stratigraphy consists of aeolian sand with an underlying, noncalcareous, and poorly-sorted deposit of silty sand. Buried soils in the upper part of the silty sand are extremely well developed with Ab horizons overlying thick Btb horizons that are occasionally vertic in character. Aeolian deposits at each site consist of massive to horizontally stratified, noncalcareous sand that is medium to pale-brown in color. Although sorting varies between and within localities, the sand is usually moderately well sorted and is occasionally cross-stratified, such as at the Crocket Cutbank. At least two stratigraphic units were observed in the dune sand at each locality. Buried soils are generally weakly developed with A/C profiles. At the Crocket Cutbank, Stafford 6, and Reno 3 sites, two buried soils were recognized in the dune sand, with the lower one being best developed (Fig. 5).

Three possible source areas for late-Holocene dune sand are present in the study area. Although late Wisconsin deposits contain high percentages of silt and clay, they are also rich in sand which could be deflated upon exposure. Another possible source is Holocene floodplains, which consist largely of sand and gravel. Lastly, older aeolian sands may have been reworked to form late Holocene dunes. Although the relative contribution of each potential source has not been quantitatively determined, it is believed that present dunes consist mostly of reworked aeolian sand.

Several radiocarbon ages were derived from deposits underlying dunes, with those obtained from the silty sand estimating the unit's time of deposition or subsequent burial by aeolian sand. An age of 16,670 ± 160 years B.P. from the lower silty sand at Reno 4 indicates a late Wisconsin age for the basal part of the unit. In contrast, ages from the upper part of the deposit range from 5370 ± 120 (Reno 4) to 810 ± 120 (GWMD2) years B.P. and provide maximum-limiting dates for the overlying aeolian sand. At the Crocket Cutbank, an alluvial silt drape at the base of the exposure yielded

Table 1. *Radiocarbon ages derived from the Great Bend Sand Prairie*

Location	Stratigraphic position*	Horizon (depth)	Lab No. (Tx-)	Uncorrected ^{14}C age	$\delta^{13}C$-corrected ^{14}C age†	$\delta^{13}C$ (‰)	Calibrated age‡
Buster Dune	ds	2Ab (0·82–0·87)	7980	modern	modern	–17·9	modern
Stafford 6	ds	2Ab (0·53–0·58)	7983	110±80	270±80	–15·2	464(299)146
Rice Roadcut	ds	2Ab (1·28–1·33)	7978	230±80	380±80	–16·0	504(467)315
Stafford 6	ds	3Ab (1·13–1·18)	7982	320±100	480±100	–15·0	560(510)320
Rice Roadcut	ds	2Ab (1·69–1·74)	7977	340±80	490±80	–15·9	559(517)454
Stafford 6	ds	3Ab (1·47–1·52)	7981	360±80	550±80	–13·4	644(542)507
Reno 3	ds	3Ab (2·57–2·62)	8119	520±80	700±80	–14·4	701(657)554
Reno 4	ds	2Ab (1·10–1·15)	8012	510±80	710±80	–12·4	717(660)556
GWMD5 #2§	uss	2Ab (1·63–1·68)	9743	660±60	810±120	–15·5	910(700)650
Crocket Cutbank	ds	3Ab (5·88–5·93)	8214	750±80	880±80	–16·6	913(774)695
Stafford 2	ds	2Ab (1·14–1·19)	9313	840±80	1030±80	–13·3	1056(936)792
14KW7	ds	2Ab (5·12–5·17)	7777	920±60	1090±120	–14·5	1170(970)910
Stafford 11	uss	3Btb1 (1·07–1·12)	8218	1350±80	1500±80	–15·7	1502(1354)1301
Buster Quarry	ds	3Ab (4·55–4·60)	7979	1350±100	1500±100	–15·8	1510(1350)1300
Cornwell Trench	ds	2Ab (1·48–1·53)	7998	2140±100	2310±100	–14·3	2380(2340)2150
Phillips Trench	uss	2Btb1 (0·33–0·38)	8216	2250±100	2400±130	–15·8	2710(2360)2330
Edwards 4	uss	3Btb1 (1·60–1·65)	8314	2610±90	2730±180	–17·3	3080(2790)2710
GSMD5 #10[5]	uss	2Ab (1·43–1·48)	6745	2810±160	2940±160	–17·0	3450(3070)2750
Edwards 1	uss	2Btb1 (1·15–1·20)	8003	1690±80	3220±80	–13·2	3555(3425)3349
Crocket Cutbank	ds	3C5 (8·06–8·11)	8215	3160±50	3280±100	–17·7	3630(3470)3380
Cullison Quarry	uss	3Btb1 (4·70–4·75)	8221	3660±100	3820±100	–14·8	3822(3677)3478
Reno 4	uss	3Btb1 (2·27–3·32)	8011	5260±120	5370±120	–17·7	7020(6720)6390
Stafford 3	ds	2Ab (1·96–2·01)	8118	6050±160	6160±160	–17·9	7900(7690)7580
Cullison Quarry	lss	4Btgb1 (5·65–5·70)	8220	7770±140	7850±140	–20·0	8950(8560)8780
Edwards 1	lss	3Btb1 (1·65–1·70)	7697	8990±560	9050±560	–22·2	10,883(10,000)9453
Stafford 2	lss	4Btb (3·08–3·13)	8117	10,440±720	10,460±720	–23·6	13,096(12,370)10,964
Stafford 11	lss	3Btb4 (1·82–1·87)	8219	10,970±180	11,100±180	–16·5	13,230(13,010)12,810
Reno 4	lss	3Btb3 (3·50–3·55)	8010	16,590±360	16,670±360	–19·9	20,260(19,450)18,960

