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Late Pleistocene dune activity in the central Great Plains, USA

J.A. Mason [a,*], J.B. Swinehart [b], P.R. Hanson [b], D.B. Loope [c], R.J. Goble [c], X. Miao [d], R.L. Schmeisser [e]

[a] Department of Geography, University of Wisconsin Madison, 160 Science Hall, 550 N. Park St., Madison, WI 53706, USA
[b] School of Natural Resources, University of Nebraska-Lincoln, Lincoln, NE 68588-0517, USA
[c] Department of Geosciences, University of Nebraska-Lincoln, Lincoln, NE 68588, USA
[d] Illinois State Geological Survey, Champaign, IL 61820-6964, USA
[e] St. Norbert College, De Pere, WI 54115, USA

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ABSTRACT

Stabilized dunes of the central Great Plains, especially the megabarchans and large barchanoid ridges of the Nebraska Sand Hills, provide dramatic evidence of late Quaternary environmental change. Episodic Holocene dune activity in this region is now well-documented, but Late Pleistocene dune mobility has remained poorly documented, despite early interpretations of the Sand Hills dunes as Pleistocene relicts. New optically stimulated luminescence (OSL) ages from drill cores and outcrops provide evidence of Late Pleistocene dune activity at sites distributed across the central Great Plains. In addition, Late Pleistocene eolian sands deposited at 20–25 ka are interbedded with loess south of the Sand Hills. Several of the large dunes sampled in the Sand Hills clearly contain a substantial core of Late Pleistocene sand; thus, they had developed by the Late Pleistocene and were fully mobile at that time, although substantial sand deposition and extensive longitudinal dune construction occurred during the Holocene. Many of the Late Pleistocene OSL ages fall between 17 and 14 ka, but it is likely that these ages represent only the later part of a longer period of dune construction and migration. At several sites, significant Late Pleistocene or Holocene large-dune migration also probably occurred after the time represented by the Pleistocene OSL ages. Sedimentary structures in Late Pleistocene eolian sand and the forms of large dunes potentially constructed in the Late Pleistocene both indicate sand transport dominated by northerly to westerly winds, consistent with Late Pleistocene loess transport directions. Numerical modeling of the climate of the Last Glacial Maximum has often yielded mean monthly surface winds southwest of the Laurentide Ice Sheet that are consistent with this geologic evidence, despite strengthened anticyclonic circulation over the ice sheet. Mobility of large dunes during the Late Pleistocene on the central Great Plains may have been the result of cold, short growing seasons with relatively low precipitation and low atmospheric CO_2 that increased plant moisture stress, limiting the ability of vegetation to stabilize active dune sand. The apparent coexistence of large mobile dunes with boreal forest taxa suggests a Late Pleistocene environment with few modern analogs.

1. Introduction

The Nebraska Sand Hills form the largest dunefield in North America, covering at least 50,000 km^2 of the central Great Plains. Dunes of the Sand Hills include forms found mainly in warm desert environments, including barchanoid ridges more than one hundred meters high and tens of kilometers long (Swinehart, 1990; Loope and Swinehart, 2000). Despite this impressive evidence of past eolian activity, the Sand Hills are almost entirely stabilized by native grassland vegetation under the modern climate. Other stabilized dunefields on the central Great Plains are individually smaller in area than the Sand Hills, but together cover a large area (Forman et al., 2001; Muhs and Zarate, 2001) and can include large compound parabolic dunes several kilometers long (Muhs et al., 1996, 1999b).

The Sand Hills and other Great Plains dunes have drawn the attention of geomorphologists and Quaternary scientists for more than 75 years, often focused on the timing of dune activity and the nature of the paleoenvironments that allowed it to occur. Lugn (1935, pp. 160–161) interpreted the Sand Hills dunes and the thick Peoria Loess deposits to the southeast as coarse and fine facies of eolian sediment dispersed across the region during the Late Pleistocene. In the first major work on the geomorphology of the Sand Hills, H.T.U. Smith (1965) defined three *series* of dunes. Smith's

* Corresponding author. Tel.: +1 6082626316.
E-mail address: mason@geography.wisc.edu (J.A. Mason).

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first series includes megabarchans and large barchanoid ridges, and the second is primarily made up of smaller longitudinal dunes, often superimposed on larger dunes of the first series. The third series mainly consists of small parabolic dunes associated with blowouts (deflation hollows). Smith concluded that the dunes of the first and second series developed mainly under relatively cold and dry conditions of the Late Pleistocene, although he correlated the second series with the Bignell Loess, now known to be of Holocene age (Johnson and Willey, 2000; Mason et al., 2003). Warren (1976) also assumed the large Sand Hills dunes were of Pleistocene age in his interpretation of paleowind directions. Wright et al. (1985) argued that the basal ages of interdune peats and lacustrine sediment imply a Pleistocene age for the large dunes.

By the 1980s, however, new radiocarbon dating clearly demonstrated substantial Holocene dune activity in the Sand Hills; in fact, more than 40 m of eolian sand was deposited in the middle to late Holocene at several sites (Ahlbrandt et al., 1983; Swinehart and Diffendal, 1990; Loope et al., 1995). Holocene activity has also been documented in other dunefields across the central Great Plains of Nebraska, Kansas, and Colorado (Muhs, 1985; Forman and Maat, 1990; Madole, 1994, 1995; Forman et al., 1995; Muhs and Holliday, 1995; Muhs et al., 1996; Arbogast and Johnson, 1998; Forman et al., 2001; Hanson et al., 2010). Optically stimulated luminescence (OSL) dating, which determines the time since deposition of eolian sand, has provided important new insights on the timing of Holocene dune activity (Stokes and Swinehart, 1997; Miao et al., 2007; Hanson et al., 2010). In the Sand Hills, OSL dating at multiple sites consistently indicates that the longitudinal dunes of Smith's second series formed in the late Holocene (Goble et al., 2004; Mason et al., 2004; Sridhar et al., 2006; Schmeisser, 2009).

In contrast, evidence of Late Pleistocene dune or sand sheet activity in the Sand Hills has remained quite limited. Goble et al. (2004) reported a single Late Pleistocene OSL age from a deep blowout in the northern Sand Hills (Kroeger Blowout, discussed below). At Gudmundsen Ranch in the central Sand Hills, peat that formed at 13,160 ± 450 ^{14}C yr BP (14,195–16,995 cal yr BP; Reimer et al., 2009), was subsequently buried by a large dune, possibly in the Late Pleistocene (Swinehart, 1990; Swinehart and Diffendal, 1990). Late Pleistocene environmental conditions on the central Great Plains clearly did favor at least one form of eolian activity: Peoria Loess accumulated at very high rates near the Sand Hills during that time period, at sites such as Bignell Hill, discussed below (Roberts et al., 2003). Furthermore, Late Pleistocene eolian sands have been identified in northeastern Colorado, based on radiocarbon and luminescence dating, pedologic evidence, and stratigraphic relations with archaeological artifacts (Forman et al., 1995; Muhs et al., 1996). Muhs et al. (1997) noted that the mineralogical maturity of Sand Hills dune sand probably reflects a long history of eolian activity over more than one glacial–interglacial cycle. One explanation for the limited evidence of Pleistocene dune activity in Nebraska dunefields is that Late Pleistocene eolian sand is often deeply buried by Holocene sediment, especially in areas where late Holocene longitudinal dunes developed. Stokes et al. (1999) reported initial results of OSL dating using core samples from deep within dunes of the Sand Hills, and noted evidence for both Pleistocene and Holocene dune construction. The final results of that study have not been published, and it was based on early, now superceded OSL methodology.

In this paper we report new OSL dating results that demonstrate Late Pleistocene eolian sand activity at numerous localities in the central Great Plains, not only within the Nebraska Sand Hills and other dunefields, but also where eolian sand was subsequently covered with thick, Late Pleistocene loess. While some evidence reported here is from outcrops, much of it is based on core samples collected from large dunes of the Sand Hills (not the same cores sampled by Stokes et al., 1999). We also discuss the environmental factors that allowed dune activity during the Late Pleistocene.

2. Study sites and methods

2.1. Study sites

The new OSL ages reported here are from fifteen localities, including ten in the Nebraska Sand Hills, three in smaller dunefields of Nebraska and Colorado, and two in the loess-mantled region south of the Sand Hills (Fig. 1, Table 1). Cores were collected at eight sites, by drilling either on the dune crest to sample the greatest possible thickness of eolian sand, or somewhat below the crest on the north or northwest slope of the dune. The latter location was used in some cases where the dune form recorded migration toward the south or southeast, to increase the likelihood of sampling the oldest sand within the dune. The other five localities are outcrops where the presence of Late Pleistocene eolian sand was identified by OSL dating, carried out as part of recent research projects on eolian sediments of the central Great Plains. The Hwy 97 Milepost 81 roadcut and Vinton Blowout are two of only three sites in the Sand Hills where Pleistocene eolian sand has been identified in outcrop using OSL dating; the third site, Kroeger Blowout, was reported by Goble et al. (2004). The Wach site is an outcrop in a small unnamed dunefield of southwestern Nebraska. Bignell Hill and Moran Canyon are primarily loess sections, but contain eolian sand interbedded with or buried by Late Pleistocene loess.

