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Holocene stratigraphy and chronology of the Casper Dune Field, Casper, Wyoming, USA

Alan F. Halfen,[1] Glen G. Fredlund[2] and Shannon A. Mahan[3]

Abstract

Activation chronologies of dune fields within the North American Great Plains are significant sources of paleoclimate information. Although many regional chronologies exist, several dune fields have been understudied, including the Casper Dune Field of central Wyoming. This study investigated aeolian dune sediment and buried soils of the Casper Dune Field. Complex parabolic and hairpin parabolic dunes dominate the eastern dune field, while simple parabolic and linear dunes dominate the western dune field. Buried soils are found throughout the dune field, though their distribution and degree of development varies. Buried soils in the eastern dune field are weakly developed with typical A-C profiles, whereas soils in the western dune field typically exhibit A-Bt-C profiles. Optically stimulated luminescence (OSL) and radiocarbon ages were used to provide a chronology of dune field activation that spans most of the Holocene. At the onset of the Holocene, alluvium was deposited first, followed by widespread dune activity ~ 10.0–6.2 ka. Following activity, the dune field stabilized until about 4.1 ka. During this stabilization period, however, reactivation occurred in at least one locality within the dune field at 5.1 ka. Subsequent aeolian activity occurred at 4.1 ka and between 1.0 ka and 0.4 ka. The resulting activation chronology is compared with those obtained from elsewhere in Wyoming and from other west-central Great Plains dune fields.

Keywords

aeolian, Holocene, optically stimulated luminescence, sand dunes, Wyoming

Introduction

Aeolian dune fields are found throughout the west-central, semi-arid Great Plains of North America (Figure 1), and large dune fields (e.g. Nebraska Sand Hills) have been examined to reconstruct prehistoric periods of activation (Forman *et al*., 2005; Goble *et al*., 2004; Miao *et al*., 2007; Muhs and Zárate, 2001; Muhs *et al*., 1997, 1999). Smaller, subregional dune fields, however, have not been studied to the same extent, but limited research suggests that these dune fields provide similarly useful paleoclimatic data (Clarke and Rendell, 2003; Gaylord, 1982, 1990; Mayer and Mahan, 2004; Stokes and Gaylord, 1993). Better chronological control on activity within these dune fields will provide better understanding of subregional histories of dune activation during the Holocene, as well as help to establish a better regional chronology for the Great Plains. Many subregional chronologies exists for west-central Great Plains dune fields, including the Fort Morgan Dunes, Greeley Dune Field, and Sterling Dune Field of Colorado (Clarke and Rendell, 2003; Forman *et al*., 2001; Madole, 1994, 1995; Muhs, 1985; Muhs *et al*., 1996, 1999); dunes adjacent to aeolian cliff-top deposits in the Badlands of South Dakota (Rawling *et al*., 2003); and the Killpecker Dune Field, Ferris Dune Field, and Casper Dune Field of Wyoming (Albanese, 1974a,b; Albanese and Frison, 1995; Eckerle, 1997; Gaylord, 1982, 1990; Mayer and Mahan, 2004; Stokes and Gaylord, 1993) (Figure 1).

Herein we report a stratigraphic chronology for several localities within the Casper Dune Field, thereby establishing the timing of dune activation and landscape stability throughout the Holocene. We provide new radiocarbon (^{14}C) ages and the first optically stimulated luminescence (OSL) ages for the Casper Dune Field. This chronology serves to fill a gap in Wyoming dune field studies and to constrain subregional chronologies of landscape stability throughout the Holocene.

Study area

The Casper Dune Field (CDF) is located in the Central Wyoming Basin north of Casper, Wyoming and covers an area of ~ 2000 km^2 (Figure 2). The CDF is linear in shape, oriented east–west and extending 180 km from Glenrock to Shoshoni, Wyoming. Dissecting the dune field near Powder River, Wyoming, is the Casper Arch Thrust Fault, an Eocene-aged remnant of the Laramide Orogeny (Montgomery *et al*., 2001). The North Platte River drains the far eastern part of the dune field while ephemeral reaches of the Powder River and Poison Creek drain part of the dune field to the north and the west, respectively. The region is a semi-arid, midlatitude steppe with a mean annual temperature of 7.2°C. Summer winds are from the southwest and average 7.6 m/s, whereas January winds are from the west-northwest and average 7.1 m/s. Mean

[1]University of Kansas, USA
[2]University of Wisconsin-Milwaukee, USA
[3]United States Geological Survey, USA

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Corresponding author:
Alan F. Halfen, University of Kansas, Department of Geography, 1475 Jayhawk Blvd, Room 213, Lawrence KS 66045, USA
Email: afhalfen@ku.edu