*ds=dune sand; uss=upper silty sand; lss=lower silty sand.

†Conventional ages are corrected for isotopic fractionation but not reservoir effects. For a discussion of the $\delta^{13}C$-correction procedure, see Stuiver & Polach (1977) and Taylor (1987).

‡Calibrated from conventional $\delta^{13}C$-corrected radiocarbon age to calendar years using a tree-ring curve. All calibrations reported here were based upon the 20-year atmospheric curve (e.g. Linick *et al.*, 1985; Stuiver *et al.*, 1986). Program used is discussed in Stuiver & Reimer (1993).

§Reported in Johnson (1991).

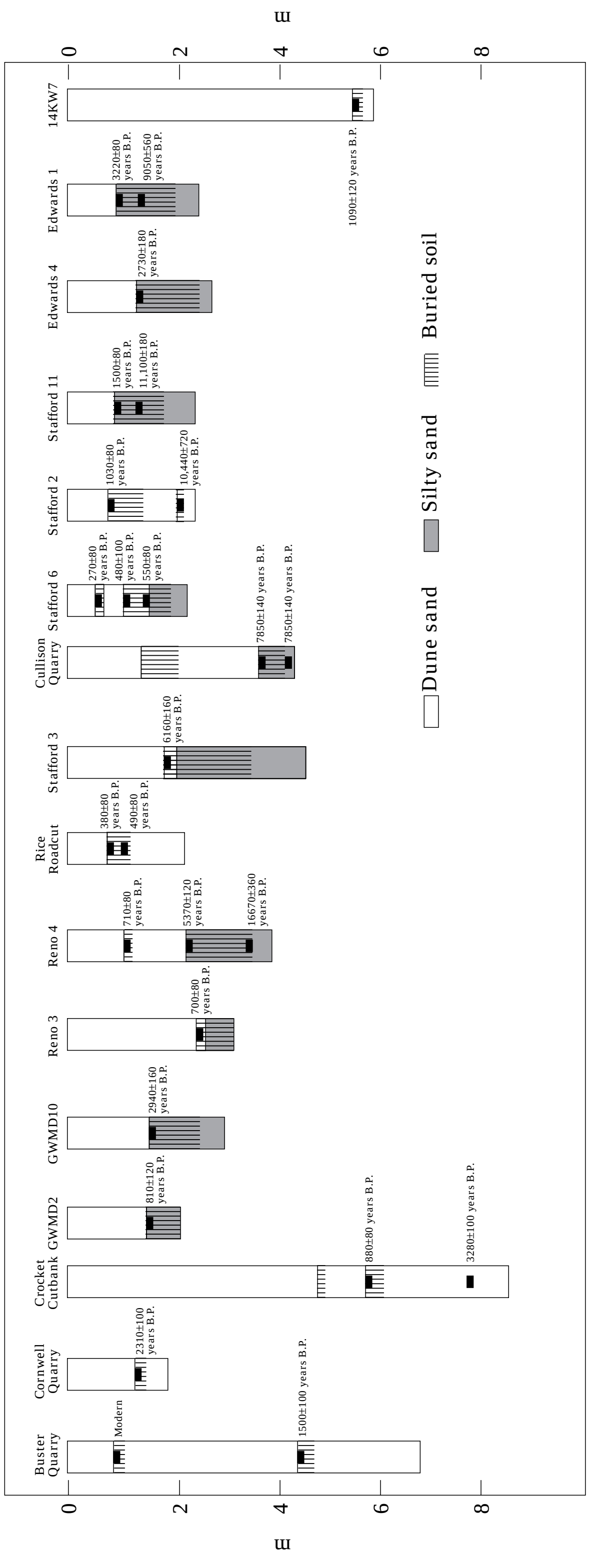

Figure 5. Site stratigraphy and radiocarbon ages at study sites on the Great Bend Sand Prairie.

an age of 3280 ± 1000 years B.P., indicating that approximately 8 m of aeolian sand has accumulated in the past 3000 years at this site.

Radiocarbon ages of Holocene age were derived from buried soils in dune sand at nine localities. A middle Holocene age of 6160 ± 160 years B.P. was obtained from the upper 5 cm of a buried soil in a dune at Stafford 3 (Figs 2 and 5), suggesting that older dunes were present and are occasionally preserved. At five sites (Fig. 5), buried soils provided late-Holocene ages greater than 1000 years B.P. In the central part of the study area, for example, an age of 2310 ± 100 years B.P. was obtained from the upper 5 cm of a buried soil at the Cornwell Quarry (Figs 2 and 5). At two sites, 14KW7 and Stafford 2, buried soils in dunes provided ages of approximately 1000 years B.P.

Significant mobilization and deposition of aeolian sand since 1000 years B.P. is documented at five, widely scattered sites (Fig. 5). The thickest accumulation of sand occurred at the Crocket Cutbank (Figs 2 and 5), where an age of 880 ± 80 years B.P. from the upper 5 cm of a buried soil is a maximum age for deposition of an approximately 6-m thick unit of aeolian sand. The episodic nature of aeolian sand mobilization in the past 1000 years is best illustrated at Stafford 6 (Fig. 5), located in the north-central part of the study area (Fig. 2), where two periods of soil formation are documented to have occurred in approximately the past 500 years. Two ages were obtained from the lowermost buried soil at the site: 550 ± 80 years B.P. and 480 ± 100 years B.P. from the basal and upper 5 cm, respectively. Following