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Temporal and spatial variability in dune reactivation across the Nebraska Sand Hills, USA

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Abstract

The Nebraska Sand Hills is a stabilized dune field on the Great Plains of North America. Although it is well known that this dune field, like several others on the Great Plains, last experienced widespread activity during the Medieval Climatic Anomaly (MCA, ~AD 900–1300), spatial variation in the timing and nature of drought development is poorly constrained. To elucidate spatial trends in dune reactivation, samples potentially representing MCA activity across the Sand Hills were collected and dated using optically stimulated luminescence (OSL). Ages from the older part of the MCA were obtained from eolian sediments in the northwestern Sand Hills, while ages from later in the episode were obtained to the southeast, suggesting a geographic trend in the timing of revegetation of the dunes near the end of the drought. Revegetation likely occurred to the northwest initially as a result of renewed moisture availability from a rising water table in the interdunes, which serve as refugia for vegetation during times of drought. Vegetation then gradually spread to the southeastern Sand Hills. An additional spatial trend in ages is apparent in the chronology of linear dune mobilization across the Sand Hills. Linear dunes in the northwest are superimposed on megadunes and originated during the last reactivation, while linear dunes in the southeast are built around older cores of dunes and formed during several reactivations. Our geochronology reveals three episodes of eolian transport, including the MCA, in the formation of linear dunes in the southeast.

Keywords: Great Plains, Holocene, linear dune, Nebraska Sand Hills, optical dating, OSL

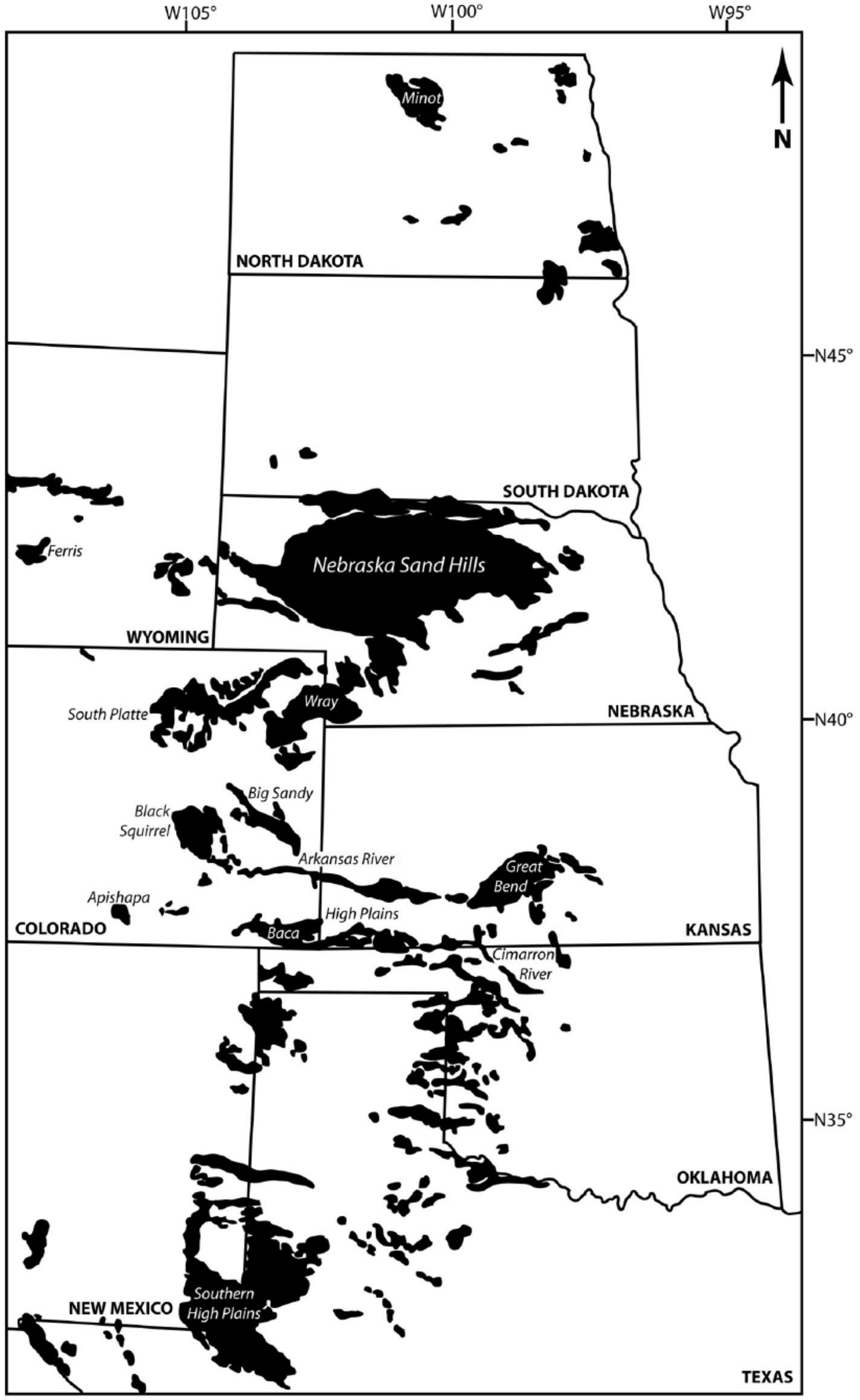
Introduction

Many stabilized dune fields in the Great Plains of North America (Figure 1) are susceptible to reactivation during periods of prolonged, severe drought. Forman et al. (2001) suggested that droughts must be a decade or longer in duration, with at least a 25% decrease in precipitation during the growing season, to cause complete dune reactivation. While the exact threshold for full activation is difficult to determine, these so-called 'megadroughts' must have been longer and more severe than droughts known in the historical record, which only caused limited dune activation (Forman et al., 2001; Miao et al., 2007). The megadroughts that are most clearly identifiable from a wide variety of evidence occurred during the 'Medieval Climatic Anomaly' (MCA; also known as the 'Medieval Warm Period'). The MCA was a prolonged period of increased warmth in the Northern Hemisphere and recurrent widespread drought across much of North America, from AD ~900 to 1300 (Cook et al., 2004; Helama et al., 2009). A variety of causes for the MCA droughts in North America have been proposed, generally linked to sea surface temperature anomalies related to the El Niño-Southern Oscillation, La Niña, the North Atlantic Oscillation, and/or the Atlantic Multidecadal Oscillation (Helama et al., 2009; Oglesby et al., 2012; Trouet et al., 2009). Dust emission during droughts may have had a feedback effect that made the droughts more prolonged (Cook et al., 2014).

Dune activity during the MCA has been recognized in large and small dune fields across the Great Plains of North America (Halfen and Johnson, 2013), including the Minot dune field of North Dakota (Muhs et al., 1997), the Nebraska Sand Hills (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007), small dune fields east of the Nebraska Sand Hills (Hanson et al., 2009; Puta et al., 2013), dune fields in eastern Colorado (Clarke and Rendell, 2003; Madole, 1995), the Great Bend Sand Prairie of Kansas (Arbogast, 1996), small dune fields in Kansas (Halfen et al., 2012; Hanson et al., 2010), the Cimarron River dune fields of Oklahoma (Brady, 1989), and the Southern High Plains of Texas (Holliday, 2001).

Evidence for drought in the Great Plains during the MCA has also been recognized in other proxies. Streams in southwestern Nebraska experienced channel incision around the time of the MCA, interpreted as a response to widespread drought (Daniels and Knox, 2005). Diatom-inferred salinity from lakes in North Dakota point

Figure 1. Map of Great Plains dune fields (black shading, modified from Schmeisser et al., 2010) with dune fields (names in italics) mentioned in the text.



to a prolonged period of drought from AD 1020 to 1150, concurrent with the MCA (Fritz et al., 2000; Laird et al., 1996). Tree ring records indicate multiple droughts in areas surrounding the Great Plains during a similar time frame (Cook et al., 2004; Woodhouse and Overpeck, 1998).

Dune fields in the Great Plains are susceptible to changes in climate, particularly precipitation levels. An increased understanding of the response of these dunes during previous droughts will provide insight into possible future reactivations. The major goal of this paper is to accurately determine the spatiotemporal patterns of MCA dune mobility in the Nebraska Sand Hills, the largest Great Plains dune field. In addition, we investigate whether linear dune formation in the Nebraska Sand Hills only occurred during the MCA or was initiated in earlier droughts.

