A 10,000 year record of dune activity, dust storms, and severe drought in the central Great Plains

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ABSTRACT

Dune fields and loess deposits of the Great Plains of North America contain stratigraphic records of eolian activity that can be used to extend the short observational record of drought. We present a 10,000 yr reconstruction of dune activity and dust production in the central Great Plains region, based on 95 optically stimulated luminescence ages. The integration of data from both eolian sand and loess is an important new aspect of this record. Clusters of ages define episodes of extensive eolian activity, which we interpret as a response to frequent severe drought, at 1.0–0.7 ka and 2.3–4.5 ka (with peaks centered on 2.5 and 3.8 ka); sustained eolian activity occurred from 9.6 to 6.5 ka. Parts of this record may be consistent with hypotheses linking Holocene drought to sea surface temperature anomalies in the Pacific or Atlantic oceans, or to the El Niño-Southern Oscillation phenomenon, but the record as a whole is difficult to reconcile with any of these hypotheses.

Keywords: drought, eolian sand, loess, OSL dating, Great Plains, Holocene, Medieval Climate Anomaly.

INTRODUCTION

Droughts of the 1930s and 1950s had severe economic and environmental consequences across central North America, although their most visible impacts were dust storms on the Great Plains (Worster, 1979). Paleoclimatic data extracted from tree rings and lake sediments provide evidence for Holocene droughts much more severe than any in the historical period (Laird et al., 1996; Woodhouse and Overpeck, 1998; Fritz et al., 2000). Given the potential impact of similar dry periods in the future, a better understanding of the timing and causal mechanisms of Holocene drought is an important goal of paleoclimatic research.

Here we present a new 10,000 yr geologic record of dune activity and dust transport in the central Great Plains that is much more continuous and better-dated than any previously available data. Our results combine data from both eolian sand and loess sections, and indicate multiple well-defined intervals of extensive eolian activity, which we interpret as times of reduced effective moisture (precipitation minus evapotranspiration), more extreme and/or longer lasting than historical droughts.

The extensive dune fields of the central Great Plains are largely stabilized by grassland or shrub steppe vegetation today. Great Plains winds are frequently strong enough to mobilize sparsely vegetated dune sand; thus, vegetation cover is the key limitation on dune mobility, and vegetation density is in turn strongly affected by effective moisture (Muhs and Maat, 1993). Most of the limited dune activity observed today occurs in the southwestern Great Plains where effective moisture is lowest (Muhs and Maat, 1993; Muhs and Holliday, 1995). A significant exception occurs in the Canadian prairies, where dunes may still be recovering from severe drought in the late 1700s (Hugenholtz and Wolfe, 2005). Elsewhere in the Great Plains, however, dunes were activated by a few years of drought in recent times, and recovered within decades (Muhs and Maat, 1993), indicating rapid response to changing effective moisture. Dune activity is certainly affected at limited spatial or temporal scales by grazing, wildfire, or other disturbance, but it is unlikely that such nonclimatic mechanisms can explain centuries to millennia of persistent activity, recorded over hundreds of square kilometers.

A late Holocene example provides evidence of a strong relationship between eolian activity and drought. Dune activation between 650 and 950 yr ago in Nebraska was approximately synchronous with local hydrological drought, manifested by water table decline (Mason et al., 2004), and was associated with replacement of a moist southerly winds by dry southwesterly winds (Sridhar et al., 2006). Tree-ring-based drought reconstructions indicate frequent widespread drought across western North America at about the same time, from A.D. 900 to 1300 during the Medieval Climatic Anomaly (MCA; Cook et al., 2004), and a variety of other evidence indicates dry conditions in the Great Plains 800–1000 yr ago (Daniels and Knox, 2005). Dune activity during the MCA is recorded in several Great Plains dune fields (e.g., Madole, 1994; Arbogast, 1996; Holliday, 2001).

The 1930s dust storms are generally attributed to the effects of drought on cultivated soils (e.g., Worster, 1979), but Great Plains loess stratigraphy indicates extensive dust transport predating widespread agriculture. Loess deposits can record changing effective moisture in regions like the central Great Plains, where Holocene loess is thickest and coarsest immediately downwind of dune fields (Mason et al., 2003). Much of this proximal Holocene loess was probably last entrained by the wind within the dune fields, through "sand-blasting" of fine-grained material by saltating sand grains, and high rates of dust emission would have required active dune fields (Mason et al., 2003; Miao et al., 2005). Thus, episodes of rapid loess accumulation should reflect extensive climatically driven dune activation. In contrast, dune field sections often contain large unconformities, because dune migration requires both erosion and deposition (Muhs and Zárate, 2001). Also, the loess sections that we studied contain multiple depositional units of light-colored loess, representing more rapid accumulation, separated by buried soils that formed when dust influx was slower. This provides clear independent evidence of well-defined episodes of eolian activity.