deposition of about 60 cm of aeolian sand, a brief period of soil formation occurred as indicated by an age of 270 ± 80 years B.P. on the top 5 cm of the uppermost buried soil. There is also evidence for post-settlement mobilization of aeolian sand on the Great Bend Sand Prairie, as manifested by a strand of barbed wire buried by approximately 1 m of sand at the Cullison Quarry (Figs 2 and 5).

Summary and conclusions

Stratigraphic data obtained from sites widely scattered across the Great Bend Sand Prairie indicate that dune fields in the region are largely late-Holocene landforms that have episodically mobilized. An underlying, poorly sorted alluvial deposit of sand, silt and clay (i.e. silty sand), late Wisconsin in age, often serves as a temporal boundary for late Holocene dune development. Radiocarbon ages from the upper part of the silty sand suggest simultaneous deflation of sand at some localities and burial at others by aeolian sand during the late Holocene.

Although some older, aeolian sand deposits are apparently preserved (e.g. Site Stafford 3; Fig. 5), radiocarbon and stratigraphic evidence indicates that dune fields on the Great Bend Sand Prairie are primarily late-Holocene landforms that have episodically mobilized following brief periods of soil formation. Central values of calibrated radiocarbon ages, plotted in a cumulative frequency histogram with intervals of at least 300 years, suggest five periods of stability; modes occur at approximately 1900, 1250, 850, 550 and 250 years B.P. (Fig. 6). If error bars are included at 2σ, four distinct age groupings can conservatively be discerned where little or no statistical overlap exists: around 2300, 1400, 1100 to 900, and 700 to 200 calibrated years B.P. (Fig. 7). When stratigraphic information derived from dunes is included, the episodic nature of stability and mobilization is even better resolved. Specifically, two buried soils recognized in the dune at Stafford 6 yielded calibrated ages, from bottom to top, of about 540 and 300 years B.P. (Figs 5 and 7). As a result, it is concluded that at least five periods of late-Holocene soil formation, generally bracketing intervals of aeolian sand mobilization, are preserved in dunes of the Great Bend Sand Prairie at approximately 2300, 1400, 1100 to 900, 700 to 500 and 300 calibrated years B.P.