Geologic setting

The Nebraska Sand Hills is the largest sand sea in the western hemisphere (Smith, 1965), comprising 57,000 km^2 of vegetated sand dunes on the central Great Plains of North America (Figure 1). Barchanoid ridge, megabarchan, parabolic, and linear dunes are present within the dune field (Swinehart, 1998). Linear dunes are present in the southeastern Nebraska Sand Hills. Their crests are oriented roughly N65°W and have been interpreted morphodynamically as longitudinal dunes

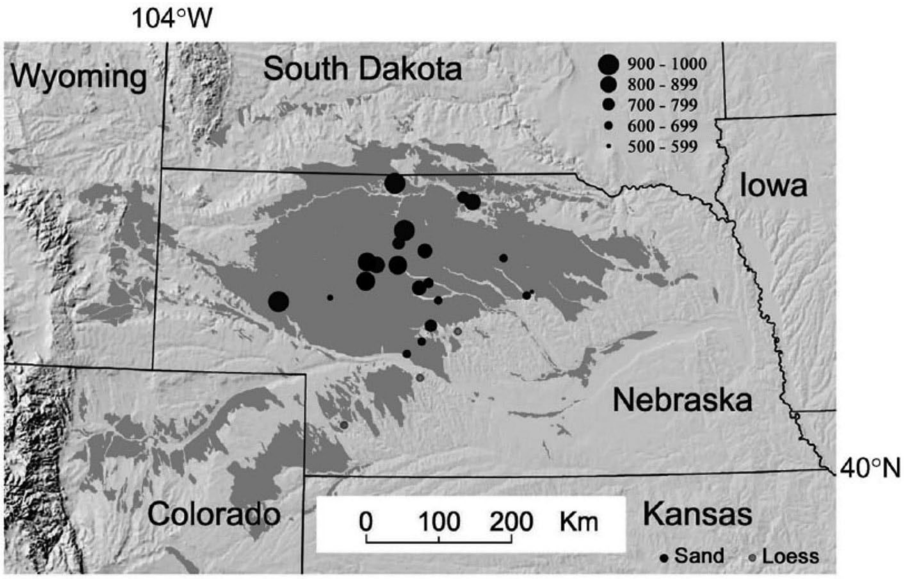


Figure 2. Map view of spatial distribution of optically stimulated luminescence eolian sand (black circle) and loess (gray circle) ages from the last reactivation of the Nebraska Sand Hills (modified from Goble and Mason, 2007). Size of circle corresponds to relative age of sample at a given site.

indicative of bidirectional winds of subequal strength (Sridhar et al., 2006). Several Holocene reactivations from the Sand Hills have been identified using optically stimulated luminescence (OSL) dating (Goble et al., 2004; Miao et al., 2007; Stokes and Swinehart, 1997). Extensive reactivation of the dune field has occurred three times in the last 4000 years, centered around 3.8, 2.5, and between ~1.0 and 0.7 ka during the MCA (Miao et al., 2007). Partial reactivations of the dunes (involving increased areas of bare sand and partial movement) have occurred since the MCA, including the 1930s Dust Bowl and other prehistoric episodes (Forman et al., 2005), but none have led to such extensive reactivation.

Previous studies

Timing of dune reactivations in the Nebraska Sand Hills

The dunes in the Nebraska Sand Hills have been the focus of many recent studies focused on determining the timing of dune reactivations (Forman et al., 2005; Goble et al., 2004; Mason et al., 2004, 2011; Miao et al., 2007; Muhs et al., 1997; Stokes and Swinehart, 1997; Stokes et al., 1999). Early researchers considered the Sand Hills to be primarily Pleistocene relicts, with little to no movement of the dunes during the Holocene (Smith, 1965). Starting in the mid-1980s, researchers began using radiocarbon analyses to test this hypothesis, and discovered evidence of extensive movement of eolian sands during the Holocene (Ahlbrandt et al., 1983; Muhs et al., 1997; Stokes and Swinehart, 1997). Combining radiocarbon analyses with optically stimulated luminescence (OSL), a relatively new dating technique, improved temporal resolution and provided indications of eolian activity during the middle and late Holocene, including the last 800 years (Stokes and Swinehart, 1997). Studies of the mineralogical maturity of the sands, however, indicate they are well mixed and depleted of potassium feldspar, suggesting a longer history extending back into the Pleistocene (Muhs et al., 1997). Subsequently, OSL dating provided concrete evidence of late Pleistocene dune activity in the Sand Hills, with dates centered around 17–15 ka, likely representing the end of the Pleistocene dunebuilding phase (Mason et al., 2011).

Extensive OSL dating of dune sediments in the Sand Hills has contributed toward a better understanding of Holocene periods of dune movement (Forman et al., 2005; Goble et al., 2004; Mason et al., 2004; Miao et al., 2007). Mason et al. (2004) applied OSL dating to several upland and interdune sites across a large area of the Sand Hills and recognized a short period of dune movement from about 1000–700 years ago. The wide spatial distribution of sampling localities (Mason et al., 2004) suggests a regional rather than local cause for remobilization. This time frame also correlates well with the MCA. OSL dating of eolian sediments in combination with radiocarbon dating of paleosols by Goble et al. (2004) provided additional evidence for reactivation of dune sediments during the MCA. Forman et al. (2005) found evidence from OSL dating for six reactivations during the past 1500 years at two sites in the Nebraska Sand Hills, including one potentially correlative with 16th century drought identified in other parts of the western United States. Miao et al. (2007) used OSL to date eolian sediments and loess sediments from numerous sites in the central Great Plains, including the Nebraska Sand Hills, and found three major peaks of eolian activity during the last 4000 years, centered at 3.8, 2.5, and between ~1.0 and 0.7 ka. The youngest peak corresponds to a high number of dates (Miao et al., 2007), roughly concurrent with the MCA. An additional period of sustained loess accumulation and dune activity was recognized from approximately 9.4–6.5 ka (Miao et al., 2005, 2007). Halfen and Johnson's (2013) review of dune chronologies supports these peaks of activity for the Nebraska Sand Hills and nearby areas of the central Great Plains.

More recent work has looked specifically at the timing and extent of eolian activity within the Nebraska Sand Hills during the MCA. Researchers (Goble and Mason, 2007; Goble et al., 2008) recognized a spatial trend in ages from the MCA (Figure 2), with the oldest ages (~750–900 years) present in the northwestern Sand Hills, and the youngest ages (~550–750 years) present in the southeastern Sand Hills. This is consistent with either a continuous spatial trend representing earlier stabilization of the dunes to the northwest or with two distinct drought episodes during the MCA (perhaps two of the discrete MCA droughts identified by Cook et al., 2004). The first goal of this study is to determine which of these hypotheses is correct by gathering additional data in each of these areas and from the center of the Sand Hills.

Dating of linear dunes

Linear dunes occupy a large area of the Sand Hills (simple linear dunes alone occupy 7500 km^2; Sridhar et al., 2006) and consist of single elongate ridges with straight to sinuous crestlines (Lancaster, 1982; Tsoar, 1989). Linear dunes run parallel to one another and are typically regularly spaced (Lancaster, 1982). This regular spacing gave rise to the original theory for the formation of linear dunes, in which counter-rotating parcels of air were thought to converge at the surface, pushing sand up into dunes in the spaces between (Hanna, 1969). This theory has since been dismissed, with wind and flume studies showing that linear dunes typically form under bimodal flows (Rubin and Ikeda, 1990; Tsoar, 1983; Tsoar and Yaalon, 1983), with winds from two directions approaching the crest at an angle (Ping et al., 2014; Tsoar and Yaalon, 1983). Morphodynamically, linear dunes can be grouped into oblique and longitudinal dunes; longitudinal dune crests are oriented nearly parallel (0°–15°) to the resultant sand transport direction while oblique dune crests are oriented at an angle (15°–75°; Hunter et al., 1983). In the Nebraska Sand Hills, the linear dune crests are oriented approximately N65°W and suggest northerly winds between about 340° and 20° and southwesterly winds between 212° and 250° during the time of their formation (Sridhar et al., 2006).

