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P. E. Baldauf

Nova Southeastern University, pb501@nova.edu

P. A. Burkhardt

Slippery Rock University of Pennsylvania, patrick.burkhardt@sru.edu

Paul R. Hanson

University of Nebraska - Lincoln, phanson2@unl.edu

M. Miles

University of Maine, maraina.miles@maine.edu

Ashley Larsen

University of Nebraska - Lincoln, aklarsen@huskers.unl.edu

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Chronology of dune development in the White River Badlands, northern Great Plains, USA

P. E. Baldauf,¹ P. A. Burkhardt,² P. R. Hanson,³
M. Miles,⁴ & A. Larsen³

1 Nova Southeastern University, Department of Marine and Environmental Sciences, Halmos College of Natural Sciences and Oceanography, 3301 College Avenue, Parker 356, Fort Lauderdale, FL 33314, USA

2 Slippery Rock University of Pennsylvania, Department of Geography, Geology and the Environment, Slippery Rock, PA 16057, USA

3 University of Nebraska–Lincoln, Conservation and Survey Division, School of Natural Resources, HARH 904, UNL 68583-0996, USA

4 University of Maine, School of Earth and Climate Sciences, 5790 Bryand Global Sciences Center, Orono, ME 04469-5790, USA

Corresponding author — P. E. Baldauf

E-mail addresses: pb501@nova.edu (P. E. Baldauf), patrick.burkhardt@sru.edu (P. A. Burkhardt), phanson2@unl.edu (P. R. Hanson), maraina.miles@maine.edu (M. Miles), aklarsen@huskers.unl.edu (A. Larsen).

Abstract

Aeolian dune field chronologies provide important information on drought history on the Great Plains. The White River Badlands (WRB) dunes are located approximately 60 km north of the Nebraska Sand Hills (NSH), in the western section of the northern Great Plains. Clifftop dunes, sand sheets, and stabilized northwest-southeast trending parabolic dunes are found on upland mesas and buttes, locally

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called tables. The result of this study is a dune stabilization history determined from samples collected from stratigraphic exposures and dune crests. Thirty-seven OSL ages, from this and previous investigations, show three periods of dune activity: 1) ~21,000 years ago to 12,000 years ago (a), 2) ~9 to 6 ka, and 3) post-700 a. Stratigraphic exposures and low-relief dune forms preserve evidence of late Pleistocene and middle Holocene dune development, while high-relief dune crests preserve evidence of late Holocene dune development. Results of 12 OSL ages from the most recent dune activation event indicate that Medieval Climate Anomaly (MCA) droughts and Little Ice Age (LIA) droughts caused dune reactivation on the tables. Dune reactivation was accompanied by other drought-driven geomorphological responses in the WRB, including fluvial incision of the prairie and formation of sod tables. Regional significance of the MCA and LIA droughts is supported by similarities in the aeolian chronologies of the NSH at 700–600 a and some western Great Plains dune fields at 420–210 a. Aerial photographs of the WRB show little activity during the Dust Bowl droughts of the 1930s.

Keywords: White River Badlands, Northern Great Plains, Nebraska Sand Hills, Medieval Climate Anomaly drought, Little Ice Age drought, Last glacial period

1. Introduction

Aeolian deposits, including dune sands, sand sheets, and loess, preserve a record of climate change, including drought, on the northern and central Great Plains from the late Pleistocene to the modern era (Fig. 1). Much of the aeolian research on the Great Plains has focused on the area's largest dune field, the Nebraska Sand Hills (NSH) (Ahlbrandt and Fryberger, 1980; Forman et al., 2005; Goble et al., 2004; Mason et al., 2004; Mason et al., 2011; Miao et al., 2007b; Muhs and Holliday, 1995; Schmeisser McKean et al., 2015; Sridhar et al., 2006), and the midcontinental, last glacial loess (Peoria Loess), which crops out widely on the Great Plains and Central Lowlands of North America (Bettis et al., 2003; Mason, 2001; Miao et al., 2007a; Muhs et al., 2003; Muhs and Bettis, 2000; Muhs et al., 2008; Muhs et al., 2013; Muhs et al., 2018). Nonetheless, chronologies of aeolian activity in dune fields on the periphery of the NSH and the margins of the Great Plains are necessary to demonstrate the timing and extent of drought in the region (Halfen and Johnson, 2013; Halfen et al., 2016; Hanson et al., 2010).

Multiple climate proxies and dune reactivation chronologies support the interpretation that droughts and megadroughts occurred on the Great Plains in the past 1500 years, associated with the Medieval Climate Anomaly (MCA) and, to a lesser extent, the Little Ice Age (LIA). The MCA is a period of warm global temperatures lasting from approximately 1050 to 750 years ago (a), which has been correlated with anomalously cool Pacific sea surface temperatures (SST) and extended periods of La Niña-like climate conditions (Mann

Fig. 1. Dune fields and major streams of the northern and central Great Plains modified from Muhs and Holliday (1995).

Fig. 2. White River Badlands aeolian and loess deposits (shaded), adapted from United States Geological Survey 1:5,000,000 scale surficial deposit map (Soller and Reheis, 2004). Diamond symbols mark the approximate sample localities in this study. Circle symbols mark the approximate sample localities from Burkhart et al. (2008).

et al., 2009a; Mann et al., 2009; Sridhar et al., 2006). During the MCA, periods of drought significantly longer than those of the modern era (megadroughts) (Feng et al., 2008; Woodhouse and Overpeck, 1998), caused reactivation of dunes in the NSH and other dune fields on the Great Plains (Forman et al., 2005; Forman et al., 2001; Goble et al., 2004; Hanson et al., 2010; Mason et al., 2004; Schmeisser McKean et al., 2015; Schmeisser et al., 2010). Droughts coincident with the LIA also appear to have reactivated dunes, especially in the western and southern sections of the Great Plains (Clarke and Rendell, 2003; Forman et al., 2008; Forman et al., 2005; Halfen et al., 2010). The LIA is less well defined than the MCA, but Mann et al. (2009) state that the coldest period occurred between 1400 and 1700 CE, or approximately 600–300 a. Evidence of the MCA megadroughts and LIA droughts is preserved in tree rings (Cook et al., 2007; Cook et al., 2010; Cook et al., 2004), lake sediments (Fritz et al., 2000; Hobbs et al., 2011; Laird et al., 1996; Schmieder et al., 2013; Schmieder et al., 2011), and incised stream channels (Burkhart et al., 2008) throughout the region.