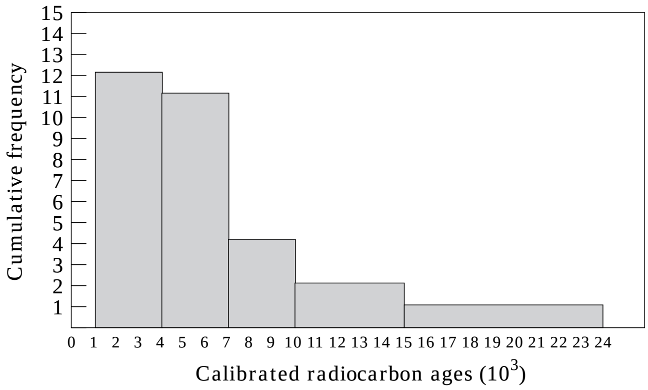

Figure 6. Cumulative frequency histogram (minimum 300-year interval) of radiocarbon ages on the Great Bend Sand Prairie.

Results from this study compare favourably with other findings derived from the central Great Plains in the past 10 years. Late-Holocene dune formation has been reported throughout the region (e.g. Ahlbrandt *et al*., 1983; Muhs, 1985; Madole, 1986, 1994, 1995; Forman & Maat, 1990; Ponte *et al*., 1994; Forman *et al*., 1995; Muhs *et al*., 1996), with significant reactivation of dunes in both north-eastern Colorado and the Great Bend Sand Prairie in past 1500 years B.P. Mobilization of aeolian sand in the Colorado piedmont and Kansas was apparently episodic, and periods of stability and soil formation may have occurred regionally in dunes at approximately 1400 and 900 years B.P. The record suggests, however, that stability has transpired more frequently in the past few hundred years in south-central Kansas because soils dated at *c*. 700 to 500 and 300 years B.P. on the Great Bend Sand Prairie

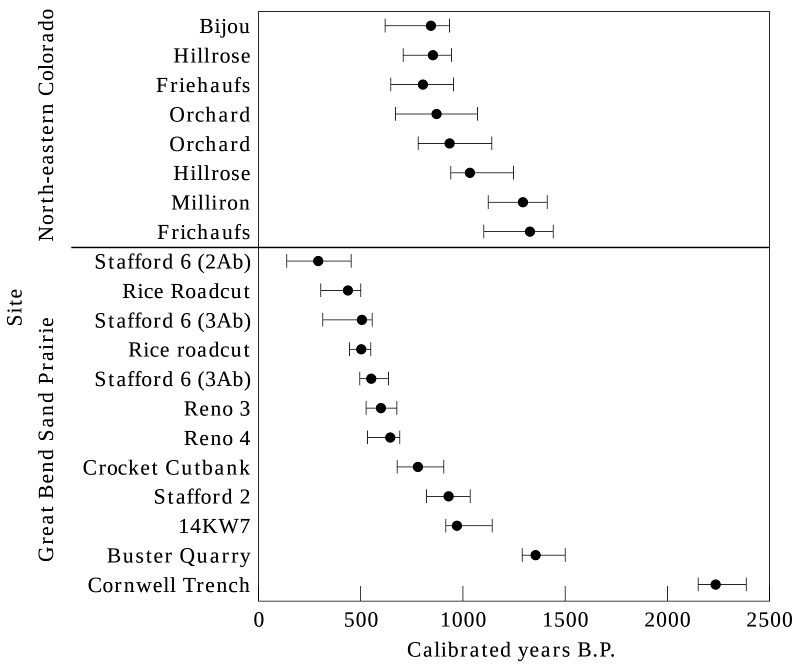

Figure 7. Distribution of calibrated radiocarbon ages (2σ) derived from late-Holocene dunes at sites on the Great Bend Sand Prairie, and north-eastern Colorado (from Madole, 1995).

have not yet been recognized in north-eastern Colorado (Fig. 7). Fundamentally, this is a logical conclusion because north-eastern Colorado is currently more arid (< 40 cm of precipitation annually; NOAA, 1982) than the Great Bend Sand Prairie (*c.* 75 cm of precipitation annually).

