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# Quaternary Science Reviews

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## Modern and late Holocene wind regimes over the Great Plains (central U.S.A.)

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### ARTICLE INFO

#### Article history:

Received 31 January 2009

Received in revised form

29 October 2009

Accepted 8 November 2009

### ABSTRACT

The Great Plains of the central United States contain numerous presently stabilized dune fields that were active during the late Holocene. The most recent period of reactivation occurred about 700–1000 years ago during the Medieval Climatic Anomaly, a period of frequent, severe drought recognized throughout the North American West. Dune orientations and internal bedding preserve information about paleowinds from this time period. We compared paleowind information with modern winds and potential sand transport analyzed from meteorological data. While both reconstructed paleowinds and modern winds include a strong northwesterly component over the northern to central portions of the Great Plains, a significant difference exists to the south. During the late Holocene, southwesterly winds had a strong influence on dune forms over the central and southern Great Plains, while modern potential sand transport is dominated by southerly to southeasterly winds that bring moisture to the region from the Gulf of Mexico. Hypothetical dune types forming under modern winds would be different and have different crestal orientations than those preserved from the late Holocene. In order for such a shift in southerly winds to take place it is likely that: 1) the typical position of the Bermuda High in summer was shifted either to the east or to the south resulting in weaker low-level winds from the south and southeast and greater extent of southwesterly winds on the Great Plains, and/or 2) drought, likely enhanced by evapotranspiration and soil moisture feedbacks, brought the normally higher-level southwesterly flow down to the land surface. Given our understanding of megadroughts over the Great Plains as well as recent climate predictions for increased warmth and drought over this area, future reactivation of the dunes seems likely.

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### 1. Introduction

The Great Plains of North America is covered with numerous dune fields that have been active during the Holocene. Within the United States, the dune fields occur sporadically across an area from North Dakota to parts of Texas and from the eastern part of Colorado to eastern Nebraska (Fig. 1). These dune fields serve as an indicator of past decades to millennia of frequent, severe drought in the region. Presently, nearly all of these dunes are stabilized and are part of large grassland ecosystems. The productivity of the vegetative cover correlates strongly with the west to east gradient in precipitation over the central United States, with greater amounts of precipitation to the east. There is also a strong north to south temperature gradient across the region, with warmer temperatures to the south (National Map, 2009).

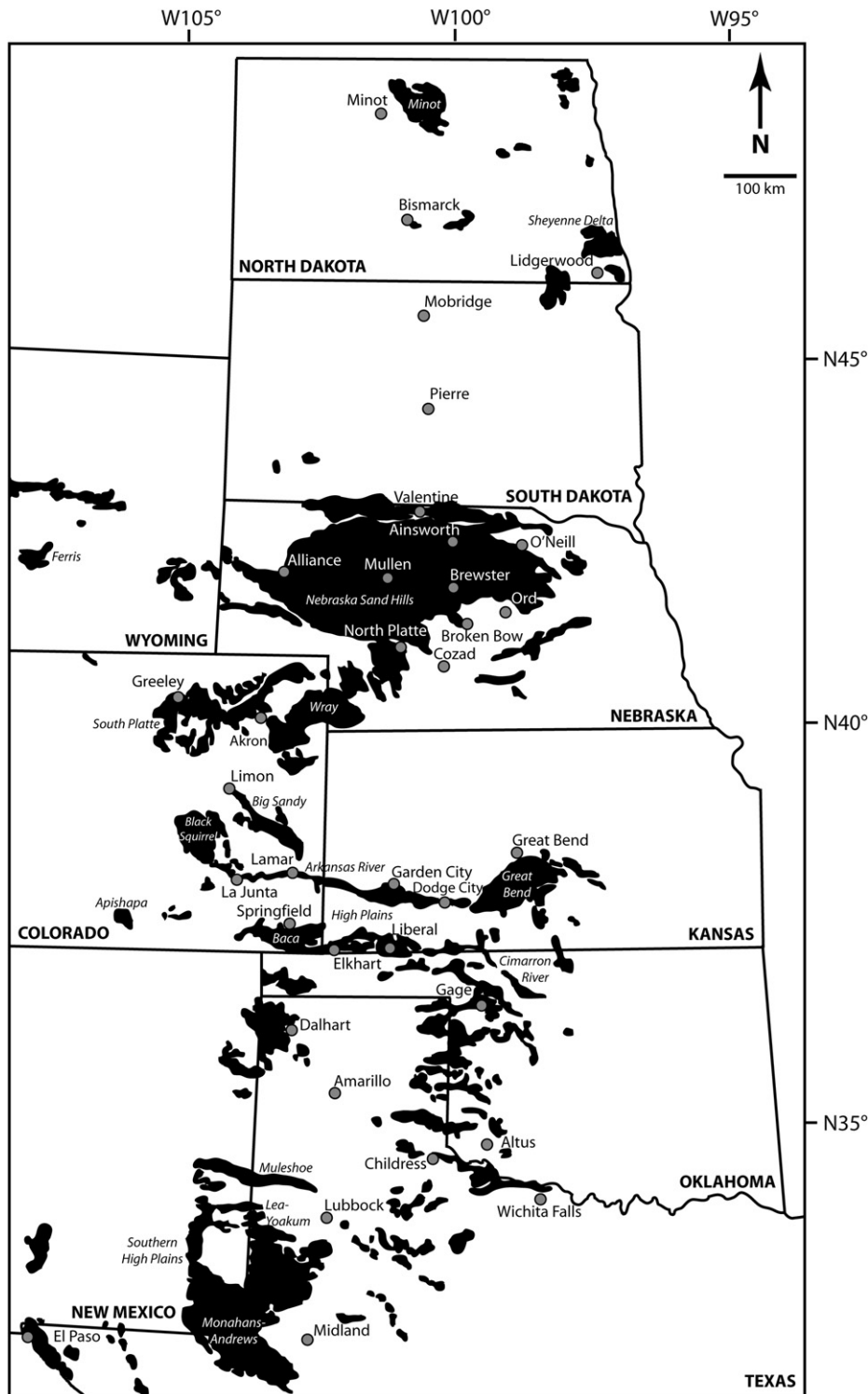
The goal of this study is to gain an understanding of how winds have shifted over the Great Plains since the last major dune reactivation (1050–650 years B.P.). Past directions of sand-transporting winds are preserved in dune orientations and internal structures while meteorological stations from the last few decades record detailed information about the strength and direction of modern winds. We use these two records of winds across the Great Plains to examine if and how winds have changed from a time of significant drought (the Medieval Climatic Anomaly) to a time of relatively high moisture (the present). This information may help to explain how the dunes have reactivated in the past. This is particularly important given the consensus of recent modeling studies that show that temperatures will rise substantially and summer precipitation may decrease across the Great Plains over the next century (Christensen et al., 2007), increasing the likelihood of drought during the growing season.

### 2. Previous work

Early studies concluded that the dune fields across the Great Plains formed and were active mainly during the Pleistocene, under

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**Fig. 1.** Map of Great Plains dune fields (black shading, after Muhs and Holliday (1995)-central and southern Great Plains and Muhs and Wolfe (1999)-northern Great Plains) and station locations (gray-filled circles). Dune field names are given in italics.

cool and dry glacial conditions (Smith, 1965; Watts and Wright, 1966; Warren, 1976; Sarnthein, 1978; Wells, 1983; Kutzbach and Wright, 1985). More recent radiocarbon and luminescence dating of the dunes throughout the region have shown that while the dunes may have initially formed during the Pleistocene, major dune activity occurred periodically throughout the Holocene (Ahlbrandt et al., 1983; Holliday, 1991, 2001; Madole, 1995; Arbogast, 1996; Muhs et al., 1996, 1997; Stokes and Swinehart, 1997; Loope and

Swinehart, 2000; Forman et al., 2001; Clarke and Rendell, 2003; Goble et al., 2004; Miao et al., 2007).