Because of the broad interest in causal mechanisms of central North American drought, we investigated whether our eolian sediment record is consistent with hypotheses on the causes of major dry periods during the Holocene. Recent work on this issue has emphasized observed relationships between decadal-scale historical drought, sea surface temperature (SST) anomalies, and the El Niño–Southern Oscillation (ENSO). The 1930s "Dust Bowl" drought coincided with anomalously cool SST in the eastern tropical Pacific (ETP) and warm SST in the tropical and northern Atlantic (Schubert et al., 2004). During widespread Northern Hemisphere drought in 1998–2002, SST was anomalously cool in the ETP and warm in the western tropical

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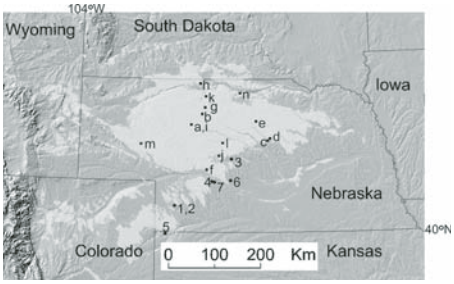

Figure 1. Loess (circles with numbers) and eolian sand (rectangles with letters) study sites. Light-colored areas are the Nebraska Sand Hills and other smaller dune fields. Loess sites: 1—Old Wauneta Roadcut, 2—New Wauneta Roadcut, 3—Logan, 4—Moran Canyon, 5—Mills, 6—County Line Ranch, 7—Bignell Hill. Eolian sand sites: a—Gudmundsen Ranch, b—HWY 97 MP81 linear dune transect 3, c—Calamus, d—Calamus GP03-SH4, e—Barta Brothers, f—Hanson Ranch, g—Briefcase Wayside, h—Kroeger, i—Yao's blowout, j—Diamond Bar Ranch, k—Merritt Reservoir, l—Collier Ranch, m—Crescent Lake, n—Johnson Ranch.