The second goal of this study is to use optical dating to determine the timing of linear dune formation within the Nebraska Sand Hills. A greater understanding of the formation and evolution of linear dunes in the Sand Hills is critical because linear dunes are very rarely recognized in the geologic record (Rubin and Hunter, 1985). As linear dunes are one of the most common modern dune types, occupying one-half to two-thirds of all sand seas (Lancaster, 1982), the lack of linear dunes in the geologic record is likely because of misidentification, and not lack of preservation (Rubin and Hunter, 1985). Originally, the internal structures of linear dunes were thought to consist of bimodal dipping beds resulting from the influences of the bimodal winds acting to form them (Bagnold, 1941; McKee and Tibbitts, 1964), although neither of these studies analyzed the internal structures of the dunes at a significant depth. Rubin and Hunter (1985) provided one of the first suggestions that bimodal winds of subequal strength might play variable roles in the development of linear dunes, illustrating a dune with the main cross-beds dipping in one direction and a thin layer of bimodal beds on top. This reconstruction showed that with lateral migration taken into account, linear dune internal structures could look remarkably like those of transverse dunes (Rubin and Hunter, 1985). Bristow et al. (2000) used ground penetrating radar (GPR) in combination with OSL and found evidence for lateral migration in linear dunes in Namibia, mapping offset stacks of cross-beds in different directions, indicating repeated lateral shifts in two directions. A recent study in Inner Mongolia observed lateral migration in oblique dunes over a period of 3 years while monitoring an area that had been flattened at the start of the study (Ping et al., 2014). Other studies have argued against lateral migration in linear dunes, arguing that the lower regions (plinths) of the dunes remain very stable while the crest is active (Livingstone, 2003; Tsoar, 1982; Tsoar et al., 2004). Therefore, the idea of lateral migration in linear dunes remains unresolved.

Luminescence dating provides an excellent mechanism for studying the evolutionary history of linear dunes. Thermoluminescence (TL) dating was applied to linear dunes and interdunes in the Negev Desert in Israel to determine that several cycles of activation took place (Rendell et al., 1993). More recently, OSL has been applied to linear dunes in several dune fields around the world, including a dune field in Mauritania (Lancaster et al., 2002), the Kalahari Desert in Africa (Stokes et al., 1997; Stone and Thomas, 2008; Telfer, 2011; Telfer and Thomas, 2007), and the Negev Desert (Roskin et al., 2011). Some of these studies found multiple periods of sand accumulation in dunes, showing Holocene activity and a central core of sand that accumulated during older activations (Roskin et al., 2011), or even more or less continuous long-term accumulation that could not be clearly separated into discrete episodes (Telfer and Thomas, 2007). Other studies have found evidence for complete reworking of linear dunes, as in Australia, where multiple phases of activity were recognized, but not in all dunes in the field (Fitzsimmons et al., 2007). Additionally, linear dunes in the Namib sand sea, while presently active, were thought to have formed during the Pleistocene because of their large size. Recent OSL dating in these linear dunes has revealed only Holocene ages, suggesting that sediment within these dunes has been completely reworked during the Holocene with no older Pleistocene core (Bristow et al., 2005, 2007). Finally, Telfer et al. (2010) argue for caution when interpreting OSL dates from linear dunes. They used a simple model to evaluate reworking in linear dunes and discovered that while major periods of activity are highly likely to be preserved, smallscale activations were unlikely to be preserved given strong reworking of sand on the upper surfaces of the dunes.

Sampling locations and methods

Samples were collected at six new localities across the Nebraska Sand Hills for OSL dating (Figure 3). To the northwest, three small linear dunes at the Gudmundsen Sand Hills Laboratory (Figure 3, #3) were sampled extensively; two small dunes adjacent to one another (42.07°N, 101.36°W), and the dune that is cut by 'Yao's Blowout' (42.08°N, 101.37°W; Goble et al., 2004). 'Yao's Blowout', one of the sampling localities, has been previously dated, with nearly identical ages of approximately 800 years occurring throughout the height of the dune (Goble et al., 2004). A welded paleosol occurs below the uppermost eolian sediments at 'Yao's Blowout' (see Goble et al., 2004: Figure 1). This paleosol, likely the same as that previously dated in the blowout, was encountered during sampling for this study at a depth of 1.3 m below the crest of the northwestern side of the dune. Correlative paleosols occur at several other Sand Hills sites (Goble et al., 2004; Mason et al., 2004, 2011) and in all Holocene loess sections (Miao et al., 2007), but were not encountered at the other sites newly sampled for this study.

Samples for dating were also collected along a southwest– northeast transect through the center of the Sand Hills: Schmidt Ranch (41.69°N, 101.71°W; Figure 3, #5), Goeke Ranch (41.87°N, 101.25°W; Figure 3, #7), Peterson Ranch (42.03°N, 100.96°W; Figure 3, #8), and Southeast of Brownlee (42.13°N, 100.54°W; Figure 3, #11). To the southeast, one large linear dune in the Nebraska National Forest was sampled extensively (41.90°N, 100.47°W; Figure 3, #12) with a Geoprobe, allowing some analysis of sedimentary structures in cores. All samples were taken from light-colored eolian sediments. Thinly bedded (1–5 mm) sand deposits with low angle dips (<10°) could be seen. Bedding in these cores consisted of inversely graded wind-ripple laminations with occasional thin (<3 mm), lighter, coarser layers. Subsoil lamellae (Rawling, 2000) were recognized in some cores, but were uncommon. All sand was fine to medium grained in size.

Samples of eolian sand previously collected from 13 localities across the Sand Hills and dated using an older OSL reader (Goble and Mason, 2007; Goble et al., 2004, 2008; Mason et al., 2004; Miao et al., 2007) were re-dated for this study (Figure 3; Table 1). These include sites at Crescent Lake (41.83°N, 102.58°W; Figure 3, #1), Kroeger Blowout (42.95°N, 101.15°W; Figure 3, #2), additional sites at the Gudmundsen Sand Hills Laboratory (42.09°N, 101.37°W; Figure 3, #3), Briefcase Wayside (42.39°N, 101.03°W; Figure 3, #4), Hwy 91 (42.24°N, 101.03°W; Figure 3, #6), GP-04-7 (42.77°N, 100.06°W; Figure 3, #9), Johnson Ranch (42.70°N, 100.08°W; Figure 3, #10), Collier Ranch (41.78°N, 100.31°W; Figure 3, #13), Diamond Bar Ranch (41.53°N, 100.50°W; Figure 3, #14), Hansen Ranch (41.26°N, 100.78°W; Figure 3, #15), GP-04-06 (41.66°N, 100.36°W; Figure 3, #16), Barta Brothers Ranch (42.24°N, 99.65°W; Figure 3, #18), and Calamus Reservoir (41.86°N, 99.27°W; Figure 3, #21). Samples of loess previously collected and dated (Miao et al., 2007) that were re-dated in this study

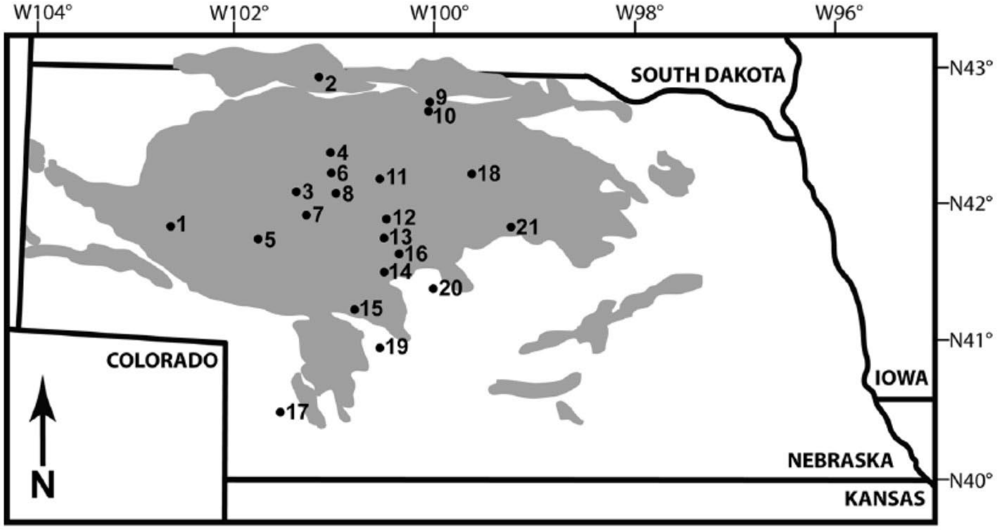


Figure 3. Map of Nebraska with the extent of the Nebraska Sand Hills (gray shading; after Forman et al., 2001) and sample locations. 1 = Crescent Lake; 2 = Kroeger Blowout; 3 = Gudmundsen Sand Hills Laboratory; 4 = Briefcase Wayside; 5 = Schmidt Ranch; 6 = Hwy 91; 7 = Goeke Ranch; 8 = Peterson Ranch; 9 = GP-04-7; 10 = Johnson Ranch; 11 = Southeast of Brownlee; 12 = Nebraska National Forest; 13 = Collier Ranch; 14 = Diamond Bar Ranch; 15 = Hansen Ranch; 16 = GP-04-06; 17 = Wauneta Roadcut; 18 = Barta Brothers Ranch; 19 = Moran Canyon; 20 = Logan Roadcut; 21 = Calamus Reservoir.