During the transition from the Pleistocene to the Holocene, about 11,500 calendar years ago, the ice sheets retreated as climate rapidly warmed, but the Great Plains remained fairly dry (Ahlbrandt et al., 1983). Widespread dune mobilization has been recognized following this transition, from about 9000 to 4500 years ago (Arbogast and Johnson, 1998; Forman et al., 2001; Holliday,

2001; Miao et al., 2007). Since approximately 5000 years ago, dune movement has been highly variable, with a number of discrete drift events throughout the region (Madole, 1994; Arbogast and Johnson, 1998; Muhs and Wolfe, 1999; Forman et al., 2001; Holliday, 2001; Lepper and Scott, 2005; Miao et al., 2007).

The most recent period of full dune reactivation (the Medieval Climatic Anomaly) is recognized in dune fields across the Great Plains from approximately 1050–650 years B.P. This event coincides with the Medieval Warm Period, a period of warm and variable climate recognized in Europe (Cook et al., 2004). This extended drought has been documented within North America using several types of proxies including lake levels and salinity, tree ring records (Cook et al., 2004), and timing of dune activity (Mason et al., 2004; Miao et al., 2007). Smaller, more recent droughts are recognized in some dune fields in the Great Plains (Clarke and Rendell, 2003; Forman et al., 2005, 2008), although these events were not extensive enough to promote complete dune reactivation across the area (Muhs and Holliday, 1995; Wolfe et al., 2001). These small periods of dune activity are recognized in single dune fields, suggesting localized drought (rather than regional drought, as in the Medieval Climatic Anomaly).

The episodes of drought recognized in the Great Plains have been dated using two main methods. First, organic material gathered from paleosols found within the dunes has been dated using the radiocarbon method (Ahlbrandt et al., 1983; Forman and Maat, 1990; Arbogast and Johnson, 1998; Holliday, 2001; Lepper and Scott, 2005). These dates provide limiting ages for sand layers present above or below the organic material. More recently, luminescence geochronology, typically optically stimulated luminescence, has been used to date the eolian sands themselves (Forman and Maat, 1990; Goble et al., 2004; Lepper and Scott, 2005; Miao et al., 2007; Forman et al., 2008), providing specific information about periods of dune movement.

### 3. Dune types and dune crest orientations

Dunes are classified in two main ways, morphologically and morphodynamically. Dune types based on morphology include crescentic dunes, dome dunes, parabolic dunes, linear dunes, and star dunes. Crescentic dunes are asymmetric dunes with sinuous crestlines typically oriented perpendicular to the wind and include barchan dunes and transverse or crescentic ridges. Barchan dunes typically occur in regions with low sediment supply while transverse ridges typically occur in regions with abundant sediment. Dome dunes are classified as circular to elliptical dunes without slipfaces. Some dome dunes may be remnants of star dunes. Parabolic dunes are considered to be deflation features and occur in areas of sparse vegetation. These dunes are U-shaped with the arms anchored and the noses pointing downwind. Linear dunes are symmetrical with sinuous to straight crestlines and slipfaces on both sides. Finally, star dunes are classified as multi-armed dunes with multiple slipfaces and crestlines (McKee, 1979; Kocurek, 1996).

The morphodynamic classification of dunes divides elongate dunes into three categories based on the angle between the orientation of the dune crestline and the resultant sand transport direction. Longitudinal dunes have crests oriented nearly parallel (0–15°) to the resultant sand transport direction. Crests of transverse dunes are oriented nearly perpendicular (75–90°) to the resultant sand transport direction. Oblique dunes have crests oriented at an angle (15–75°) to the resultant sand transport direction (Hunter et al., 1983).

The classification of dunes is particularly important when examining their response to various wind regimes (Fryberger, 1979). Unimodal wind regimes are those with a single peak or

mode, with the majority of the drift potential for an area occurring in the same general direction. Transverse, barchanoid, and barchan dunes form under these conditions and are oriented roughly perpendicular to the resultant drift direction. Wind regimes with two peak distributions of drift potential are called bimodal wind regimes. Linear dunes typically form under bimodal wind regimes. Finally, complex wind regimes have greater than two peak distributions of drift potential and typically form star dunes.

### 4. Methods

The morphology, orientation, and internal structures of stabilized dunes reflect the wind direction(s) from the last time the dunes were mobile. We made interpretations of ancient wind directions from dune fields in North Dakota, Nebraska, Colorado, Kansas, Oklahoma, and Texas from the literature. Those studies use dune orientations and dune type to obtain paleowind information. Internal structures were also used in several studies. Additional paleowind information from the Nebraska Sand Hills was obtained by measuring internal structures in dunes at several locations throughout the dune field.

We studied modern winds across the Great Plains using data on wind direction and speed from 35 modern meteorological stations. The data were compiled into a series of sand roses, circular histograms which graphically represent an index of potential sand transport that can occur in a given time (the drift potential) for all directions (Fryberger, 1979). The lengths of the arms on a sand rose are proportional to the drift potential, which is given in vector units. The following equation was used to calculate the drift potential ( $Q$ ) for each direction:  $Q = V^2 (V - V_t)t$ , where  $V$  = the velocity of wind as measured at 10 m height,  $V_t$  = the impact threshold wind velocity for sand with a mean diameter of 0.25–0.30 mm at a 10 m height, given as 6 m/s in this study, and  $t$  = the amount of time the wind blew given as a percentage (Fryberger, 1979). The drift potential for every 10° around 360° was calculated for each station and results were compiled to create a sand rose. Annual and seasonal roses were compiled for each station, with spring defined as March through May, summer defined as June through August, fall defined as September through November, and winter defined as December through February. The resultant drift direction (RDD) for each rose was calculated as the vector sum of drift potentials for individual directions. The RDD gives the hypothetical net direction that sand would move over time. The resultant drift potential (RDP) was also calculated for each rose and is the magnitude of the RDD or the net potential for sand movement, and is given in vector units (Fryberger, 1979). Hypothetical dune orientations were calculated using a modified version of the program Trend (Rubin and Ikeda, 1990; Lancaster et al., 2002; Sridhar et al., 2006). Dune type was determined by taking the angle between the calculated hypothetical dune orientation and RDD and using the morphodynamic classification of dunes as defined by Hunter et al. (1983).

Sand roses were compiled for a total of 35 stations spaced throughout the Great Plains in or near ancient dune fields in North Dakota, Nebraska, Colorado, Kansas, Oklahoma, and Texas (Table 1). Two of the 35 stations are located in South Dakota and are not near ancient dune fields, but provide necessary information between the North Dakota and Nebraska sites. Where possible, the last 35 years of data (1973–2007) were used to compile sand roses, however data from this duration were not available for all stations (Table 1).

### 5. Late Holocene dune fields and wind directions

Ancient wind directions have been interpreted by previous researchers within dune fields throughout the Great Plains (Muhs

**Table 1**  
Station locations used in the study, including years of data available, hypothetical modern resultant drift direction (RDD), resultant drift potential (RDP), and dune orientation.

Station name	State	Years of data	RDD	RDP	Dune orientation
Minot	North Dakota	1973–2007	117	65	33
Bismarck	North Dakota	1973–2007	134	54	47
Lidgerwood	North Dakota	1984–95	53	12	27
Mobridge	South Dakota	1973–2007	160	52	53
Pierre	South Dakota	1973–2007	144	80	45
Valentine	Nebraska	1973–2007	102	56	65
Ainsworth	Nebraska	1973–2007	103	90	69
O'Neill	Nebraska	1984–90, 96–2007	124	102	61
Alliance	Nebraska	1973–2007	115	85	52
Mullen	Nebraska	1973–94	129	106	62
Brewster	Nebraska	1974–80, 96–2007	166	72	74
Ord	Nebraska	1982–2007	130	94	68
Broken Bow	Nebraska	1973–2007	142	112	67
North Platte	Nebraska	1973–2007	158	52	66
Cozad	Nebraska	1986–90	114	74	67
Greeley	Colorado	1988–2007	151	52	57
Akron	Colorado	1973–2007	148	69	56
Limon	Colorado	1973–99, 2004–07	152	62	78
Lamar	Colorado	1975–91, 96–2007	36	26	95
La Junta	Colorado	1973–2007	152	55	125
Springfield	Colorado	1999–2007	50	97	75
Great Bend	Kansas	1992–2007	20	96	84
Garden City	Kansas	1973–2007	139	103	87
Dodge City	Kansas	1973–2007	46	117	87
Liberal	Kansas	1973–2007	79	114	96
Elkhart	Kansas	1993–95, 2003–06	1	57	77
Gage	Oklahoma	1973–2007	11	85	88
Altus	Oklahoma	1973–2007	195	42	88
Dalhart	Texas	1973–2007	92	84	111
Amanillo	Texas	1973–2007	50	101	108
Childress	Texas	1973–2007	97	63	93
Wichita Falls	Texas	1973–2007	32	63	81
Lubbock	Texas	1973–2007	72	76	114
Midland	Texas	1973–2007	26	61	113
El Paso	Texas	1972–2007	83	29	172

