GLOBAL AND PLANETARY CHANGE

Global and Planetary Change 29 (2001) 1–29

www.elsevier.com/locate/gloplacha

Temporal and spatial patterns of Holocene dune activity on the Great Plains of North America: megadroughts and climate links

Steven L. Forman [a,*], Robert Oglesby [b,1], Robert S. Webb [c]

[a] Department of Earth and Environmental Sciences, University of Illinois at Chicago, Chicago, IL 60607-7059, USA
[b] Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 47907, USA
[c] Climate Diagnostics Center, Office of Atmospheric Research, National Oceanographic and Atmospheric Administration, 325 Broadway, Boulder, CO 80305, USA

Accepted 7 December 2000

Abstract

The Holocene record of eolian sand and loess deposition is reviewed for numerous presently stabilized dune fields on the Great Plains of North America. Dune field activity reflects decade-to-century-scale dominance of drought that exceeded historic conditions, with a growing season deficit of precipitation > 25%. The largest dune fields, the Nebraska Sand Hills and ergs in eastern Colorado, Kansas and the Southern High Plains showed peak activity sometime between ca. 7 and 5 cal. ka. Loess deposition between ca. 10 and 4 cal. ka also signifies widespread aridity. Most dune fields exhibit evidence for one or more reactivation events sometime in the past 2 cal. ka; a number of localities register two events post 1 cal. ka, the latest potentially after 1400 AD. However, there is not a clear association of the latest dune remobilization events with up to 13 droughts in the past 2 cal. ka identified in dendroclimatic and lacustrine records. Periods of persistent drought are associated with a La Niña-dominated climate state, with cooling of sea surface temperatures in the tropical Pacific Ocean and later of the tropical Atlantic Ocean and the Gulf of Mexico that significantly weakens cyclogenesis over central North America. As drought proceeds, reduced soil moisture and vegetation cover would lessen evaporative cooling and increase surface temperatures. These surface changes strengthen the eastward expansion of a high-pressure ridge aloft and shift the jet stream northward, further enhancing continent-wide drought. Uncertainty persists if dune fields will reactivate in the future at a scale similar to the Holocene because of widespread irrigation, the lack of migratory bison herds, and the suppression of prairie fires, all of which enhance stabilization of dune fields in the Great Plains.

Keywords: dune fields; Holocene climate; Great Plains; USA; droughts

1. Introduction

Presently, stabilized dune fields are common on the Great Plains of central North America (Fig. 1). These landforms (Fig. 2B) attest to periods of pronounced aridity during the past 10,000 years that

* Corresponding author.
E-mail address: SLF@uic.edu (S.L. Forman).
[1] Present address: Global Hydrology and Climate Center, Marshall Space Flight Center, NASA, 320 Sparkman Drive, Huntsville, AL 35801, USA.

PII: S0921-8181(00)00092-8

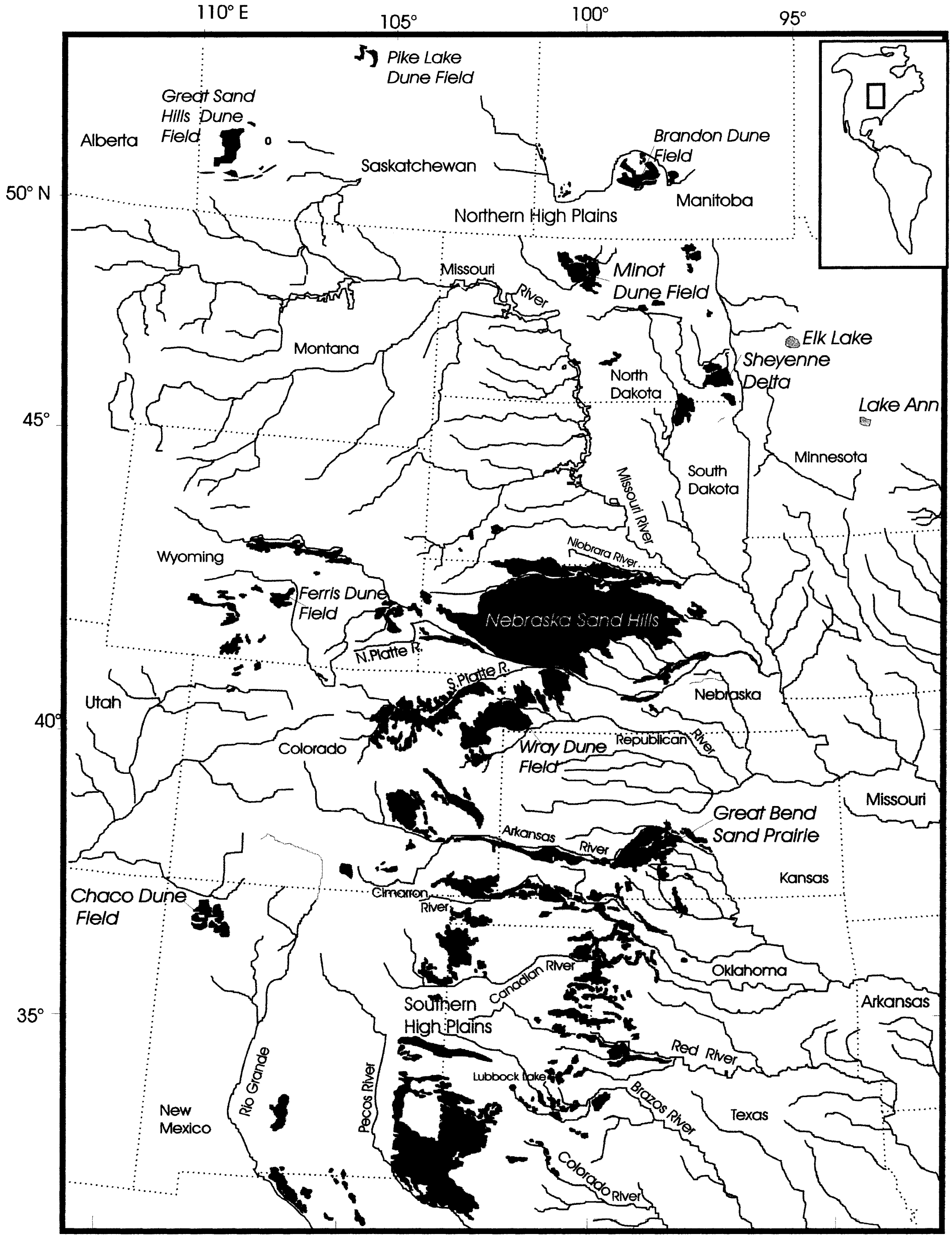

Fig. 1. The Great Plains of North America with presently stabilized dune fields in black. Map derived from Ostercamp et al. (1987) and Muhs and Wolfe (1999).