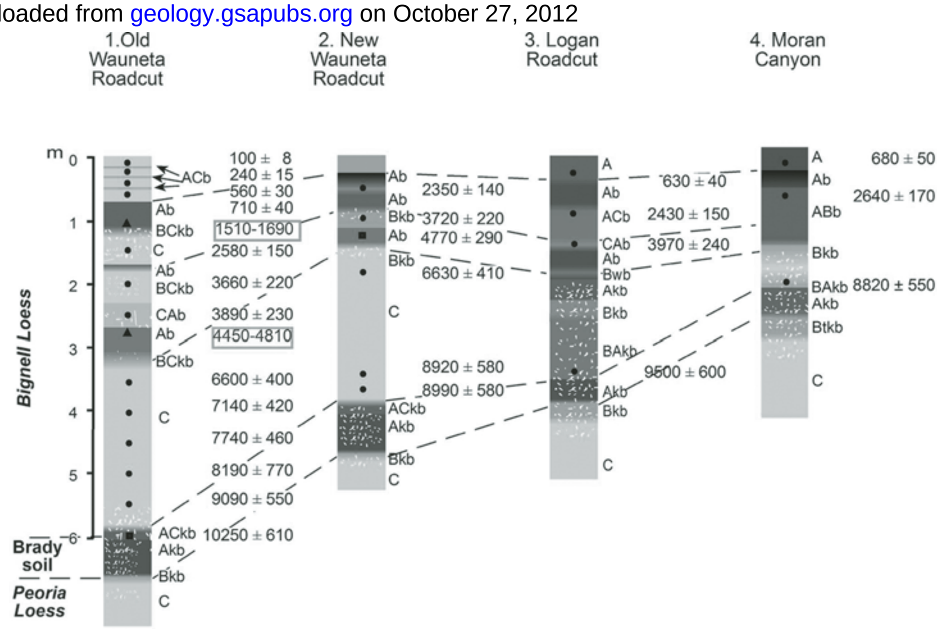

Figure 2. Stratigraphy and geochronology of four Bignell Loess sections in Nebraska (locations in Figure 1), showing optically stimulated luminescence ages from loess (circles) and paleosols (rectangles). Triangles in Old Wauneta Roadcut column are radiocarbon ages, with 95% C.I. in cal yr B.P. given in box at right of column. Lower age is on humic acid extracted from paleosol organic matter in roadcut; upper age is on charcoal from nearby core and correlated by soil stratigraphy. White spots in the column signify carbonates. Letters to the right of the column are soil horizon designations. Logan Roadcut section is 20 m west of Logan Core reported in Miao et al., 2005, and all ages can be found in the GSA Data Repository[1].

Pacific (WTP) and Indian Ocean (Hoerling and Kumar, 2003). Both studies indicate, by modeling, that tropical SST anomalies generate mid-latitude circulation patterns with high-pressure anomalies over drought-affected regions, though soil moisture feedbacks may amplify these teleconnections (Schubert et al., 2004). Similar hypotheses link drought in the central United States with La Niña conditions (Trenberth and Guillemot, 1996), while McCabe et al. (2004) found that historical drought frequency in North America is high with a warm North Atlantic.

It has been proposed that similar relationships between drought, SST anomalies, and ENSO also apply at millennial timescales. For example, Holocene episodes of frequent or long-lasting drought have been attributed to persistent "La Niña–like" conditions (Forman et al., 2001; Cook et al., 2004). Our new data set, along with other paleoclimatic records, can be used to evaluate such hypotheses, although potential complications related to dating resolution and lags in eolian system response must be taken into account.

STUDY SITES AND METHODS

We sampled 7 stratigraphic sections in thick Holocene loess, and 14 in dune fields, (Fig. 1) for optically stimulated luminescence (OSL) dating, using 90–125 μm quartz grains under the Single Aliquot Regenerative protocol (Murray and Wintle, 2000). The OSL ages represent the time since quartz grains were buried after light exposure during wind transport. The dune field OSL ages were obtained from eolian sand, often displaying sedimentary structures indicative of wind transport, in cores or exposures in dunes of the Nebraska Sand Hills, North America's largest dune field. Previous work indicates that OSL ages from the Sand Hills are consistent with radiocarbon dating (Stokes and Swinehart, 1997; Goble et al., 2004; Mason et al., 2004).

The loess ages are from sections immediately downwind of the Sand Hills or other dune fields (Fig. 1), where Holocene Bignell Loess is distinguished from underlying late Pleistocene Peoria Loess by the prominent Brady Soil (Mason et al., 2003). Samples were taken from light-colored loess, rather than paleosols. Because of the extraordinary 6-m thickness of Bignell Loess at Old Wauneta Roadcut, we obtained 13 OSL and 2 radiocarbon ages there (Fig. 2). Other Bignell Loess sections demonstrate broadly consistent loess-soil stratigraphy.

RESULTS AND DISCUSSION

The dune field and loess records are in excellent agreement, supporting the interpretation that both represent landscape response to the same regional episodes of dry climate (Mason et al., 2003; Miao et al., 2005; Fig. 3A). This suggests that similar integration of loess and dune field records holds great potential for reconstructing the history of eolian activity in other drylands.

Using clusters of ages from loess sections, targeted to define dust production peaks, we infer maxima of eolian activity centered on ~0.7, 2.5, and 3.8 ka, with sustained rapid loess accumulation from ~9.4–6.5 ka (Fig. 3A). Where the Holocene loess is thickest (Old Wauneta Roadcut; Fig. 2), it contains discrete depositional units corresponding to all major clusters of ages from other loess and dune field sites, separated by paleosols. Only one loess section (Old Wauneta Roadcut), provides evidence for significant loess deposition after 0.6 ka. Importantly, even considering the ±2σ errors of Holocene ages, there are well-defined gaps between clusters (Fig. 3A), representing periods of minimal dune activity and dust flux; these gaps correspond to paleosols in loess sections (Fig. 2). Dune field ages display more scatter, but most fall within the periods of rapid dust influx defined from loess ages. The dune ages suggest ongoing eolian activity between ~4.5 and 2.3 ka, however, rather than discrete episodes at 2.5 and 3.8 ka. Two dune ages fall between 4.5 and 6.5 ka, during formation of a prominent soil in loess sections (Miao et al., 2005); such limited dune activity may reflect local disturbance rather than regional climate. A multi-proxy record from a Sand Hills interdune wetland closely agrees with the data presented here (Nicholson and Swinehart, 2005).