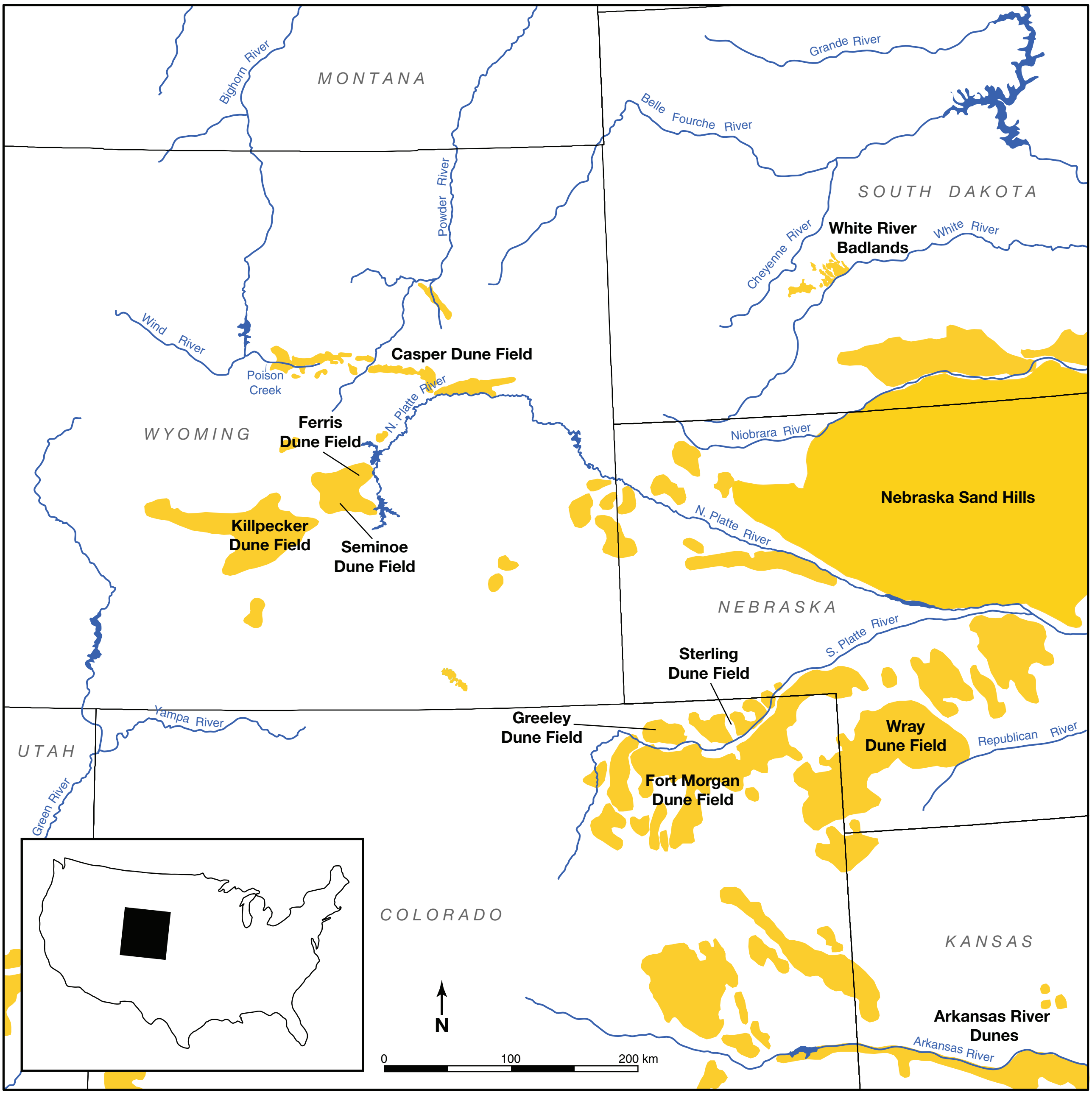

Figure 1. Dune fields and major streams of the west-central Great Plains. Dune field boundaries, other than the Casper Dune Field, were modified from Wolfe *et al.* (2009)

annual rainfall is ~300 mm, whereas annual snowfall is ~192 cm (Western Regional Climate Center, 2009) but only accounts for an additional 100 mm of precipitation (Curtis and Grimes, 2004). Where vegetated, the dune field is dominated by grassland-sage-brush mixed steppe species including *Bouteloua* ssp. (grama grasses), *Agropyron smithii* (wheat grass), and *Artemisia* spp. (sagebrush) (Kücher, 1964).

Based on surface soil development and dune morphology, we divided the dune field into eastern and western sections (Figure 2). Morphology of the eastern dune field is predominantly complex and hairpin parabolic dunes, up to 0.5 km wide and 15 km long (Figure 3A). Dunes exceed 30 m in height and consist of well-sorted sand derived from the North Platte River (Muhs, 2004). Stabilized dunes exhibit poorly developed A-C surface soils, with buried soils having profiles similar to those of the surface soils. Active dunes are found in close proximity to stabilized dunes, suggesting that the eastern dune field is presently at a reactivation threshold.

The western dune field differs from the eastern dune field in three notable ways: (1) individual dune morphology is less complex and less pronounced (Figure 3B), (2) surface soils are generally well developed with typical A-Bt-C or A-Btk-C profiles, and (3) table-like dune morphology, not found in the eastern dune field, is present. The less-complex dune morphology and the mature surface soils are the result of prolonged stability in the western dune field. Wind data suggest that the North Platte River is not the present sediment source for the western dune field, and consequently, the western dune field presently lacks a regular and constant supply of sediment.

Located near Hiland, Wyoming are six large individual parabolic aeolian features found only in the western dune field. These six dunes, termed ‘table-dunes’ for purposes of this study,

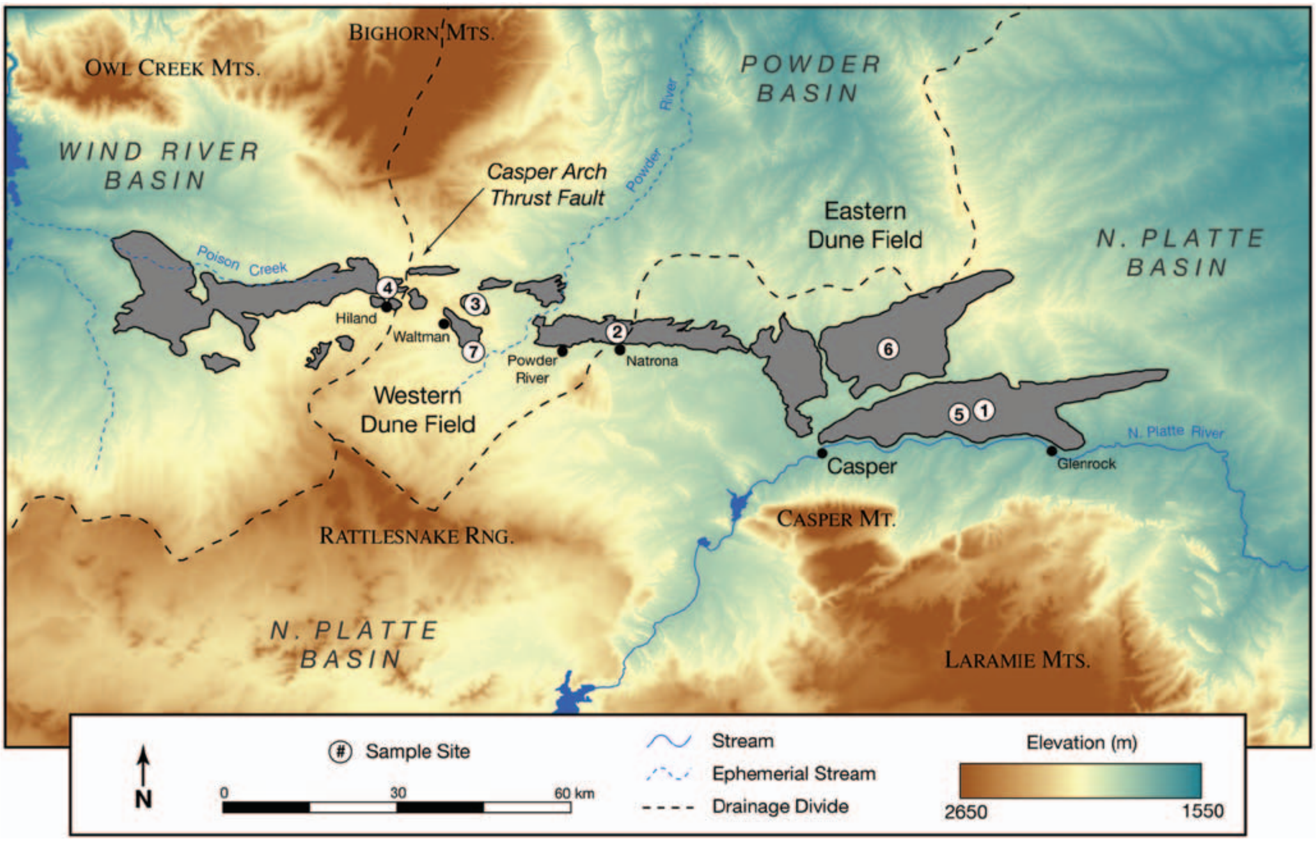

Figure 2. USGS hill shade image of the Central Wyoming Basin showing the Casper Dune Field, basin drainage networks, and study sample sites

have a footprint ranging from 0.75 to 2.5 km^2 (Figure 3C). We classified these features as table-dunes, because the overall appearance is that of a large flat, gently sloping, landform. The table-dunes exhibit characteristics similar to smaller dunes throughout the dune field, in that dune sediment is well-sorted medium to coarse sand, a west-southwest paleowind direction is indicated, the surface of the dune dips upwind at 5–8°, and cross-bedding is present. The large sizes of the table-dunes suggest that sediment was once abundant in the western dune field.