Fig. 3. Fig. 3A shows the central section of the WRB dune fields with vegetation-stabilized dunes and blowouts. The dune forms are aligned to the NW, consistent with the modern wind direction. Analysis of historic photographs taken between 1948 and 2016 show that less than 1% of the dunes and blowouts were unvegetated and possibly active from 1948 to 2008. White rectangles are the locations of inset photos 3B and 3C. Fig. 3B and C show unvegetated dunes and blowouts in 1948 at Conata Ranch (3B) and Bouquet Table (3C). It is unclear whether the activity from 1948 represents a reactivation during the 1930s Dust Bowl droughts or some previous drought.

The major goal of this study is to construct a chronology of the most recent aeolian activity for the White River Badlands (WRB) dune field that can be compared with both aeolian chronologies on the northern and central Great Plains and with regional climate proxies for drought, including alluvial incision in the WRB. This study of the WRB dune fields is important because 1) few studies have been conducted in this section of the northern Great Plains, 2) the WRB are located close to (60 km north) and upwind of the western NSH (Figs. 1 and 2), and 3) the WRB has been identified as a possible source for nonglacial sediment in the Peoria Loess (Aleinikoff et al., 2008; Aleinikoff et al., 1999; Muhs et al., 2013).

2. Geographic and geologic setting

2.1. Geography and bedrock geology

The WRB are located within the Northern Rolling Pierre Shale Plains, an ecoregion dominated by a mixed-grass prairie community of drought-tolerant grasses, shrubs, and scattered trees (Boltz, 2010). Climatologically, this region is classified as a cold, semiarid steppe, with cold dry winters and hot summers subject to infrequent but intense convective storms (Fisichelli et al., 2016). Temperatures range from 7.4 °C to 13.4 °C, with a mean of 10.3 °C, and annual precipitation ranges from 27 cm to 69 cm, with a mean of 43 cm. The dominant wind direction is from the northwest (NW), averaging 5.3 m/s, with NW winds frequently exceeding 12 m/s in the fall and winter months (IEM, 2018). The WRB are bounded to the north by the south facing escarpment of the White River valley and to the south by the Pine Ridge escarpment, which defines the northern boundary of the High Plains.

The WRB has been incised by perennial and ephemeral streams, dividing the prairie surface into mesas and buttes of various sizes. Large mesas, known locally as tables, range in height from tens of meters to approximately 100m and typically are named features on 1:24,000-scale topographic maps of the area. Smaller tables and buttes, known locally as sod tables (Benton et al., 2015; Burkhart et al., 2008), are typically less than 10m in height and unnamed at the 1:24,000 scale. Both tables and sod tables are covered with alluvial and aeolian sediments of varying thickness, deposited on Cretaceous marine strata of the Pierre Shale and Late Oligocene-Early Miocene fluvial overbank, lacustrine, and volcanic ash deposits of the White River and Arikaree Groups (Benton et al., 2015; Raymond et al., 1976). Miocene and Pliocene strata of the High Plains (Ogallala) aquifer, present in the NSH, are absent in the WRB. The presence of fluvial gravels, found at the bedrock interface of the tables, supports the interpretation that the tables are fluvial terraces of the ancestral White River, Cheyenne River, or their tributaries (Harksen, 1974).

2.2. Quaternary geology

Three sets of Quaternary aeolian deposits have been identified in the WRB: 1) aeolian sand, of the sand sheets and dunes in the WRB, which is the focus of this paper, 2) ACT deposits, formed by processes not directly related to parabolic dune development, and 3) the Red Dog Loess, described below, together with the Peoria Loess. Aeolian sand, mapped as Quaternary aeolian (Raymond et al., 1976) or Sand Hills Formation (Harksen and Haywood, 1969), occurs as sand sheets and parabolic dunes on upland tables throughout the WRB. Thickness of the aeolian sand ranges from 2 to

60 m, generally increasing in thickness in the downwind (southern) sections of the tables. Aeolian sand is typically moderately well-sorted, contains less than 10% silt and clay, is mineralogically immature, and is low in CaCO_3 (< 3% to 4.5%).

WRB dune forms are dominantly vegetation-stabilized parabolic dunes and associated blowouts (Figs. 3 and 4). These parabolic dunes are variably low-relief dunes with shallow slopes of 5° – 10° and heights of less than 10m and high-relief dunes with steep slopes of 15° – 35° and heights of 10–30 m. Low-relief dunes appear to be older, eroded dune forms, which is confirmed by OSL ages from this study. However, both high- and low-relief parabolic dunes open to the NW, consistent with the modern wind direction (Schmeisser et al., 2010). Table surfaces and dunes are above the regional water table, but small springs and wetlands can be found near the sand-bedrock interface at Bouquet Table and Cuny Tables. Stratigraphic exposures of the aeolian sand are rare and limited to cliff edges and roadcuts (Fig. 4).