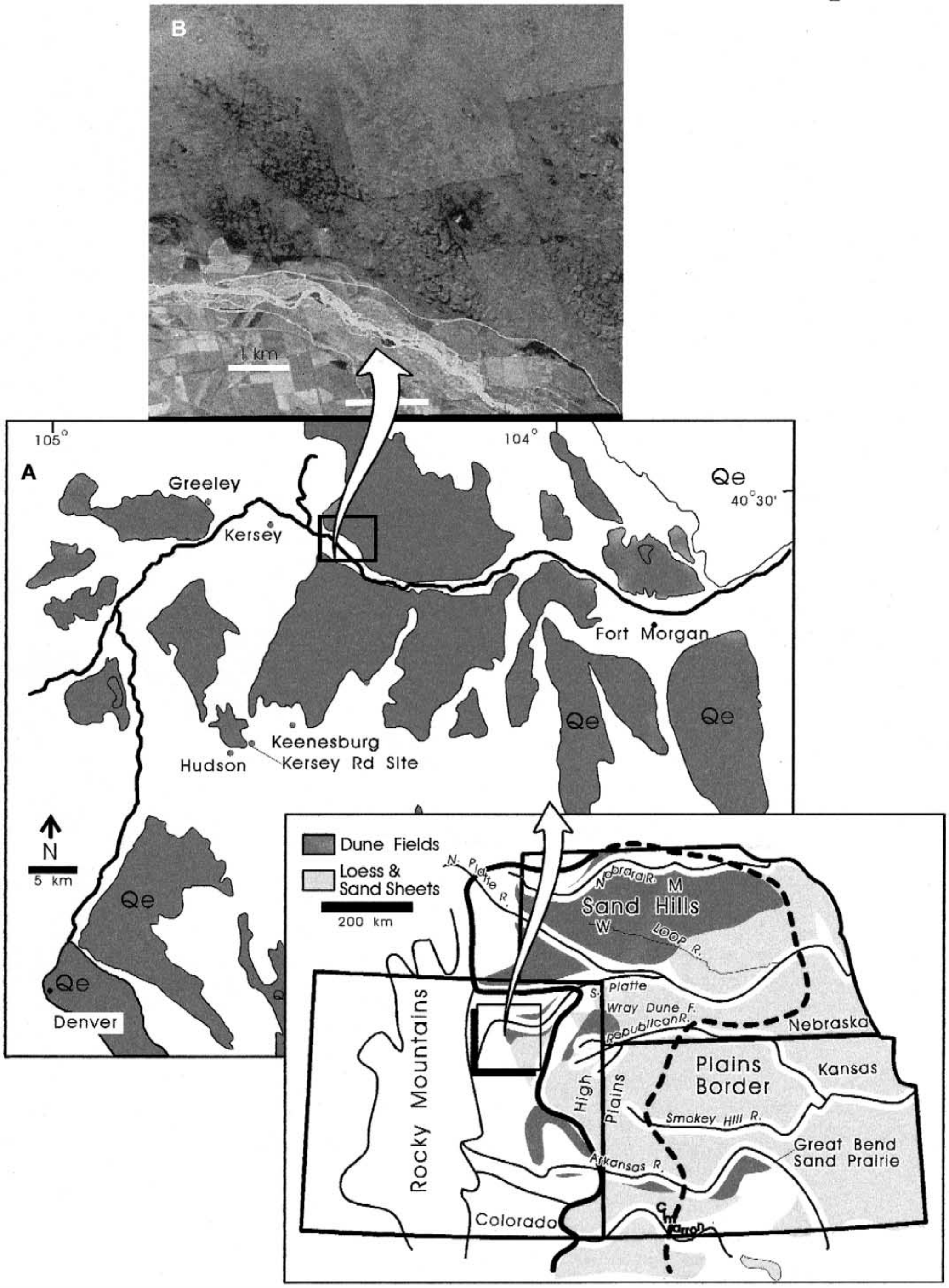

Fig. 2. General distribution of dune fields, loess and sand sheets for Colorado, Nebraska and Kansas. Inset (A) shows dune fields of eastern Colorado and (B) Landsat image of compound parabolic dunes (modified from Forman et al., 1995).

exceeded drought conditions in the 20th century. Periods of dune reactivation reflect sustained moisture deficits for a number of growing seasons and herald broader environmental change with diminished surface and groundwater resources and reduced net-primary productivity of grasslands (Schlesinger et al., 1989). Future large-scale droughts, similar to Holocene events, would have a significant impact on North American society with reductions in water availability and quality, crop failure, rangeland stress, suspension of recreational and tourist activities, and heat-related deaths in nearby urban centers (Riebsame et al., 1991; Chestnut et al., 1998).

Recent reviews underscore that droughts in the past 2000 years had broad impacts across North America (Woodhouse and Overpeck, 1998; Stahle et al., 2000). Multi-year droughts (2 to 10 years) with a range of severity (Palmer drought indexes of < -2) occurred at least once in each of the past four centuries affecting $> 40\%$ of the conterminous US. Tree-ring time series show particularly severe droughts in duration and extent prior to 1600 AD across North America (Woodhouse and Overpeck, 1998). However, it remains unknown if local or regional dune reactivation and other land surface changes are associated with these prehistoric droughts. In turn, regional eolian activity provides a definitive indicator of extreme climate conditions with drought impact, duration (multi-decades) and extent beyond historic events (Forman et al., 1995).

The history of dune mobilization on the Great Plains is critical to gauge the severity, recurrence and extent of megadroughts in context of the past 10,000 years. There is compelling evidence on the Great Plains for repeated large-scale droughts when many dune systems reactivated and challenged survival of indigenous people (Meltzer, 2000). Further understanding is also needed on the concomitant changes of the land surface, which can exacerbate or mitigate regional drought. In this review, geomorphic and stratigraphic records of eolian activity for a number presently stabilized dunes fields on the Great Plains of North America are summarized to assess spatial and temporal patterns of dune mobilization for the past 10,000 years. Potential climate system teleconnections, synoptic controls and feedbacks that may cause and sustain megadrought and lead to dune activation are also considered.