Methods

Sediments and soils were described and collected from dunes where fluvial erosion and or active blow-outs exposed the internal stratigraphy. These locations were determined by both aerial imagery and field reconnaissance, and sediment was sampled from four of seven sites for detailed laboratory analysis and dating. Samples were analyzed for particle size using laser diffraction (Beuselinck, 1998). A ratio of clay-to-sand size particles was used to analyze increased pedogenic fine particles because the percent of silt size particles remains relatively constant throughout the dune field (Figure 4). Moisture, organic matter (OM), and $CaCO_3$ concentrations were measured using 100°C, 550°C, and 1050°C loss-on-ignition temperatures, respectively (Heiri *et al*., 2001). Numerical age data were obtained with ^{14}C and OSL dating.

Samples collected for ^{14}C dating were from primarily buried soils found in the CDF: eight soil samples from site 1, two soil samples from site 2, and one soil sample from site 3. Other samples dated using ^{14}C included one charcoal sample and one organic-rich (1.4% versus 0.7% above and 0.7% below) sediment sample from site 1. Samples were picked to remove rootlets and treated with 3N HCl solution to remove carbonates and fulvic acids, followed by a 1N NaOH solution wash to remove humic acids. Lastly, samples were re-washed in 3N HCl solution to maintain acidity prior to combustion. Ages were determined using the accelerator mass spectrometry (AMS) method at the National Science Foundation – Arizona Acceleratory Mass Spectrometry Laboratory. Age data were corrected for $\delta^{13}C$ fractionation and calibrated using the Fairbanks *et al*. radiocarbon calibration curve (Fairbanks *et al*., 2005) (Table 1).

OSL has been shown to be highly effective in dating aeolian sediments (Forman *et al*., 2008, 2009; Hanson *et al*., 2009; Mahan *et al*., 2009; Mason *et al*., 2004, 2008; Mayer and Mahan, 2004; Miao *et al*., 2007; Rawling *et al*., 2003, 2008). Quartz-dominated aeolian sediments were dated using OSL at the United States Geological Survey Luminescence Dating Laboratory in Denver, Colorado. OSL estimates the time a mineral grain was last exposed to sunlight, and hence its burial age. Buried sediments no longer exposed to the sun store electrons mostly produced from the active decay of radioactive elements K, Th and U.

The cosmic-ray portion of the total dose rate was estimated for each sample as a function of depth, elevation above sea level and geomagnetic latitude (Prescott and Hutton, 1994; Prescott and Stefan, 1982). Moisture was estimated from samples collected together with the OSL samples. Measured elemental concentrations, associated dose rates, and cosmic ray contributions for instrumental neutron activation analyses (INAA) are presented in Table 2.

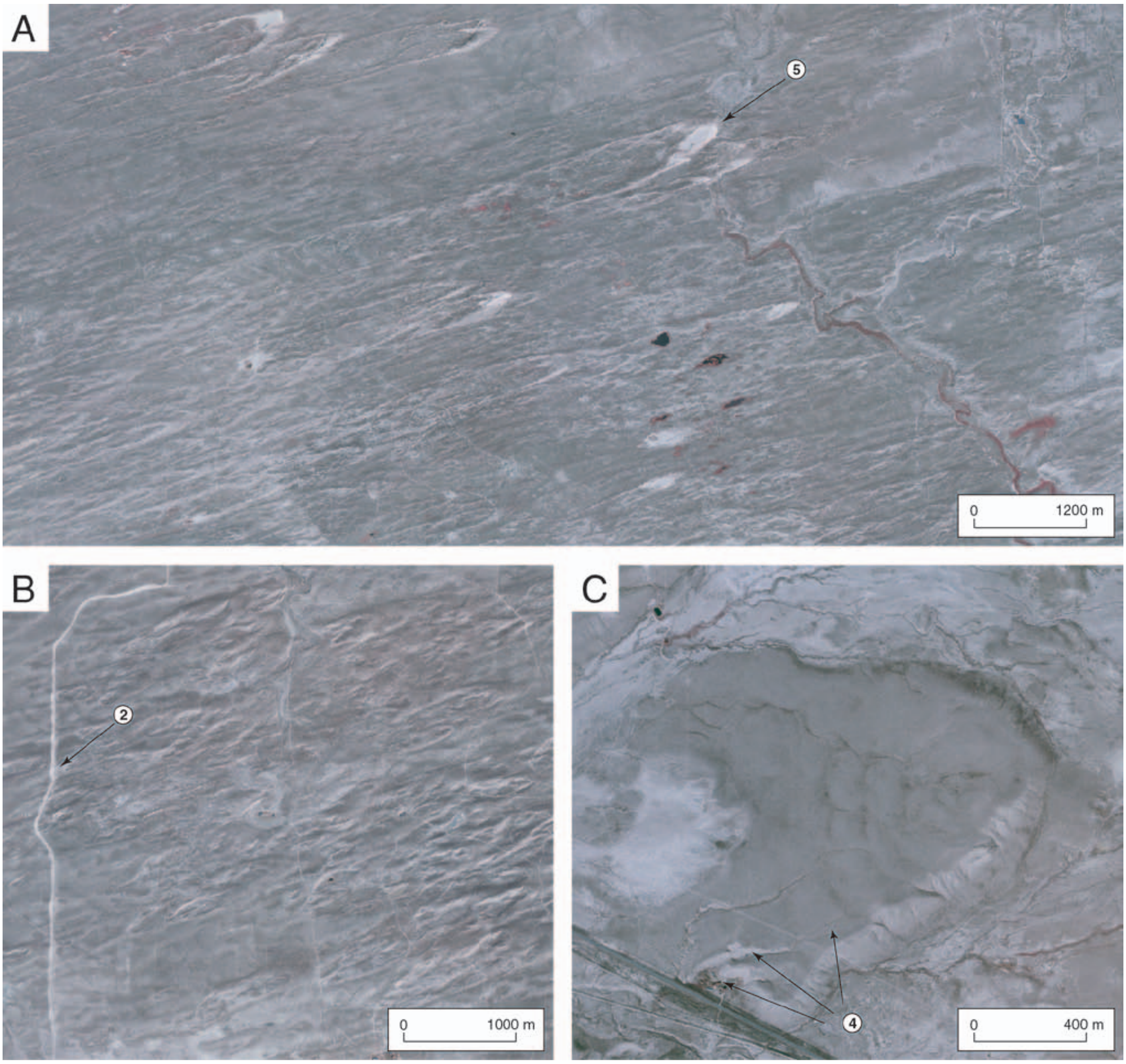

Figure 3. USGS aerial images of (A) the eastern dune field showing complex and hairpin parabolic dunes including site 5 (not sampled for chronology), (B) less complex linear dunes of the western dune field including sample site 2, and (C) one table-dune feature of the western dune field including sample site 4