In contrast to the aeolian sand facies, ACT deposits are typically found on upwind cliff edges where gusting winds transport material from unvegetated cliff faces to table surfaces (Rawling et al., 2003; White, 1960). Within 10–15m of cliff edges, ACT deposits of up to 2m thickness, composed mostly of fine sand and some pebbles, rest unconformably on dunes, aeolian sand sheets, or the Red Dog Loess. While not sampled here, Rawling et al. (2003) created a chronology of sedimentation based on ^{14}C analysis of paleosols preserved in the dunes. Because these dunes are not related directly to the parabolic dune forms on the tables, they are not included in the dune development chronology of this study.

2.3. Peoria and Red Dog loesses

The WRB dune fields may yield important information on the deposition and source of the western sections of the Peoria Loess. The significance of the Peoria Loess includes its agricultural importance for the region and its preservation of information on the cold, dusty climate of the last glacial period (Bettis et al., 2003; Muhs et al., 2003; Muhs and Bettis, 2000; Muhs et al., 2008; Muhs et al., 2013). The wind-blown silt of the Peoria Loess crops out, north to south, from Wisconsin to Louisiana and, west to east, from Colorado to Ohio. Deposition of the Peoria Loess coincides approximately with the Last Glacial Maximum (LGM) through to near the end of the Pleistocene (Aleinikoff et al., 2008; Muhs et al., 2008; Roberts et al., 2003). While much of the Peoria Loess is composed of glacial sediments (Bettis et al., 2003), in central Nebraska, the Peoria Loess was likely derived from non-glacial sources (Aleinikoff et al., 2008). Comparisons of chemical composition (Muhs et al., 2008)

Fig. 4. A. Exposure of approximately 10m thickness of cross-bedded aeolian sand at the northern end of 185th Avenue Table, north to the left. Black lines highlight aeolian cross-stratification. Fig. 4B. Drone image, facing approximate south, of young, high-relief parabolic dunes on Bouquet Table (image courtesy of Gregory Baker of Geoavatar).

and ages of detrital zircons (Aleinikoff et al., 2008) demonstrate the Peoria Loess contains significant input from the Oligocene- aged White River Group (WRG) strata from outcrops in the western Great Plains, including the WRB.

The Red Dog Loess in the WRB is unlikely to provide information on the Peoria Loess as it is unlikely to be equivalent to the Peoria in age and, in fact,

may not be a loess. The Peoria Loess has not been mapped in South Dakota, but Harksen (1968) proposed the name Red Dog Loess for massive, calcareous sandy-silt deposits in southwest South Dakota that he believed to be the temporal equivalent to the Peoria Loess. At the type locality, the Red Dog Loess reaches a thickness of 18 m, but mostly the loess in the WRB is too thin to be mapped as a separate formation. Field observations, made in this and previous studies (Burkhart et al., 2008; Rawling et al., 2003), identified fluvial gravels and coarse-grained material in the Red Dog Loess that suggests the unit may in fact consist of silty ephemeral stream deposits. Thus, neither the origin of the Red Dog Loess of southwestern South Dakota nor its relationship to the Peoria Loess is clear.

3. Previous studies

3.1. Aeolian sedimentation

Aeolian sand and ACT deposits were previously studied to determine periods of drought in the WRB (Burkhart et al., 2008; Rawling et al., 2003). Analysis of ^{14}C from paleosols preserved in ACT deposits indicated three periods of stabilization and soil formation at 3.7 ka, 2.5 ka, and 1.3 ka, with each period of soil formation followed by drought-driven aeolian sedimentation. Rawling et al. (2003) interpret periods of soil formation as indicative of mesic climate conditions occurring between periods of drought-related aeolian sedimentation at cliff edges. In addition, Burkhart et al. (2008) collected samples for OSL analysis from cross-bedded sand exposures at the margins of tables throughout the dune field (Fig. 2). Resulting OSL ages were shown to be significantly older than the ACT paleosols, yielding ages from 21.0 to 12.4 ka (Burkhart et al., 2008).

3.2. Alluvial incision

Like the aeolian sedimentation, alluvial sedimentation and subsequent incision of the WRB prairie have been linked to periods of late Holocene drought. Throughout the WRB, there have been multiple episodes of terrace formation and alluvial deposition, followed by dissection of the landscape by rapidly downcutting perennial and ephemeral streams. Sod tables, reported in the Badlands National Park and throughout the WRB (Benton et al., 2015), are incised pediments, defined here as prairie-covered buttes and tables, generally less than 10m height, consisting of eroded WRG bedrock with a veneer of alluvium ranging from a few centimeters to several meters thickness. The youngest paleosols, preserved in alluvium at the sod

table surface, constrain the maximum age for the initiation of stream incision. The ^{14}C calibrated ages of paleosols from the stratigraphic exposures of 14 sod tables range from 3870 to 590 a, with the youngest paleosols ranging from 1370 to 590 a. These results were interpreted to link MCA droughts with denudation of vegetation and subsequent incision of the prairie by ephemeral streams draining the upland areas of the badlands (Burkhart et al., 2013). In addition, previous studies of perennial stream-channel cut and fill in the WRB suggest a complex Holocene fluvial history with periods of stream incision between 5.0 and 2.5 ka, and post-850 a (Harksen, 1974; Patton and Schumm, 1981; White and Hannus, 1985).

4. Field and laboratory methods

In this study, two methods were used to determine the timing of dune development. First, archival aerial photographs dating from 1948 to 2016 were used to identify areas of historical activity at Cuny Table, Bouquet Table, and Conata Ranch. High-resolution 1:17,000-scale aerial photographs, from the USGS Single Frame Records collection and the National Agriculture Imagery Program (NAIP) programs, were accessed through the USGS Earth Explorer (<https://earthexplorer.usgs.gov>). Second, OSL dating was used to determine the ages of the most recent period of dune movement in both the high- and low-relief dunes. OSL ages of samples collected at shallow depths, between 0.8 and 2.9 m below dune crests, were interpreted as dune stabilization age following the most recent episode of dune development (Muhs and Maat, 1993; Wolfe and Hugenholtz, 2009; Wolfe et al., 2013). Sampling was conducted over nearly the entire east to west extent of the WRB dune field to create a data set with the greatest regional significance (Fig. 2).