2.2. Field methods

Cores were collected using either a hollow-stem auger technique or direct push with a Geoprobe (Table 1 includes method used at each site). The 5-cm diameter hollow-stem auger cores were collected in a split-barrel that travels downward inside the lead auger. The stack of augers acts as a casing that prevents contamination of the core sample with material from higher in the section. The core was extracted after each 1.5 m of drilling, with core recovery usually representing 30–60% of that depth increment, typical for eolian sand, because friction prevents the core

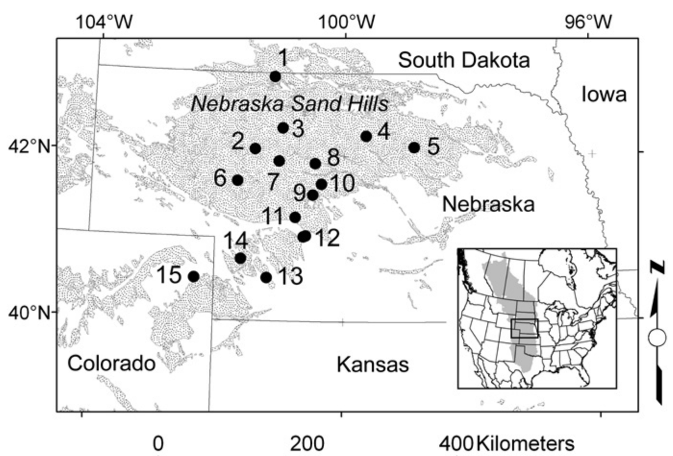

Fig. 1. Dunefields of the central Great Plains (stippled) and sites discussed in text: 1. Kroeger Blowout, 2. Gudmundsen Ranch, 3. Highway 97 Milepost 81, 4. Barta Brothers Dune, 5. Haake Dune, 6. Schmidt Ranch, 7. Vinton Blowout, 8. Nebraska National Forest, 9. Diamond Bar Ranch, 10. Wild horse Creek Ranch, 11. Hansen Ranch, 12. Moran Canyon and Bignell Hill, 13. Wach, 14. Cornelius Dune, 15. Hamm Dune. Inset shows study area location (box) within the Great Plains region of the U.S.A. and Canada (gray shade).

Table 1
OSL age estimates referred to in this paper, with equivalent dose and dose rate data. Ages are grouped by study site, with geographic location and sampling method indicated.

UNL lab number (reference)	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
Hansen Ranch (Auger core 13-A-04, 41°15′27″ N 100°46′34″ N)									
UNL-1078 (this paper)	6.6	1.0	5.3	2.0	1.1	2.33 ± 0.15	34.32 ± 0.84	28/34	14,700 ± 1200
UNL-1079 (this paper)	9.3	0.6	2.9	1.7	0.4	1.82 ± 0.13	30.95 ± 0.62	23/24	17,000 ± 1300
UNL-1080 (this paper)	14.2	0.8	3.7	2.0	0.9	2.13 ± 0.15	33.06 ± 0.73	20/32	15,500 ± 1300
UNL-1081 (this paper)	22.0	0.7	3.3	1.8	0.5	1.92 ± 0.14	30.52 ± 0.67	23/24	15,700 ± 1300
UNL-931 (this paper)	29.7	0.9	4.4	2.1	5.2	2.09 ± 0.16	32.48 ± 0.98	16/24	15,500 ± 1400
UNL-932 (this paper)	36.9	1.1	5.8	2.2	5.8	2.30 ± 0.17	34.69 ± 0.83	22/23	15,100 ± 1300
Diamond Bar Ranch (Auger core 14-A-04, 41°31′52″ N 100°30′10″ W)									
UNL-1082 (this paper)	11.0	0.5	2.2	1.6	0.4	1.68 ± 0.12	26.07 ± 0.59	20/24	15,600 ± 1300
UNL-1083 (this paper)	15.7	0.8	3.7	1.8	0.6	1.95 ± 0.13	31.50 ± 0.64	21/22	16,200 ± 1300
UNL-1084 (this paper)	18.8	0.6	3.3	1.8	0.4	1.88 ± 0.13	30.58 ± 0.46	21/23	16,300 ± 1300
UNL-933 (this paper)	21.6	0.7	3.4	2.0	4.7	1.89 ± 0.14	26.70 ± 0.51	23/24	14,100 ± 1200
UNL-934 (this paper)	27.7	1.0	4.2	2.0	11.6	1.87 ± 0.21	34.75 ± 0.89	35/37	18,500 ± 2300
Haake Dune (Geoprobe core GP05-4, 42°6′50″ N 98°52′23″ W)									
UNL-1111 (this paper)	7.1	0.7	3.5	1.7	3.6	1.87 ± 0.14	2.78 ± 0.03	22/23	1480 ± 120
UNL-1112 (this paper)	22.0	0.7	3.7	1.8	6.8	1.81 ± 0.16	26.81 ± 0.41	22/24	14,900 ± 1400
UNL-1114 (this paper)	22.8	0.6	2.8	1.7	3.2	1.74 ± 0.13	26.71 ± 0.69	20/23	15,400 ± 1300
Wild horse Creek Ranch (Geoprobe core GP04-6, 41°39′43″ N 100°21′44″ W)									
UNL-980 (this paper)	1.0	0.6	3.4	1.8	1.5	2.00 ± 0.12	0.98 ± 0.06	24/24	490 ± 50
UNL-1122 (this paper)	6.0	0.7	3.7	1.8	5.1	1.93 ± 0.15	1.38 ± 0.05	21/24	710 ± 90
UNL-1124 (this paper)	10.6	0.7	3.7	1.7	4.6	1.80 ± 0.14	4.99 ± 0.09	21/23	2800 ± 200
UNL-981 (this paper)	14.0	0.7	3.5	2.0	6.6	1.88 ± 0.15	35.14 ± 1.10	23/25	18,700 ± 1800
Cornelius Dune (Geoprobe core GP05-1, 40°44′55″ N 101°37′32″ W)									
UNL-1097 (this paper)	1.0	1.1	5.9	2.6	7.3	2.77 ± 0.24	1.50 ± 0.04	20/23	540 ± 50
UNL-1099 (this paper)	6.0	1.4	6.0	2.6	4.3	2.86 ± 0.21	8.51 ± 0.11	24/24	3000 ± 200
UNL-1101 (this paper)	12.0	1.5	7.4	2.4	7.0	2.74 ± 0.24	41.33 ± 0.69	21/23	14,700 ± 1400
Moran Canyon (Outcrop, 41°1′29″ N 100°38′38″ W)									
UNL-525 (Mason et al., 2008)	3.2	2.7	15.2	1.9	6.0[c]	3.19 ± 0.17	49.38 ± 0.81	21/28	15,460 ± 950
UNL-526 (Mason et al., 2008)	3.5	2.6	14.0	2.0	6.0[c]	3.14 ± 0.16	48.84 ± 0.75	29/32	15,550 ± 950
UNL-299 (Mason et al., 2008)	4.0	2.7	14.0	1.9	6.0[c]	3.11 ± 0.16	50.30 ± 0.95	29/38	16,150 ± 1010
UNL-464 (this paper)	6.0	3.1	13.6	2.5	6.0[c]	3.62 ± 0.24	52.34 ± 1.45	39/41	14,500 ± 1100
UNL-463 (this paper)	7.0	1.0	7.0	2.1	6.0[c]	2.36 ± 0.17	47.78 ± 0.91	44/51	20,300 ± 1600
Bignell Hill (Outcrop, 41°2′17″ N 100°36′20″ W)									
UNL-116 (this paper)	48.0	3.2	12.4	2.7	1.8	3.71 ± 0.20	90.63 ± 2.63	31/40	24,400 ± 1700
UNL-048 (this paper)	40.0	3.2	14.3	2.7	5.8	3.73 ± 0.25	65.52 ± 2.13	25/29	17,600 ± 1700
UNL-048 dup (this paper)	40.0	2.4	10.6	2.8	6.1	3.36 ± 0.24	82.61 ± 2.22	29/30	24,600 ± 2000
UNL-049 (this paper)	35.0	1.2	7.2	2.3	1.0	2.65 ± 0.16	57.53 ± 2.48	33/39	21,700 ± 2100
UNL-050 (this paper)	35.0	1.8	7.4	2.5	0.5	2.96 ± 0.17	67.14 ± 2.02	33/34	22,700 ± 2000
UNL-117 (this paper)	30.0	2.6	11.6	2.8	2.8	3.62 ± 0.21	80.71 ± 1.83	23/25	22,300 ± 2000
Hamm Dune (Geoprobe core GP05-2, 40°30′37″ N 102°21′32″ W)									
UNL-1103 (this paper)	2.3	1.2	7.3	3.1	1.2	3.48 ± 0.23	2.43 ± 0.14	23/26	700 ± 60
UNL-1105 (this paper)	16.0	1.4	8.7	3.1	2.6	3.45 ± 0.24	8.54 ± 0.20	23/28	2500 ± 200
Hamm Dune (Geoprobe core GP05-3, ground surface is 15.2 m below top of GP05-2)									
UNL-1107 (this paper)	4.6	1.1	6.8	3.1	2.1	3.33 ± 0.23	6.98 ± 0.24	20/23	2100 ± 200
UNL-1109 (this paper)	24.0	0.9	4.8	3.1	1.1	3.08 ± 0.22	29.50 ± 1.36	25/32	9600 ± 1000
Kroeger Blowout, North Side (Outcrop, 42°57′14″ N 101°09′15″ W)									
UNL-072 (Goble et al., 2004)	1.3	1.2	7.0	1.9	3.5	2.43 ± 0.06	2.05 ± 0.06	15	840 ± 60
UNL-070 (Goble et al., 2004)	12.0	1.1	4.1	1.8	5.2	2.00 ± 0.05	12.36 ± 0.12	31	6180 ± 370
UNL-069 (Goble et al., 2004)	12.3	1.2	5.7	2.0	6.4	2.20 ± 0.05	18.50 ± 0.28	29	8430 ± 510
UNL-068 (Goble et al., 2004)	18.0	1.2	6.5	1.9	4.3	2.17 ± 0.05	28.60 ± 0.48	25	13,100 ± 800
Highway 97 Milepost 81 (Outcrop, 42°14′26″ N 101°1′56″ W)									
UNL-487 (Miao et al., 2007)	1.5	0.7	4.6	1.9	2.3	2.12 ± 0.05	2.04 ± 0.06	25	960 ± 140
UNL-521 (Miao et al., 2007)	3.0	0.7	4.4	1.9	3.2	2.05 ± 0.05	1.88 ± 0.19	20	920 ± 110
UNL-486 (Miao et al., 2007)	4.0	0.8	4.8	1.9	3.0	2.11 ± 0.05	1.88 ± 0.06	22	890 ± 130
UNL-570 (Miao et al., 2007)	7.0	0.6	3.8	1.8	3.6	2.40 ± 0.17	4.32 ± 0.07	31	2400 ± 180
UNL-563 (this paper)	10.0	0.8	5.2	1.9	4.2	2.05 ± 0.14	27.72 ± 0.58	24/30	13,500 ± 1100
Vinton Blowout (Outcrop, 41°55′60″ N 101°2′60″ W)									
UNL-754 (this paper)	4.0	0.7	3.7	1.8	2.3	1.91 ± 0.12	32.10 ± 0.83	24/24	16,800 ± 1300
UNL-651 (this paper)	4.0	0.7	3.4	1.8	1.0	1.94 ± 0.12	30.52 ± 0.46	24/24	15,700 ± 1200
Barta Brothers (Geoprobe core GP03-SH2, 42°14′30″ N 99°38′43″ W)									
UNL-782 (Miao et al., 2007)	9.0	1.0	6.2	2.2	3.5	2.40 ± 0.06	19.59 ± 1.41	20	8150 ± 590
UNL-785 (Miao et al., 2007)	9.5	1.1	6.7	2.3	4.5	2.51 ± 0.06	19.66 ± 1.50	17	7820 ± 590
UNL-746 (this paper)	11.8	0.8	4.5	1.7	4.3	1.86 ± 0.13	26.31 ± 0.56	24/24	14,100 ± 1200
Wach Site (Outcrop, 40°31′31″ N 101°12′53″ W)									
UNL-1366 (this paper)	0.8	1.6	8.0	2.3	7.5	2.78 ± 0.15	20.74 ± 0.65	20/21	7500 ± 500
UNL-1365 (this paper)	1.5	1.3	7.2	2.3	2.6	2.77 ± 0.15	29.68 ± 0.92	17/22	10,700 ± 700
UNL-1364 (this paper)	4.0	1.2	5.7	2.3	6.4	2.46 ± 0.14	33.82 ± 1.21	19/21	13,700 ± 1000
UNL-1363 (this paper)	6.0	1.3	6.8	2.2	6.0	2.48 ± 0.14	33.63 ± 1.17	11/15	13,600 ± 1000
Nebraska National Forest (Geoprobe core GP06-3, 41°54′33″ N 100°28′8″ W)									
UNL-1604 (this paper)	0.6	0.7	3.5	1.6	4.2	1.88 ± 0.12	1.29 ± 0.03	17/20	680 ± 50
UNL-1605 (this paper)	6.6	0.8	4.0	1.7	4.4	1.86 ± 0.12	1.43 ± 0.06	19/20	740 ± 60
UNL-1606 (this paper)	10.0	0.8	4.4	1.6	6.9	1.79 ± 0.12	30.22 ± 0.46	40/40	17,300 ± 1300
Schmidt Ranch (Bucket auger sample, 41°41′24″ N 101°42′36″ W)									
UNL-2036 (this paper)	3.8	0.8	3.4	2.1	4.0	2.24 ± 0.09	29.11 ± 0.45	28/30	12,900 ± 700