Under subdued orange-light, potential light-exposed end material from each sample (~ 3 cm) was discarded, and the remaining interior part of the sample was prepared for dating using established procedures (Millard and Maat, 1994; Roberts and Wintle, 2001; Singhvi *et al*., 2001). Samples were first treated with 10% HCl and 30% H_2O_2 to remove carbonates and organic matter, and were then sieved to extract the 250–180 µm-size fraction. Heavy liquid separation (lithium tungstate 2.58/2.66 g/cm^3) was used to separate heavy minerals from quartz and feldspar grains. The quartz fraction was etched using 40% HF for 40 min to remove the outermost layer affected by alpha radiation, followed by treatment of 6N HCl for 10 min to remove any fluorides that may have been produced during HF treatment. Approximately 200–250 quartz grains were mounted on the inner 2 mm of multiple stainless steel discs using Silkospray®.

Blue-light OSL analysis was performed on 250–180 µm quartz using the single-aliquot regenerative dose (SAR) protocol (Murray and Wintle, 2000) to determine the paleodose. A five-point measurement strategy was adopted with three dose points to bracket the paleodose, a fourth zero dose and a fifth repeat-paleodose point. The repeat paleodose was measured to correct for sensitivity changes and check that the protocol was working correctly. All measurements were made at 125°C for 40 s after a pre-heat at 220°C or 240°C for 10 s. For all aliquots, the accepted recycling ratio between the first and the fifth point ranged within 0.85–1.15. Data were analyzed using the ANALYST program of Duller (1999). In each case, at least 20 aliquots, and sometimes as many as 45 aliquots, from each sample were analyzed. Dose recovery and preheat plateau tests were performed to ensure that the sediments were responsive to optical techniques and that the proper temperatures were used in