Samples were collected from the crests of low- and high-relief dunes at three WRB tables: Cuny Table, Bouquet Table, and the unnamed table at the Conata Ranch (Fig. 2). The majority of samples were collected using hand augers at depths between 1 and 3 m below ground surface to minimize potential effects of bioturbation (Hanson et al., 2015). At auger and exposure localities, sediment was collected by inserting tubes into a full bucket auger or exposure face. Tubes were tightly packed and taped at both ends to prevent shifting of sediment during shipping. An additional five sites were sampled at Bouquet Table using a truck-mounted soil corer, which was available for one field season. Samples collected from the truck-mounted corer were collected in black plastic liners to ensure samples were not exposed to sunlight.

OSL analyses were conducted at the University of Nebraska's Luminescence and Geochronology Laboratory. Quartz grains (90–150 μm) were isolated by sieving, treated with hydrochloric acid, and separated by flotation

in heavy liquid, and treated with hydrofluoric acid to etch quartz grains and remove feldspars. The quartz grains were checked for purity by visual inspection and using IR diodes on the luminescence reader. D_e values were determined on a Risø model DA 20 TL/OSL reader, and samples were run on 5mm aliquots using a minimum of 23 accepted aliquots using the Central Age Model (Galbraith et al., 1999). Preheat temperatures were determined by preheat plateau tests (Wintle and Murray, 2006), and data reliability was checked through dose recovery tests. Environmental dose rate estimates were determined using the concentrations of K, U, and Th as determined by high-resolution gamma spectrometry, and long-term moisture contents were estimated to be 5%. The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and the final dose rate values were calculated following equations from Aitken (1998). All OSL age estimates are presented as calendar years before 2017. Radial plots for all samples are provided in the supplemental data.

Stratigraphy was described for five cores of 2.3m to 3.6m length collected for OSL analysis at Bouquet Table. These cores were photographed, described, and analyzed for grain-size distribution using a laser-diffraction analyzer at the University of Nebraska-Lincoln laboratory. Samples collected with augers for OSL analysis were analyzed for grain-size distribution and mineralogical composition at Nova Southeastern University using an optical particle analyzer. Preliminary petrographic analysis was performed on two grain-mounts from materials collected from sites OSL1 and OSL20 on Cuny Table and Bouquet Table, respectively. Samples were rinsed and sieved to remove material finer than 125 μ , and analyzed using standard point-counting methodology (Folk, 1974).

5. Results

5.1. OSL results

A summary of the OSL results from this study indicates that the activity preserved in the WRB dune field spans the late Pleistocene through the modern era (Table 1). From oldest to youngest, 1) the oldest activity is preserved in older, low-relief dunes and cross-bedded sand exposures, ranging from 21.0 to 12.4 ka, 2) a second period of activity from approximately 9 to 6 ka is preserved in crests of older dunes, and 3) a third period from 720 to 210 a is preserved in the crests of younger high-relief dunes, with one sample (OSL2) from 1.5m depth that yielded a modern age. Core profiles showing the elevation and depth for each sampling site are given in Fig. 5. Dispersion values were lower than 20% for 19 of the 26 samples analyzed

Table 1. Equivalent dose, dose rate data, and OSL age estimates.