2. Grassland-climate connections on the Great Plains

The Great Plains of North America support one of the largest grassland biomes in the Northern Hemisphere and before European settlement covered 2.6 million km^2 in the US, Canada and Mexico (Lauenroth, 1979). This grassland reflects two prominent climatic gradients (Sala et al., 1988). Mean annual precipitation exhibits a strong west to east gradient, increasing from ~ 250 mm/year at the Piedmont of the Rocky Mountains (107°E), to ~ 700 mm/year at the deciduous forest border (~ 90°W). Mean summer temperatures have a north to south trend ranging from ~ 18°C in southern Canada to ~ 27°C in northern Mexico. The occurrence of grassland ecosystems generally parallels precipitation receipts (Lauenroth, 1979). Short-grass steppe vegetation primarily occurs in the western Great Plains to about the 100° meridian, dominated by the C_4 grass, *Bouteloua gracilis*, with some C_3 grasses and shrubs locally abundant. Mixed grass prairie occurs in the central part of Great Plains and supports a variety of short and tall C_3 and C_4 grasses. The tall grass prairie extends east of the Missouri River and is dominated by C_4 grasses.

Net primary productivity of grasses on the Great Plains is strongly correlated with precipitation (Fig. 3A) increasing from 80 g/m^2/year at the western margin to 700 g/m^2/year at the eastern border near the Mississippi River (Fig. 3A,B). Grassland productivity dropped by 30% to 90% during 10% of the driest years in the 1960s and 1970s. The greatest decrease in productivity is registered in the central area of the grassland, encompassing most of Kansas, southeastern Colorado and adjacent areas in northern New Mexico, Oklahoma and Texas (Fig. 3C). As drought persists, productivity remains depressed with reduced grass cover, and a dominance of shrubs, which exposes more topsoil to eolian erosion. The net effect of vegetation changes associated with regional drought is to reduce the availability of moisture and nutrients across the landscape, favoring the heterogeneous expansion of shrubs and erosion of subsoil (Judd, 1974; Schlesinger et al., 1989).

The stratigraphic and geomorphic records of eolian dune deposition on the Great Plains provide proxy information on the timing and magnitude of

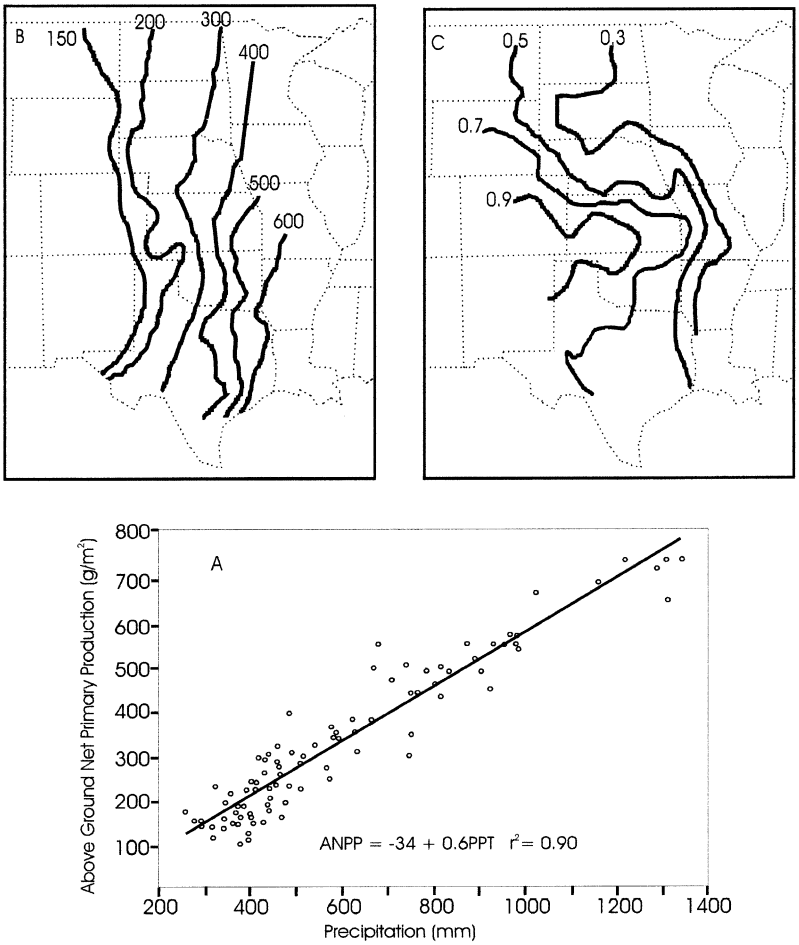

Fig. 3. (A) The relation between mean annual precipitation and mean above ground net primary productivity (ANPP g/m^2) for the Great Plains (Sala et al., 1988). (B) Isopleths of ANPP for Great Plains grasslands during years of average precipitation for the period 1960–1979. (C) Isopleths of relative variability in ANPP between wet and dry years estimated by : (ANPP wet years) − (ANPP dry years)/average ANPP.

large-scale droughts when landscape conditions were favorable for the movement and accumulation of eolian sand. Droughts associated with regional reactivation of dune systems exceed conditions during the ‘dust bowls’ of the 1930s and 1950s, when precipitation fell $>25\%$ of the average (Tomanek and Hulett, 1970).

Accumulation of eolian sediment occurs when there is adequate sediment supply, when winds exceed the threshold velocity for particle movement and there is a lack of stabilizing vegetation or landforms (Pye and Tsoar, 1990, pp. 127–145). Sediment supply is often adequate on the Great Plains from preexisting, but stabilized dune systems, and from many low-gradient rivers with broad floodplains. Wind velocity is not a limiting factor for dune formation on the Great Plains. The drift potential, a unitless measure of the efficacy of wind to entrain eolian sand (Fryberger and Dean, 1979) is intermediate to high for the central and northern Great Plains (Muhs et al., 1996; Muhs and Wolfe, 1999). Thus, if vegetation cover is reduced below a threshold of $\sim 30\%$ (Pye and Tsoar, 1990, p. 100) in response to a decrease in effective moisture and other landscape disturbance (e.g. grazing, fire), dune systems on the Great Plains should reactivate with prevailing winds.

The delivery of moisture to the Great Plains is controlled principally by the interaction of upper-level air masses from the Pacific Ocean and surface outflow from the Gulf of Mexico (cf. Barry and Chorley, 1987, pp. 249–258). Historic droughts in the central US are associated with a weakened flux from the subtropical Atlantic and the Gulf of Mexico and persistent zonal flow (Oglesby, 1991).