include the localities of Wauneta Roadcut (40.51°N, 101.48°W; Figure 3, #17), Moran Canyon (40.99°N, 100.53°W; Figure 3, #19), and Logan Roadcut (41.42°N, 100.02°W; Figure 3, #20).

Most of the samples were collected by hand augering holes approximately 4.5 m deep. At the desired depth, aluminum tubes were driven into sand extracted with the auger bucket and both ends were capped with light resistant covers. Sand from the ends of each tube was later discarded during processing because of exposure to light. In some localities, single auger holes were drilled, with samples collected at various depths. On linear dunes, three or four auger holes were made at the crest of each dune, along the trend of the dune, with samples collected at various depths. Additional samples were collected with the use of a Geoprobe, a hydraulically powered drilling device. This device allowed sampling at much greater depths than is possible with the use of a hand auger. During drilling, a 1-m-long core barrel with an opaque black plastic core liner was pushed down into the hole, filled with sediment, and then removed. Both ends were capped with light resistant caps, with the end portions of the sediment removed during processing. Four holes were drilled along the crest of a linear dune, along the length of the dune, with samples collected at various depths (0.7–13.0 m).

OSL sample preparation and analysis methods

All samples were processed and analyzed at the University of Nebraska–Lincoln Geosciences Luminescence Geochronology Laboratory. Chemical analysis (concentrations of potassium (as K or K_2O), rubidium (Rb), thorium (Th), and uranium (U)), was carried out by ALS Laboratory Group and Activation Laboratories Ltd, using a combination of ICP-MS and ICP-AES. In situ moisture content was determined by measuring weight loss during heating. Samples were processed in a dark room, lighted solely by amber lights. Samples were sieved to obtain the 90–150 μm size fraction and then treated overnight with dilute hydrochloric acid to remove carbonate minerals. Heavy minerals were removed by centrifuging in 2.7 g/cm$_3$ sodium polytungstate. The bottoms of the tubes were frozen using liquid nitrogen and the top portions with the lighter minerals (quartz and feldspar) were recovered. Samples were then treated with concentrated hydrofluoric acid to remove feldspar minerals and to etch the surfaces of the quartz grains. This was followed by a 60 min treatment with concentrated hydrochloric acid to remove any fluorides formed during the previous step. Samples were subsequently re-sieved to remove all remaining grains smaller than 90 μm. Disks used in the optical reader were prepared by spraying a silicon-based spray on 1 cm diameter aluminum disks masked to 2 or 5 mm and dipping them into the purified quartz grains.

OSL measurements on the samples were carried out on a Risø Automated OSL Dating System, Model TL/OSL-DA-15B/C, equipped with blue and infrared diodes and an 80 mCi $_{90}$Sr source. The Single Aliquot Regenerative (SAR) protocol (Murray and Roberts, 1998; Murray and Wintle, 2000, 2003) was used on all samples. The Central Age Model (Galbraith et al., 1999) was used to determine the equivalent dose (D_e). A preheat of 240°C at 10 s was used with a cutheat of 220°C based upon preheat plateau tests between 180°C and 280°C. Four regenerative doses and a zero dose were applied, each followed by a test dose of approximately 1 Gy. The first three regenerative doses were chosen to bracket the expected equivalent dose (D_e), the fourth was the zero dose, and the fifth repeated the first. Data from individual disks were analyzed based on detectable feldspar, recycling ratio, decay curve shape (dominant fast relative to intermediate component), test dose error, and estimated error on the calculated D_e. Unacceptable disks were discarded from the data set. Samples previously analyzed in the UNL Geosciences Luminescence Geochronology Laboratory (Goble and Mason, 2007; Goble et al., 2004, 2008; Mason et al., 2004; Miao et al., 2005, 2007) using a Daybreak Nuclear and Medical Systems reader equipped initially with green and later with blue diodes and a 100 mCi $_{90}$Sr source were re-run within a 2-month period on the Risø TL/OSL-DA-15B/C reader in order to eliminate any inter-instrument, inter-calibration systematic differences.

Results

Spatial trend of ages in the Nebraska Sand Hills

The optical dates corresponding to the MCA show a linear trend across the Nebraska Sand Hills, with ages generally decreasing (becoming younger) toward the southeast (Figures 2 and 4). The northwest–southeast trend is parallel with the resultant of the dominant sand drift direction for this time period, as preserved in dune crest orientations and slipfaces within the dunes (Muhs et al., 1997; Schmeisser et al., 2010; Sridhar et al., 2006; Swinehart, 1998). During the last major

Table 1. Field and laboratory data including optical dating results for samples from the Nebraska Sand Hills, USA.