UNL Lab #	Field #	Depth (m)	U (ppm)	Th (ppm)	K ₂ O (wt %)	In Situ H ₂ O (%) ^a	Dose Rate (Gy/ka)	CAM ^b De (Gy) ±1 Std. Err.	Aliquots (n) ^c	OSL Age ±1σ	O.D. ^d %
Bouquet Table (43°39.62'N 102°16.25'W)											
UNL-4286	OSL12A	1.9	1.2	4.8	2.3	2.1	2.60 ± 0.15	23.8 ± 0.7	24/33	9200 ± 700	13.9
UNL-4287	OSL12B	2.7	1.4	6.0	2.3	2.8	2.68 ± 0.15	24.2 ± 0.5	25/33	9100 ± 700	10.4
UNL-4293	OSL13	1.0	1.1	3.6	2.6	2.2	2.69 ± 0.16	1.1 ± 0.1	21/54	400 ± 40	1.0
UNL-4379	OSL14	1.3	1.1	4.5	2.5	5.0	2.65 ± 0.16	1.9 ± 0.1	34/39	720 ± 70	31.1
UNL-4380	OSL15	1.0	1.4	5.4	2.4	5.0	2.67 ± 0.16	0.6 ± 0.1	38/63	210 ± 20	13.9
UNL-4288	OSL16A	1.0	1.2	5.6	1.9	2.2	2.37 ± 0.13	1.5 ± 0.1	28/33	600 ± 50	12.2
UNL-4289	OSL16B	2.9	1.1	5.1	2.1	3.5	2.36 ± 0.14	21.1 ± 0.8	26/33	8900 ± 700	18.1
UNL-4381	OSL17	1.4	1.4	7.4	2.5	5.0	2.84 ± 0.16	0.6 ± 0.1	38/48	210 ± 20	17.4
UNL-4291	OSL18A	0.8	1.2	5.7	2.6	1.1	2.92 ± 0.17	0.9 ± 0.1	25/51	300 ± 40	8.6
UNL-4292	OSL18B	1.9	1.0	4.2	2.4	2.5	2.56 ± 0.15	1.6 ± 0.1	25/48	600 ± 60	24.7
UNL-4290	OSL19	1.6	1.3	5.4	2.6	2.2	2.82 ± 0.16	17.7 ± 0.6	26/31	6300 ± 500	16.4
UNL-4313	OSL20A	1.0	1.3	4.3	2.4	5.0	2.57 ± 0.15	41.7 ± 1.2	36/40	16200 ± 1300	17.0
UNL-4312	OSL20B	2.1	1.1	4.1	2.4	5.0	2.50 ± 0.15	38.5 ± 0.8	32/38	15000 ± 1100	10.3
Conata Table (43°41.61'N 102°26.27'W)											
UNL-4310	OSL4	2.0	1.5	6.7	2.0	5.0	2.48 ± 0.14	21.7 ± 0.4	35/43	8700 ± 600	10.4
UNL-4311	OSL5	1.7	1.2	4.9	2.6	5.0	2.72 ± 0.17	32.6 ± 0.4	34/38	12000 ± 900	6.7
UNL-4308	OSL6A	1.8	1.5	6.2	2.2	5.0	2.60 ± 0.15	22.1 ± 0.4	28/35	8500 ± 600	8.5
UNL-4309	OSL6B	2.6	1.0	3.6	2.3	5.0	2.34 ± 0.15	25.4 ± 0.4	35/40	10800 ± 800	9.6
UNL-4064	OSL7	1.7	1.6	7.1	2.1	5.0	2.60 ± 0.15	15.6 ± 0.7	27/33	6100 ± 500	22.5
UNL-4062	OSL8	1.3	1.4	5.2	2.0	5.0	2.34 ± 0.13	17.4 ± 0.5	26/28	7400 ± 600	15.7
UNL-4060	OSL9	1.2	1.3	5.6	2.0	5.0	2.39 ± 0.14	1.0 ± 0.1	23/33	420 ± 50	29.6
UNL-4056	OSL10	1.1	1.7	6.4	2.2	5.0	2.62 ± 0.15	1.1 ± 0.1	30/40	420 ± 50	38.5
UNL-4058	OSL11	1.2	1.4	6.3	2.1	5.0	2.52 ± 0.14	0.8 ± 0.1	27/37	320 ± 50	21
Cuny Table (43°32.18'N 102°38'W)											
UNL-4307	OSL1	1.9	1.3	5.6	2.1	5.0	2.39 ± 0.14	17.2 ± 0.3	31/35	7200 ± 500	8.1
UNL-4306	OSL2	1.5	1.3	4.8	2.0	5.0	2.30 ± 0.13	0.1 ± 0.1	28/49	0 ± 20	0.0
UNL-4304	OSL3A	2.1	1.2	6.1	2.1	5.0	2.44 ± 0.14	0.6 ± 0.1	28/57	250 ± 20	16.0
UNL-4305	OSL3B	2.7	1.1	5.3	1.7	5.0	2.01 ± 0.11	0.5 ± 0.1	28/58	260 ± 40	42.2

a. Assumes 50% long-term in either estimated or measured long-term moisture content.

b. Central Age Model (Galbraith et al., 1999).

c. Accepted disks/all disks.

d. Overdispersion.

(Table 1), suggesting that the samples were likely adequately bleached prior to burial and that they were not likely to have been disturbed after they were deposited. Seven samples had dispersion values that were higher than 20%; however, in each case radial plots of samples showed relatively symmetrical distributions, indicating that the samples were not adversely impacted by partial bleaching or some other related problem. In one case, two samples (OSL3A and OSL3B) collected from the same drill core had very significantly different dispersion values (0.0 vs. 42.2), but their ages overlapped well within their 1 σ errors (Table 1).

Fig. 5. Depth relationships of OSL samples from Cuny Table (CT), Bouquet Table (BT), and Conata Ranch (CR). OSL ages are reported in years before 2017 and shown with 1σ errors. Elevations of auger, core, and exposure sites are given in meters above sea level.

5.1.1. Cuny Table

Three samples were collected at Cuny Table (Figs. 2, 5, and 6), including one from the head of a gently sloping, low-relief parabolic dune (OSL1), and two from the heads of steep sloped, poorly developed parabolic dunes in the downwind section of the dune field (OSL2 and OSL3). Sample OSL1 taken from 1.9m below ground surface yielded an age of 7200 ± 500 a, OSL2, collected from a depth of 1.5 m, yielded an age of 0 ± 20 a, and OSL3A and OSL3B, collected from depths of 2.1m and 2.7 m, yielded ages of 250 ± 20 and 260 ± 40 , respectively.

5.1.2. Conata Ranch

The Conata Ranch site is located at the northern section of an unnamed table in the central section of the study area (Figs. 2, 5, and 7). Samples OSL4, OSL5, and OSL6 were collected from the crests of gently sloping, low-relief parabolic dunes at the northern end of the table. Samples OSL4 and OSL5, collected at depths of 2.0m and 1.7m respectively, yielded ages of $8700 \pm$

Fig. 6. Cuny Table sample locations. The dashed line marks the boundary between low-relief dunes to the north and high-relief dunes to the south. North of the dashed line, dune heights are approximately 5m with slopes of 5°–10°. South of the line, dune heights are 10–30 m, and slopes are 15°–35°. OSL ages with 1 σ error are shown in years before 2017.

600, $12,000 \pm 900$ a. At OSL6, samples were collected at 1.8m (OSL6A) and 2.6m (OSL6B) below ground surface and yielded ages of 8500 ± 600 and $10,800 \pm 800$ a. Sample OSL8 was collected from a blowout exposure in the transition from low- to high-relief dunes, at a depth of 1.3m below the top of the outcrop, yielding an age of 7400 ± 600 a. Samples OSL7, OSL9, OSL10, and OSL11 were collected from the crests and arms of steep sloped, high-relief dunes at Conata Ranch. These samples, collected at 1.7 m, 1.2 m, 1.1 m, and 1.2m below ground surface, respectively, yielded ages of 6100 ± 500 , 420 ± 50 , 420 ± 50 , and 320 ± 50 a.