[a] Assumes 100% error in measurement.
[b] Where ratio is given, it represents accepted disks/all disks.
[c] Estimated from similar samples.

from sliding all the way up the barrel and eventually sand is pushed aside rather than entering the core. Sedimentary structures were often preserved within the cores with minimal deformation (Fig. 2a), however, so we assume the recovered core represents only the upper part of the cored interval and assigned depths accordingly. Samples for OSL dating were collected by pushing steel or brass tubes into sand in the lower end of the core before the split-barrel was opened. The Geoprobe uses percussion to drive 1.2 m-long, 3-cm inside-diameter core barrels with plastic liners, with typical recovery of 75% or more. Cores in opaque liners were sampled in the lab for OSL dating, while clear liners were split in the field to describe sedimentary structures, which were usually well-preserved (Fig. 2b). Outcrops were sampled for OSL dating by pushing metal tubes into freshly excavated faces. One OSL sample was collected by pushing a metal tube into sand brought to the surface in a bucket auger, without light exposure.

Outcrops and cores were described in detail, including observations of sedimentary structures (Fig. 2), paleosols, trace fossils, and sediment grain size. The broad geomorphic setting of each study site was assessed using 10-m digital elevation data, aerial photographs, and regional mapping and interpretation of Sand Hills dune forms by Swinehart (1990).

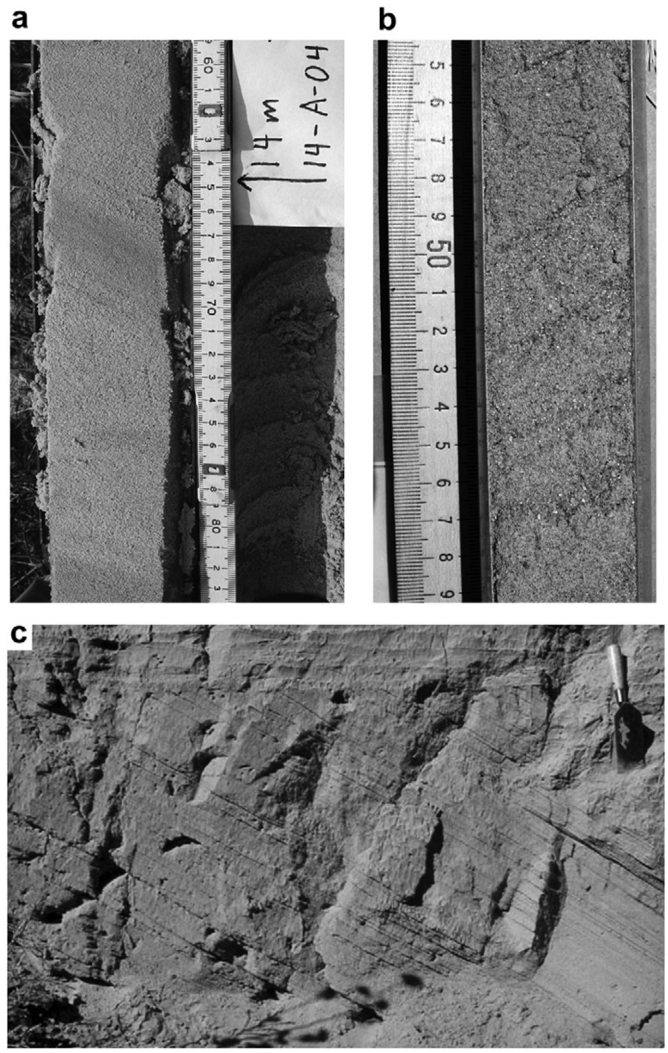

Fig. 2. Cross-bedded eolian sand at study sites, typical of material with well-preserved sedimentary structures used for most OSL ages: a. hollow-stem auger core at Diamond Bar Ranch (13.95–14.2 m depth); b. Geoprobe core at Hamm Dune (10.3–10.45 m depth); c. outcrop at Moran Canyon (eolian sand overlain by Peoria Loess, east is to the right, trowel is ca 25 cm long). In a and b, up is toward ground surface, scale is in cm.

2.3. *OSL dating methods*

OSL dating analyses were conducted at the University of Nebraska's Luminescence Geochronology Laboratory. The methodology used was similar to numerous other studies that used OSL in the Nebraska Sand Hills (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007) and adjacent loess hills (Mason et al., 2003, 2008). 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. Equivalent dose (D_e) values were determined on the 90–150 μm quartz grains using the single aliquot regenerative (SAR) method (Murray and Wintle, 2000). OSL dating analyses were carried out on both Daybreak and Risø TL/OSL readers. Individual aliquots were rejected if their recycling ratios were $>\pm 10\%$. Aliquots were also monitored for contamination with feldspars, the presence of which typically results in ages that are younger than expected. Therefore, aliquots were rejected if they were suspected of containing feldspars based on their shinedown curves and/or their response when stimulated with infrared diodes. Equivalent dose distributions including histograms are given for each sample in the Supplementary material.

Dose rate estimates were based on elemental concentrations of K, U, Th, and Rb from bulk sediment samples 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). All optical ages are presented in ka, thousands of calendar years ago. New ages reported in this paper that were older than 1.5 ka were rounded to the nearest hundred years, and the younger ages were rounded to the nearest ten years; other ages are listed as originally published.