Given the concerns regarding the potential response of aeolian sand sheets on the Great Plains to increased warming, a primary goal is to better determine the causes of instability. Toward that end, Muhs & Holliday (1995) applied a general model for aeolian activity, one that largely associates mobilization with decreased vegetation caused by a reduction in the ratio of precipitation to evapo-transpiration, to the Great Plains. Intuitively, it would appear that dune fields in the central Great Plains in general and the Great Bend Sand Prairie in particular are the result of dramatic shifts toward less effective moisture because these and other results (e.g. Madole, 1994, 1995, Ponte *et al.*, 1994; Forman *et al.*, 1995; Muhs *et al.*, 1996) document mobilization of aeolian sand in the past 1000 years. Theoretically, major drought and aeolian sand mobilization has occurred during intervals when atmospheric circulation over the central Great Plains has been more zonal (e.g. middle Holocene), resulting in the dominance of relatively dry Pacific air (Borchert, 1950; Bryson, 1966). Data from Elk Lake in north-central Minnesota, for example, show the onset of drought, increased windiness, and aeolian deposition of quartz grains because the Pacific airstream migrated to a position overhead at A.D. 1200 (Bradbury *et al.*, 1993).

Although extended drought has occurred periodically (e.g. 1890s, 1930s, 1950s) since climate data have been compiled for the central Great Plains, however, it has not been sufficiently severe to promote aeolian sand mobilization on a regional scale (e.g. Tomanek & Hulett, 1970). Although the tendency is to consider dune mobilization within a regional climatic framework, perhaps the record more accurately reflects the cummulative effect of countless episodes of localized instability through time. Madole (1995), for example, noted that some buried soils may not have resulted from the regional activation of sand, but were buried on the lee side of blowouts that were active within otherwise stable dune areas. In contrast, the likelihood of all paleosols being preserved is slim because localized erosion may erode soils at specific sites. In fact, it seems that dune activation has varied spatially within a given drought during the historic period. Muhs & Holliday (1995) correlated sighting of active sand by 19th-century explorers with the dendroclimatic record, noting references to ‘naked sand’ at several localities on the Great Bend Sand Prairie that were adjacent to dunes densely populated by sunflowers. Even in the present relatively moist climate regime, blowouts are common in the western part of the study area (Fig. 4). Clearly, the bulk of evidence derived from the central Great Plains indicates that most dunes can easily be destabilized with only a subtle shift to less effective moisture (Muhs & Maat, 1993). The specific causes of dune mobilization, including the potential influence of migrating bison herds (e.g. Schlesinger *et al.*, 1989), have, however, yet to be quantified. In order for a detailed record and better understanding of causal effects to emerge, therefore, even more research needs to be conducted in these sensitive areas.

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References

Ahlbrandt, T.S. & Fryberger, S.G. (1980). Eolian deposits in the Nebraska Sand Hills. *U.S. Geological Survey Professional Paper*, **1120**: 28 pp.

Ahlbrandt, T.S., Swinehart, J.B. & Maroney, D.G. (1983). The dynamic dune fields of the Great Plains and Rocky Mountain basins, U.S.A. In: Brookfield, M.E. & Ahlbrandt, T.S. (Eds), *Eolian Sediments and Processes*, pp. 379–406. New York: Elsevier. 660 pp.

Arbogast, A.F. (1995). Paleoenvironments and desertification on the Great Bend Sand Prairie in Kansas. Ph.D. dissertation, University of Kansas, Lawrence, Ks. 385 pp.

Borchert, J.R. (1950). Climate of the central North American grassland. *Association of American Geographers Annals*, **40**: 1–39.