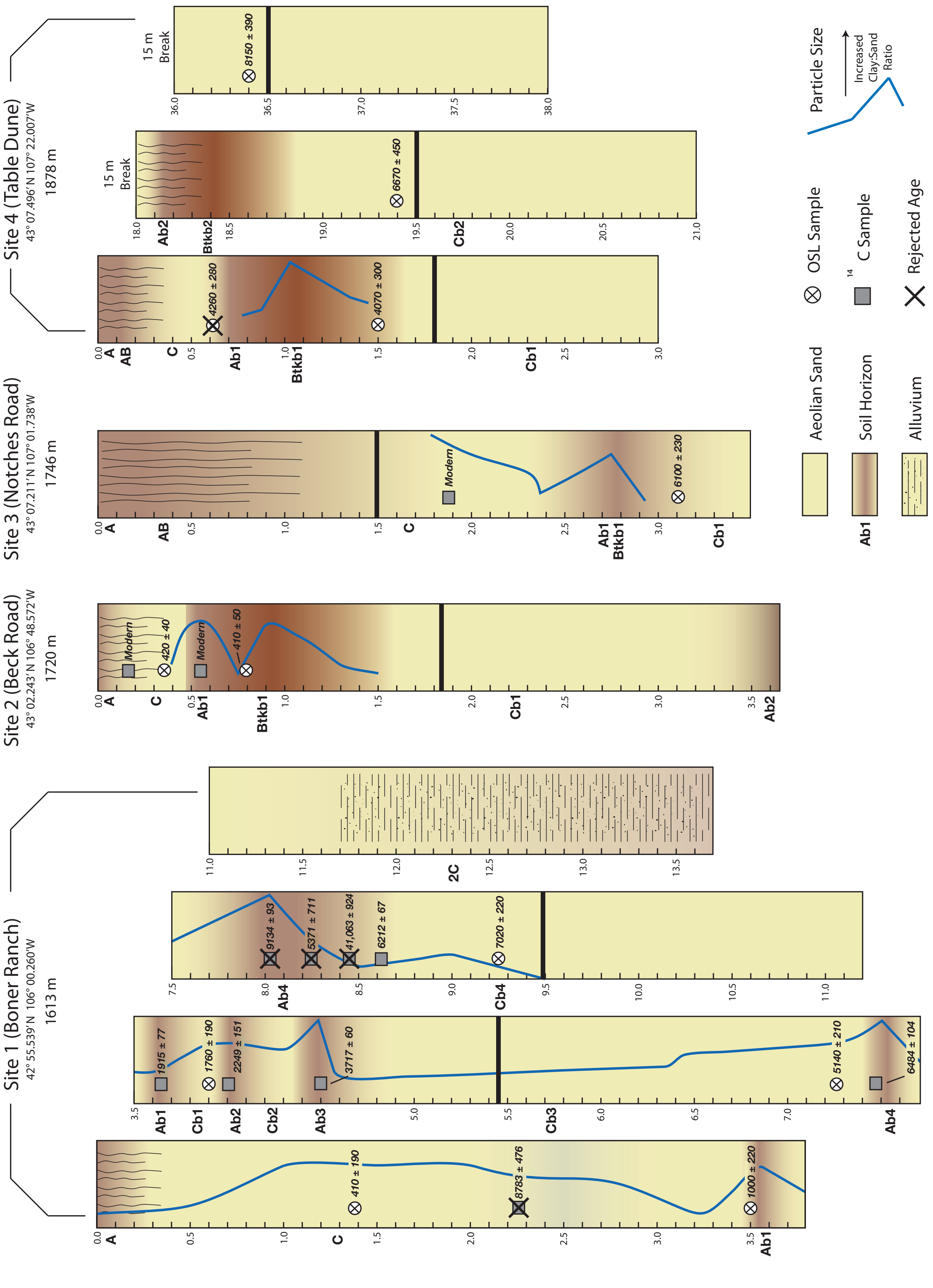

Figure 4. Stratigraphic profiles of sample sites

Table 1. Calibrated radiocarbon ages from the Casper Dune Field

Field number	Lab. number	Material dated	$\delta^{13}C$ (‰)	Sample depth (m from surface)	Corrected age (^{14}C yr BP)	Calibrated age[a] (yr BP)
Site 1 (Boner Ranch)						
6007	AA-72641	Total OM[b]	–23.9	2.25–2.30	7910 ± 400	8783 ± 476
6013	AA-72651	Total OM	–23.2	3.60–3.65	1970 ± 70	1915 ± 77
6015	AA-72650	Total OM	–24.2	4.25–4.30	2240 ± 120	2249 ± 151
6022	AA-72642	Total OM	–22.7	4.45–4.50	3460 ± 40	3717 ± 60
6027	AA-72655	Total OM	–22.0	7.45–7.50	5700 ± 90	6484 ± 104
6029	AA-72645	Total OM	–21.9	8.00–8.05	8190 ± 60	9134 ± 93
6067	AA-72654	Total OM	–25.4	8.25–8.30	4710 ± 580	5371 ± 711
6068	AA-72648	Total OM	–22.1	8.60–8.65	5410 ± 60	6212 ± 67
6069	AA-72652	Charcoal	–23.4	8.40–8.50	35,800 ± 1000	41,063 ± 924
Site 2 (Beck Road)						
6043	AA-72640	Total OM	–21.5	0.30–0.35	Post Bomb	-
6045	AA-72644	Total OM	–27.4	0.50–0.55	Post Bomb	-
6048	AA-72638	Total OM	–22.9	0.95–1.00	3730 ± 50	4078 ± 74
Site 3 (Notches Road)						
6035	AA-72639	Total OM	–21.5	2.00–2.05	Post Bomb	-

[a]Radiocarbon ages were calibrated using the Fairbanks *et al.* calibration curve (Fairbanks *et al.*, 2005).
[b]Organic matter.

Table 2. Luminescence ages from the Casper Dune Field

Field Number	Sample Depth (m from surface)	K (%)	Th (ppm)	U (ppm)	H_2O[a,b](%)	Dose Rate (Gy/ka)[c]	De (Gy)[d]	Aliquots[e]	Age[f]
Site 1 (Boner Ranch)									
6055	1.45–1.50	2.39	3.97	1.27	0.4 ± 0.5	2.93 ± 0.05	1.19 ± 0.54	16 (45)	410 ± 190
6056	3.60–3.65	2.09	3.87	1.45	4.0 ± 0.5	2.64 ± 0.03	2.63 ± 0.53	13 (40)	1000 ± 220
6057	4.00–4.05	2.25	3.86	1.07	1.0 ± 0.5	2.67 ± 0.03	4.71 ± 0.51	14 (23)	1760 ± 190
6058	7.25–7.30	2.29	6.00	1.32	5.0 ± 0.5	2.87 ± 0.04	14.7 ± 0.33	18 (25)	5140 ± 210
6059	9.25–9.30	2.38	7.42	1.43	4.0 ± 0.5	3.03 ± 0.04	21.3 ± 0.80	25 (35)	7020 ± 220
Site 2 (Beck Road)									
6061	0.35–0.40	2.03	11.0	2.22	1.0 ± 0.5	3.35 ± 0.03	1.38 ± 0.15	17 (20)	410 ± 50
6062	0.90–0.95	2.07	5.07	1.70	2.0 ± 0.5	2.87 ± 0.04	1.20 ± 0.12	16 (30)	420 ± 40
Site 3 (Notches Road)									
6060	3.10–3.15	2.04	5.37	1.46	3.0 ± 0.5	2.77 ± 0.04	16.9 ± 0.59	16 (25)	6100 ± 230
Site 4 (Table-Dune)									
6063	0.60–0.65	1.96	7.20	1.82	1.0 ± 0.5	2.87 ± 0.04	12.2 ± 0.78	22 (40)	4260 ± 280
6064	1.45–1.50	2.03	5.68	1.61	3.0 ± 0.5	2.76 ± 0.04	11.2 ± 0.82	17 (20)	4070 ± 300
6065	1.50–1.55	1.92	7.08	1.94	4.0 ± 0.5	2.79 ± 0.04	18.6 ± 1.22	22 (30)	6670 ± 450
6066	0.50–0.50	2.27	6.28	1.91	2.0 ± 0.5	3.00 ± 0.04	24.6 ± 1.15	29 (35)	8150 ± 390

[a] Field moisture, ages measured at 10% moisture contact, recording wetter than field but drier than saturation moisture values.
[b] Total dose rate is calculated from 10% water content.
[c] Reported to one sigma, fit to an exponential + linear regression.
[d] Accepted disks (all disks).
[e] Lab used fine sand grains (250–180 micron size).
[f] Reported in yrs ka.

producing the equivalent dose values. Run parameters for the blue-light OSL are given in Table 2. Acceptable preheat temperatures ranged from 200 to 280°C, although 220°C or 240°C were used exclusively. An IRSL stimulation of 100 s before the blue-light stimulation of 40 s was used to completely drain any residual feldspar contamination. OSL age and dosimetry data are reported in Table 2.

Stratigraphy

Site 1 (42°55.539′N, 106°00.260′W, 1613 m)

Site 1, on the Boner Ranch, is located in the eastern dune field on the north wing of a stable parabolic dune and consists of 11.5 m of aeolian sediment deposited on an alluvial substrate at an elevation of 1602 m. Aeolian sediments are medium to coarse sand, with less than 1.0% OM and 0.1–2.0% $CaCO_3$, whereas buried soils are typically silty clay to fine sand, 0.5–2.0% OM, and highly variable in $CaCO_3$ content (0.5–4.5%). A weak surface soil (A-C) is present. Though an active blowout partially exposed the dune stratigraphy, the complete stratigraphic column had to be assembled from four individual profiles created on the dune wing (Figure 4). Profile depths are relative to the top of the dune wing at profile 1.

Profile 1, consisting of 3.6 m of aeolian sand, exhibited a buried soil (Ab1) at 3.6 m. Two OSL samples, collected at 1.4 and 3.6 m, yielded ages of 0.4 ka (6055) and 1.0 ka (6056), respectively. A ^{14}C age of 8.8 ka (6007) was obtained from sediment at 2.5 m. Ab1 can be traced west along the dune wing to profile 2, which consist of 5.0 m of aeolian sand. Buried soils occurred within the profile at 3.6 m (Ab1), 4.0 m (Ab2), 4.4 m (Ab3), and 7.4 m (Ab4) and date to 1.9 ka (6013), 2.3 ka (6015), 3.7 ka (6022), and 6.5 ka (6027), respectively. Sediment between Ab1 and Ab2 was dated 1.8 ka (6057), and sediment above Ab4 was dated at 5.1 ka (6058). Ab4 is traceable though the dune wing to profile 3, which consists of 4.0 m of aeolian sand. Ab4 is not easily recognizable in profile 3, though increased OM and $CaCO_3$ suggest that the soil lies between 8.0 and 8.5 m. Three ^{14}C ages were determined for Ab4 in profile 3: 9.1 ka (6029), 5.4 ka (6067), and 6.2 ka (6068). A high concentration of charcoal, found within Ab4 at 8.4 m dated to 41.0 ka (6069). Aeolian sediment at 9.2 m was dated 7.0 ka (6059).