The last major episode of eolian activity (~1.0–0.7 ka) reinforces the results of Mason et al. (2004) with many additional OSL ages, and strengthens the evidence for synchroneity

[1]GSA Data Repository item 2007034, optically stimulated luminescence dating methods and detailed ages (Table DR1), is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

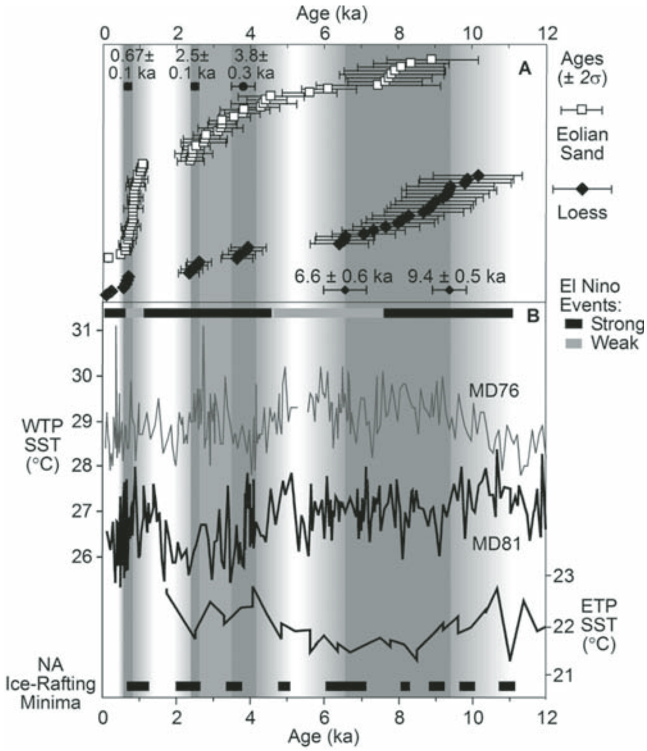

Figure 3. A: Optical ages from loess (bottom, filled diamonds) and eolian sand (top, open rectangles); see Data Repository (see footnote 1) for details. No ages from paleosols are included. Dark gray bands represent intervals of rapid loess deposition. Lighter gray bands with fuzzy boundaries represent broader intervals of dune activity indicated by sand ages. Loess ages from each of three tight clusters younger than 5 ka pass χ^2 test at the 95% confidence level; thus the Combine function in OxCal 3.9 (Ramsey, 2003) was used to calculate $\mu \pm 2\sigma$ ages for each cluster as a whole (values at upper left, with dark gray band width based on $\pm 2\sigma$ interval). Older and younger bounds of sustained early-to-middle Holocene eolian activity were calculated from optically stimulated luminescence ages near top and bottom of corresponding loess increment in each section, which also pass χ^2 tests ($\mu \pm 2\sigma$ values in lower right of panel A; dark gray band marks interval between these bounds). B: Relationship of eolian activity in the central Great Plains (gray bands) to reconstructed El Niño-Southern Oscillation activity (Rein et al., 2005), SSTs of Eastern tropical Pacific (ETP; V21–36: 1°13S, 89°41W; Koutavas et al., 2002), Western tropical Pacific (WTP; MD76: 5°00S, 133°27E; MD81: 6°18S, 125°49W; Stott et al., 2004) and North Atlantic (54°16N, 16°47W; Bond et al., 2001) during the Holocene.

of extensive eolian activity in the central Great Plains with frequent severe droughts of the MCA (Cook et al., 2004). It is likely that this cluster of OSL ages actually spans multiple decadal-scale droughts, as suggested by tree-ring data from surrounding regions. There may well have been lags in eolian system response to such decadal-scale climatic variation, but overall, there is no detectable offset between this cluster of ages and the period of MCA droughts identified by Cook et al. (2004).

We interpret the ages between 4.5 and 2.3 ka as evidence of a similar period of frequent severe drought in our study area. We cannot rule out lagged response of eolian systems to climate, but the example of MCA droughts and dune activity suggests that such a lag lasted no more than a few centuries. The loess ages indicate either two discrete episodes, or at least two maxima of eolian activity centered on 2.5 ka and 3.8 ka.