3. Results

3.1. *OSL ages*

All OSL ages discussed in this paper are listed with associated data in Table 1, including some previously published ages that are important for stratigraphic interpretation. Other less relevant published ages from the study sites are noted below but are not included in Table 1. New ages are also plotted in Fig. 3 along with all of the Holocene ages from central Great Plains dunefields reported by Miao et al. (2007). Following standard practice, we present OSL ages with $\pm 1\sigma$ errors throughout this paper; however, the $\pm 2\sigma$ error range (95% probability) should be considered when assessing the significance of age inversions, age trends, or differences between ages. For example, while there are apparent age inversions in some of the cores and outcrops we do not consider these to be significant if the $\pm 2\sigma$ error ranges of the ages involved include values that would allow all ages to be in stratigraphic order. Similar to other Nebraska Sand Hills samples (e.g. Goble et al., 2004; Mason et al., 2004; Miao et al., 2007), none of the samples displayed anomalous behavior that would call their validity into question. Variability in equivalent dose values is fairly low for these samples. In addition, very few aliquots were rejected (Table 1), and there was little difference in the age calculated using all of the disks run compared with the age calculated using the final weighted disks (see equivalent dose distributions in Supplementary material). We

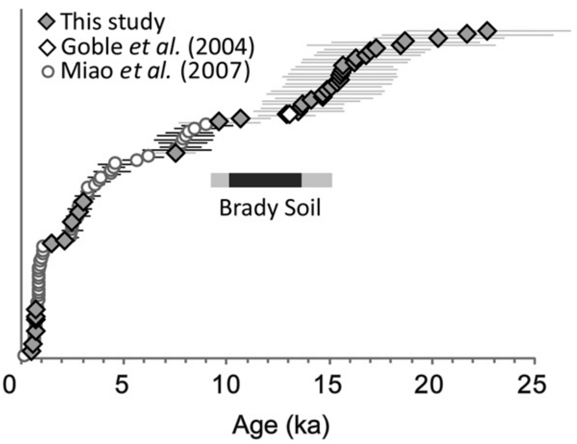

Fig. 3. OSL ages from this study and Miao et al. (2007), arrayed vertically from youngest (bottom) to oldest (top). Time intervals with abundant OSL ages where the plot rises steeply indicate widespread dune activity, intervening plateaus with few ages presumably indicate dunefield stability. Time represented by Brady Soil is shown with shaded bar, based on dating described in Mason et al. (2008). Darker tone indicates time during which Brady Soil was forming at almost all sites (13.5–10 ka); lighter tone includes additional time of soil formation suggested by dating at some sites (15–13.5 ka and 10–9 ka).

interpret all of our ages as indicating the time since the sediments were deposited, because there was minimal evidence for bioturbation or other soil processes that would have acted to reset the luminescence clock in the cores and outcrops sampled for dating (e.g. Fig. 2).

3.2. Subsurface samples from dunefields

The Barta Brothers core (Fig. 4a) was collected on the crest of a "dome-like" dune with superimposed longitudinal dunes in the northern Sand Hills. Much of the core penetrated Holocene sand, based on ages reported by Miao et al. (2007). Early Holocene sand was identified at 9.0–9.5 m depth, and at 12 m (only about 3 m above local interdune elevations), eolian cross-strata with a dip of about 20° yielded a Pleistocene age of 14.1 ± 1.2 ka (Fig. 4a). The direction of maximum dip cannot be determined because of core rotation during extraction, and the dune is too poorly defined to infer direction of migration. At the Wild Horse Creek Ranch (Fig. 4b), a core was collected on a poorly defined large dune with superimposed longitudinal dunes in the south-central Sand Hills. The upper 10.6 m of this core yielded Late Holocene OSL ages, but a sample at 14 m depth, in eolian cross-strata dipping at 25–30°, produced a Pleistocene age of 18.7 ± 1.8 ka. This sample was >10 m above local interdunes; thus, the dune contains a substantial body of Late Pleistocene eolian sand.

The Diamond Bar Ranch and Hansen Ranch core sites (Fig. 4c and d) are in similar settings on the north or northwest slope of moderately large dunes in the southern Sand Hills. Holocene ages obtained from shallow depths in these cores were reported by Miao et al. (2007). Both cores reached the elevation of adjacent interdunes, and much of the dune sand in both cores is Late Pleistocene, with ages between 14 ka and 19 ka. There are OSL ages out of stratigraphic sequence at both sites; however, we do not consider these inversions to be significant because the 2σ error estimate for all of the Pleistocene ages overlap substantially. All of the Pleistocene ages are from fine sand typical of Sand Hills dunes, generally containing eolian sedimentary structures. The dune cored at Diamond Bar Ranch is poorly defined, but fairly distinct steep lee slopes are preserved on the cored dune and its neighbors at the Hansen Ranch, indicating migration toward the south–southeast. At the Nebraska National Forest site (Fig. 4e), a core was collected on the crest of a longitudinal dune, located on the north slope of a poorly defined larger dune. Two OSL ages within the longitudinal dune are late Holocene, but an age of 17.3 ± 1.3 ka was obtained from sand at 10 m depth, just into the underlying larger dune form. At the Schmidt Ranch in the western Sand Hills (location in Fig. 1), a single Late Pleistocene age of 12.9 ± 0.7 ka was obtained from a bucket auger sample at a depth of 3.8 m on the northern slope of a large dune, well above interdune elevation.

Two other core sites provided evidence of Late Pleistocene eolian sand deposition that was not clearly related to construction of the present dunes, and the latter may have been built largely or entirely during the Holocene. At the Haake site (Fig. 4f), a core was collected on the northwest slope of a large dune located in the transition zone where dunes give way to the low-relief sand sheets that dominate the easternmost part of the Sand Hills. The upper 7 m of this core is late Holocene eolian sand, overlying a zone with pedogenic lamellae that may represent a truncated paleosol. Ages of 14.9 ± 1.4 and 15.4 ± 1.3 ka were obtained from laminated fine-medium sand well below the lamellae at depths of 22.0 and 22.8 m, respectively, near the elevation of adjacent interdunes. The Cornelius dune (Fig. 4g) is located in a small dunefield north of Imperial, Nebraska, southwest of the Sand Hills. At least the upper 6 m of a core taken on the crest of this dune is late Holocene, and we obtained one additional age of 14.9 ± 1.4 ka, in laminated fine-medium sand at a depth of 12 m, just above Miocene bedrock.

Cores drilled on a large compound parabolic dune at the Hamm site (Fig. 4h), in the Wray dunefield of northeastern Colorado yielded only Holocene ages. The entire upper 16 m of the core collected on the dune crest at this site is younger than 2.5 ± 0.2 ka. An age of 9.6 ± 0.9 ka was obtained from laminated fine and medium sand near interdune level, in a second core that started partway down the dune flank.

3.3. Outcrops in dunefields

The Vinton Blowout (Fig. 5a) exposes eolian sand on the lower stoss slope of a large barchan dune, one of several similar dunes with forms clearly indicating migration toward the southeast. Two OSL ages of 15.7 ± 1.2 and 16.8 ± 1.3 ka were obtained from large-scale eolian cross-strata dipping 30° toward the southeast (120° azimuth), recording sedimentation on the slip face of a dune migrating in that direction. The Hwy 97 Milepost 81 section (Fig. 5b) is a roadcut through a longitudinal dune that was sampled when newly excavated. While sand forming the longitudinal dune is Late Holocene, based on OSL ages previously reported by Miao et al. (2007), it rests at least in part on wind-ripple laminated eolian sand dated to 13.5 ± 1.1 ka (some Late Holocene sand is also present below the base of the longitudinal dune near the south end of the exposure; Fig. 5b). The Kroeger Blowout (Fig. 5c) is a deep deflation hollow near the crest of a large dune. As reported by Goble et al. (2004), most of the eolian sand exposed at this site is Holocene, but an age of 13.1 ± 0.8 ka was obtained 18 m below the top of the blowout face, just below a truncation surface. This sample was collected at least 20 m above the level of the nearest interdunes, so there is a substantial core of Pleistocene sand within the large dune at this locality. The form of the dune is poorly defined, but it is steepest on its south–southeast face, as are adjacent large dunes, indicating migration toward the south–southeast.

The Wach site (Fig. 5d) is a blowout in a small unnamed field of parabolic dunes in southwestern Nebraska. These dunes are distinctive in several respects, based on field observations and the county soil survey (Scheinost, 1982). Compared to the Sand Hills, they have smoother surfaces and surface soils that often have more silt and thicker A horizons, all consistent with more limited