3. Geomorphic and stratigraphic record of Holocene eolian activity

Presently, stabilized dune fields are often adjacent to rivers (Fig. 1), one of the potential sources for sediment, with cover sands and loams and loess common within and beyond the dune fields (Ostercamp et al., 1987). Initial studies concluded that formation of these eolian landforms occurred during glacial periods in the Pleistocene with only minor reworking in the Holocene (Smith, 1965). Early investigators asserted that the Nebraska Sand Hills formed entirely prior to the Holocene during glacial intervals based on sedimentologic and geomorphic assessments (Warren, 1976; Wells, 1983) and the analysis of interdune lake records (Wright et al., 1985). However, fluvial deposits found directly beneath the Nebraska Sand Hills yield ^{14}C ages between 3 and 10 cal. ka and indicate a more recent and complex history (Ahlbrandt et al., 1983). The morphology of surface and buried soils developed in stabilized dunes in Nebraska and Colorado also indicate recent activity, with two potential dune formation events in the past 10 cal. ka, and the latest in the past ca. 1.5 cal. ka (Muhs, 1985).

There is a rich geomorphic and stratigraphic record of Holocene eolian activity across the Great Plains. Many studies identify intercalated soils within eolian sand sequences that indicate repeated dune reactivation during the Holocene. This stratigraphic sequence is first order information indicating landscape stability (paleosol) that was repeatedly disturbed by deposition of eolian sand and silt associated with drought conditions. At most sites, the thickness of eolian sediments and preservation of intercalated soils varies laterally, reflecting spatial and temporal discontinuities in eolian erosion and deposition and ensuing pedogenesis. Uncertainty remains if dune migration in one field reflects primarily an endemic response rather than broad-scale climate-driven processes. Any one eolian sequence on the Great Plains provides a conservative record of environmental events. This review provides a regional assessment of the temporal and spatial patterns of Holocene eolian activity on the Great Plains.

The majority of age control for Holocene dune activity is provided by conventional or accelerator mass spectrometry (AMS) ^{14}C dating of soil organic matter. Most of the ^{14}C ages are from dating bulk organic-matter or humic acid separates (acid–base–acid pretreatment) from buried-soil horizons. The soil A horizon is a reservoir of carbon of various ages, and thus yields a ^{14}C age older than the known age of the surface horizon (Sharpenseel, 1971). The presence of “old” organic matter in a soil, mostly in disseminated form, is termed the mean residence time (MRT) effect. Radiocarbon measurements indicate that the MRT effect of bulk organic matter and humic fractions in the upper 5-to-10 cm of A horizons of mollisols on the Great Plains varies from 100 to 500 years (Broecker et al., 1956; Harrison et al., 1993 and references therein); to as much as 1400 years old (Muhs et al. 1999). Modern contamination may dominate some shallowly buried (< 2 m) paleosols and yield ^{14}C ages that are underestimates. To ease comparison with luminescence ages and other records, all ^{14}C ages are calendar corrected (cal. ka; Stuiver and Reimer, 1993) and presented with two sigma error ranges.

Many studies have utilized luminescence geochronometry to decipher the timing of eolian events in midcontinental North America, which yields an age reflecting the time since the sediment’s last exposure to sunlight (e.g. Forman et al., 1992a, 1995; Stokes and Gaylord, 1993; Maat and Johnson, 1996; Stokes and Swinehart, 1997; Rodbell et al., 1997). Eolian sediments are preferred for luminescence dating because the requisite sunlight exposure, that resets the luminescence, readily occurs prior to deposition. Another advantage of eolian deposits for luminescence dating is the physical homogeneity of sediments simplifies calculations of environmental radioactivity (dose rate), which controls the rate of luminescence ingrowth within silicate minerals. Early studies demonstrated the concordance between ^{14}C and thermoluminescence (TL) ages for eolian sequences in the mid-continental North America (Forman and Maat, 1990; Forman et al., 1992a). The advent of optically stimulated luminescence in the 1990s provides a more sensitive geochronometer, with solar resetting of the luminescence signal occurring in minutes versus hours for TL (Godfrey-Smith et al., 1988; Stokes, 1992). The recent development of quartz single aliquot and ultimately quartz single grain regenerative optically stimulate luminescence analysis provides increased precision (errors $\pm$ 5%) for dating eolian sands deposited in the past 10 ka (Stokes, 1999).

Records of dune activity and associated loess deposition are summarized for Chaco Dune Field in New Mexico, eolian systems on the Southern High Plains, ergs on eastern Colorado, Kansas, and Wyoming, the Nebraska Sand Hills and smaller dune fields on The Northern High Plains in the US and Canada (Fig. 1). Holocene records from Elk and Ann lakes in Minnesota are also included, although marginal to the High Plains, these systems reflect regional eolian activity and aridity (Keen and Shane, 1990; Dean, 1997). These lake records provide a more continuous time series of environmental change, but spatially restricted. Integration of key lake records with stratigraphic and geomorphic studies may provide improved temporal resolution for deciphering past eolian depositional events.

4. The Southern High Plains

A variety of eolian sediments dominate the low relief surface of the Southern High Plains, a plateau covering about 130,000 km^2 in northwest Texas, eastern New Mexico and western Oklahoma (Fig. 1). Dune fields occur in distinct landscape positions either parallel to the Pecos River Valley or built against the west-facing High Plains escarpment or trending west to east, breaching the escarpment through low passes. The Holocene record of eolian activity is culled principally from sediments exposed in the many "draws", headwater tributaries of the Red, Brazos and Colorado rivers, and associated archaeological excavations (Holliday, 1995, 1997a) (Fig. 4). A key locality, amongst many on the Southern High Plains is the Lubbock Lake Archaeological Site in Yellowhouse Draw, one of the best-dated archeological sites in North America, with over 100 ^{14}C ages (Holliday, 1985, 1995, 1997a; Johnson, 1987). Another eolian record considered is the stratigraphy of lunette dunes, which form down wind