Site 2 (43°02.243′N, 106°48.572′W, 1720 m)

Site 2 is located on the eastern edge of the western dune field, north of Natrona, Wyoming, along Beck Road, which cuts through several parabolic dune wings, exposing dune stratigraphy. A 3.6-m profile, constructed on the east side of the road on a well-exposed dune wing (Figure 4), exposed aeolian sediments similar to those of the eastern dune field, i.e. typically medium to coarse sand, 0.7–1.5% OM, and 1.0–2.5% $CaCO_3$. A weak surface soil with no subsoil development is underlain by a well-developed Ab-Btb-Cb buried soil located between 0.5 and 1.5 m. An OSL sample above the soil dated 0.4 ka (6061), and another below the soil A horizon was dated to 0.4 ka (6062). A bucket auger was used to extend the profile to 3.6 m where another buried soil (Ab2) was encountered, but was not accessible for sampling. Two ^{14}C samples collected from Ab1 yielded modern ages (6043, 6045). Collectively, the OSL and ^{14}C ages indicate that surface sediment (i.e. the upper 0.5 m of sediment) was recently deposited.

Site 3 (43°07.211′N, 107°01.738′W, 1746 m)

Site 3 is located in a small isolated section of the dune field north of Waltman, Wyoming. Parabolic dunes are present but are less pronounced than those of the eastern dune field. Notches Road cuts through several dune wings, providing natural exposures of dune stratigraphy where a 3.6 m profile was excavated on the east side of the road (Figure 4). Unlike other sample sites, Site 3 has a silt-dominated surface soil (A-B) with 1–2% OM and 2–3% $CaCO_3$. A buried soil is was located at 2.6 m above sediment OSL dated at 6.1 ka (6060).

Site 4 (43°07.496′N, 107°22.007′W, 1878 m)

Site 4 is located west of Hiland, Wyoming, on the south flank of a table-dune. The surface of Site 4 is stabilized by vegetation, and, because of the size of the dune, it was not possible to expose the complete internal stratigraphy. However, three profiles, created from natural exposures within an ephemeral stream dissecting the dune, are believed to be representative of the upper, middle, and lower stratigraphic units of the dune (Figure 4). Aeolian sediment is medium to coarse sand and contains 0.5–1.0% OM and 1.3–2.5% $CaCO_3$. A downward coarsening of sediment was noted at the base of the dune.

Profile 1, located at the top of the dune, is characterized by an A horizon formed in 3.0 m of aeolian sand. A buried soil (Ab-Btkb1), located at 0.8 m, yielded an OSL age of 4.3 ka (6063, 6064). Bedding planes are visible within the profile and dip in the upwind direction between 5 and 8°. A bucket auger used to extend the profile into the dune detected no visible changes in grain size or color. Profile 2 is located in the middle of the dune, ~ 15.0 m down in elevation from profile 1, and is characterized by 3.0 m of aeolian sand underlain by a buried soil (Ab-Btkb2) at 0.3 m. A bucket auger was used to extend the profile to 3.0 m, again with no discernable color or texture changes. Aeolian sediment below the Ab-Btkb2 dated with OSL to 6.7 ka (6065). Profile 3 is located at the base of the dune, ~ 15.0 m down in elevation from profile 2 yielded an OSL age of 8.2 ka (6066) and is characterized by an overall coarsening of sediment and lack visible buried soils.

Discussion

Problematic ^{14}C and OSL ages

Over- and underestimation of ^{14}C ages can occur for multiple reasons, especially when total organic matter dating is used to derive the age (see Mathews, 1985; Mayer *et al*., 2008; Wang and Amundson, 1996). Nevertheless, investigations have used ^{14}C dating with good results in similar studies (Holliday, 2001; Mason *et al*., 2004; Mayer and Mahan, 2004; Rawling *et al*., 2003). Though the majority of ^{14}C ages reported in this study are stratigraphically consistent and support the OSL-derived chronology of aeolian activation, four ^{14}C ages derived from site 1 are rejected (6007, 6029, 6067 and 6069). Upon re-examination, modern root contamination, bioturbation, and the presence of Pleistocene-aged charcoal collectively have probably influenced ages of these samples. An age of 8783 ± 476 (6007) was obtained from sediment with higher organic concentrations than the surrounding soils (1.4% versus 0.7 % above and 0.7% below). This age, bracketed between two OSL ages of 0.4 ka and 1.0 ka, is too old and is therefore excluded from our chronology. Also from site 1, two ^{14}C ages of soil Ab4, 9134 ± 93 (6029) and 5371 ± 711 (6067) are very different. We speculate that the discrepancies in these ages can be attributed to contamination by older charcoal and modern rootlets, respectively. An age of 6484 ± 104 (6027), taken from the base of profile 2, is likely the best representative age of soil Ab4. This age was sampled below stratified sediment with no evidence of current or past sediment mixing by soil biota; furthermore, no charcoal was found in profile 2. The age of 6218 ± 67 (6068), dated from profile 3, corroborates the previous age from the same buried soil. Together the ages of 6.5 and 6.2 ka provide a good age range for soil Ab4. Finally, the age of 41,063 ± 924 (6069) likely represents older charcoal incorporated into the dune during aeolian sedimentation but does not represent an age of dune formation.

Two OSL samples (6055, 6056) from site 1 produced questionable ages because of a low number of accepted aliquots (<20 out of 45). These sediments suffered from unacceptable recycle ratios on equivalent dose analyses (e.g. >20%) and poor test dose responses (e.g. ranges from >25% to <50%). This sort of behavior is seen in sediment that has not been through repeated cycles of erosion and deposition (e.g. debris flows, some colluvium and alluvium), sediment that is either very young or very old, sediment that contains quartz without a common OSL component, or sediment that contains inclusions of other minerals within the quartz (Arnold *et al*., 2009; Preusser *et al*., 2009; Sohn *et al*., 2007).

We ruled out several possibilities (e.g. old samples, inclusions of minerals in quartz, no common OSL component), since we tested for many of these problems and did not find them. Three possibilities remain: the last burial of the quartz was recent and without single grain analyses this can not be adequately determined; some of the quartz has not been through multiple erosion/deposition cycles; and finally, the quartz is a mixture of very young aeolian and older partially bleached alluvium. There remain too few aliquots to address the problem of partial bleaching, but the averaged age from the samples (0.4 ka and 1.0 ka) could still be a true depositional age based on observable stratigraphy in the CDF. Nevertheless, these ages are duplicated elsewhere in the CDF (e.g. Beck Road samples show the same 0.4 ka activation ages) and the previously reported chronology of the Killpecker dune field shows that aeolian sedimentation occurred after 1.0 ka (Mayer and Mahan, 2004).

Finally, two OSL ages at site 4 have similar ages but are separated by a distinctive Ab-Btkb soil. Considering the time needed to form Btk horizons, it is unlikely that both of these ages are correct. Based on site stratigraphy, specifically that sample 6064 below the soil in undisturbed sediment, we accept the age of 4.1 ka (6064) as most likely a correct age. We reject the age of 4.3 ka (6063).