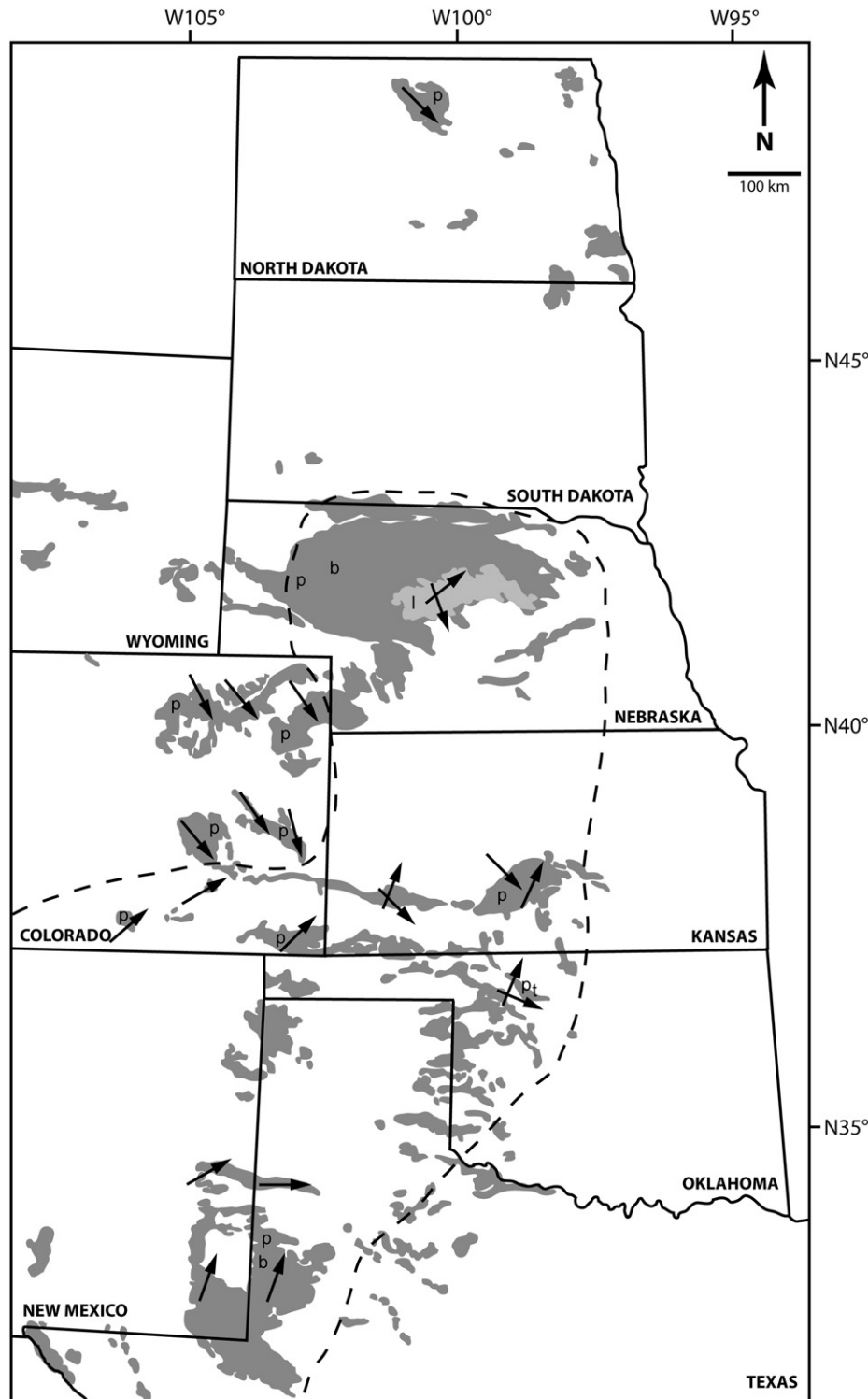
and Zárate, 2001; Sun and Muhs, 2007). Compiling this information provides a picture of ancient circulation patterns (Fig. 2) that can then be compared to modern circulation. Dune fields in this study cover an area from North Dakota to Texas.

Holocene dune fields in North Dakota include the Sheyenne Delta dune field and the Minot dune field (Fig. 1). Both are thinner (typically less than 30 m in thickness; Muhs and Wolfe, 1999) and less extensive than other Great Plains dune fields (Forman et al., 2001). The Minot dune field (Table 2) consists of stabilized dunes and eolian sand sheets. The last major reactivation that affected these dunes occurred about 1000 years ago (Muhs et al., 1997a,b). The sand sheets are low, flat lying features present mainly in the northwestern part of the dune field. Parabolic dunes dominate the remainder of the dune field. The arms of the parabolic dunes trend N45°W with the noses pointing to the southeast (Muhs et al., 1997a,b). The dune crests are oriented perpendicular to the paleowinds, southwest–northeast (or N45°E). The dunes thus record the direction of paleowinds from the last period of reactivation as mainly northwesterly (Fig. 2; Muhs et al., 1997a,b).

The Nebraska Sand Hills is the largest dune field in North America (Table 2; Ahlbrandt and Fryberger, 1980) and contains dunes up to 135 m tall (Swinehart, 1998). The sediment within the Sand Hills is mineralogically mature, suggesting that the dunes were likely active during the Pleistocene as well as the Holocene (Muhs et al., 1997a,b). Multiple Holocene reactivations have been recognized using optically stimulated luminescence dating throughout the dune field (Stokes and Swinehart, 1997; Forman et al., 2005; Miao et al., 2007). Major droughts long enough to result in major reactivation of the dunes are centered around 3.8 ka, 2.5 ka, and 0.7 ka (Miao et al., 2007). The latest period of reactivation (the Medieval Climatic Anomaly) spanned from 1050 to

650 years B.P. (Cook et al., 2004). Several less severe droughts have occurred after the Medieval Climatic Anomaly, such as the 1930s Dust Bowl, that have caused increased areas of bare sand and some movement, but not complete reactivation as are seen in the major droughts outlined above (Forman et al., 2005).

There are a variety of dune types and orientations within the Nebraska Sand Hills (Fig. 2). In the west-central Sand Hills, the greatly elongated crests of large Pleistocene/Early Holocene barchanoid-ridge dunes lie up to 120 m above interdune surfaces, and are typically oriented east–west with their steepest slopes facing south (Warren, 1976; Ahlbrandt and Fryberger, 1980; Swinehart, 1998). Further to the west, the crest orientation shifts to become N120°W. To the east, near the 100th meridian, these dunes are up to 55 m high and crest orientations are N47°W. In the western and southwestern portions of the Nebraska Sand Hills, simple and compound parabolic dunes are oriented with the noses of the dunes pointing to the southeast, indicating paleowinds from the northwest. Compound barchan dunes within the western part of the dune field are oriented with slipfaces sloping southeast and east, indicating northwesterly to westerly paleowinds (Swinehart, 1998). Smaller (12–15 m high) linear dunes occupy 7500 km<sup>2</sup> in the southeastern Nebraska Sand Hills. These dune crests are oriented roughly N65°W and have been interpreted morphodynamically as longitudinal dunes indicative of bidirectional winds of subequal strength. They suggest northerly winds between about 340 and 20° and southwesterly winds between 212 and 250° (Fig. 2; Sridhar et al., 2006). The orientation of these dunes is similar to that of the larger, older dunes that lie just to the west, strongly suggesting that, in the eastern Sand Hills, the wind regime during dune-building episodes remained unchanged from Late Pleistocene to Late Holocene. We measured 85 cross-bed orientations within trenches cut



**Fig. 2.** Map of Great Plains dune fields (gray shading, after Muhs and Holliday (1995)–central and southern Great Plains and Muhs and Wolfe (1999)–northern Great Plains) with late Holocene paleowind directions (black arrows). Light gray shading designates location of linear dunes in the Nebraska Sand Hills. Ancient dune type are given in letters where b = barchanoid-ridge, l = linear, p = parabolic, and t = transverse.

through eight longitudinal dunes throughout the southeastern Sand Hills. These measurements are consistent with bidirectional paleowinds coming from the north and southwest that caused sand to accrete along both sides of the bed forms during the late Holocene (Fig. 3).