5.1.3. Bouquet Table

Samples were collected from dunes in the downwind, southeastern section of the Bouquet Table (Figs. 2, 5, and 8), the easternmost table in the study area. Eight samples (OSL12A and B, OSL13, OSL16A and B, OSL18A and B, and OSL19) were collected using a truck-mounted coring device, and three samples (OSL14, OSL15, and OSL17) were collected with a hand auger. Two additional samples (OSL20A and B) were collected from a roadcut exposure near the western margin of the table, near the base of the aeolian sand unit, approximately 40m lower elevation than the samples collected from the dune crests.

Samples OSL12A, OSL12B, and OSL19 were collected from the heads of gently sloping, low-relief parabolic dunes at depths of 1.9 m, 2.7 m, and

Fig. 7. Conata Ranch sample sites. The dashed line marks the boundary between low-relief dunes to the north and high-relief dunes to the south. OSL ages with 1 σ error are shown in years before 2017.

Fig. 8. Bouquet Table sample locations. The dashed line marks the boundary between low-relief dunes to the north and high-relief dunes to the south. OSL ages with 1 σ error are shown in years before 2017.

1.6 m, yielding ages of 9200 ± 700 , 9100 ± 700 , and 6300 ± 500 a, respectively. Samples OSL16A and OSL16B were collected at the transition from the low- to high-relief dunes at depths of 1.0m and 2.9 m, yielding ages of 600 ± 50 and 8900 ± 700 a, respectively. A paleosol was encountered between OSL16A and OSL16B at a depth of 1.8 to 2.6m below ground surface,

recognized by a color change and carbonate root fillings. Samples OSL20A and OSL20B, collected from the roadcut exposure at depths of 1.0m and 2.1m below the top of the outcrop, yielded ages of $16,200 \pm 1300$ and $15,000 \pm 1100$ a, respectively, an apparent stratigraphic reversal but within the 1σ error.

Samples OSL13, OSL14, OSL15, OSL17, OSL18A, and OSL18B were collected from the arms of steep, well-developed parabolic dunes. Samples OSL13, OSL14, OSL15, and OSL17, collected from 1.0m below ground surface, yielded ages of 400 ± 40 , 720 ± 70 , 210 ± 20 , and 210 ± 70 a, respectively. Samples OSL18A and OSL18B, collected at 0.8m and 1.9m below ground surface, yielded ages of 300 ± 40 and 600 ± 60 a, respectively.

5.2. *Photographic analysis*

While the modern dune surfaces are nearly completely stabilized, high-resolution aerial photographs of 1:17,000 scale from 1948 show that some dune crests and blowouts at Conata Ranch and Bouquet Table were unvegetated and possible active at that time (Fig. 3). Using the Google Earth polygon tool, the estimated area of each unvegetated dune or blowout was determined to be less than 1% the area of the dune fields at Conata Ranch (6 ha) and Bouquet Table (4 ha). It is unclear whether this represents activity from the Dust Bowl droughts or some earlier period of drought in the WRB. Analysis of the photographs indicates that the dunes at Conata Ranch and Bouquet Table had completely revegetated by 2008. No OSL samples were collected from dunes identified as active during the modern era.

5.3. *WRB dune stratigraphy*

In general, dune stratigraphy was characterized by poorly developed soils and unlaminated or weakly laminated strata at depth. Five sites were sampled using a truck-mounted corer, two from low-relief dune crests (OSL12 and OSL19), two from high-relief dune crests (OSL13 and OSL18) and one at the transition (OSL16). Cores ranged in length from 234 cm to 364 cm, with a loss to compaction of upper 15 cm and 19 cm at sites OSL16 and OSL19. Each core was dominated by noncalcareous, fine- to medium-grained sands, with planar laminations faint or absent. Generally, silt and clay content decreased down core, with the exception of site OSL5 where silt and clay content increased at approximately 160 cm, and an 80-cm thick paleosol was encountered. Paleosols were identified at auger localities by changes in color, generally darkening from brown (10YR 5/4) to dark brown (10YR 3/2). Similarly, in the core samples, suspect paleosols were darker and contained carbonate filaments and root fillings. At site OSL13, between 125 cm and 232 cm, alternating light and dark high-carbonate content lenses of sediment

Fig. 9. Plots of combined data set of 37 OSL ages from the WRB dunes. Age bars marked with hollow squares are OSL ages from cross-stratified sand exposures (Burkhart et al., 2008), and solid squares are from this study. Circles are OSL ages from dune surfaces and blowouts from this study. Vertical gray bars are (left) the MCA and LIA periods from Mann et al. (2009) and right NSH activity from 9.6 to 6.6 ka (Goble et al., 2004; Miao et al., 2007b). Horizontal bars are (left) maximum age of alluvial incision in the WRB (Burkhart et al., 2008) and (right) period of deposition of the midcontinental Peoria Loess (Aleinikoff et al., 2008; Mason, 2001; Muhs et al., 2008; Roberts et al., 2003). Vertical scale is arbitrary.

were encountered that were interpreted as lacustrine sediments, possibly deposited in a deflation basin. Soil development was variable, with the best-developed soils found at sites OSL12 (A and B-horizons 65 cm) and OSL14 (A and B-horizons 63 cm) in the low-relief sections of the dune field. In the high-relief dune cores, A/C soil thickness ranged from 12 to 20 cm.

Dune sand is typically medium-grained ($\mu=0.217\text{mm}$ to 0.369 mm), yellow brown (Munsell color 10YR 3-5/2-4 wet and 10YR 4-6/2-3 dry), and moderately well-sorted ($\sigma=1.4$ to 2.0). Following Folk (1974), the sands analyzed are mineralogically immature feldspathic litharenites (quartz 39%, 19% feldspar, and 42% lithic fragments and quartz 63%, feldspar 14% and lithic fragments 23%), which generally is consistent with field observations of the aeolian sand throughout the WRB.