Field Sample #	UNL Sample #	Depth (m)	In situ moisture content (%)	K_2O (%)	Th (ppm)	U (ppm)	D_{total} (Gya-1 × 10^3)	D_e (Gy ± 1σ)	Aliquots (*n*)	Age (a ± 1σ)	Latitude	Longitude	Distance SE (km)
Crescent Lake													
C3T-1 0.5 m	896^a	0.5	3.0	1.59	2.9	0.7	1.86 ± 0.07	0.66 ± 0.06	20	354 ± 39	41.83	102.58	209
C3T-5 5.3 m	900^a	5.3	5.2	1.76	2.7	0.8	1.85 ± 0.07	1.7 ± 0.05	20	917 ± 56	41.83	102.58	209
C3T-5 5.8 m	901^a	7.0	5.7	1.54	3.1	0.8	1.69 ± 0.07	1.54 ± 0.03	20	915 ± 52	41.83	102.58	209
Kroeger Blowout													
00RJG17	67^a	1.3	8.4	1.83	4.3	0.8	2.03 ± 0.08	2.02 ± 0.06	20	999 ± 61	42.95	101.15	228
00RJG22	72^a	1.3	3.5	2.00	4.7	0.8	2.30 ± 0.09	1.96 ± 0.02	20	854 ± 45	42.95	101.15	228
Gudmundsen Sand Hills Laboratory													
00RJG3	53^a	1.0	3.8	1.84	4.0	0.8	2.13 ± 0.08	1.93 ± 0.04	20	904 ± 50	42.09	101.37	283
00RJG4	54^a	6.3	8.3	1.84	4.0	0.8	1.93 ± 0.08	1.79 ± 0.05	20	926 ± 55	42.09	101.37	283
OJS02-1	480^a	1.8	5.6	1.81	4.4	1.0	2.11 ± 0.08	1.80 ± 0.05	20	852 ± 50	42.07	101.36	285
OJS02-16	493^a	1.0	2.9	2.07	4.8	0.8	2.39 ± 0.09	1.93 ± 0.06	20	808 ± 49	42.07	101.36	285
Yao's Blowout superimposed dune													
RLS07-01	1778^b	2.1	4.6	1.94	3.6	0.7	2.10 ± 0.14	1.74 ± 0.04	20	827 ± 63	42.08	101.37	283
RLS07-02	1779^b	3.4	5.7	1.89	3.6	0.8	2.04 ± 0.14	4.73 ± 0.09	20	2,320 ± 177	42.08	101.37	283
RLS07-03	1780^b	3.0	4.8	1.98	3.8	0.8	2.14 ± 0.08	1.76 ± 0.03	23	821 ± 42	42.08	101.37	283
RLS07-04	1781^b	4.0	5.5	1.95	3.8	0.8	2.09 ± 0.14	4.21 ± 0.09	20	2,010 ± 154	42.08	101.37	283
RLS07-05	1782^b	3.0	2.2	1.77	3.2	0.6	1.96 ± 0.13	1.64 ± 0.03	21	840 ± 64	42.08	101.37	283
RLS07-07	1784^b	2.1	6.6	1.94	4.0	0.8	2.11 ± 0.14	1.80 ± 0.04	22	853 ± 65	42.08	101.37	283
Superimposed dunes at Gudmundsen Sand Hills Laboratory													
RLS07-08	1785^b	2.1	11.0	1.82	3.9	0.7	1.89 ± 0.13	4.18 ± 0.11	22	2,210 ± 174	42.07	101.36	285
RLS07-09	1786^b	3.0	4.9	1.86	4.1	0.8	2.07 ± 0.14	1.75 ± 0.03	23	848 ± 63	42.07	101.36	285
RLS07-10	1787^b	4.6	4.2	1.78	3.6	0.7	1.94 ± 0.13	1.76 ± 0.05	22	908 ± 72	42.07	101.36	285
RLS07-11	1788^b	3.0	3.5	1.73	3.9	0.7	1.93 ± 0.13	1.65 ± 0.05	22	855 ± 68	42.07	101.36	285
RLS07-12	1789^b	4.6	4.1	1.77	3.9	0.7	1.95 ± 0.13	1.71 ± 0.04	25	874 ± 67	42.07	101.36	285
RLS07-13	1790^b	3.0	5.3	1.75	4.2	0.7	1.96 ± 0.13	1.73 ± 0.03	21	884 ± 66	42.07	101.36	285
RLS07-14	2039^b	4.6	3.6	1.93	3.8	0.8	2.11 ± 0.09	1.79 ± 0.03	25	848 ± 46	42.07	101.36	285
RLS07-15	2040^b	3.0	3.9	1.96	3.8	0.9	2.14 ± 0.09	1.75 ± 0.04	26	818 ± 46	42.07	101.36	285
RLS07-16	2041^b	4.6	4.1	2.07	4.6	1.1	2.32 ± 0.09	1.81 ± 0.04	27	777 ± 43	42.07	101.36	285
Briefcase Wayside													
00RJG10	60^a	2.0	7.6	1.57	4.5	0.7	1.82 ± 0.09	1.67 ± 0.07	20	917 ± 62	42.39	101.03	284
Schmidt Ranch													
SR08-1	2035^b	1.0	4.1	1.91	4.0	1.0	2.21 ± 0.09	1.24 ± 0.04	24	561 ± 33	41.69	101.71	288
SR08-2	2036^b	3.8	4.0	2.12	3.4	0.8	2.24 ± 0.09	29.1 ± 0.44	28	12,900 ± 685	41.69	101.71	288
Hwy 91													
OJS02-22	487^a	1.5	2.3	1.89	4.6	0.7	2.21 ± 0.09	1.67 ± 0.05	20	756 ± 42	42.24	101.03	297
OJS02-21	571^a	3.0	3.2	1.87	4.4	0.7	2.12 ± 0.08	1.63 ± 0.03	20	770 ± 42	42.24	101.03	297
OJS02-20	486^a	4.0	3.0	1.93	4.8	0.8	2.20 ± 0.09	1.59 ± 0.04	20	719 ± 42	42.24	101.03	297

(continued)

Table 1. (Continued)

Field Sample #	UNL Sample #	Depth (m)	In situ moisture content (%)	K_2O (%)	Th (ppm)	U (ppm)	D_{total} (Gya-1 × 10^3)	D_e (Gy ± 1σ)	Aliquots (*n*)	Age (a ± 1σ)	Latitude	Longitude	Distance SE (km)
Goeke Ranch													
G08-1	2031[b]	1.0	6.0	1.97	3.9	0.9	2.49 ± 0.10	1.75 ± 0.04	25	702 ± 40	41.87	101.25	310
G08-2	2032[b]	3.8	5.7	2.06	4.0	1.0	2.23 ± 0.09	1.85 ± 0.04	26	832 ± 46	41.87	101.25	310
Peterson Ranch													
PR08-1	2033[b]	1.0	1.3	1.77	3.9	0.8	2.13 ± 0.09	1.61 ± 0.03	20	756 ± 41	42.03	100.96	319
PR08-2	2034[b]	3.8	4.4	1.75	3.8	0.9	1.97 ± 0.08	1.67 ± 0.03	26	850 ± 47	42.03	100.96	319
GP-04-7													
GP-04-7	1115[a]	1.5	7.4	1.71	4.4	0.9	1.97 ± 0.08	1.58 ± 0.02	20	798 ± 42	42.77	100.06	330
GP-04	1118[a]	7.2	3.5	1.86	4.1	0.8	2.04 ± 0.08	1.51 ± 0.04	20	744 ± 42	42.77	100.06	330
Johnson Ranch													
GP-04-8	970[a]	1.4	2.5	1.77	3.4	0.6	2.02 ± 0.08	1.57 ± 0.04	20	784 ± 45	42.70	100.08	334
Gp-04-8	973[a]	4.4	4.1	1.89	4.5	0.7	2.09 ± 0.08	1.65 ± 0.04	20	790 ± 44	42.70	100.08	334
GP-04-8 6.7–6.8 m	975[a]	6.8	3.6	1.73	2.6	0.6	1.78 ± 0.07	1.48 ± 0.04	20	831 ± 49	42.70	100.08	334
Southeast of Brownlee													
BL08-1	2037[b]	1.0	1.6	1.72	3.5	0.8	2.05 ± 0.08	1.45 ± 0.03	26	707 ± 39	42.13	100.54	345
BL08-2	2038[b]	3.8	3.4	1.75	4.3	0.9	2.03 ± 0.08	1.59 ± 0.03	28	786 ± 42	42.13	100.54	345
Nebraska National Forest													
GP06-4	1657[b]	0.7	3.2	1.58	3.1	0.6	1.82 ± 0.12	1.17 ± 0.04	26	640 ± 51	41.90	100.47	369
GP06-4	1660[b]	6.8	2.0	1.47	2.8	0.6	1.62 ± 0.06	1.32 ± 0.05	27	813 ± 51	41.90	100.47	369
GP06-4	1659[b]	9.4	1.9	1.71	3.7	0.6	1.86 ± 0.07	3.21 ± 0.06	28	1,730 ± 88	41.90	100.47	369
GP06-4	1658[b]	10.1	1.5	1.60	3.3	0.5	1.73 ± 0.12	4.05 ± 0.12	22	2,350 ± 192	41.90	100.47	369
GP06-6	1601[b]	0.7	3.6	1.51	3.2	0.6	1.77 ± 0.11	1.22 ± 0.02	20	691 ± 50	41.90	100.47	369
GP06-6	2341[b]	3.2	2.4	1.78	3.3	0.8	2.00 ± 0.07	1.18 ± 0.02	27	590 ± 30	41.90	100.47	369
GP06-6	2342[b]	3.7	3.0	1.77	3.2	0.8	1.96 ± 0.07	1.30 ± 0.05	26	663 ± 40	41.90	100.47	369
GP06-6	2343[b]	6.4	0.3	1.77	3.3	0.8	2.00 ± 0.07	1.30 ± 0.05	24	653 ± 39	41.90	100.47	369
GP06-6	1602[b]	7.0	3.1	1.42	3.4	0.7	1.63 ± 0.11	1.41 ± 0.04	23	865 ± 69	41.90	100.47	369
GP06-6	1656[b]	10.0	2.9	1.63	3.1	0.7	1.75 ± 0.12	4.98 ± 0.10	23	2,840 ± 221	41.90	100.47	369
GP06-6	1603[b]	13.0	3.2	1.60	3.7	0.7	1.75 ± 0.12	7.20 ± 0.10	21	4,120 ± 314	41.90	100.47	369
GP06-5	1661[b]	0.7	4.7	1.69	3.5	0.7	1.93 ± 0.12	1.18 ± 0.02	23	613 ± 45	41.90	100.47	369
GP06-5	1662[b]	9.9	5.6	1.55	3.7	0.7	1.68 ± 0.11	1.17 ± 0.01	28	698 ± 53	41.90	100.47	369
GP06-3	1604[b]	0.8	4.2	1.61	3.5	0.7	1.88 ± 0.12	1.27 ± 0.02	23	679 ± 50	41.90	100.47	369
GP06-3	1605[b]	6.6	4.4	1.66	4.0	0.8	1.86 ± 0.12	1.37 ± 0.04	20	736 ± 59	41.90	100.47	369
GP06-3	1606[b]	10.0	6.9	1.64	4.4	0.8	1.79 ± 0.12	30.8 ± 0.46	24	17,300 ± 1300	41.90	100.47	369
Collier Ranch													
OJS03-6	645[a]	7.0	3.9	1.69	3.9	0.8	1.89 ± 0.08	1.22 ± 0.03	20	646 ± 37	41.78	100.31	392