Several late Holocene dune fields are present in the eastern portion of Colorado (Fig. 1; Table 2). In the northeastern part of the

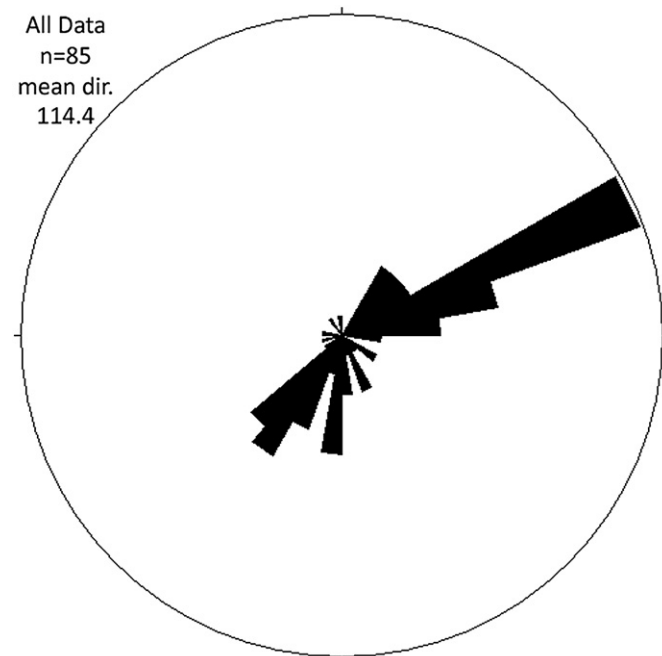
state, the South Platte dune field is divided into the Greeley dune field, on the north side of the South Platte River and the Fort Morgan dune field, on the south side of the South Platte River (Muhs, 1985; Madole, 1995; Muhs et al., 1996). Dune sand in the South Platte dune field averages 10–25 m in thickness with a maximum thickness of 30 m (Madole, 1994, 1995; Muhs et al., 1996). The Wray dune field is located southeast of the South Platte

**Table 2**  
Information about late Holocene Great Plains dune fields in North America.

Dune field	References	Size (km <sup>2</sup> )	Paleowind direction	Ancient dune type	Modern RDD	Hypothetical dune type
Minot dune field	Muhs et al., 1997a,b; Muhs and Wolfe, 1999	1500	N45°W	Parabolic	117°	Transverse or parabolic
Nebraska Sand Hills	Swinehart, 1998; Sridhar et al., 2006	57,000	N major; SW sub.	Various	128°	Oblique
South Platte dune field	Madole, 1995; Muhs et al., 1996	7500	N27°W	Parabolic	149°	Transverse or parabolic
Wray dune field	Madole, 1995; Muhs et al., 1996	6680	N35°W	Parabolic	149°	Transverse or parabolic
Black Squirrel eolian sand area	Madole, 1995	3570	NW major; SW sub.	Parabolic	152°	Oblique to transverse
Big Sandy eolian sand area	Madole, 1995	2430	NW	Parabolic	152°	Oblique to transverse
Apishapa sand area	Madole, 1995	340	SW	Parabolic	113°	Longitudinal to transverse
Baca eolian sand area	Madole, 1995	2500	SW	Parabolic	113°	Longitudinal to transverse
Great Bend Sand Prairie	Arbogast, 1995, 1996, 1998	4500	SW major; NW sub.	Parabolic	20°	Oblique
Arkansas River dune field	Olson et al., 1997; Forman et al., 2008		N–NW	Transverse, parabolic	66°	Oblique
Cimarron River dune fields	Brady, 1989	450	S–SW major; W–NW sub.	Transverse, parabolic	11°	Transverse or parabolic
Southern High Plains dune fields	Reeves, 1965; Holliday, 1991, 2001	5800	SW, W	Various	49°	Oblique

dune field and directly north of the Arikaree River and stretches east into Nebraska. The dune field has an average sand thickness of 30 m and maximum thickness of 50 m (Madole, 1995). The dune fields of northeastern Colorado (South Platte and Wray) were last active during the late Holocene, when conditions were windier and warmer than at present (Forman et al., 1995). A sample from the dunes dated using radiocarbon dating suggests a maximum limiting age of ~1500 yr B.P. (Muhs et al., 1996), but many additional dates suggest that the dunes were most likely active at or slightly after 1000 yr B.P. (Madole, 1995; Forman et al., 1995; Muhs et al., 1996). Some authors have noted evidence for dune activity in this area around 600 years ago (Forman et al., 1995; Clarke and Rendell, 2003), but these events seem to be localized, having little impact on large-scale dune migration.

Simple and compound parabolic dunes are the most common dune type in the South Platte and Wray dune fields (Fig. 2). Some sand sheets are also present (Muhs, 1985; Madole, 1994, 1995;



**Fig. 3.** Rose diagram illustrating cross-bed orientations measured in sections cut through linear dunes in the Nebraska Sand Hills.

Forman et al., 1995; Muhs et al., 1996). Additionally, dunes that appear to be longitudinal dunes may be parabolic dunes with the concentric edges deflated (Forman et al., 1995; Madole, 1995). The arms of the parabolic dunes are oriented to northwest with the concentric edge (nose) downwind, to the southeast (Muhs, 1985; Forman and Maat, 1990; Forman et al., 1995; Madole, 1995) and dune crests oriented southwest–northeast. In the Greeley dune field, the arms are oriented N27°W and in the Wray dune field the arms are oriented N35°W (Muhs et al., 1996) with the dune crests oriented southwest–northeast in both. All of the data suggest northwesterly late Holocene paleowinds for northeastern Colorado (Fig. 2).

Five other dune fields located in east-central and southeastern Colorado include the Black Squirrel, Big Sandy, Arkansas River, Apishapa, and Baca eolian sand areas (Fig. 1; Table 2). The Black Squirrel eolian sand area in east-central Colorado contains dunes up to 42 m thick. The Big Sandy eolian sand area is located along the Big Sandy Creek in east-central Colorado and has dunes up to 20 m thick (Madole, 1995). In the Arkansas River eolian sand area, located from La Junta to the border with western Kansas, dunes are up to 25 m thick. The Apishapa sand area consists of six small areas of dunes in southeastern Colorado. Finally, the Baca eolian sand area is located in the southeastern corner of Colorado and consists of dunes approximately 15 m thick (Madole, 1995).

The dune fields in east-central and southeastern Colorado are hypothesized to have been active less than 1000 years ago (Madole, 1995). High compound parabolic dunes are most common with some blowout dunes present in the Arkansas River eolian sand area. The dunes in the Black Squirrel and Big Sandy eolian sand areas suggest paleowind directions from the northwest with some component of southwesterly winds recognized in the southern part of the Black Squirrel dune field (Fig. 2). Within the Apishapa and Baca eolian sand areas, dunes are oriented suggesting southwesterly paleowinds (Fig. 2). Dunes in the Arkansas River eolian sand area are not well studied (Madole, 1995).