6. Discussion

6.1. Chronology of the WRB dune fields

Results from this study have been used to construct a preliminary chronology of late Pleistocene to recent dune activity in the WRB (Fig. 9). Previous studies (Burkhart et al., 2008) determined ages from stratigraphic exposures of cross-bedded sand to constrain the timing of early aeolian sedimentation. By selecting samples from dune crests, this study focuses on constraining

the most recent activity in the WRB dune fields. The combined data set of 37 OSL ages from this and previous works, as well as the analysis of archival aerial photographs, supports a chronology of aeolian sedimentation and dune development from 21 ka to present. The range of ages for activity in the WRB dune field is similar to the range of ages reported for dune fields on the central Great Plains and several of the older ages overlap the age of deposition of Peoria Loess.

OSL ages from this study yielded results consistent with relative stratigraphic age within 1 σ error. Results from Burkhart et al. (2008) show a stratigraphic inversion of Red Dog Loess results and the 21 ka aeolian sand sample. The 21 ka aeolian sand sample, the oldest OSL age in the data set, is considered suspect, but is included in the chronology. The Red Dog Loess ages were not used in this chronology because of the questions concerning the nature of the loess.

The oldest aeolian activity determined in this study comes from the ages of samples collected from the cross-bedded sand exposure at Bouquet Table, which yielded ages of 15.0 ± 1.1 ka and 16.2 ± 1.3 ka, and low-relief dunes found at Conata Ranch (12.0 ± 0.9 ka). These samples fall within the range of 21.0–12.4 ka reported in Burkhart et al. (2008) from cliff exposures of cross-bedded sands at Hunt Table, Imlay (Kudrna) Table, 185th Avenue Table, Cuny Table, Conata (White) Ranch, and Bouquet Table (Fig. 2). Lack of paleosols from the period 21 to 12 ka in the study area suggests this was a time of dune construction in the WRB, similar to the period of dune construction and migration in the NSH proposed by Mason et al. (2011). While the White and Cheyenne Rivers are outside the limit of direct influence of the Laurentide Ice Sheet and the Rocky Mountain glaciation, the range from 21 to 12.4 ka preserved in the cross-bedded sand is approximately the same interval as the peak cold interval (21–22 ka to 15–16 ka) and breakup (16 to 12 ka) of the Pinedale glaciation (MIS 2) reported for the Wind River range (Gosse et al., 1995; Pierce, 2003) and the central Rocky Mountain front range (Briner, 2009; Young et al., 2011).

A second period of aeolian activity is preserved in the crests of low-relief dunes, which are found typically on upwind sections of the tables. These ages, interpreted as stabilization ages of these low-relief dunes, range from 10.8 to 6.1 ka, with nine of the 11 samples falling between 9.2 and 6.1 ka. This activity is largely coincident with activity in the nearby NSH reported at 9.6 to 6.6 ka (Goble et al., 2004; Miao et al., 2007b).

Evidence for a third period of aeolian dune activity dating after 700 a, was found in the high-relief dunes on the southern sections of Cuny Table, Conata Ranch, and Bouquet Table (Table 1 and Figs. 5, 7, and 8). Ages for this period of post-700 year sedimentation includes Cuny Table (260 ± 40 , 250 ± 40 , and 40 ± 20), Conata Ranch (420 ± 50 , 420 ± 50 , and 320 ± 50), and

Bouquet Table (720 ± 70 , 600 ± 50 , 600 ± 60 , 400 ± 40 , 300 ± 40 , 210 ± 20 , and 210 ± 20). Within this period, the distribution of ages suggests two periods of dune stabilization, one centered at approximately 600 a, and a second centered at approximately 350 a (Fig. 9). While the OSL data are limited to these three tables, the presence of steep sloped, high-relief dunes throughout the WRB (Figs. 3 and 4) suggests that post- 700 a was a significant period of dune activity in the region. In addition, this period is approximately coincident with alluvial incision reported from the WRB, which has been interpreted as a response to MCA droughts (Burkhart et al., 2008).

6.2. Comparison with other dune fields on the Great Plains

6.2.1. Late Pleistocene to middle Holocene

The two early episodes of aeolian sedimentation indicated by OSL ages in the WRB, 21.0 to 12.4 ka and 9.0 to 6.1 ka, were also experienced in other dune fields in the western section of the northern and central Great Plains (Halfen and Johnson, 2013). Dune fields active between 21 and 12 ka include the Ft. Morgan dunes (Madole, 1995), the Arkansas River dunes (Forman et al., 2008), and the NSH (Mason et al., 2011; Miao et al., 2007b). Previous works (Aleinikoff et al., 1999; Mason et al., 2008) suggested that reduced vegetation cover during cold periods of the LGM may have resulted in a flood of sediments from exposures of the WRG, affecting areas like the WRB which were outside the influence of the Pinedale glaciation. The second early- to middle- Holocene event in the WRB, 9.0 ka to 6.0 ka, was also a period of dune activity elsewhere on the Great Plains. Activity during this period was recorded in the NSH (Goble et al., 2004; Miao et al., 2007b) and the Casper dunes west of the Great Plains (Halfen et al., 2010).