Bradbury, J.P., Dean, W.E. & Anderson, R.Y. (1993). Holocene climatic and limnologic history of the north-central United States as recorded in the varved sediments of Elk Lake, Minnesota: A synthesis. In: Bradbury, J.P. & Dean, W.E. (Eds), *Elk Lake, Minnesota: evidence for rapid climate change in the north-central United States. Geological Society of America Special Paper*, **276**: 309–328.

Bryson, R.A. (1966). Air masses, streamlines and the Boreal forest. *Geographical Bulletin*, **8**: 228–269.

Crowley, T.J. & North, G.R. (1991). *Paleoclimatology*. New York: Oxford University Press. 339 pp.

Forman, S.L. & Maat, P. (1990). Stratigraphic evidence for late Quarternary dune activity near Hudson on the Piedmont of northern Colorado. *Geology*, **18**: 745–748.

Forman, S.L., Goetz, A.F.H. & Yuhas, R.H. (1992). Large-scale stabilized dunes on the High Plains of Colorado: understanding the landscape response to Holocene climates with the aid of images from space. *Geology*, **20**: 145–148.

Forman, S.L., Oglesby, R., Markgraf, V. & Stafford, T. (1995). Paleoclimatic significance of Late Quarternary eolian deposition on the Piedmont and High Plains, Central United States. *Global and Planetary Change*, **11**: 35–55.

Fryberger, S.G. & Dean, G. (1979). Dune forms and wind regime. In: McKee, E.D. (Ed.), *A Study of Global Sand Seas, Chapter F. United State Geological Survey Professional Paper,* **1052**: 137–169. 429 pp.

Gaylord, D.R. (1982). Geologic history of the Ferris dune field, south-central Wyoming. In: Marrs, R.W. & Kolm, K.E. (Eds), *Interpretation of Windflow Characteristics from Eolian Landforms. Geological Society of America Special Paper*, **192**: 65–82.

Hansen, J., Fung, I., Lacis, A., Rind, D.S., Ruedy, R. & Russell, G. (1988). Global climate changes as forecast by the Goddard Institute for Space Studies three dimensional model. *Journal of Geophysical Research*, **93**: 9341–9364.

Holliday, V.T. (1985). Holocene soil–geomorphological relations in a semi-arid environment — the southern High Plains of Texas. In: Boardman, J. (Ed.), *Soils and Quarternary Landscape Evolution*, pp. 325–357. New York: John Wiley. 391 pp.

Holliday, V.T. (1989). Middle Holocene drought on the southern High Plains. *Quarternary Research*, **31**: 74–82.

Johnson, W.C. (1991). Buried soil surfaces beneath the Great Bend Prairie of central Kansas and archaeological implications. *Current Research in the Pleistocene*, **8**: 108–110.

Kansas Statistical Abstracts (1990). *Institute for public policy and business research, University of Kansas*. Lawrence, Kansas: University of Kansas Press. 380 pp.

Krishnamurthy, R.V., Deniro, M.J. & Pant, R.K. (1982). Isotope evidence for Pleistocene climatic changes in Kashmir, India. *Nature*, **298**: 640–641.

Linick, T.W., Suess, H.E. & Becker, B. (1985). La Jolla measurements of radiocarbon in south German oak tree-ring chronologies. *Radiocarbon* **27**: 20–32.

Madole, R.F. (1986). Pleistocene and Holocene dune stratigraphy, Wray Dune Field, Colorado-Nebraska. *American Quarternary Association Abstracts*: 148 pp.

Madole, R.F. (1994). Stratigraphic evidence of desertification in the west-central Great Plains within the past 1000 yr. *Geology*, **22**: 483–486.

Madole, R.F. (1995). Spatial and temporal patterns of late Quarterary eolian deposition, eastern Colorado, U.S.A. *Quarternary Science Reviews*, **14**; 155–177.

Muhs, D.R. (1985). Age and paleoclimatic significance of Holocene sand dunes in northeastern Colorado. *Association of American Geographers Annals*, **75**: 566–682.

Muhs, D.R. (1991). The potential response of Great Plains eolian sands to greenhouse warming and precipitation reduction. Geological Society of America, San Diego, California. *Abstracts with Programs*, **23**: A–285.

Muhs, D.R. & Holliday, V.T. (1995). Active dune sand on the Great Plains in the 19th century: Evidence from accounts of early explorers. *Quarternary Research*, **43**: 198–208.