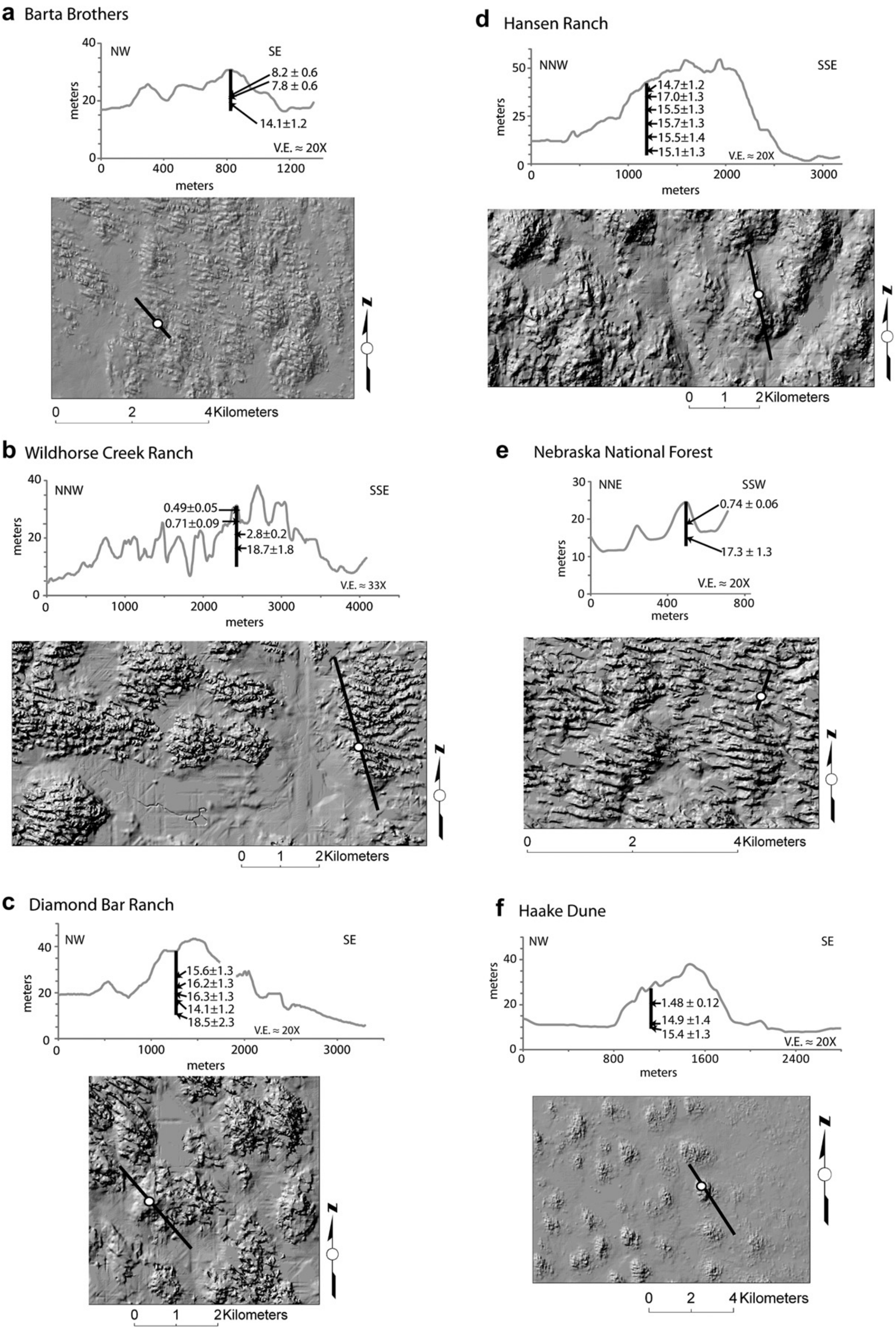

Fig. 4. Local landscape setting of coring sites. Topographic profiles show ground surface (gray line), cored location and total depth (vertical black line), and OSL sample ages and depths. Shaded relief images from USGS digital elevation models show locations of cores (white dot) and topographic profiles (black line).

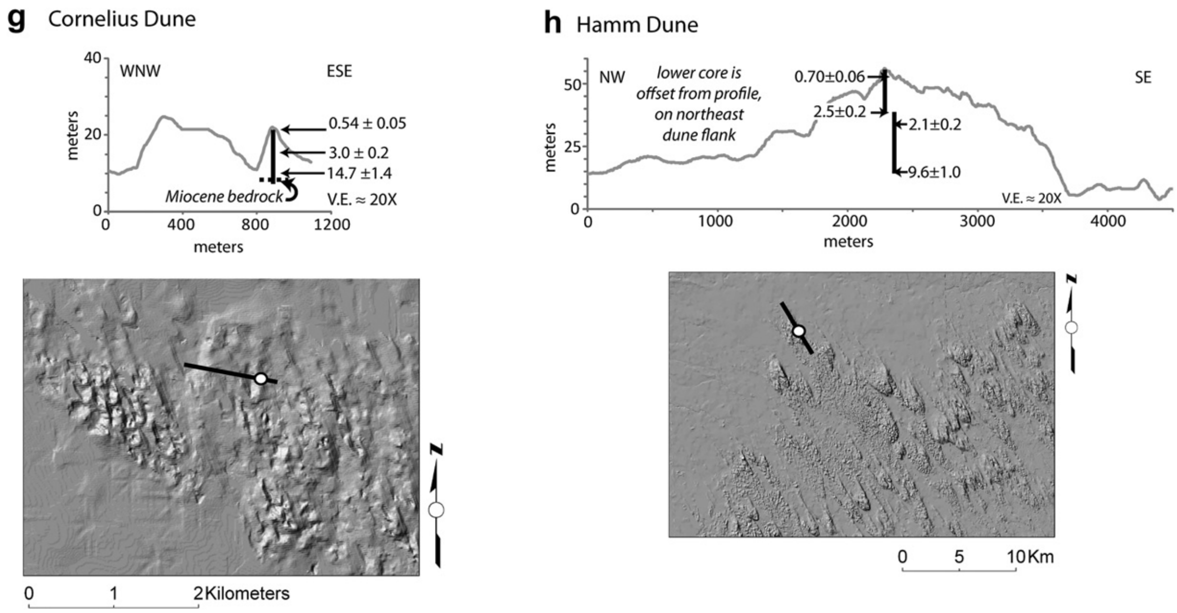

Fig. 4. (*continued*).

reactivation in the Holocene. The outcrop sampled for OSL dating at the Wach site exposes massive light-brown sand overlying a thick buried soil with an Ab-Bwb-Bkb-BCb profile. This soil is morphologically similar to the Brady Soil, a regional marker of the Pleistocene–Holocene boundary (Mason et al., 2008); however, the two OSL ages bracketing the soil (7.5 ± 0.5 ka just above the Ab horizon, 10.7 ± 0.7 ka below it) suggest it is somewhat younger than most Brady Soil profiles (typical age range shown in Fig. 3, see Mason et al., 2008, for more details). Below the BCb horizon, we obtained an OSL age of 13.7 ± 1.0 ka from 2-m thick horizontally stratified very fine sand, and a very similar age of 13.6 ± 1.0 ka from underlying high angle cross-stratified fine sand. These ages suggest

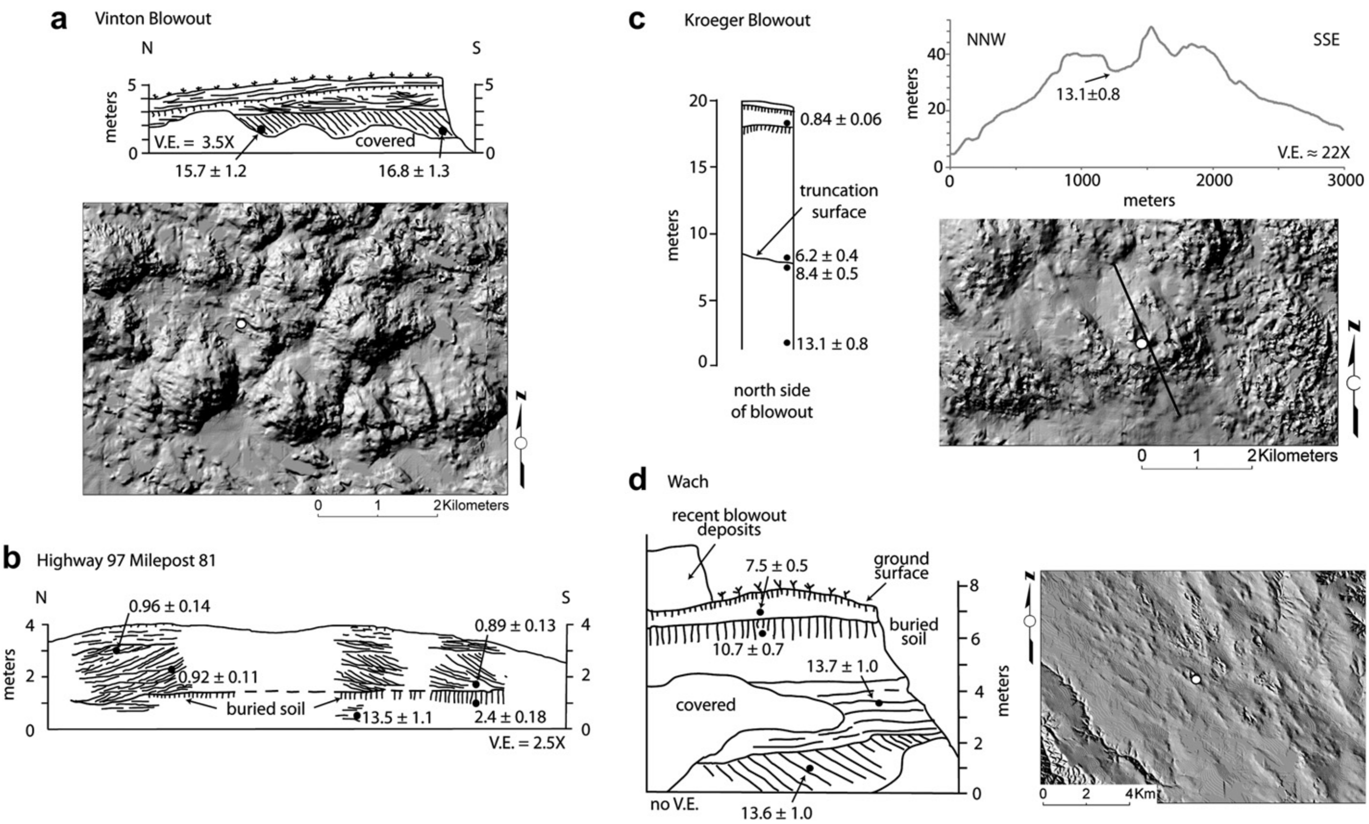

Fig. 5. Stratigraphic diagrams of dunefield outcrops, with OSL ages in ka. For three outcrops, shaded relief maps from USGS digital elevation models also show landscape setting. Topographic profile (as in Fig. 4) is included for Kroeger Blowout, but because of DEM resolution it does not capture true height of blowout rim above OSL sample location.

that the dune may contain a substantial body of Late Pleistocene sand. The cross-strata at the base of the section dip toward the southeast, and all of the parabolic dunes in the vicinity indicate a similar southeastward direction of migration.