The Great Bend Sand Prairie is located in the bend of the Arkansas River in central Kansas (Fig. 1, Table 2). Dunes in this sand prairie are about 15 m thick and were last active during the late Holocene, within the last 1000 years (Arbogast, 1995, 1996, 1998). Simple and compound parabolic dunes are the most common dune type in the Great Bend Sand Prairie. Some sand sheets with low relief and sand sheets with high relief are also present in the dune field. A large lunette dune known as Wilson Ridge is located in the west-central part of the dune field and formed during the late Wisconsin, approximately 20,000 years ago (Arbogast, 1995).

The crests of most of the parabolic dunes in the Great Bend Sand Prairie are oriented northwest–southeast with concentric edges downwind, to the northeast, suggesting southwesterly paleowind directions for the last period of reactivation. Some of the orientations of the parabolic dunes suggest northwesterly paleowind directions (Arbogast, 1995, 1996, 1998; Arbogast and Muhs, 2000). Arbogast (1995) suggested the two wind directions could be seasonal with northwesterly winds likely occurring during the winter and the stronger southwesterly winds occurring during the summer. However, as parabolic dunes form under unimodal wind regimes, it is more likely that these wind directions influenced dune activity at different times.

The High Plains of Kansas directly south of the Arkansas River and directly south of the Cimarron River also contains several small dune fields, known collectively as the Arkansas River dune field (Fig. 1; Table 2). Dune sand ranges from 1 to 18 m thick with transverse and parabolic dunes present. The oldest dates from the Arkansas River dune field range from 16 to 12 ka, while there is evidence for small, more recent events at 430, 380–320, 180, and 70 yrs ago. No evidence of dune reactivation during the Medieval Climatic Anomaly has been found, likely due to an incomplete record (Forman et al., 2008). Paleowinds are recognized as northerly to northwesterly (Forman et al., 2008) as indicated by loess distribution as well as the weak trend of dunes in the area (south–southwest to north–northeast). Some inconsistencies in loess thickness and particle size from the source region suggest variable south to southwesterly winds (Olson et al., 1997) that may also have reworked the dunes to some degree.

Small dune fields are present along the northern edge of the Cimarron River in north-central Oklahoma, (Fig. 1; Table 2; Brady, 1989). The dunes were last active in the late Holocene, about 770–880 years ago (Lepper and Scott, 2005). Transverse ridges with some barchanoid characteristics are common in the dune fields. To the northeast, parabolic dunes are more common, likely due to a lower sand supply in this area (Brady, 1989). Most of the dunes indicate south-southwesterly paleowinds based on orientations of slipfaces although some suggest west–northwesterly to northwesterly winds which may indicate bimodal paleowinds for the area (Fig. 2; Brady, 1989).

The Southern High Plains of Texas is a large plateau located in the western part of the panhandle of Texas, spreading into easternmost New Mexico. Scattered dune fields are present across the Southern High Plains (Fig. 1; Table 2) and are commonly located near playas (Reeves, 1965; Holliday, 1991). There are three main dune fields, the Muleshoe dunes, the Lea-Yoakum dunes, and the Monahans-Andrews dunes. The Muleshoe dunes are a west–east trending dune field located in and downwind of Portales Valley. The Lea-Yoakum dune field also trends west–east and is located downwind of the Simanola Valley. The Monahans-Andrews dunes follow the Pecos River Valley and are partially active (Holliday, 2001). The Muleshoe and Lea-Yoakum dunes were last active during the late Holocene, with the greatest drought occurring from 1500 to 1400 yr B.P. (Holliday, 1991, 2001).

The majority of the dune types present on the Southern High Plains formed under unimodal wind regimes. These dunes include parabolic dunes, coppice dunes, barchan dunes, barchanoid dunes, and sand sheets. The suggestion of a unimodal wind regime may be misleading as some of the dune fields are located directly downwind of major valleys roughly parallel to prevailing winds, possibly leading to funneling of the winds and an erroneous assessment of dune-building winds. In some areas, complex dunes are present suggesting bimodal wind regimes (Holliday, 2001). Orientations of the dunes imply southwesterly paleowinds (Fig. 2; Reeves, 1965; Holliday, 1991), with parabolic dunes having an average arm orientation of N20°E (Reeves, 1965), and dune crest orientations of N70°W. Dunes in the Muleshoe dune field indicate westerly paleowinds with parabolic arm orientations ranging from N79°E to S86°E (Muhs and Holliday, 2001).

All of the information from ancient dune fields provides information about late Holocene circulation patterns across the portion of the Great Plains within the U.S.A. (Fig. 2). The wind regime was unimodal on the northern end of the Great Plains, with northwesterly paleowinds. To the south, the wind regime was also unimodal, but paleowinds were south–southwesterly. Intermediate areas were under a bimodal wind regime and were influenced by both northwesterly and south–southwesterly paleowinds.

## 6. Modern wind directions

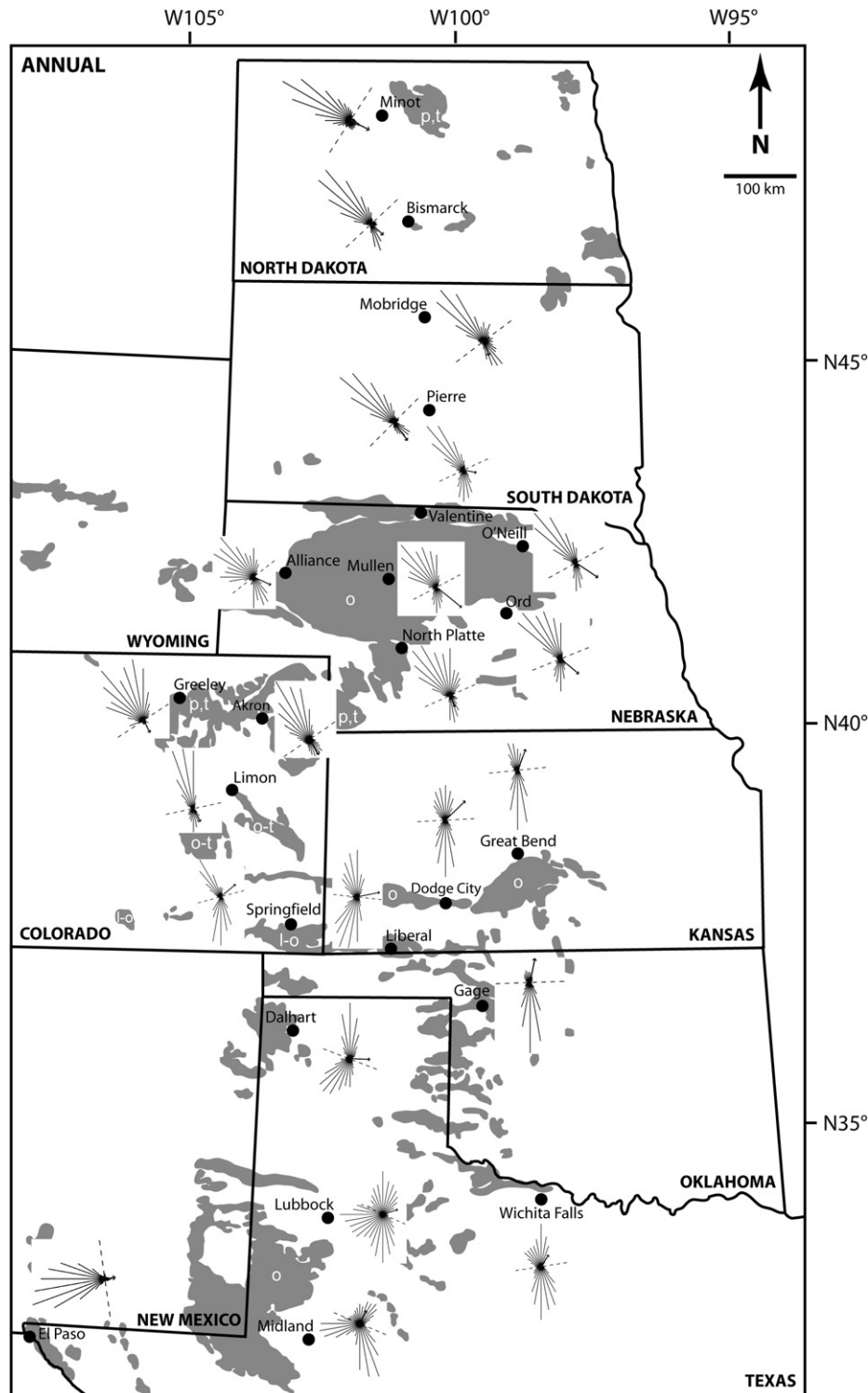
Strong winds across the Great Plains are predominantly dry and cold northwesterly winds associated with the cold front in mid-latitude cyclones. These winds dominate the mean surface winds and drift potential over the region during the winter months (Fig. 5). During spring and early summer, anticyclonic flow around the Bermuda High (the North Atlantic subtropical high) creates northward flow of moist air from the Gulf of Mexico, which is often referred to as the Great Plains low-level jet and conveys much of the moisture that ultimately falls as precipitation on the Great Plains (Sun and Muhs, 2007; Wang et al., 2007; Feng et al., 2008). These southerly to southeasterly winds also strongly influence summer drift potential over large areas of the Great Plains (Fig. 6). The strongest winds over the area occur during the spring months as evidenced by drift potential calculations. These winds could be particularly influential on dune activation because soil and sediment are particularly dry during this season.