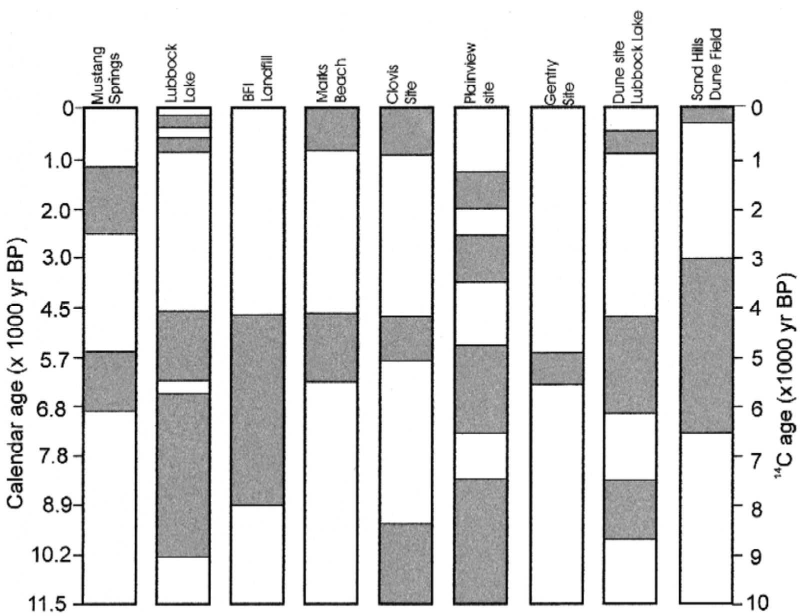

Fig. 4. Calendar and ^{14}C ages for eolian sediments (shaded) accumulated on the Southern High Plains for the Holocene (modified from Holliday, 1991).

from playa basins on the Southern High Plains (Holliday, 1997b).

Five distinctive stratums are regionally recognized that infill draws on the Southern High Plains (Holliday, 1995). The base of the stratigraphic sequence shows a succession from alluvial to lacustrine environments (stratum 1). The top of this stratum is deposited between 13 and 10 cal. ka, with Clovis cultural materials from alluvial facies. Episodic drying led to deposition of eolian cover-sands most recently associated with Folsom occupation ca. 12.5 to 11 cal. ka (Holliday, 2000). Stratum 2 is composed of eolian sands that accumulated along the flanks of draws or on upland surfaces, with paludal muds occurring in the valley axis. Spatially discontinuous eolian deposition (stratum 3) occurred during potentially numerous events in the early Holocene (11 to 8 cal. ka) across the Southern High Plains (Holliday, 1989, 2000). Carbon isotope values from buried soil A horizons, though not a closed system post-burial, indicates varying dominance of more heat tolerant C4 grasses between ca. 13 and 9 cal. ka (Holliday, 1997b, 2000).

Regional aridity was pronounced at ca. 8.5 cal. ka and occurred as two distinct regional episodes of eolian sedimentation between ca. 7.0 and >5.0 cal. ka (stratum 3) ago and from ca. 5.5 to 4.5 cal. ka (stratum 4) (Holliday, 1989, 1995, 2000). Wetter conditions and landscape stability prevailed between these eolian events and is indicated by spring activity and deposition of alluvial sediments and marsh clays in the draw axis. Middle Holocene (9 to 4 cal. ka; Altithermal) eolian sand deposits are also identified at a number of archaeological sites on the Southern High Plains (Fig. 4). The principal episode of dune building for the Sand Hills Dune Field between the Blackwater and Yellowhouse draws was between 7.0 and 5.0 cal. ka (Gile, 1979; Holliday, 1989, 1991) Lunettes on the Southern High Plains also show maximum Holocene activity between 8 and 5 cal. ka ago (Holliday, 1997a,b). An archaeologic assessment further underscores the extreme aridity of the middle Holocene (9 to 5 cal. ka) on the Great Plains, with severest conditions in southern areas (Meltzer, 2000). The human abandonment of drought-sensitive occupation sites, the redigging of wells to tap deeper groundwater sources, and the shift of the diet to include more grain and nuts and less bison is consistent with diminished groundwater and surface water resources (Meltzer, 2000).

Less is known about eolian activity in the late Holocene (4–0 ka) on the Southern High Plains. Two localities, Mustang Springs and Plainview, have eolian sands that date between ca. 3 and 1 ka (Fig. 4). A number of archaeological sites (Lubbock Lake, Mustang Springs and Clovis) show soil(s) buried by eolian sand ca. <1 ka ago (Fig. 4). One lunette dune stratigraphic sequence (Tobosa Ranch) contains two paleosols ^{14}C dated at 450 ± 30 years BP (A-6913) and 755 ± 35 years BP (A-6912) and a bone from the lowermost sand yielded a ^{14}C age of 850 ± 60 years BP, which indicates dune reactivation at ca. 900 and 500 cal. year BP (Holliday, 1997b). The earlier of these events may be correlative with inferred regional drought-induced entrenchment of the Arkansas, Red, Trinity, Brazos and Colorado rivers ca. 1 ka ago (Hall, 1990).

5. Chaco Dune Field, New Mexico

The Chaco Dune Field (3600 km^2) lies on the Colorado Plateau and is situated on the western margin of the Southern High Plains (Fig. 1). A combined geomorphic, pedologic and stratigraphic assessment, with age constraints provided by ^{14}C dating of included organic materials and associated cultural materials, identifies three major episodes of eolian activity in the past 20 ka (Fig. 5) (Wells et al., 1990). The first episode of eolian deposition, sometime between ca. 20 and 14 cal. ka, deposited extensive sand sheets and parabolic dunes (3- to 4-m thick), upon late Pleistocene alluvium. In places, a well-developed paleosol with argillic and carbonate horizons (stages 1–2) formed in the lowest eolian sand indicating an appreciable period (>2 ka) of landscape stability subsequent to eolian deposition. This paleosol is traceable in section for kilometers, thus providing evidence that older eolian and other sediments are not the prime source for younger eolian deposits (Wells et al., 1990).

Parabolic dunes, sand sheets and sand ridges are associated with a second major period of eolian deposition initiated at ca. 6.5 cal. ka, with the bulk of dune accretion between 4.0 and 2.8 cal. ka. These deposits are massive, moderately sorted, medium-to-fine-grained and attain maximum thickness of