3.4. Outcrops in the thick loess region

Lugn (1935, p. 166), Smith (1965), and Ahlbrandt et al. (1983) all noted that eolian sand overlies Peoria Loess at the southeast margin of the Sand Hills, but there are also localities where sand beds occur within or at the base of Peoria Loess. We sampled two of these localities for OSL dating (Fig. 6). We previously reported OSL ages from Bignell Loess and upper Peoria Loess in the roadcut section at Bignell Hill and a core adjacent to the roadcut at Moran Canyon (Mason et al., 2003, 2008), and a variety of other luminescence and radiocarbon ages and have been obtained from these localities (Maat and Johnson, 1996; Muhs et al., 1999b, 2008; Roberts et al., 2003). At Moran Canyon, a roadcut exposes Holocene Bignell Loess and about 4.5 m of Peoria Loess overlying more than 2.5 m of medium sand. Within the sand, a set of cross-strata more than 2 m thick record eastward migration of a dune that was subsequently buried by Peoria Loess (Fig. 2c). An OSL age of 20.3 ± 1.6 ka was obtained from about 0.4 m below the top of the sand (Fig. 6).

Bignell Hill (Fig. 6) is one of the best-known loess sections in the central Great Plains (Feng et al., 1994; Maat and Johnson, 1996; Muhs et al., 1999b, 2008; Mason et al., 2003; Roberts et al., 2003), comprising several disjunct exposures along a steep road at the margin of a loess table. The upper and lower boundaries of Peoria Loess are well-exposed and separated by a vertical distance of 51 m (Bettis et al., 2003). Fine-medium sand about 5.5 m thick is exposed about 10 m above the base of the Peoria Loess, but has not been included in most published sections, probably because the investigators were not certain of the stratigraphic relations between this sand and the loess exposed in other roadcut segments. A geologic test hole drilled near the top of the roadcut encountered sand interbedded with Peoria Loess at approximately the same elevation as the sand in the roadcut (Bettis et al., 2003), however. We also identified subhorizontal upper and lower contacts between the sand and loess in the roadcut, and observed wind-ripple lamination and fine calcite rhizoliths and insect burrows within the sand. Based on those observations, we interpret the sand in the roadcut as an eolian sand sheet that migrated over the basal increment of Peoria Loess and was then buried by renewed loess accumulation. Ages of 21.7 ± 2.1 and 22.7 ± 2.0 ka were obtained from the sand (Fig. 6). These ages overlap at 1σ with the age from dune sand at Moran Canyon, and with an age of 22.3 ± 2.0 from loess immediately overlying the sand. Two duplicate samples from loess just below the sand in the same outcrop yielded two very different ages, 17.6 ± 1.7 ka and 24.6 ± 2.0 ka. Although the latter age is more consistent with ages in the overlying sand, we have no other reason for assuming it is the more accurate of the two. Roberts et al. (2003) reported an OSL age of 18.9 ± 0.9 from loess just below the elevation of the sand, but apparently not in the same roadcut segment. This age overlaps at 2σ with our two ages from the sand.

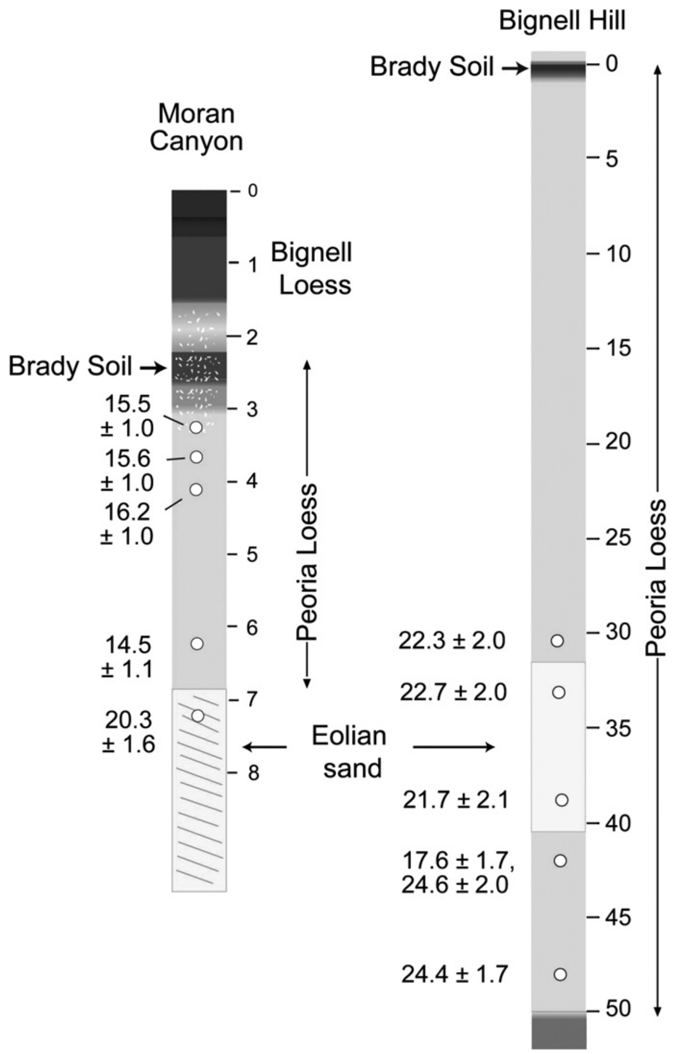

Fig. 6. Stratigraphy at two sites where eolian sand is interbedded with Peoria Loess, with OSL ages from this study (for additional ages from these sites, not shown, see Maat and Johnson, 1996; Muhs et al., 1999b; Roberts et al., 2003; Mason et al., 2008). Bignell Hill shown as vertical section based on both roadcut exposures and test hole from top of section (Bettis et al., 2003). See text for discussion of anomalous ages below eolian sand bed.

4. Discussion

4.1. Geomorphological interpretation of the OSL ages

At the most basic level, the OSL ages reported here document Late Pleistocene eolian sand activity at sites distributed across a large area of the central Great Plains. At several study sites (Barta Brothers, Kroeger Blowout, Wild Horse Creek Ranch, Diamond Bar Ranch, Hansen Ranch, Wach, Nebraska National Forest, and possibly Schmidt Ranch), the present dunes were partly constructed in the Late Pleistocene. At the same time, data from many of the new cores confirm the importance of Holocene sand dune activity. The Sand Hills are not entirely products of Holocene aridity, nor are they simply relict Pleistocene dunes, as once supposed.

The new Late Pleistocene ages extend the close correspondence in time between episodes of eolian sand activity and rapid loess deposition in the central Great Plains, previously noted for the Holocene (Miao et al., 2007). Most of the Late Pleistocene eolian sand ages coincide with OSL ages recording Peoria Loess deposition in western Nebraska (Roberts et al., 2003; Mason et al., 2008). The youngest Late Pleistocene sand ages may overlap with the early stages of Brady Soil formation (Fig. 3), which marks a minimum of loess accumulation in the central and northern Great Plains (Mason et al., 2008). To our knowledge, the 10.7 ka age from the Wach site is the only OSL date indicating eolian sand deposition in the central Great Plains within the later part of Brady Soil development, between about 12.5 and 10 ka.

Our ability to reconstruct the three-dimensional geometry of Late Pleistocene sands within the large Sand Hills dunes is limited. Muhs et al. (1999a) documented spatial variation in the geochemistry and mineralogy of eolian sands across the Sand Hills, but we have not identified temporal changes in sand composition allowing differentiation of Pleistocene and Holocene deposits without OSL dating. Our cores seldom contained paleosols or other potential stratigraphic markers, probably because of frequent erosional truncation, and efforts to use ground-penetrating radar to characterize the stratigraphy within the large dunes have been unsuccessful so far. Thus, in the rest of this section we focus on what can be inferred from the OSL ages and their position relative to the present dune morphology.

Many of the Late Pleistocene ages from eolian sands within large Sand Hills dunes range between 14 ka and 17 ka, with all ages older than 19 ka coming from eolian sands interbedded with loess (Figs. 3–6). These results could be interpreted as indicating a fairly short interval of major dune activity, but there are good reasons to treat this apparent cluster of ages with caution. First, the OSL ages should be interpreted as relatively broad probability distributions, often with $\pm 2\sigma$ ranges spanning >4000 yr. Second, OSL ages from many dunefield settings are inherently biased toward the later part of an extended period of dune activity, because much of the record of such activity is eroded through ongoing dune migration. Certainly, our dating of sand high within large dunes is unlikely to have captured the initial construction of the dunes.

Third, there is good reason to believe that the OSL ages do not adequately record the final phase of Late Pleistocene activity, either. The simplest interpretation of the ages clustered around 15–17 ka at Diamond Bar Ranch and Hansen Ranch is that they represent sedimentation on leeward slopes of the large dunes that are still present today, in an earlier stage of their migration toward the south or southeast. If so, substantial Late Pleistocene dune migration could have occurred *after* deposition of the sand that was dated, because the cores were taken 300–1000 m from the present southeast slopes of these dunes. The individual Late Pleistocene ages from Kroeger Blowout and Wild Horse Creek Ranch, located high in the modern dunes but some distance from modern leeward slopes, are also consistent with this interpretation. The cross-strata dated at Vinton Blowout could record an earlier position of the large barchan dune extending southeast from that site, implying very substantial migration after 15–17 ka. In all of these cases, it is possible that some of the large-scale dune migration post-dating our OSL ages occurred not only in the Late Pleistocene, but also during the Early to Middle Holocene, a period of sustained aridity, eolian sand activity, and dust production across the central Great Plains (Miao et al., 2007).