### 6.1. North Dakota

Modern drift potential vectors over the Minot dune field (Minot, ND) are mainly unidirectional and are out of the northwest (Fig. 4). A resultant drift direction (RDD) of 117° (indicating net hypothetical sand transport from N63°W) was calculated (Tables 1 and 2). Strong northwesterly winds (Fig. 5), most common in winter, are typically dry and cold (Muhs and Wolfe, 1999). Seasonally, a minor component of southeasterly winds (Fig. 6) from the Gulf of Mexico brings warm, moist air for the months of June, July, and August. Hypothetical dune crests forming under the present wind regime would trend southwest–northeast (33°). The difference between the hypothetical dune trend and resultant sand transport (84°) indicates that transverse or parabolic dunes would form under modern wind conditions. Parabolic late Holocene dunes within the Minot dune field also indicate winds from the northwest, indicating little change in prevailing winds from the late Holocene to the present over the Minot dune field.

### 6.2. Nebraska

Strong northwesterly winds, most frequent in winter, dominate potential sand transport in the Nebraska Sand Hills at present (Figs. 4 and 5; Ainsworth, Alliance, Brewster, Broken Bow, Cozad, Mullen, North Platte, O'Neill, Ord, and Valentine, NE). A weaker south-southeasterly component is present mainly in summer (Figs. 4 and 6). An average RDD for all of the stations around or near the Nebraska Sand Hills was calculated at 128° (net hypothetical sand transport from N52°W). A hypothetical dune forming under the present winds would be oriented southwest–northeast (65°) and would be classified morphodynamically as oblique (Table 2). In contrast, elongate late Holocene dunes in the Nebraska Sand Hills are longitudinal and are oriented northwest–southeast (Sridhar et al., 2006), indicating a major change in wind direction. While the northwesterly component of drift potential remained constant from the last reactivation to the present, the southerly component varied from southwesterly during the late Holocene to south–southeasterly at present.



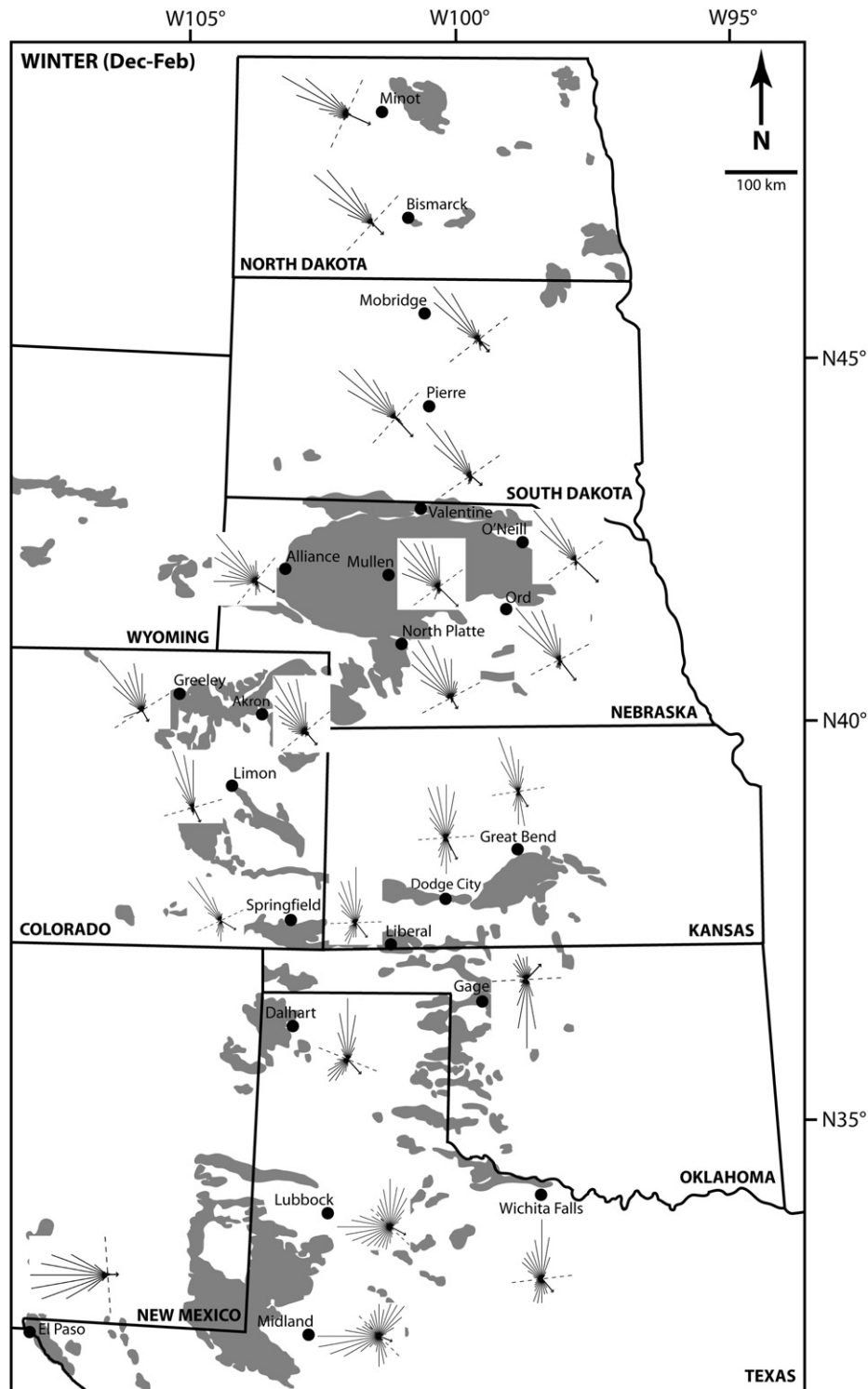
**Fig. 4.** Map of Great Plains dune fields (gray shading, after Muhs and Holliday (1995)—central and southern Great Plains and Muhs and Wolfe (1999)—northern Great Plains) with modern sand roses for stations across the region. Dashed lines indicate hypothetical modern dune orientation and arrows indicate hypothetical modern RDD. Hypothetical dune types under modern winds are given in letters where l = longitudinal, o = oblique, p = parabolic, and t = transverse.