While the middle- to late-Holocene period 6 ka to 700 a was not preserved in WRB dunes crests sampled in this study, significant episodes of aeolian sedimentation were recorded elsewhere on the Great Plains at this time. NSH episodes of aeolian activity centered on 3.8 ka, 2.5 ka, and 670 a (Goble et al., 2004; Mason et al., 2004; Miao et al., 2007b; Muhs et al., 1997; Schmeisser McKean et al., 2015; Stokes and Swinehart, 1997). Other dune fields on or adjacent to the Great Plains active at this time include the Ft. Morgan dunes, active at 4.9 ka (Clarke and Rendell, 2003); the Ferris dune fields, active from 4.3 ka to 4.0 ka (Stokes and Gaylord, 1993); the Casper dune fields, active between 1.0 ka and 400 a (Halfen et al., 2010); and the Wray dunes, active at 700 a (Mason et al., 2011). In the WRB, clifftop deposits in the WRB were accumulating episodically with periods of deposition post-3.7 ka, -2.5 ka, and -1.3 ka (Rawling et al., 2003). Because the ACT sediment source is the adjacent cliff surfaces, likely always denuded of vegetation in the WRB, the ACT sedimentation record may be more sensitive to

hydroclimate fluctuations, as well as changes in wind speed and direction. Whatever the cause, the lack of ages dating from 6.0 ka to 700 a suggests either that these events did not affect the dunes in the WRB, that sands dating to these events were not preserved, or that these sands are present, but primarily deeper in dune fills and not in dune crests.

6.2.2. Post-600 a

Post-600 a dune activity is common in dune fields of the western section of the northern and central Great Plains. Western dune fields active at this time include the Ft. Morgan dune field, active at 600 a to 500 a and approximately 370 a (Clarke and Rendell, 2003); the Arkansas River dunes, active at 400, 180, and 70 a (Forman et al., 2008); and the Casper dunes, active at 1000 to 400 a (Halfen et al., 2010). Other dune fields that showed significant post-600 a activity include the Great Bend Sand Prairie, active post-700 a and post-500 a to -300 a (Arbogast and Johnson, 1998); the Hutchison dune field, active post- 600 a (Halfen et al., 2012); and the Cimarron dunes, active at 400 a (Werner et al., 2011).

6.3. Comparison with other climate proxies

Because of the lack of perennial lakes and the scarcity of trees in the WRB, prehistoric drought records were collected from sites in the surrounding northern Great Plains. Climate proxies for the region generally point to a drier late Pleistocene-early Holocene, followed by variable hydroclimate in the middle to late Holocene. The late Pleistocene aeolian sedimentation at 21 ka approximately coincides with the LGM and subsequent collapse of the Pinedale glaciation in the Wind River Range (Gosse et al., 1995; Pierce, 2003) west of the study area and the central Rocky Mountain Front Range southwest of the study area (Briner, 2009; Gosse et al., 1995; Young et al., 2011). According to Gosse et al. (1995), the coldest period of the Pinedale glaciation was shown to last from approximately 21,000 to 16,000 years, with melt back to the cirque basin by 12 ka, which overlaps with the oldest aeolian sand sedimentation in this and previous works (Burkhart et al., 2008; Rawling et al., 2003). Results from analysis of lacustrine sediments at Kettle Lake, North Dakota (Grimm et al., 2011; Hobbs et al., 2011) indicate a dry climate event at 9.25 ka (Grimm et al., 2011) followed by moist hydroclimate periods in the middle Holocene (Hobbs et al., 2011). Multiproxy studies (Shuman and Marsicek, 2016) for multilatitude North America also show rapid changes in hydroclimate from approximately 9.3 to 8.2 ka. Studies of interdunal lakes in the NSH (Schmieder et al., 2013; Schmieder et al., 2011) indicate that 10 ka to 6 ka was the driest Holocene period on the Great Plains. This prolonged dry period was followed by shorter drought periods from 4

ka to 3 ka, at 1.5 ka to 1.2 ka, and at 1.0 ka to 700 a (Schmieder et al., 2013; Schmieder et al., 2011). Tree ring data (Cook et al., 2010) also show a dry period for the Great Plains lasting from approximately 1.2 ka to 700 a, and another period of drought lasting from approximately 650 to 550 a, followed by generally wetter conditions.

Alluvial incision and the formation of sod tables has been well established (Benton et al., 2015) and represents an important late Holocene event in the WRB (Burkhart et al., 2008). The formation of paleosols in WRB alluvium between 1.5 ka and 600 a indicates periods of fluctuating hydroclimate similar to the timing of stabilization and soil formation recorded in ACT paleosols by Rawling et al. (2003). Similar episodes of climate-driven alluvial aggradation and incision during the Holocene have been reported in other studies from the Great Plains, including southwest Nebraska (Daniels, 2008; Daniels and Knox, 2005), Kansas (Arbogast and Johnson, 1994), and South Dakota (Harden et al., 2015).

7. Conclusion

The combined data set of 37 OSL ages, from this study and Burkhart et al. (2008), defines three periods of aeolian activity in the WRB dune field at 21.0 to 12.4 ka, 9.2 to 6.1 ka, and 720 to 210 a. These periods of dune development correlate well with periods of activity in dune fields on or near the western margin of the Great Plains, including the western NSH (Fig. 9). The aeolian dune development chronology included in this work suggests the Pleistocene and early Holocene aged dunes found on tables in the WRB were reactivated within the past 700 a. Dune reactivation was caused by late Holocene droughts associated with the MCA and LIA. The interpretation that MCA and LIA droughts were important regional events, causing reactivation of dune fields on the western Great Plains, is supported by the most recent period of activity from 720 to 210 a. Finally, this third period of activity overlaps the timing of prairie incision that produced the prominent sod tables seen in the Badlands National Park and throughout the region, which supports a previous interpretation that the incision was caused by regional drought. Analysis of archival photographs of the area indicates that the WRB dune field was little affected by the Dust Bowl drought.

A sampling strategy that focused on the crests of old and young dunes likely resulted in an incomplete chronology, possibly missing well-documented periods of aeolian activity from the late Holocene. The degree to which middle and late Holocene aged sediments are preserved in the WRB dunes will be a subject of future research efforts. Similarly, our ages show that dunes in the WRB aeolian were active from 21.0 ka to 12.4 ka falls,

within the period of Peoria Loess deposition on the central Great Plains, but further study is needed to determine whether these dunes were sources of fine-grained sediments for the Peoria.

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Supplemental data @ https://nsuworks.nova.edu/occ_facdatasets/6/

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