The Wach site is near the downwind end of a fairly small parabolic dune; thus, OSL ages there are more likely to record the last major period of dune migration, than the ages from large Sand Hills dunes. The smooth topography and silt-rich surface soils of this dune and its neighbors would be expected if it had been largely stabilized by dust-trapping vegetation since the Late Pleistocene or Early Holocene. Although one age indicates some Early Holocene sand deposition at the Wach site, the preservation of Late Pleistocene sand deeper in the section suggests limited dune migration in the Holocene. Late Pleistocene eolian sand at the Barta Brothers, Haake, and Cornelius sites is not far above interdune level, and the morphology of the dunes or sand sheets in which this sand was deposited is uncertain. Ages from Bignell Hill and Moran Canyon indicate that sand sheet and dune activity occurred locally southeast of the present Sand Hills dunefield around the time of the Last Glacial Maximum (LGM), before stabilization of the sand surface allowed loess accumulation. The broader geomorphic or paleoenvironmental significance of these events is uncertain.

4.2. Late Pleistocene wind regimes

The net direction of potential sand transport by modern winds in the Sand Hills and northeastern Colorado is toward the southeast, and the overall pattern of sand transport should produce dune crests oriented southwest–northeast (Schmeisser et al., 2010). The orientations of large barchanoid ridge, barchan, and compound parabolic dunes across the region are broadly consistent with these predictions from modern wind observations (Smith, 1965; Warren, 1976; Swinehart, 1990; Muhs et al., 1996), although the east–west oriented barchanoid ridge crests of the central Sand Hills indicate a stronger northerly component than at present. A strong component of southwesterly winds is recorded by longitudinal dunes superimposed on larger bedforms of the Sand Hills (Smith's second series), and other dunes of the central and southern Great Plains, but those winds are believed to have occurred mainly during Late Holocene dry periods (Sridhar et al., 2006; Schmeisser et al., 2010).

The results reported here suggest that the regional pattern of large dune orientation could have initially developed in the Late Pleistocene, with prevailing wind directions similar to those observed today. Many of the dunes found to have cores of Late Pleistocene sand have fairly well-defined, steep leeward slopes facing south or southeast, indicating northerly to northwesterly winds, similar to winds that formed Late Pleistocene eolian cross-strata in outcrops at the Vinton Blowout, Wach, and Moran Canyon sites.

While this evidence on the Late Pleistocene wind regime is limited, it is important, given issues raised by general circulation model simulations of climate during the Last Glacial Maximum (LGM), particularly the early modeling studies of the COHMAP Group. Papers describing those studies (Kutzbach and Guetter, 1986; COHMAP, 1988) emphasized the development of anticyclonic circulation over the Laurentide Ice Sheet, suggesting the possibility of easterly surface winds south of the ice margin. Prevalence of easterly winds at the LGM would conflict not only with the evidence on paleowinds reported here, but also with most paleowinds inferred from other Late Pleistocene dunefields of the North American midcontinent (Wolfe et al., 2004; Miao et al., 2010) and with Late Pleistocene loess transport directions (Muhs and Bettis, 2000).

Closer examination shows that the initial COHMAP study and later modeling projects actually produced results that are consistent with the eolian record on the central Great Plains, however. Surface winds simulated for the LGM and the modern control in the original COHMAP study are illustrated in Fig. 7 (Kutzbach and Guetter, 1986; Wright et al., 1993; Kutzbach, 1994). Southwest of the ice sheet margin on the central Great Plains, the mean LGM winter winds are from the west to northwest, with a larger northerly component than in the modern control (Fig. 7). Winter winds in the modern control are very similar to the mean January winds in the NCEP reanalysis of modern observations (Kalnay et al., 1996). Summer winds are southerly to easterly in both LGM and modern control simulations, but are weaker than the winter winds, so winter winds dominate the annual mean. The anticyclonic winds often emphasized in discussions of climate modeling results occur mainly over the ice sheet itself, with northeasterly to northerly wind flow down the southern ice sheet margin (Fig. 7).

More recent modeling studies have produced similar results. Table 2 lists published examples of surface wind plots. Monthly wind vectors from numerous other studies are available through archives such as those maintained by NOAA Paleoclimatology (http://www.ncdc.noaa.gov/paleo/data.html) and the University of Wisconsin-Madison Center for Climatic Research (http://ccr.aos.wisc.edu/). Northeasterly downslope winds at the ice margin are especially well-developed in the regional model of Bromwich et al.

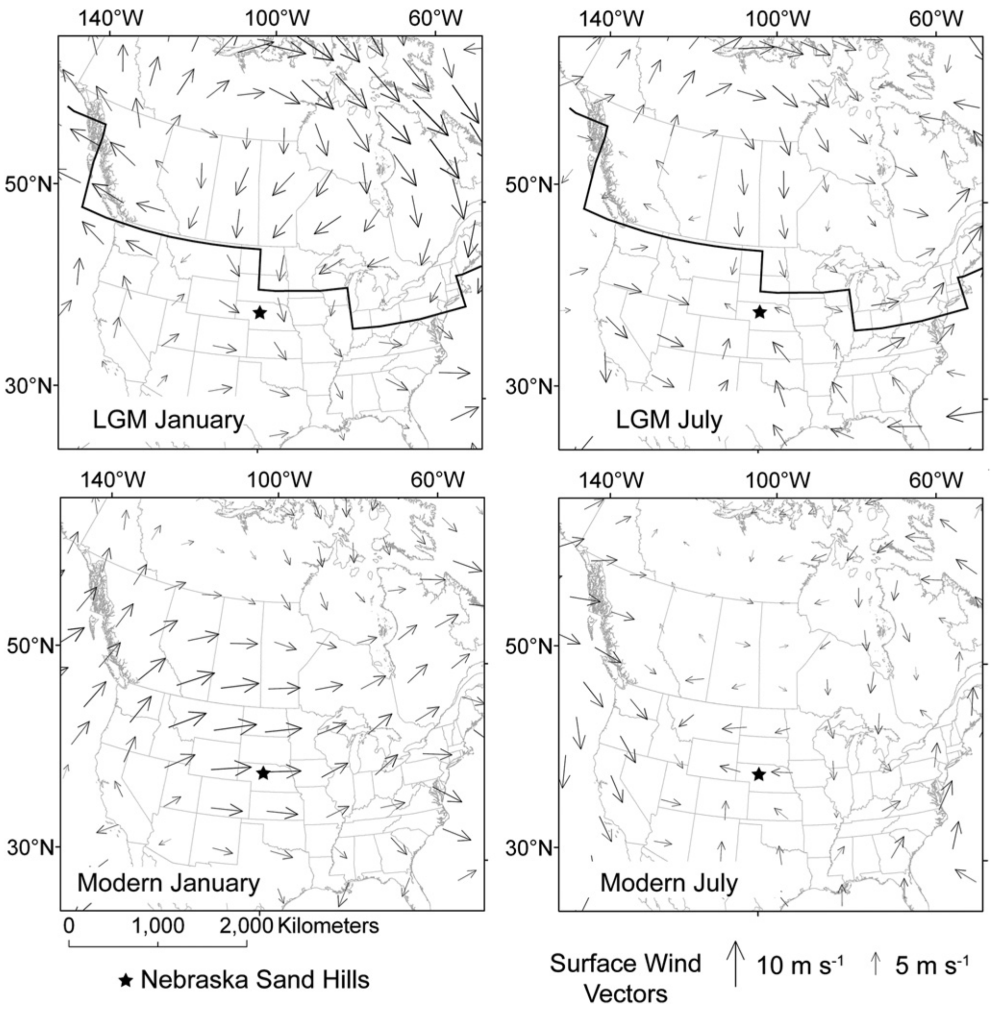

Fig. 7. Surface wind vectors in January and July, simulated by the general circulation model initially used by the COHMAP Group (CCM0), with boundary conditions appropriate for the LGM (originally assigned an age of 18K by COHMAP) and the modern pre-industrial control. Vectors plotted in ArcGIS using gridded monthly mean data obtained from NOAA NCDC Paleoclimatology data archive (Kutzbach, 1994); same vectors are shown with a different projection in Kutzbach and Guetter (1986, Figs. 7 and 12). Heavy line in LGM maps shows southern margin of ice sheet as represented in the model.

(2004); however, the simplified ice margin used in that model is apparently much farther south in the central Great Plains than the actual outermost Late Pleistocene ice margin, which was 200–500 km northeast of most Sand Hills dunes. Dunes in western Canada that formed within 200 km of a contemporaneous ice margin record southeasterly winds (Wolfe et al., 2004), which may be comparable to ice marginal downslope winds in the model results of Bromwich et al. (2004).

Northwesterly winds simulated for the LGM on the central Great Plains by the COHMAP project and later modeling studies are consistent with results of this study and with loess transport directions and provenance in the same region (Mason, 2001; Aleinikoff et al., 2008). Comparison of winds in modern control runs (Fig. 7) with the resultant drift direction for eolian sand, calculated from modern observations (Schmeisser et al., 2010), raises an important issue, however. Resultant drift direction probably has a stronger northerly component than the mean monthly modern winds because it is heavily influenced by strong northerly and northwesterly winds associated with well-developed cold fronts in mid-latitude cyclones. Such cyclones would still have played an important role in the Great Plains wind regime during the Late Pleistocene (Muhs and Bettis, 2000), even though cyclone tracks were probably affected by changes in upper-level flow induced by the ice sheet (Bromwich et al., 2004, 2005); therefore, the change in dominant sand transport directions between the LGM and the modern climate may have been even less than implied by modeling results shown in Fig. 7.