### 6.3. Colorado

Over northeastern Colorado (Akron and Greeley, CO) potential sand transport is dominated by strong winds out of the northwest that persist over the region during the fall, winter, and spring, with subordinate winds out of the southeast mainly during the summer

(Figs. 4–6). Southeasterly summer winds are stronger between the South Platte and Wray dune fields (Akron, CO) than to the west of the South Platte River (Greeley, CO), where southeasterly winds are very minor. The average RDD as calculated for stations near the South Platte and Wray dune fields is 149° (net hypothetical sand transport from N31°W). Hypothetical dune crests forming under

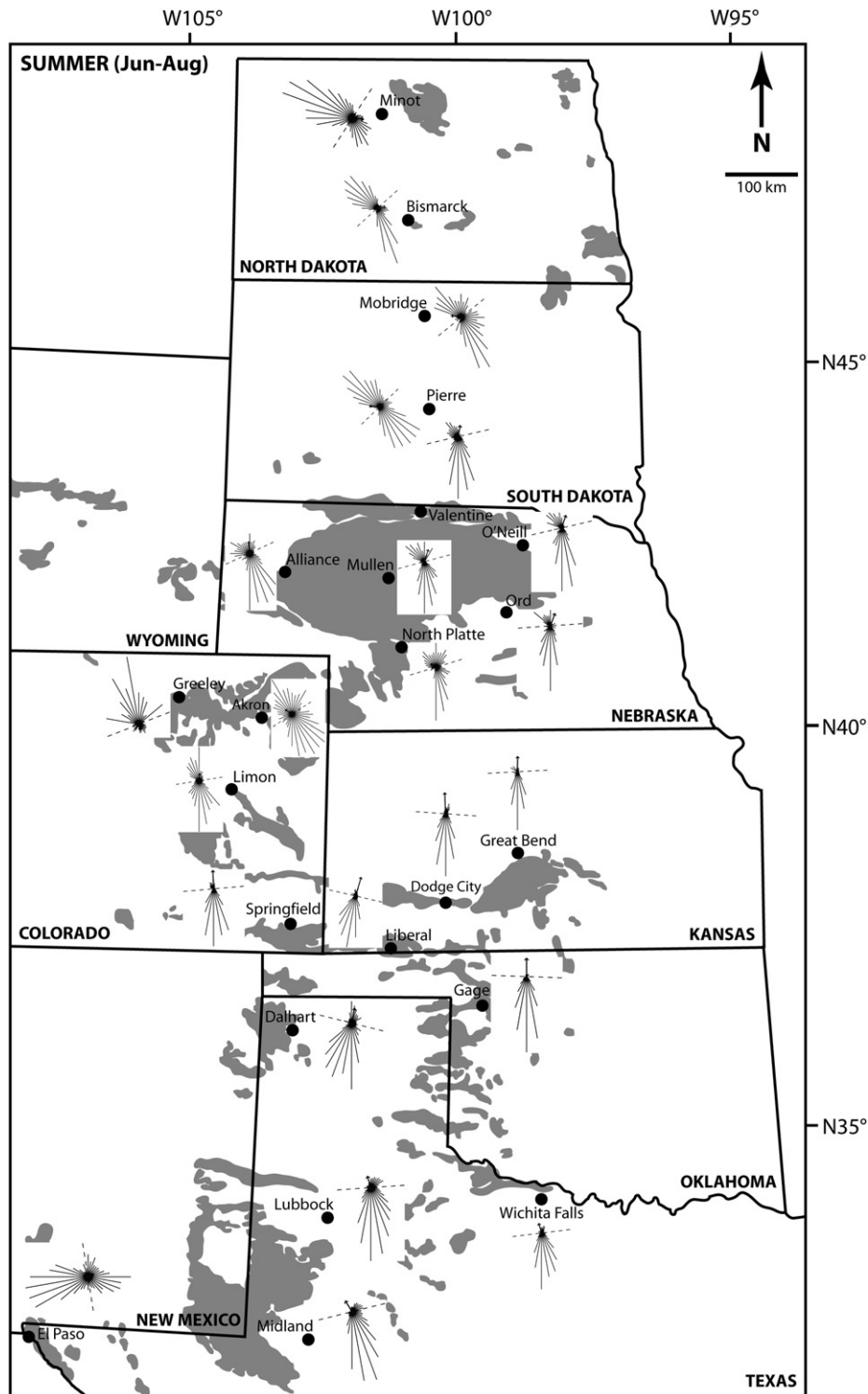




**Fig. 5.** Map of Great Plains dune fields (gray shading, after Muhs and Holliday (1995)–central and southern Great Plains and Muhs and Wolfe (1999)–northern Great Plains) with modern sand roses for winter (the months of December through February). Dashed lines indicate hypothetical modern dune orientation and arrows indicate hypothetical modern RDD.

present winds would be oriented southwest–northeast ( $56^\circ$ ). According to the morphodynamic classification, transverse or parabolic dunes would form under these conditions (Table 2). Hypothetical modern dune type and orientation match those of the late Holocene dunes, with no evidence of a stronger southerly wind component than at present, indicating little change in wind patterns since the dunes formed.

Winds out of the northwest dominate drift potential over east-central Colorado (Limon, CO), with a small component added by southerly winds, mainly in summer (Figs. 4–6) and a calculated RDD of  $152^\circ$  (net hypothetical sand transport from  $N28^\circ W$ ). A hypothetical dune forming under modern conditions would be oblique to transverse (Table 2) and oriented nearly west–east ( $78^\circ$ ) while late Holocene dunes in the region are parabolic and oriented



**Fig. 6.** Map of Great Plains dune fields (gray shading, after Muhs and Holliday (1995)-central and southern Great Plains and Muhs and Wolfe (1999)-northern Great Plains) with modern sand roses for summer (the months of June through August). Dashed lines indicate hypothetical modern dune orientation and arrows indicate hypothetical modern RDD.

southwest–northeast, suggesting a major change in wind direction. In southeastern Colorado (La Junta, Lamar, and Springfield, CO), drift potential due to southerly winds during the spring, summer, and fall is equal to or greater than potential sand transport by northwesterly winds (Fig. 4). The calculated average RDD for southeastern Colorado is  $113^\circ$  with a hypothetical dune crest orientation of  $98^\circ$  (roughly west–east). A hypothetical dune

forming in southeastern Colorado would be classified morphodynamically as longitudinal to oblique. Present winds are equivalent to paleowinds in the east-central portion of the state with northwesterly winds dominating. However, the dune fields in southeastern Colorado show paleowinds from the southwest (Madole, 1995), while modern winds originate mainly from the south with a component of northwesterly winds.

#### 6.4. Kansas

Winds that dominate potential sand transport in south-central Kansas (Great Bend, KS; Fig. 4) are presently out of the south, especially in the summer (Fig. 6) with a weaker component of northwesterly winds that occur mainly in winter (Fig. 5). An RDD of 20° (net hypothetical sand transport from S20°W) was calculated (Table 2). The modern RDD matches the paleowind direction reflected in the Great Bend Sand Prairie. However, dominant paleowinds were southwesterly while at present, strong winds are predominately southerly. Additionally, hypothetical dunes forming under modern winds would be oblique dunes oriented nearly west–east (84°) while the late Holocene dunes are parabolic dunes oriented northwest–southeast. Over southwestern Kansas (Dodge City, Elkhart, Garden City, and Liberal, KS), northerly and southerly winds have roughly equal influence on potential sand transport, or the northerly component is slightly weaker. The average RDD for this area is 66° (net hypothetical sand transport from S66°W). Hypothetical dunes forming under modern winds would be oblique dunes with crests oriented roughly west–east (87°) while late Holocene dunes are oriented south–southwest to north–northeast.

#### 6.5. Oklahoma

Modern drift potential near the Cimarron River dune fields (Gage, OK) is mainly generated by winds out of the south, with some influence of very weak northwesterly winds in winter (Figs. 4 and 5). An RDD of 11° was calculated near the Cimarron River dune fields. Modern winds would form transverse or parabolic hypothetical dunes with west–east (88°) orientations (Table 2). The late Holocene dunes are also parabolic, but are oriented northwest–southeast. The winds that shaped the dunes at the time they were last active were shifted to the southwest, as compared to the southerly winds that would dominate sand transport today. The dunes provide no evidence for a stronger northwesterly component of winds during the last reactivation than at present.