(continued)

Table 1. (Continued)

Field Sample #	UNL Sample #	Depth (m)	In situ moisture content (%)	K_2O (%)	Th (ppm)	U (ppm)	D_{total} (Gya-1 × 10^3)	D_e (Gy ± 1σ)	Aliquots (*n*)	Age (a ± 1σ)	Latitude	Longitude	Distance SE (km)
Diamond Bar Ranch													
Core 14-A-04 3.8′	929[a]	1.2	1.0	1.86	4.3	0.8	2.23 ± 0.08	1.33 ± 0.02	20	597 ± 31	41.53	100.50	397
Core 14-A-04 26.8′	930[a]	8.2	3.8	1.83	3.4	0.7	1.94 ± 0.08	1.44 ± 0.04	20	748 ± 44	41.53	100.50	397
14-A-04 8.6′–9.0′	1216[a]	2.7	0.4	1.60	2.8	0.7	1.76 ± 0.07	1.31 ± 0.04	20	741 ± 43	41.53	100.50	397
14-A-04 16.4′–16.9′	1217[a]	5.1	0.4	1.71	3.3	0.7	1.84 ± 0.07	1.33 ± 0.03	20	724 ± 42	41.53	100.50	397
Hansen Ranch													
Core 13A-A-04 4.5′	927[a]	1.4	6.8	2.01	5.2	0.9	2.28 ± 0.09	1.45 ± 0.05	20	634 ± 39	41.26	100.78	398
13-A-04 5.3′-5.7′	1218[a]	1.7	0.6	1.86	4.7	0.9	2.16 ± 0.08	1.36 ± 0.03	20	629 ± 34	41.26	100.78	398
GP-04-06													
GP-04-6	1122[a]	6.0	5.1	1.82	3.7	0.7	1.93 ± 0.08	1.31 ± 0.05	20	678 ± 44	41.66	100.36	398
Wauneta Roadcut – Loess													
WRT50	468[a]	0.5	4.7	2.43	13.8	2.4	3.62 ± 0.15	1.82 ± 0.03	20	503 ± 29	40.51	101.48	404
WRT63	469[a]	0.6	6.2	2.49	11.8	2.4	3.47 ± 0.14	2.36 ± 0.04	20	682 ± 39 4	0.51	101.48	404
Barta Brothers Ranch													
GP03-SH2-1.85	748[a]	1.9	3.8	1.64	3.5	0.7	1.89 ± 0.08	1.30 ± 0.05	20	686 ± 45	42.24	99.65	406
GP03-SH2-2.15	750[a]	2.2	6.7	1.76	3.8	0.7	1.93 ± 0.08	1.29 ± 0.04	20	667 ± 41	42.24	99.65	406
GP03-SH2-4.2	779[a]	4.2	3.4	2.11	4.5	0.8	2.31 ± 0.09	1.29 ± 0.03	20	558 ± 32	42.24	99.65	406
GP03-SH2-4.7	781[a]	4.7	4.2	2.04	5.4	0.9	2.31 ± 0.09	1.39 ± 0.05	20	602 ± 38	42.24	99.65	406
GP03-SH2-6.4	765[a]	6.4	4.3	2.05	8.3	1.1	2.54 ± 0.11	1.25 ± 0.03	20	493 ± 28	42.24	99.65	406
Moran Canyon – Loess													
PRH5G01C-1	529[a]	0.2	6.0	2.69	13.6	2.3	3.74 ± 0.16	2.28 ± 0.09	20	610 ± 40	40.99	100.53	440
Logan Roadcut – Loess													
LR-3	428[a]	0.3	6.5	2.53	12.0	2.6	3.55 ± 0.15	2.17 ± 0.03	20	610 ± 35	41.42	100.02	444
Calamus Reservoir													
OJS02-36	569[a]	2.0	2.8	1.83	4.0	0.6	2.07 ± 0.08	1.23 ± 0.03	20	595 ± 34	41.86	99.27	467
GP03-SH4-1.65	757[a]	1.6	3.4	2.02	5.1	0.8	2.34 ± 0.09	1.13 ± 0.02	20	483 ± 26	41.85	99.21	473
GP03-SH4-1.85	758[a]	1.9	3.8	2.01	5.2	0.8	2.32 ± 0.09	1.16 ± 0.02	20	502 ± 27	41.85	99.21	
GP03-SH4-4.25	762[a]	4.3	3.9	1.96	5.4	0.8	2.25 ± 0.09	1.33 ± 0.03	20	590 ± 33	41.85	99.21	473

a. Designates samples previously collected and dated by Goble et al. (2004), Mason et al. (2004), Miao et al. (2007), Goble and Mason (2007), and Goble et al. (2008) and re-dated for this study.
b. Designates samples collected and dated in this study only.

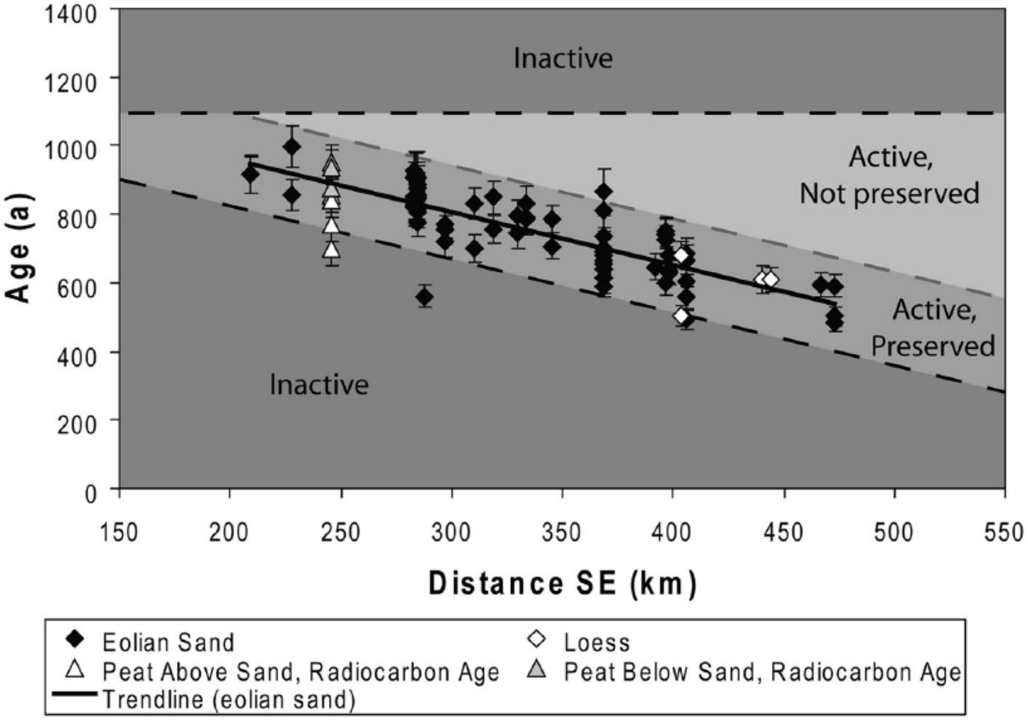


Figure 4. Spatial distribution of optically stimulated luminescence eolian sand (black diamond) and loess (white diamond) ages and radiocarbon ages (triangle) from the Nebraska Sand Hills from the last reactivation of the dunes, during the Medieval Climatic Anomaly. Dashed lines on either side of the majority of the optical dates were calculated as 2-sigma errors. Areas of dark shading indicate times of relatively high precipitation and vegetated dunes for the given area across the Sand Hills. The area of lighter shading indicates a time of drought and lower precipitation, where eolian sand was freely migrating across the given area in the Sand Hills. The area of lighter shading below the dashed gray line represents the time period of the last drought that is preserved in eolian sand and loess sediments, while that above the dashed gray line represents the time period that is not preserved because of reworking.

reactivation of the dunes, the dominant winds were out of the northwest and southwest (Schmeisser et al., 2010; Sridhar et al., 2006). The MCA optical dates from the Sand Hills thus decrease in age downwind. While the majority of the dates used in this study came from eolian sand, loess ages generally agree with this trend in decreasing age to the southeast (Figure 4). In addition, radiocarbon ages from wetlands in the Nebraska Sand Hills are consistent with this trend (Loope and Swinehart, 2000; Mason et al., 2004; Figure 4).