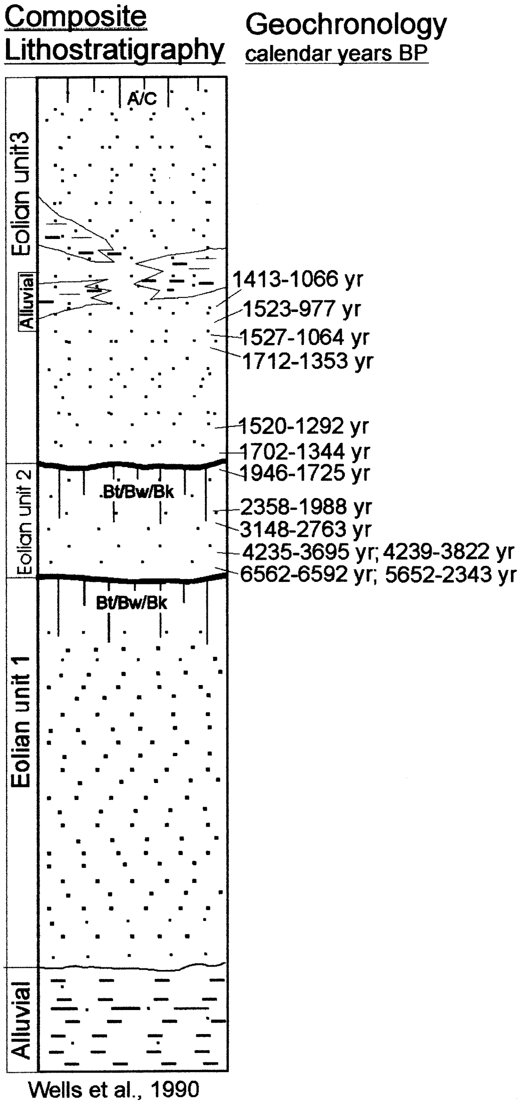

Fig. 5. Composite stratigraphy and ^{14}C ages on eolian sand deposition in the Chaco Dune Fields, New Mexico (Wells et al., 1990). A dark horizontal line with connected vertical lines indicates a buried soil. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

about 1 m. The total volume of sand for the middle Holocene episode is about 20% of sand accumulated during the late Pleistocene.

The third and latest period of eolian deposition produced the most diverse suite of eolian landforms and associated deposits, including barchan, linear, ridge coppice and parabolic dunes and sand sheets. Thickness of deposits varies from < 1 to about 4 m and internal stratification is often well preserved. These eolian features formed since ca. 1.9 cal. ka with some forms active today.

6. Central and western Kansas

The Great Bend Sand Prairie is situated in western Kansas along the Arkansas River and covers an area of 4500 km^2 (Fig. 1). Simple, compound, and complex parabolic dunes and sand sheets characterize this erg. The dunes exhibit two predominant orientations, reflecting distinct periods of formation. Parabolic dunes accreted with winds from the northwest are associated with the Late Wisconsinan (25 to 12 ka), whereas Holocene dunes show southwesterly alignments (Arbogast, 1996).

The surficial deposits of the Great Bend Sand Prairie are composed of two diachronous Quaternary units (Fig. 6). The lower unit is a widely occurring fluvial and playa silt, clay, and sand; organic matter from the lower part of this deposit yields a ^{14}C age of ca. 19.5 cal. ka (Arbogast, 1996). The upper unit is a complex sequence of Holocene eolian sands that are moderately well sorted and display both horizontal and cross stratification. Organic matter recovered from waterlain sediments immediately below 3.5 m of eolian sand gives a maximum limiting ^{14}C age of 8.8 cal. ka for early Holocene eolian activity. A closer limiting age on dune mobilization is provided by a ^{14}C age of ca. 7.7 cal. ka on a buried A horizon developed in the lower eolian sands. Widespread eolian activity occurred south of the Arkansas River in southwestern Kansas, where proximal eolian sand and distal loess facies buried a paleosol that yielded ^{14}C ages of 7.0 to 7.5 cal. ka (Olson et al., 1997). The duration of an potential eolian event starting at ca. 7.7 cal. ka is unconstrained, but dune sand was deposited at ca. > 6.7 and > 3.5 cal. ka (Arbogast and Johnson, 1998).

There is compelling evidence for dune reactivation in the Great Bend Sand Prairie in the late Holocene. Up to three weakly developed buried soils (A/C profile; Birkeland, 1999, p. 5) occur in the upper 1-to-4-m of sequences of eolian sands. Radiocarbon dating of the A horizons of these paleosols indicate potentially five episodes of eolian deposition during the past 2.5 cal. ka at ca. 2.3, 1.4, 1.1, 0.7 and

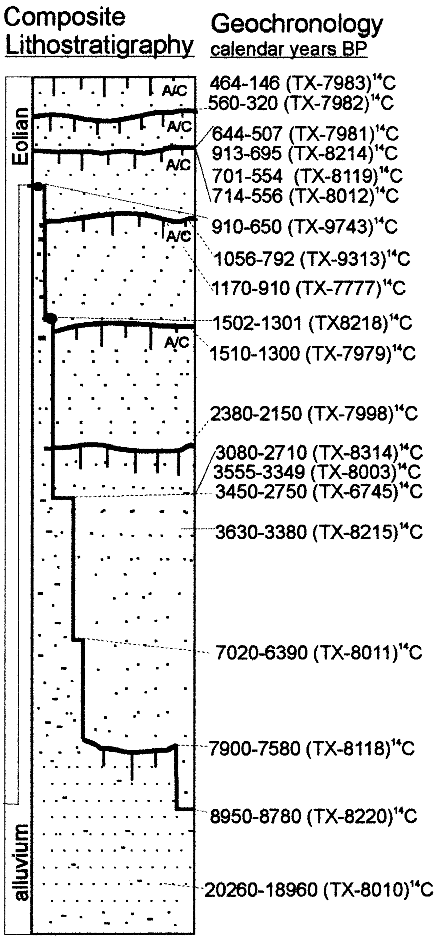

Fig. 6. Composite stratigraphy and ^{14}C ages on eolian sand deposition in the Great Bend Sand Prairie, Kansas (Abrogast, 1996). A dark horizontal line with connected vertical lines indicates a buried soil. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

0.3 cal. ka (Arbogast, 1996; Arbogast and Johnson, 1998).

7. Northwestern Oklahoma, Cimarron River Dune fields

Prominent dune fields occur north and south of the Cimarron River in northwestern Oklahoma and remain one of the least studied eolian systems on the Great Plains. Dunes occur on the modern floodplain and on higher Holocene and Pleistocene terraces associated with the Cimarron River and tributaries. A tripartite relative age dune sequence is assessed by elevation from the valley axis and extent of soil development (Brady, 1989). The youngest dunes, transverse ridges or barchanoid forms, occur on the modern floodplain often in association with former channel banks. Alignment of dunes indicates accretion by winds from the southwest. The next oldest dunes are the "Tivoli dunes", which are single and compound parabolic-dunes 100's m in length. Dune and slipface orientations indicate paleowinds from two directions, southwest and northwest. A ^{14}C age of 1200 ± 70 years BP (GX-14706) from a paleosol A horizon beneath a 2-m thickness of eolian sand provides the sole maximum limiting age constraint on dune activity. The dunes on the highest and oldest terrace are predominantly parabolic forms, though isolated barchonoid transverse and barchan dunes do occur. Like the Tivoli dunes, dune orientations indicate accretion by southwesterly and northwesterly winds. Three ^{14}C ages of 6385 ± 285 (GX-14709) and 7645 ± 380 (GX-14708) and $11,345 \pm 425$ years BP (GX-14707) from buried A horizons within the oldest dune sequence provides maximum limiting ages on Holocene eolian activity (Brady, 1989).