#### 6.6. Texas

Presently, northerly winds generate the greatest drift potential in the winter (Fig. 5) and southerly to southwesterly winds are most important during the summer (Fig. 6) across the Southern High Plains (Lubbock and Midland, TX; Fig. 4). A calculated average RDD of 49° (net hypothetical sand transport from S49°W) shows that resultant winds are southwesterly at present unlike the westerly paleowinds. Hypothetical dunes forming under present winds would have crests oriented west–northwest to east–southeast (S66°E) and would be classified morphodynamically as oblique dunes (Table 2). Simple late Holocene dunes in the region are oriented more strongly southwest–northeast (N20°E). The influence of southwesterly winds is consistent between late Holocene episodes of dune activity and the present, but the strong northerly winds that currently blow over the region today have replaced more westerly winds that shaped late Holocene dunes.

#### 6.7. Summary of changes in wind patterns

In the northern parts of the Great Plains, few changes are seen in wind regimes between the present and late Holocene episodes of dune mobility (compare Figs. 2 and 4). North Dakota and northern Colorado dune fields indicate unidirectional wind regimes with the same strong northwesterly winds during the late Holocene dune activity and at present. Further south, within Nebraska, differences in wind regimes are apparent. While both paleowinds reconstructed from late Holocene dunes and present wind regimes are

bidirectional with a component of northwesterly winds, predominant summer winds at present are south to southeasterly while summer winds that shaped late Holocene dunes were southwesterly. Dune fields in southeastern Colorado also record this shift in winds, indicating a unidirectional wind regime with strong southwesterly winds during late Holocene dune activity. The modern sand roses for southeastern Colorado reflect mainly northwesterly and southerly winds. To the east in central Kansas, a similar change in wind regime is recorded. Late Holocene dunes indicate a bidirectional wind regime with southwesterly and northwesterly components. The present wind regime is also bidirectional, but with southeasterly and north to northwesterly components. In Oklahoma and Texas, the furthest southern extent of the Great Plains, late Holocene dunes indicate a unidirectional wind regime with predominance of southwesterly winds. The present wind regime is bidirectional with northerly and south–southwesterly components.

### 7. Possible cause for late Holocene megadroughts

During winter months, the Great Plains are relatively dry, but during summer, moist air flow from the Gulf of Mexico (the Great Plains low-level jet) is generated by anticyclonic circulation around the Bermuda High, resulting in increased precipitation (Wang et al., 2007; Feng et al., 2008). For drought to persist over the region, this moisture transport must be reduced, which can occur when the Bermuda High weakens and/or its center shifts to the east or south (Forman et al., 2001; Wang et al., 2007). Modeling studies indicate that broader controls on Great Plains drought may include both unusually warm sea-surface temperature (SST) in the subtropical North Atlantic and anomalously cool SST in the eastern tropical Pacific, both of which result in reduced moisture transport into the Great Plains (Feng et al., 2008). A weakened Great Plains low-level jet, resulting from a weakened and/or shifted Bermuda High could allow more frequent southwesterly winds in the Great Plains. Presently, dry and hot southwesterly winds flow from Mexico and the southwestern U.S. towards the Great Plains during the spring and summer months, generally rising over the moist southerly to southeasterly flow from the Gulf in the southern Great Plains. If the moist air flow from the Gulf was weakened, hot and dry southwesterly surface winds could often extend much farther north and northeast over the Great Plains (Sridhar et al., 2006). In eastern New Mexico, west Texas, and western Oklahoma, however, southwesterly flow needn't always be dry. Summer flow into this area from the Gulf of California can bring considerable moisture, but has relatively little effect further east and north. The southwesterly flow of air could also have been brought to the surface through a feedback mechanism involving land surface changes resulting from drought (Sridhar et al., 2006). Either or both of these mechanisms can explain the southwesterly paleowinds that are recognized from the late Holocene dunes throughout the lower parts of the Great Plains.

It is also extremely important to consider feedback mechanisms that may contribute to persistence of dry conditions over the Great Plains, allowing full dune reactivation to take place. Evapotranspiration from plants is an additional source of atmospheric moisture that can be recycled as precipitation. The reduction in vegetative density by drought decreases that source of moisture, leading to further diminishing of the vegetative cover. A soil moisture feedback mechanism works in a similar manner (Oglesby and Erickson, 1989; Sridhar et al., 2006).

### 8. Conclusions

Paleowind information from late Holocene dunes across the Great Plains of North America provides a detailed picture of past

circulation patterns (Fig. 2). A comparison between past and present wind regimes over the region shows one major difference, strong southwesterly winds were more frequent than at present across much of the central and southern Great Plains during late Holocene episodes of dune activity (compare Figs. 2 and 4), changing the predominant direction(s) of potential sand transport. Unimodal northwesterly winds dominate potential sand transport in the northern part of the Great Plains (North Dakota) at present, and were also dominant when late Holocene dunes were active. If dunes were to form under present conditions in the northern Great Plains, they would be very similar in morphology (transverse or parabolic) and orientation to those that formed during the late Holocene. In the central Great Plains (Nebraska) late Holocene and present wind regimes were bimodal, with one important difference. While potential sand transport by northwesterly winds was high during both time periods, secondary modern winds are southerly to southeasterly while secondary late Holocene winds were southwesterly. Consequently, dunes forming under present winds would have remarkably different crestral orientations (SW–NE) than those from the late Holocene (NW–SE). The pattern of stronger southwesterly winds during late Holocene dune activity is also evident farther south. While bimodal winds from the south and northwest currently dominate southern Colorado and Kansas, and would lead to oblique or transverse dune formation, parabolic dunes formed by southwesterly winds are recognized from the late Holocene. Furthest to the south (in Texas), modern prevailing winds are quite variable, ranging from south–southwesterly to westerly to northerly. Dunes forming over the region would also be quite variable and include oblique dunes. Late Holocene parabolic dunes were formed by unimodal southwesterly winds.

Strong northwesterly winds have provided a persistent component of drift potential across the northern and central Great Plains from at least the late Holocene to the present. The other major component of drift potential, resulting from winds out of the south has undergone a major shift over central to southern portions of the Great Plains, from southwesterly during late Holocene dune activity to southerly or southeasterly at present. It is likely that this shift in wind directions resulted from the weakened northward flow of moist air from the Gulf of Mexico that produced late Holocene megadroughts and allowed dune reactivation. Reduced air flow and moisture transport from the Gulf resulted in turn from a weakened or shifted Bermuda High and possible broader connections with the Atlantic and Pacific SST.

The likelihood of further reactivation of the dune fields is an obvious concern. Droughts recognized from the 19th and 20th centuries (the Dust Bowl being one example) have shown that the dunes are extremely sensitive to changes in climate. Minor reactivation of the dunes took place during several of the longer lasting droughts (Ahlbrandt et al., 1983; Muhs and Holliday, 1995). Several authors have reported dune fields in northeastern Colorado, western Nebraska, and central Kansas as currently being near the threshold for reactivation, with numerous small areas of bare sand (Madole, 1994; Muhs et al., 1996). Dunes in the northern part of the Great Plains, such as those within the Minot dune field, may be more vulnerable to reactivation due to their small size and the shorter growing season. These dune fields may actually be the first to reactivate in the event of another megadrought (Muhs and Wolfe, 1999). Future predictions of increased temperatures and decreased summer precipitation across the Great Plains (Christensen et al., 2007) suggest that global climate changes will almost certainly have a major impact on the Great Plains. Given the geologic record of sensitivity of the dune fields in this area to climate change, future dune reactivation could occur again, but the influence of invasive plant species and the advent of new land management techniques make this difficult to assess.

## Acknowledgments

The authors thank the two reviewers (Dan Muhs and Steve Forman) for their comments, which greatly improved the quality of the paper. We also greatly appreciate the support of the Department of Geosciences at the University of Nebraska–Lincoln as well as the following committee members for assistance with this project: Dr. Tracy Frank, Dr. Ron Goble, Dr. Matt Joeckel, and Professor Jim Swinehart. Many thanks go to Dr. Xiadong Miao, who provided invaluable help in teaching the process of analyzing meteorological data. We also thank Andy Applegarth, for assistance in countless things while research was conducted at the Gudmundsen Sand Hills Laboratory, and to the national park service for help obtaining permits to conduct work at the Nebraska National Forest. Finally, many thanks go to Diane Schmeisser for support and field work assistance. Funding for this project was provided by National Science Foundation Grant DEB 0233067.

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