Because the optical dates from the Sand Hills are from sand deposited and preserved during periods of sediment mobility, the spatial trend in ages can be used to calculate the timing of activity across the region (Figure 4). In addition, the range of dates from one locality can provide a minimum estimate of the duration of dune mobility. Sediment deposited in the early stages of activity has low potential to be preserved rather than reworked by later activity, and with a finite number of samples per site, the oldest sand in the dune may not be sampled. The most complete record is best obtained from sites with the most data. Dates from eolian sand at the Diamond Bar Ranch (397 km to the SE; Figure 3, #14) and the Barta Brothers Ranch (406 km to the SE; Figure 3, #18) point to a minimum duration of activity of 151 ± 71 and 193 ± 79 years, respectively. At the Gudmundsen Sand Hills Laboratory (285 km to the SE; Figure 3, #3), 16 dates from eolian sand indicate that dunes were active in this area for a minimum of 149 ± 39 years. At the Nebraska National Forest (369 km to the SE; Figure 3, #12), 275 ± 83 years of activity are recorded from 11 dates from eolian sand. The mean duration of *preserved* activity during the MCA at these four sites is 192 ± 59 years.

Linear dunes in the Nebraska Sand Hills

Linear dunes are present across a wide area of the Nebraska Sand Hills, and they vary spatially in size and composition. Linear dunes in the northwestern part of the Sand Hills are smaller (about 6–9 m tall and a few hundred meters in length) and are superimposed on the sides of large megadunes. These linear dunes are oriented roughly NW-SE. Linear dunes in the southeastern part of the Sand Hills are much larger (12–15 m high and several kilometers in length) and are oriented roughly WNW-ESE (Swinehart, 1998). Paleowinds for the region were bimodal, with subequal northwesterly and southwesterly winds (Schmeisser et al., 2010; Sridhar et al., 2006). The paleowinds also indicate elongation of the dunes to the southeast, roughly concurrent with the resultant drift direction. Our OSL data show that linear dunes across the Sand Hills young to the southeast.

The linear dunes in the northwestern part of the Sand Hills were formed during the MCA, as evidenced by OSL dating. Paleosols, representing times of stability in the dune field, were encountered at several localities. Two samples were collected from the paleosol in the dune cut by 'Yao's Blowout', giving ages of 2320 ± 177 and 2010 ± 154 years before present (Table 1). All other samples gathered from linear dunes in this region were taken in eolian sand, representing times when the dunes were mobile. These samples gave ages consistent with the timing of the MCA (Table 1). As discussed in the previous section, older dates for this reactivation are present to the northwest. The linear dunes to the northwest were active from approximately 1000–800 years ago (Table 1 – see superimposed dunes at Gudmundsen Sand Hills Laboratory). In the majority of the sections, the optical ages decrease with elevation in the dune, but two sections in one dune show reversed ages, with older ages above younger. This could be because of analytical errors associated with determination of the dose rate, although it is unlikely as the highest dose rates are associated with the oldest ages. Another more likely explanation is bioturbation of the sediments by burrowing rodents. Pocket gophers are common throughout the Sand Hills. Their burrows are also common in older sediments, including those that are attributed to the MCA (Schmeisser et al., 2009). Bioturbation has been found to significantly affect the optical age of sediments (Bateman et al., 2007).

The linear dunes in the southeastern part of the Sand Hills were active during the MCA, but are built up around an older core of sediments (Figure 5). Pleistocene dune sediments were dated below a linear dune in the Nebraska National Forest (Mason et al., 2011). All samples gathered in this area were taken in eolian sand, representing

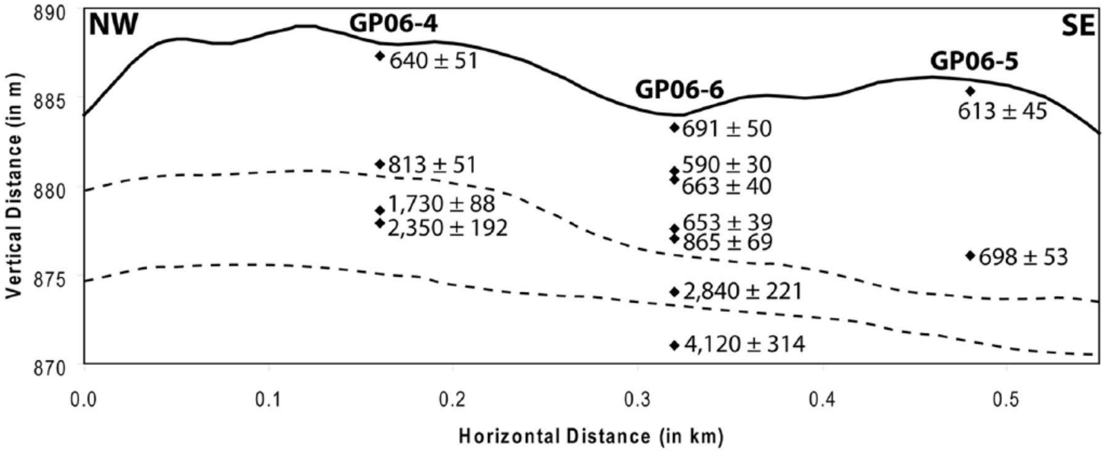


Figure 5. Cross-section parallel to dune crest orientation through a large linear dune in the southeastern part of the Nebraska Sand Hills, in the Nebraska National Forest. Black line is a topographic profile of the linear dune; black diamonds represent sampling localities with optical dating ages and errors provided. Dashed lines separate three periods of reactivation that are recognized within the dune, the oldest centered at 3.8 ± 0.3 ka (as recognized by Miao et al., 2007), the middle centered at 2.5 ± 0.1 ka (as recognized by Miao et al., 2007), and the youngest which took place during the Medieval Climatic Anomaly.

times of activity. The samples that were highest in the dune gave ages consistent with the MCA, although as previously discussed, these ages are younger than those to the northwest. Dates from the MCA range from approximately 850– 600 years ago in this area (Table 1 – see Nebraska National Forest). In two of the sections, ages young upward, although in one section the ages are reversed. As discussed above, this is likely because of bioturbation of the sediments and not analytical errors as the dose rates are highest in the lowest samples. Sediments accumulated vertically at a minimum rate of 2.29 ± 0.63 to 3.53 ± 1.47 cm/yr. These are minimum accumulation rates because other sections have ages that are statistically indistinguishable throughout the depth of the sampling hole. Older ages are present at greater depths (> about 10 m) within the dunes in the southeast (Figure 3; Table 1). These ages represent episodes of sand movement that have been recognized by previous workers in the Sand Hills (Miao et al., 2007). Two samples correspond to a peak of eolian activity centered at around 2.5 ± 0.1 ka (Miao et al., 2007). Another sample corresponds to an earlier peak of eolian activity centered at around 3.8 ± 0.3 ka (Miao et al., 2007). Even older (late Pleistocene) sediments have been recognized in the centers of large megadunes in the Sand Hills (Mason et al., 2011).