8. Eastern Colorado

Studies in eastern Colorado have examined eolian dunes, sand sheets and loess that mantle more than 20,000 km^2 of the area east of the Rocky Mountains (Figs. 1 and 2). Straddling the Platte River, kilometer-long parabolic and compound parabolic dunes are common with alignments indicating a northwesterly paleowind direction for dune migration (Forman and Maat, 1990). Ergs near the northern tributaries of the Arkansas River also show dunes formed by northwesterly winds (Madole, 1995). However, parabolic dunes in southeastern Colorado, exhibit a southwesterly orientation (Madole, 1995). Loess commonly occurs on interfluves in eastern Colorado (Forman et al., 1995; Blecker et al., 1997; Muhs et al., 1999).

A variety of eolian stratigraphic units spanning the past ca. 20 ka are identified in eastern Colorado from dune morphology, soil development, stratigraphy, and radiocarbon and luminescence dating (Forman and Maat, 1990; Forman et al., 1992b, 1995; Madole, 1994, 1995; Muhs et al., 1996; Muhs et al., 1999) (Fig. 7). The oldest eolian unit is characterized by extensive sand sheets and low-amplitude (1- to 3-m high) dunes in lowland areas (> 1480 m) and loess on upland surfaces (> 1500 m). A well-developed surface soil (> 20-cm thick Bt and Bk horizons) occurs where this eolian material is not covered by younger eolian sand (Madole, 1995). A potentially correlative soil is buried by loess with the buried A horizon yielding ^{14}C ages of between 20 and 23 ka (Muhs et al., 1999). The age of the lower eolian sediments is well constrained by an AMS ^{14}C age of 17 cal. ka on an in situ gastropod shell from the sand facies and TL ages between ca. 20 and 14 cal. ka on eolian sand and loess facies (Forman et al., 1995; Madole, 1995). Another study by Muhs et al. (1999) also identifies loess deposited between 23 and 14 cal. ka and potentially a later loess depositional event between 13 and 11 cal. ka in eastern Colorado. Well-developed soils of the Vona and Osgood series (A/Bt/Bk/C profile) formed in the sand sheet facies and are correlated with soil development on the Kersey Terrace of the South Platte

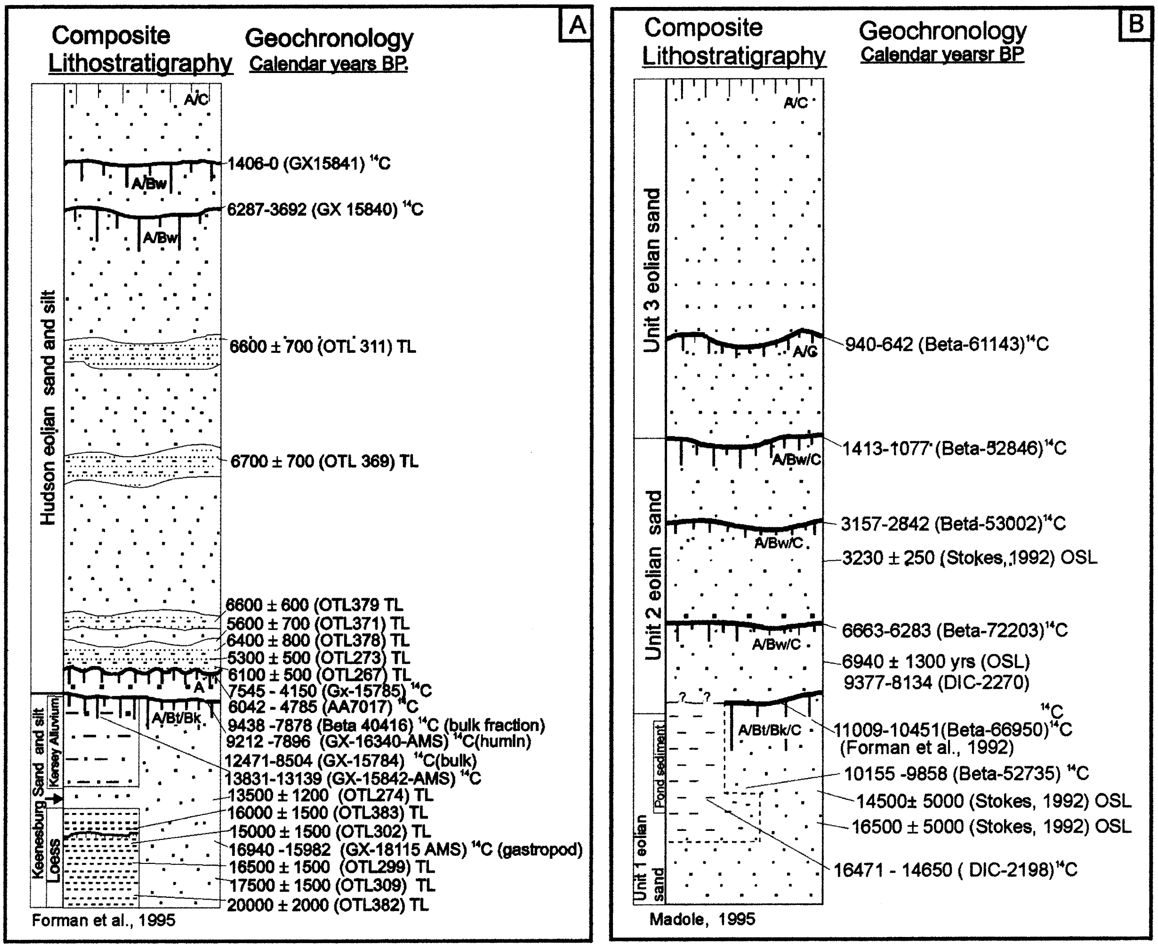

Fig. 7. Composite stratigraphy and chronometric constraints on eolian sand deposition for ergs of Eastern Colorado: (A) Forman et al. (1995) highlights early and middle Holocene record with radiocarbon and thermoluminesence (TL) ages. (B) Madole (1995) gives evidence for dune reactivation for the late Holocene with ^{14}C ages and optically stimulated luminescence (OSL) ages. A dark horizontal line with connected vertical lines indicates a buried soil. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