It is unclear whether frequent drought and/or eolian activity between 4.5 and 2.3 ka extended far beyond our study area. Activity between 4 and 2 ka is recorded in several Great Plains dune fields (Arbogast, 1996; Forman et al., 2001; Holliday, 2001) but existing age control from buried-soil radiocarbon ages is inadequate for more definite correlation. Some lake-sediment records in the northern Great Plains record low lake level or high salinity between 4.5 and 2.3 ka, while others suggest wetter conditions at that time (Fritz et al., 2001). Such contrasting records in part reflect local hydrological controls superimposed on regional climate (Fritz et al., 2000). Our 2.5-ka and 3.8-ka peaks of eolian activity approximately coincide with dry intervals centered on 2.5 and 4.1–4.2 ka, inferred from groundwater-level reconstructions in northern Michigan (Booth et al., 2004). Finally, century-scale fire-drought cycles recorded in a North Dakota lake-sediment core weakened or became shorter at ~4–3.8 ka, 2.6–2.4 ka, and 1.0–0.6 ka (Brown et al., 2005), times of eolian activity peaks in our record; however, a mechanism that would damp the high-frequency cycles during major dry periods is unclear. Evidence for sustained eolian activity from 9.4 to 6.5 ka is consistent with independent evidence of an early to mid-Holocene dry period on the Great Plains (e.g., Baker, 2000; Fritz et al., 2001).

Comparison of our results with recent reconstructions of SST in the tropical Pacific, El Niño, and North Atlantic ice-rafted debris (Fig. 3B) indicates that the eolian record as a whole is difficult to reconcile with drought mechanisms developed from historical observations. Only in the past 2500 yr is it possible to identify temporal relationships consistent with a link between central Great Plains drought and La Niña-like conditions or warm WTP SST. Eolian activity from 1.0 to 0.7 ka occurred during an interval containing many peaks of SST in the WTP (Fig. 3B) and few strong El Niño events (Rein et al. 2005). Furthermore, there is no evidence of eolian activity between 2 and 1.2 ka, a time of lower WTP SST, high ETP SST, and frequent strong El Niño events. These relationships do not become substantially weaker if we assume that the onset or end of eolian activity lags climate change by several hundred years.

On the other hand, eolian activity in our study area from ~2.3–4.5 ka spans centuries of both high and low SST in the ETP and in the WTP (the two WTP records differ in this interval; Fig. 3B). Rein et al. (2005) also suggest strong El Niño activity throughout this interval. We cannot rule out the possibility that dunes were active throughout this period because of slow recovery from brief severe droughts (e.g., Hugenholtz and Wolfe, 2005) during decades of high WTP SST or persistent La Niña conditions. It would then be difficult, however, to explain minimal eolian activity between 6 and 4.5 ka, a time of frequently high WTP SST, low ETP SST, and few strong El Niño events. Persistent eolian activity from 9.4 to 6.6 ka began and ended significantly earlier than the mid-Holocene period of very weak El Niño, and this dry condition can alternatively be explained by direct or indirect effects of high Northern Hemisphere summer insolation (Harrison et al., 2003).

Episodes of rapid loess accumulation at ~0.7, 2.5 and 3.8 ka approximately coincide with ice-rafted debris minima (presumably indicating warm SST) in the North Atlantic (Fig. 3B). Such a correlation is highly sensitive to dating errors and even short lags in eolian system response, however. Many dune field ages actually fall within ice-rafting peaks, and there was little eolian activity during the ice-rafting minimum between 4.3 and 5.9 ka.

There are several possible explanations for these apparent inconsistencies between our record and drought mechanisms identified from historical observations. Multiple mechanisms may be responsible for millennial-scale dry periods of the Holocene, including some not observed in historical times (e.g., high summer insolation). Proxy records of SST or ENSO may be affected by errors in dating or interpretation, and parts of our record may not be representative of the broader Great Plains region. Intensive OSL dating of eolian sediments elsewhere in the Great Plains could test the latter possibility.

CONCLUSIONS

We generated a well-dated, 10,000 yr-long record of episodic dune activity, dust accumulation, and droughts in the central Great Plains. Ages from both eolian sand and loess indicate the well-defined episodes of eolian activity, suggesting that these coupled eolian systems can yield similar high-resolution records elsewhere in the world. Our data suggest the possibility of multiple mechanisms for millennial-scale dry periods in central North America, and the need for more research on spatial patterns of Holocene drought.

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