Muhs, D.R. & Maat, P.B. (1993). The potential response of eolian sands to greenhouse warming and precipitation reduction on the Great Plains of the U.S.A. *Journal of Arid Environments*, **25**: 351–361.

Muhs, D.R., Stafford, T.W., Jr., Cowherd, S.D., Mahan, S.A., Kihl, R., Maat, P.B., Bush, C.A. & Nehring, J. (1996). Origin of late Quarternary dune fields of northeastern Colorado. *Geomorphology*, **17**: 129–149.

NOAA. (1982). *Climatography of the United States no. 81, monthly normals of temperature, precipitation, and heating and cooling degree days 1951–1980, Colorado*. Ashville, N.C. 19 pp.

Nordt, L.C., Boutton, T.W., Hallmark, C.T. & Waters, M.R. (1994). Late Quarternary vegetation and climatic changes in central Texas based on the isotopic composition of organic carbon. *Quarternary Research*, **41**: 109–120.

Ponte, M.R., Loope, D.R. & Swinehart, J.B. (1994). Significance of interbedded eolian sand and peat beneath interdunes of the central Nebraska Sand Hills. Geological Society of America. *Abstracts with Programs*, **26**: A–62.

Rosner, M.L. (1988). The stratigraphy of the Quarternary alluvium in the Great Bend Prairie. Unpublished M.S. thesis, University of Kansas. 35 pp.

Schlesinger, M.E. (1989) Model projections of the climatic changes induced by increased atmospheric CO_2. In: Berger, A., Schneider, S.H. & Duplessy, J.C. (Eds), *Climate and Geo-Sciences*, pp. 375–415. Dordrecht, Netherlands: D. Reidel. 724 pp.

Schlesinger, W.H., Reynolds, J.F., Cunningham, G.L., Huenneke, L.F., Jarrel, W.M., Virginia, R.A. & Whitford, W.G. (1989). Biological feedbacks in global desertification. *Science*, **247**: 1043–1048.

Smith, H.T.U. (1940). Geologic studies in southwestern Kansas. *Kansas Geological Survey Bulletin*, **34**: 212 pp.

Stokes, S. & Gaylord, D.R. (1993). Optical dating of Holocene dune sands in the Ferris dune field, Wymoing. *Quarternary Research*, **39**: 274–281.

Stuiver, M. & Polach, H.A. (1977) Reporting of ^{14}C data. *Radiocarbon*, **19**: 355–363.

Stuiver, M. & Reimer, P.J. (1993). Radiocarbon Calibration Program Revision 3·0. *Radiocarbon*, **35**: 215–230.

Stuiver, M., Pearson, G.W. & Braziunas, T. (1986). Radiocarbon age calibration of marine samples back to 9000 cal. yrs B.P. *Radiocarbon*, **28**: 980–1021.

Swinehart, J.B. (1990). Wind-blown deposits. In: Bleed, A. & Flowerday, C. (Eds), *An Atlas of the Sand Hills*, pp. 29–42. Resource Atlas No. 5a. University of Nebraska-Lincoln. Lincoln, Nebraska. 265 pp.

Taylor, T.L. (1987). *Radiocarbon Dating — An archaeological perspective*. Orlando, FL: Academic Press. 212 pp.

Tomanek, G.W. & Hulett, G.K. (1970). Effects of historical droughts on grassland vegetation in the Central Great Plains. In: Dort, J.W. & Jones, J.D. (Eds), *Pleistocene and Recent Environments of the Central Plains*, pp. 203–210. Lawrence, Kansas: University of Kansas Press. 433 pp.

Washington, W.M. & Meehl, G.A. (1984) Seasonal cycle experiment on the climatic sensitivity to doubling of CO_2 with an atmospheric general circulation model coupled to a simple mixed-layer ocean model. *Journal of Geophysical Research*, **89**: 9475–9503.

Wetherald, R.T. & Manabe, S. (1988). Cloud feedback processes in a general circulation model. *Journal of the Atmospheric Sciences*, **45**: 1397–1415.

Wright, H.E., Almendinger, J.C. & Gruger, J. (1985). Pollen diagram from the Nebraska Sand Hills and the age of the dunes. *Quarternary Research*, **24**: 115–120.