Discussion

The 150–200 years of activity that are represented by ages from any given locality (Figure 4) are unlikely to record the entire time of local dune mobilization. The time required to turn over sand stored in a particular segment of a linear dune and reexpose it to light cannot be estimated without knowing rates of sand transport and the extent to which these dunes migrated, downwind and potentially laterally. However, we hypothesize that 150–200 years may be enough time for much of the dune sand to turn over, leaving only a patchy core of older sand as we found at the Nebraska National Forest site. If so, the ages at each locality record only the last 150–200 years of activity there. Furthermore, this interpretation implies that the spatial trend in ages from the MCA is not necessarily reflective of an offset in the timing of activity, beginning and ending later in the southeast. In fact, we believe it is more likely that the removal of vegetation from the dunes likely occurred during a relatively consistent time frame across the Sand Hills early in the MCA (~1100 years ago), in response to droughts that affected much of western North America. We cannot rule out the possibility that initial dune mobilization was not contemporaneous across the dune field. Older eolian landforms are more resistant to activation as they retain moisture within fine sediments that accumulate as soil formation takes place (Werner et al., 2011). If some dunes had been stable longer than others at the start of the MCA, it could have taken longer for them to be activated.

Regardless of the spatial and temporal pattern of reactivation across the Sand Hills, if we assume the youngest ages at each locality accurately record the final phase of activity there, the trend in decreasing ages to the southeast is representative of a trend in the timing of revegetation and stabilization of the dunes (Figure 4).

The ages suggest that vegetation returned to dunes in the northwest first, stabilizing them. At the same time, dunes to the southeast remained active and mobile. Gradually, vegetation spread to the southeast, stabilizing the dunes and preventing further movement. The trendline slope of 0.43 km/yr (Figure 4; trendline) approximates the overall rate at which the stabilized area expanded southeastward, although the actual pattern of stabilization may have been much more complex in detail. Eventually, the entire dune field was stabilized and inactive, with a protective cover of vegetation (Figure 4).

The results given in this paper do not support the hypothesis proposed by Goble et al. (2008) that two separate drought episodes occurred during the MCA. Instead, these results are consistent with the alternate hypothesis suggested by Goble and Mason (2007) and Goble et al. (2008) that a single episode of drought occurred during the MCA, with dunes to the northwest stabilizing before those to the southeast.

The most likely explanation for the spatial trend in the restabilization of the Sand Hills relates to the depth of the water table. Interdunes in the Sand Hills vary in soil moisture conditions; some have surface soils that are dry and well above the water table, while others have a shallow water table and wet soils or even contain lakes year-round. Most of the interdune lakes are present in the northwestern part of the Sand Hills, where wet interdunes are more common and are often maintained by local groundwater flow systems (Mason et al., 2004). Sediments below these wet interdunes contain layers of peat mixed with sand layers that range from <1 to 3 m in thickness (Loope and Swinehart, 2000; Mason et al., 2004; Nicholson and Swinehart, 2005). These sand layers represent extension of the dune sands across the interdunes during times of drought, when the water table dropped and eolian sand migrated across the interdune. The last period of dune sand extension across the interdunes was 650–950 cal. BP, during the MCA, as determined by radiocarbon dating of plant macrofossils (Mason et al., 2004).

This observation provides crucial evidence that dune activation during the MCA was associated with hydrological drought.

Most vegetation on the dunes is shallow-rooted, and is far above the water table, so lowering of the water table did not directly affect dune vegetation. In the northwest, however, it seems likely that parts of the presently wet interdune areas would have remained vegetated because the water table was still shallow enough to influence soil moisture. These areas could have served as refugia for many upland plant species during droughts and, as the climate ameliorated, as a source of seeds for revegetation of the adjacent dunes (Harvey et al., 2007; Nicholson and Swinehart, 2005). Wetlands are not extensive between the dunes in the southeastern Sand Hills because there is a better integrated drainage network there and rivers have become incised onto the land surface, lowering the water table over large areas. In that region, vegetation colonization of the dunes could have required longer distance dispersal, and therefore proceeded more slowly, although eventually the entire dune field was stabilized once again.

The Mu Us dune field of northern China provides a modern analogue supporting this hypothesis (Xu et al., 2015). In this rapidly stabilizing dune field, vegetative cover is presently greater and is increasing more rapidly in areas of lower elevation, probably because the water table is shallower there and vegetation has expanded from wet interdunes. Vegetation appears to expand from existing patches, rather than forming isolated new patches, supporting the idea that processes such as seed dispersal and/or expansion by rhizomes limit the rate of stabilization.

Although drought during the MCA is well-documented (Cook et al., 2004), changing moisture conditions may not have been the only factor causing activation and stabilization of the Sand Hills. Wind strength plays a large part in the transition of a dune field from stable to active or vice versa (Tsoar, 2005). Windiness is given as the average percentage of days with winds above the threshold velocity for sand movement (Tsoar, 2005). Increasing windiness above a certain point (see Tsoar, 2005: Figure 3) leads to a decrease in the vegetative cover. When wind power is lowered, vegetation can encroach upon dune fields at much higher wind strengths than are present under areas of increasing wind power. In other words, vegetation can return to a region more easily than it is lost (Tsoar, 2005). In the Sand Hills, it is possible that a drop in wind power from one direction may have allowed vegetation to return to the area. Dune-forming paleowinds across the Great Plains during the MCA were subequal in strength and came out of the northwest and the southwest (Schmeisser et al., 2010; Sridhar et al., 2006). Modern winds are dominated by winds out of the northwest with a smaller component of winds out of the south to southeast (Schmeisser et al., 2010). Relative increase in the northwesterly and southerly winds and decrease in the southwesterly winds (and the accompanying increase in precipitation) may have allowed vegetation to return to the Sand Hills dunes after megadroughts. It is difficult to explain how a change in wind regime would not affect all of the Sand Hills at the same time, so the pattern of revegetation described in this paper is not easily explained by this process.

Conclusion

Optical dating has proven to be an extremely useful tool for deciphering the timing of dune building in the Nebraska Sand Hills. In this study, we determined the timing of dune mobility during the MCA, the most recent megadrought clearly recorded across much of the Great Plains. According to our results, dune activation associated with the MCA extended from ~1100 to 500 years ago in the Sand Hills. The timing of the MCA varies spatially across the Nebraska Sand Hills, parallel to the resultant of the paleowinds. The oldest ages associated with this drought come from dunes to the northwest while the youngest come from dunes to the southeast. The spatial trend in ages is a reflection of the pattern of the return of vegetation to the dunes at the end of the drought. Dunes in the northwestern Sand Hills were revegetated first, likely because of the persistence of upland plants in interdune refugia in that area, where the water table is presently higher and near the land surface in most interdunes. Dunes to the southeast took longer to revegetate because refugia with surviving upland plants were more distant from the dunes.

This work has also established that the timing of linear dune mobility varies spatially across the Nebraska Sand Hills. Linear dunes in the northwestern Sand Hills are smaller, and we did not find evidence that they were active before the MCA, so they may have originated then. Linear dunes in the southeastern part of the Nebraska Sand Hills are larger and have been active during several periods; three are recognized in this study alone. The most recent reactivation of these dunes occurred during the MCA, throughout which a large amount of eolian sand was deposited. At this time, the dunes built up around older cores of dunes that formed during earlier reactivations thousands of years prior. Some reworking must have occurred during each reactivation, but not enough to entirely remove the sediments that built up during the previous reactivation.

The response of dune fields around the globe to current and future climate change has been the focus of much attention recently (Ashkenazy et al., 2011; Bristow et al., 2011; Wang et al., 2009; Wolfe and Hugenholtz, 2009). Future reactivations of dune fields in the Great Plains would present a great challenge to human populations. While this paper has mainly discussed droughts lasting a decade or longer, other less severe droughts (such as the 1930s Dust Bowl) have also resulted in some minor reactivation of the dunes (Ahlbrandt et al., 1983; Muhs and Holliday, 1995). Therefore, it seems that the dunes in the Great Plains, including the Nebraska Sand Hills, are extremely sensitive to changes in climate. Recent modeling studies (Christensen et al., 2007; Feng et al., 2014) have shown that temperatures will rise substantially across the Great Plains over the next century. As temperatures rise, summer precipitation across the region will also decrease, thereby increasing the likelihood of drought over the area during the growing season. Such droughts would be the key requirements for any future reactivation of the dunes. Former droughts on the Great Plains, including the MCA, have had drastic impacts on the landscape, including increased channel incision (Daniels and Knox, 2005), lowering of the water table (Schmieder et al., 2011), and reactivation of the dunes. Careful management of water resources is critical to maintain the stable state of the dunes in the Sand Hills.

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