Table 2
Examples of near-surface wind vectors at the Last Glacial Maximum simulated by global or regional models (published maps showing monthly or seasonal means).

Reference	Figures illustrating wind vectors
Kutzbach and Guetter (1986)	Figs. 7 (July) and 12 (January)
Bartlein et al. (1998)	Fig. 2 (January and July)
Dong and Valdes (1998)	Fig. 5 (DJF) and Fig. 6 (JJA)
Whitlock et al. (2001)	Fig. 10 (January and July)
Shin et al. (2003)	Fig. 16 (DJF and JJA)[a]
Bromwich et al. (2004)	Fig. 2 (January) and Fig. 3 (July)

[a] 850 hPa winds, shown as anomalies for the LGM; direction can be inferred by comparison with modern control.

4.3. *Implications for Late Pleistocene environments*

Sediment supply is a basic requirement for dunefield development (Kocurek and Lancaster, 1999), and in the central Great Plains, broad channel belts of major streams are an obvious potential source of eolian sand. Episodes of Late Pleistocene dune activity near those channel belts could have occurred at times when extensive areas of fluvial sand were frequently exposed to the wind, either because of high sediment loads and variable discharge related to glaciation in the Rocky Mountains, or because of broader effects of climate change on the fluvial system. Similar sediment supply effects have been proposed for Holocene dune activity on the Great Plains (Muhs and Holliday, 1995; Muhs et al., 1996; Muhs and Zarate, 2001) and Late Pleistocene dune development elsewhere in the midcontinent (Rawling et al., 2008; Miao et al., 2010). While this conceptual model could apply to sand interbedded with loess near the Platte River at Moran Canyon and Bignell Hill, it is difficult to apply to other occurrences of Late Pleistocene eolian sand, which are relatively far from any major fluvial sediment source. A direct effect of fluvial sediment supply on Late Pleistocene dune activity in the Sand Hills seems particularly unlikely, given the mineralogical maturity of dune sand there compared to potential fluvial sources and the availability of sand from underlying Pliocene eolian sand sheets (Muhs et al., 1997).

Besides sediment supply, major variables influencing eolian system state include the transport capacity of the wind and sediment availability for wind entrainment, often controlled by the extent of stabilizing vegetation cover (Kocurek and Lancaster, 1999). The importance of wind power has been emphasized in research on dunes in other regions (e.g. Tsoar, 2005), but increased transport capacity has generally not been considered the primary explanation for initiation of Holocene dune activity on the Great Plains, because the dunefields there are largely stable today despite winds with very high transport capacity (Muhs and Maat, 1993; Muhs and Holliday, 1995; Muhs and Wolfe, 1999). There is no compelling evidence that winds even stronger than those on the Great Plains today could have enhanced dune mobility in the Late Pleistocene, although this issue merits further investigation. As noted above, strong downslope winds simulated in a regional modeling study of the LGM (Bromwich et al., 2004) are confined to areas near the ice margin and are not consistent with the field evidence of Late Pleistocene sand- and loess-transporting wind directions (Muhs and Bettis, 2000; Mason, 2001).

With that background, the key factors allowing Late Pleistocene dune activity were probably those limiting dune-stabilizing vegetation growth. For the Holocene, most researchers have focused on effective moisture as the critical control of dunefield vegetation, a view supported by the similar timing of eolian activity and independent evidence for a dry climate (Madole, 1994; Forman et al., 1995, 2001; Muhs et al., 1996; Arbogast and Johnson, 1998; Mason et al., 2004; Miao et al., 2007). For example, significant dune activity occurred in the central Great Plains during the Medieval Climatic Anomaly, when severe drought across the western U.S. is well-documented by other evidence (Cook et al., 2004; Mason et al., 2004; Daniels and Knox, 2005; Miao et al., 2007). In the Canadian Prairies, however, growing-season length and temperature have been identified as additional important factors limiting dune stabilization (Muhs and Wolfe, 1999). In that region, the coldest part of the Great Plains, short growing seasons may allow dune mobility despite effective moisture high enough to sustain fully stabilized dunes in warmer areas; furthermore, dune stabilization has occurred as the climate of the Canadian Prairies warmed during the historical period (Wolfe and Hugenholtz, 2009).

Drawing on that insight, we propose that growing-season length and temperature played important roles in allowing Late Pleistocene dune activity, in combination with lower than modern precipitation and low atmospheric CO_2. This explanation is at least partially consistent with paleoecological data, and is more plausible than attributing Late Pleistocene dune activity to aridity alone, although paleoclimatic modeling does provide a basis for assuming that precipitation was lower than modern under full-glacial conditions (Forman et al., 1995). Most paleoclimatic research has focused on the LGM ($\sim$21 ka), earlier than most of our eolian sand ages, but the insight provided on glacial climates is still valuable. Numerical modeling of the LGM climate using global and regional models of widely varying complexity and resolution consistently indicates much colder winter and summer temperatures than at present south of the ice margin in central North America (e.g. Kutzbach and Guetter, 1986; Bartlein et al., 1998; Shin et al., 2003; Bromwich et al., 2004; Kim et al., 2008). These climate simulations often also indicate substantially less summer precipitation in the Great Plains region at the LGM than in the modern climate (e.g. Bartlein et al., 1998; Shin et al., 2003; Kim et al., 2008), but the regional model used by Bromwich et al. (2005) indicated episodic heavy rainfall related to cyclones tracking over the southern part of the ice sheet.

Jackson et al. (2000) reconstructed the LGM climate of eastern North America using pollen and plant macrofossil assemblages, and concluded that July temperatures were 14–18 °C lower than modern and annual precipitation was 40–60% less than modern in the region just east of the central Great Plains. These estimates suggest more extreme contrasts between the LGM and modern conditions than is indicated by numerical modeling; however, Jackson et al. (2000) did not take into account the effects of much lower atmospheric CO_2 on plant physiology during the last glaciation. These are the subject of ongoing discussion, but it appears that lower water use efficiency and other effects of lower CO_2 contributed to the open vegetation and relatively low tree cover evident in Late Pleistocene pollen data, which would otherwise be attributed to aridity and possibly low temperatures (Cowling and Sykes, 1999; Williams et al., 2000; Williams, 2002; Loehle, 2007; Prentice and Harrison, 2009). More open vegetation and lower primary productivity would probably favor eolian sand mobility, regardless of the relative contributions of climate and low CO_2 to these conditions.

Within the central Great Plains, Late Pleistocene paleoecological evidence clearly indicates a cold climate, and strongly suggests an open mosaic of vegetation including both grasses and trees. Muhs et al. (1999b) concluded that the environment of Peoria Loess deposition in northeastern Colorado was predominantly a cool-season grassland, based on mammal and insect fossil assemblages described by Graham (1981) and Elias and Toolin (1990), also noting the interpretation of a cold steppe environment from fossil gastropods in Peoria Loess of western Nebraska (Rousseau and Kukla, 1994; Rossignol et al., 2004). On the other hand, Late Pleistocene pollen and plant macrofossils confirm the local presence of spruce (*Picea glauca*, white spruce, where species-level identification is possible) in Kansas and Nebraska, including the Sand Hills (Watts and Wright, 1966; Grüger, 1973; Wells and Stewart, 1987; Loope and Swinehart, 2000). Fredlund and Tieszen (1997) interpreted pollen and phytoliths from Late Pleistocene sediments in Nebraska and Kansas as indicating an environment with some trees and abundant grass-covered openings, at about the same time as many of our dunefield OSL ages. Small mammals represented by Late Pleistocene fossils in western Kansas and Nebraska are found today in boreal forest, Rocky Mountain conifer forest, and cool grassland or parkland (Wells and Stewart, 1987; Corner and Voorhies, 1994). Assuming that moisture stress related to low CO_2 had an important role in favoring open vegetation rather than closed forest, it is possible that patches of forest occurred mainly in landscape settings with greater soil moisture availability, such as interdune valleys in the Sand Hills.

Regardless of the specific nature of the vegetation mosaic during the Late Pleistocene on the central Great Plains, it must have been a very different environment from the deserts in which most large fully mobile dunes similar to those of the Sand Hills occur at present. It should be noted, however, that active inland dunes surrounded by boreal forest do occur today in Alaska and northern Alberta, where a cold, short growing season occurs together with relatively low precipitation (David, 1977; Mann et al., 2002). We suggest that during the Late Pleistocene on the central Great Plains, short, cool, dry growing seasons, with increased moisture stress related to low CO_2 levels, severely limited the ability of vegetation to colonize bare dune sand with low moisture retention. Thus, even though soil moisture was sufficient to sustain spruce and other boreal forest species in certain parts of the landscape, and grassland vegetation in many areas, large areas of bare sand remained mobile.

5. Conclusions

Research over the last several decades has conclusively demonstrated that substantial dune activity occurred during the Holocene in the central Great Plains. The results of this study represent an important step toward understanding the earlier, Late Pleistocene history of the Nebraska Sand Hills and neighboring dunefields. While these results comprise a very small sample from the thousands of dunes across this region, they clearly suggest that many of the large dunes still present today may have been constructed in the Pleistocene. Late Pleistocene OSL ages of eolian sand sampled in this study cluster between 17 and 14 ka, but it is likely that dune construction and migration began well before that time, and the OSL ages also do not capture the final phases of large-dune migration at several sites. Late Pleistocene dune activity occurred in a very different environment than Holocene activity, with cold, short growing seasons and low atmospheric CO_2. In this setting, fully mobile dunes were juxtaposed with boreal forest biota in a landscape with few modern analogs.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.quascirev.2011.10.005.

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