Correlations between the Casper Dune Field and other Wyoming dune fields

Numerical age data presented in this study support a variable dune field response to landscape changes throughout the Holocene. Diverse sample sites and disparate age control limit our chronological interpretations to select areas within the CDF. Nevertheless, our data suggest an activation and stabilization chronology similar to previous CDF chronologies (Albanese, 1974a, b; Albanese and Frison, 1995), and to other Wyoming dune fields, specifically an episode of dune activation around ~4.2–4.1 ka (Gaylord, 1982, 1990; Mayer and Mahan. 2004; Stokes and Gaylord, 1993) (Figure 5). Prior to aeolian activation, alluvium was deposited in the Central Wyoming Basin at the onset of the Holocene (Albanese and Frison, 1995), which is corroborated by the presence of alluvium found at the bottom of the dune documented at site 1.

Albanese (1974a, b) suggested that activation began in the CDF after 10.3 ka, based on the presence of bison bones within aeolian dune sediment at the Casper Archeological Site, north of Casper, Wyoming. Ages in our study suggest that aeolian activity occurred in both the eastern and western dune fields at 7.0 and 8.2 ka, respectively, and supports the assertion that activation had occurred after ~ 10.0 ka. Dune activity occurred throughout the early Holocene in both eastern and western parts of the CDF and lasted until about ~ 6.1–6.7 ka. The ^{14}C ages of 6.2 and 6.5 ka on a buried soil at site 1 document this period of stability. Soils above aeolian sediment at site 1, 3 and site 4 suggest that some degree of stability occurred after 7.0, 6.1 and 6.7 ka, respectively. Dune activity between 8.2 and 6.1 ka coincides with an interval of warming and drought recorded throughout the Great Plains (Holliday *et al*., 2008; Nordt *et al*., 2008).

Albanese (1974a, b) and Albanese and Frison (1995) described a subregional soil, termed the Haplargid soil (informal term, derived from inferred soil taxonomic classification), in the Ferris Dune Field and on the eastern and western edges of the CDF. The Haplargid soil has an aeolian-derived clay-rich B horizon that at some locations is highly calcareous (Albanese and Frison, 1995). Albanese and Frison (1995) bracket the Haplargid soil formation as beginning at 5.7 ka. Eckerle (1997) also found a soil with similar characteristics south of Casper, Wyoming within aeolian sediment, which dated to 4.5 ka. Mayer and Mahan (2004) dated Farson soil development in the Killpecker Dune Field to 5.9 ka. Based on ages of soil development, the Farson soil and Haplargid soil may represent the same period of stability.

Our study also documents stability and soil development (sites 1, 3, and 4) between ~ 6.7 and 6.1 ka. Ages of dune field stability presented in this study support an older regional soil than that suggested by Albanese and Frison (1995) and Eckerle (1997). However, Mayer and Mahan (2004) also support older dune stabilization in the Killpecker Dune Field at 5.9 ka, and Stokes and Gaylord (1993) show a minor degree of stability in one section of the Ferris Dune Field at ~ 6.8 to ~ 6.7 ka. It is likely that all Wyoming dune fields stabilized in the middle Holocene, although the stabilization for some areas occurred earlier than others.

The length of the middle Holocene stabilization was variable within our sample sites with some sites suggesting relatively short stability and others, long periods of stability. At site 1, in the eastern dune field, another episode of dune activity stratigraphically above the 6.5 ka soil was dated at 5.1 ka suggesting a period of stability of less than 1.5 ka. At site 4, in the western dune field, dune activity was dated at 4.1 ka and suggests that stability at 6.7 ka lasted for ~ 2.5 ka. At site 3, in the western dune field, no ages directly support the reactivation of the dune following stability at ~ 6.1 ka. Although reactivation is not supported by numerical ages, a gap in soil development at 2.0 to 2.5 m suggests that a minor episode of reactivation occurred following 6.1 ka. It is possible that the episodic dune activation recorded in site 1 at 5.1 ka and within the stratigraphy at site 4 represents localized dune mobilization rather than a broader response to regional climate change.

One OSL age from site 4 indicates that aeolian activity in the CDF began again around 4.1 ka. Although reactivation is not supported by ages from all sample sites in the CDF, OSL ages from the Killpecker Dune Field and the Ferris Dune Field also show activation around 4.2 ka. These ages, coupled with ages from our study, suggest that regional activation of Wyoming dune fields occurred at 4.2 to 4.1 ka. Following a brief period of dune activity at 4.1 ka, the CDF appeared to stabilize. At sites 2, 3, and 4, stratigraphy suggests that stability prevailed for the rest of the Holocene, except for a possible short reactivation at sites 2 and 4. At site 2, two OSL samples indicate aeolian activity at 0.4 ka. Reactivation is documented at site 1 through the late Holocene: activation at 1.8 ka is noted between two bracketed ^{14}C ages on buried soils. This period of activation at site 1 around 1.8 ka also coincides with that in the Killpecker Dune Field (Mayer and Mahan, 2004). Most recent dune activation is indicated at site 1 around 1.0 ka and coincides with the Medieval Climate Anomaly (MCA) drought. Similar aeolian activation is noted in the Killpecker and Ferris Dune Fields.

The chronology established from four sites in the CDF suggests that three widespread periods of dune activation occurred during the Holocene. These periods of activation are ~10.0–6.2, ~4.2–4.1 ka, and from 1.0 ka to 0.4 ka, and are also noted in other Wyoming dune fields. It is evident that localized reactivation occurred at specific sites throughout the Holocene, with greater localized reactivation occurring in the eastern dune field. Dune morphology supports a more active eastern dune field and more frequently stable western dune field. In the eastern dune field parabolic dunes are more elongated, suggesting long-term movement and development. Many of these elongated dunes have paleocrest features downwind of the current crest, suggesting multiple stability and activation cycles. The complex dune morphology of the eastern dune field also indicates that it remains closer to a reactivation threshold, making dunes more susceptible to changes in environmental conditions. We hypothesize that one localized control of reactivation in the eastern dune field is

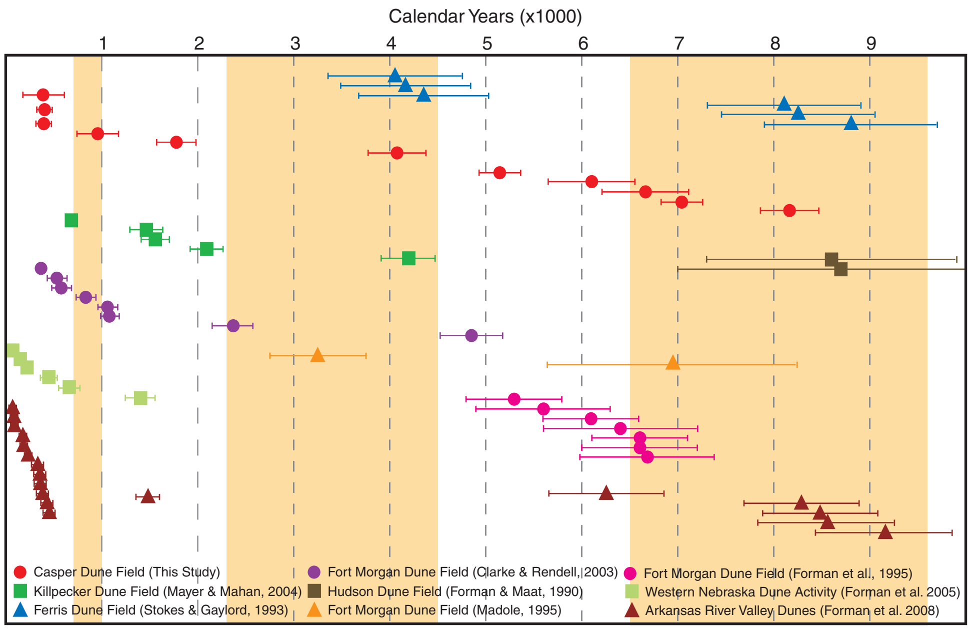

Figure 5. Comparison of OSL ages from this study to ages of other west-central Great Plains dune field studies. Vertical shading represent periods of dune activity identified in the Nebraska Sand Hills (Miao *et al.*, 2007)

related to an influx of sediment from the North Platte River. Sediment influx could explain why the eastern dune field was reactivated several times, while the western dune field, lacking a regular supply of sediment, remained relatively stable.

Variation in luminescence dating techniques may account for some of the age variability between our ages and those reported in other studies. For example, early IRSL and OSL ages were likely reported with larger errors, on the order of 10 to 20% (e.g. Stokes and Gaylord, 1993; Forman *et al*., 1995). Ages produced using SAR (e.g. Forman *et al*., 2008, 2009; Goble *et al*., 2004; Mayer and Mahan, 2004) have smaller errors, on the order of 15 to 5%. Examples of variables that can affect OSL ages include the use of different equivalent dose protocols (i.e. multiple aliquot additive dose on silt, multiple aliquot regeneration on sand-sized grains, or single aliquot regeneration on sand-sized grains) and different approaches to measurement of the signal (i.e. continuous-wave, linearly modulated, pulsed, etc.).

Correlation with the west-central Great Plains

Although age data regarding timing and duration of dune activation in the CDF are limited, several ages correlate with dune activation in other west-central Great Plains dune fields (Figure 5). Dune activation was widespread in most dune fields during the early Holocene, including the CDF (Albanese and Frison, 1995; this study), Ferris Dune Field (Stokes and Gayloard, 1993), Hudson Dune Field (Forman and Maat, 1990), Arkansas River valley dunes (Forman *et al*., 2008), and the Nebraska Sand Hills (Miao *et al*., 2007). Original dune activity in these dune fields is dated to the early Holocene, and activity continued through 8.2 ka, a globally recognized drought event (Alley and Ágústsdóttir, 2005; Bond *et al*., 2001). The correlation of dune activation in west-central Great Plains dune fields during early Holocene drought supports a region-wide drought prior to the 8.2 ka event, and drought at 8.2 ka may have intensified dune activity in some dune fields of the west-central Great Plains. Many dune fields were active into the middle Holocene, though activation did not cease simultaneously in all dune fields. For example, Forman *et al*. (2001) documents dune activity within the Fort Morgan Dune Field from ~7.0 to 5.5 ka, whereas the Nebraska Sand Hills are stable from ~6.5 to 4.5 ka (Miao *et al*., 2007). Whereas the Nebraska Sand Hills were generally stable from 6.5 to 4.5 ka, local activation occurred during this interval (Miao *et al*., 2007). Similarly, at least one site in the CDF (Site 1) exhibits episodic aeolian activity throughout the middle Holocene. It is hypothesized that this localized signal may represent aeolian sediment influx to the dune field rather than regional climate change.

Following regional stabilization in the middle Holocene, drought again appeared to cause widespread dune activity in the west-central Great Plains. Clarke and Rendell (2003) reported dune activation beginning at ~ 4.9 ka in the Fort Morgan Dune Field, and the Killpecker Dune Field, Ferris Dune Field, and the Casper Dune Field all indicate activity beginning around ~ 4.2 ka (Mayer and Mahan, 2004; Stokes and Gaylord, 1993; this study). Activation of these dune fields at this time may be coincident with the 4.2 ka event, a global cooling event (Bond *et al*., 2001). Booth *et al*. (2005) reported that this event is recorded in North America and suggested that it may be linked to La Niña-like sea surface temperature gradients in the tropical Pacific Ocean. Dune activity at 4.2 ka in Wyoming and is short lived and may be tied to drought recognized in the Nebraska Sand Hills centered at 3.8 ka (Miao *et al*., 2007). It is possible that dry conditions persisted longer in the Nebraska Sand Hills than in Wyoming. The difference in age may not be significant, however, given the estimated errors.

Activation is documented in the Fort Morgan Dune Field at ~ 1.1, 0.8, 0.6 and 0.4 ka (Clarke and Rendell, 2003), the Nebraska Sand Hills at 1.4, 0.7, 0.5, 0.2, and 0.1 ka (Forman *et al*., 2005), the Arkansas River valley dunes centered at 1.5, 0.4, 0.4–0.3, 0.2, and 0.1 ka (Forman *et al*., 2008), and the Killpecker Dune Field at 2.0 and by at least 0.7 ka (Mayer and Mahan, 2004). Miao *et al*. (2007) attributed activity in the Nebraska Sand Hills to drought during the MWP. Drought at ~0.5 ka has been recorded in tree rings and may coincide with aeolian activity recorded in the Nebraska Sand Hills (e.g. Forman *et al*., 2005). Miao *et al*. (2007) suggested that lags in aeolian system response might explain some age variability of aeolian activations during the latest Holocene. Undocumented, lagged responses and variations in dating techniques might adequately explain the variable aeolian activity in many of the west-central Great Plains dune fields. It is apparent from the many chronologies that dune fields were active throughout the region during the late Holocene in response to widespread droughts.

Conclusions

Widespread dune activity occurred in the CDF after ~ 10 ka, following deposition of alluvium at the end of the Pleistocene. Activity continued through the middle Holocene until about 6.2 ka and was followed by stability and soil development. Another episode of activation occurred around ~ 4.1 ka, followed by stability and a final episode of activation between 1.0 and 0.4 ka. Localized activation occurred in at least one site several times during noted periods of regional stability. These activations suggest that localized factors, such as sediment supply and water-table fluctuations, may play an important role in dictating dune field stability. Activity in the CDF, the Killpecker Dune Field, and the Ferris Dune Field occurred at 8.2, and correlate very well at 4.1, and 1.0 ka. Activity in the CDF also corresponds to activity in other west-central Great Plains dune fields. This study supports the contention that widespread droughts throughout the Holocene led to dune field activation, and also suggests that localized controls on dune fields can also play significant roles in landscape instability.

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