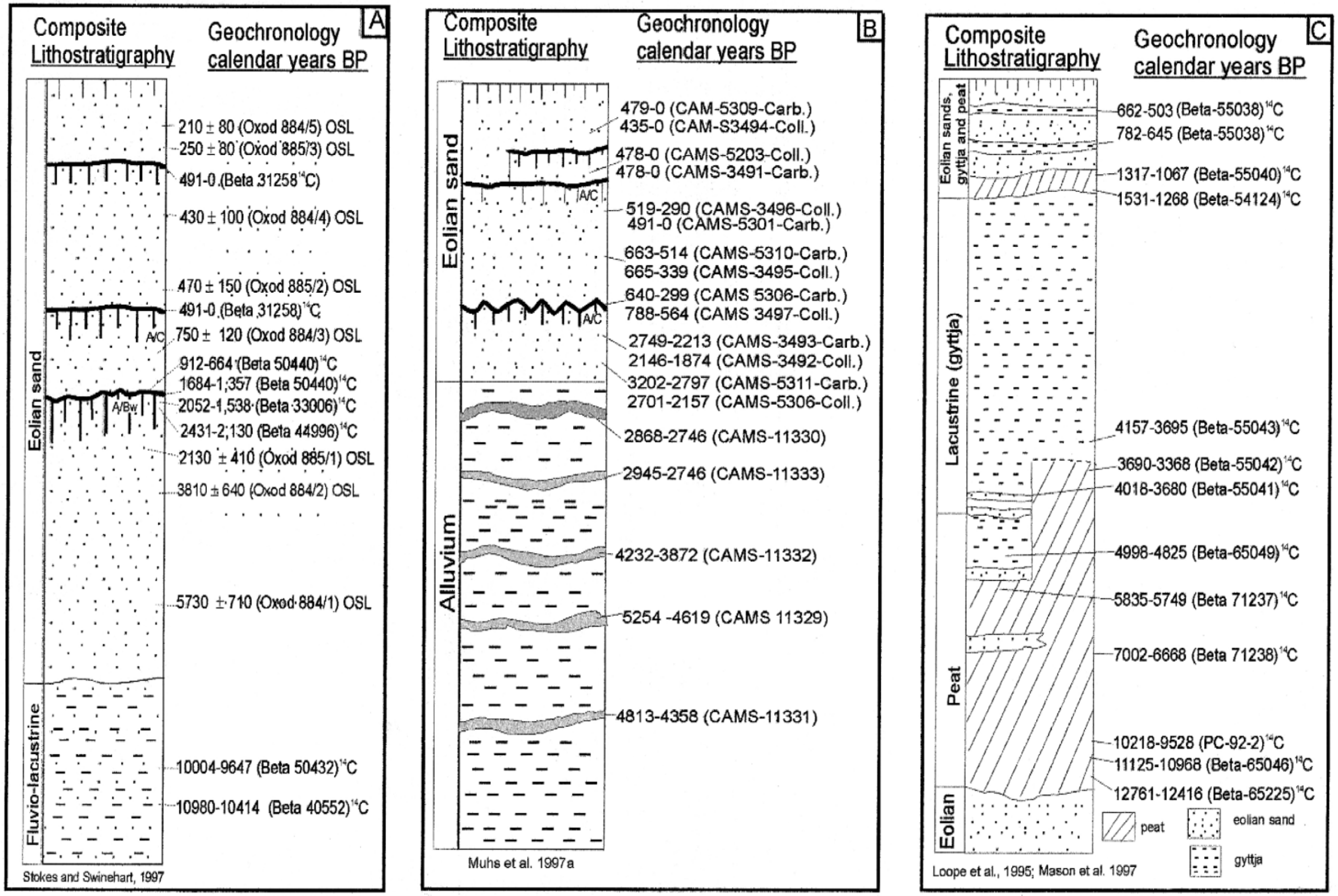

Fig. 8. Composite stratigraphy and chronometric constraints on eolian sand deposition in the Nebraska Sand Hills: (A) Study sites at Whitman, Ne and Merritt Reservoir (Stokes and Swinehart, 1997). (B) Barchan dune history flanking the Middle Loup River (Muhs et al., 1997a). Grey represents organic rich zones. (C) History of dune-dammed lakes in western Nebraska. Peat and gyttja accumulate with formation of Swan Lake during a period of active dune migration (Loope et al., 1995; Mason et al., 1997). Beds of eolian sand near the top of the sequence indicate dune sand deposition events in the past 1 cal. ka. A dark horizontal line with connected vertical lines indicates a buried soil. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

River (Madole, 1995). The upper part of this terrace contains Clovis diagnostic artifacts and thus eolian sedimentation is inferred to end at ca. 12 to 11 cal. ka (Madole, 1995; Muhs et al., 1996). In addition, ^{14}C ages on organic coatings from sand grains recovered from the basal eolian sediments places dune movement before ca. 10.5 cal. ka (Muhs et al., 1996).

Eolian stratigraphy, principally at the Kersey Road site (Fig. 2) provides insight into landscape changes during the Pleistocene to Holocene transition (Fig. 7A) (Forman et al., 1995). The presence of a well-developed paleosol (A/Bt/Bk profile) in the lower eolian sand indicates relative landscape stability between ca. 13.5 and 10 cal. ka. A buried A horizon is over thickened by the addition of eolian silt and sand that buries this soil and demarcates a period of drying from ca. 9.0 to 6.5 cal. ka. (Fig. 8). This drying is probably regional indicated by loess deposits dated between 10 and 4 cal. ka in eastern Colorado (Blecker et al., 1997), eastern Kansas (Olson et al., 1997) and eastern Nebraska (Martin, 1993; Maat and Johnson, 1996).

A major eolian event is indicated by the subsequent truncation and burial of the “Kersey soil” by up to 10 m of low angle, cross-bedded eolian sands. Luminescence and ^{14}C dating place the burial of this surface and accumulation of the eolian sands between ca. 7 and 5.5 cal. ka (Fig. 7B). A period of landscape stability followed, indicated by a paleosol with modest pedogenesis (A/Bw profile). This paleosol was buried subsequently by eolian sand; ^{14}C dating of disseminated organic matter from the buried A horizon place burial sometime between 6.3 and 3.7 cal. ka. A similar paleosol sequence yielded the AMS ^{14}C age of 3.6 cal. ka from the interior of pedogenic rhizoliths, providing a minimum age estimate for the enclosing eolian sand (Muhs et al., 1996). Madole (1995) dated a buried A horizon in an analogous stratigraphic sequence, which yielded a younger burial age of ca. 2.9 cal. ka or may represent a separate event. A 1 + m-thick loess deposit in eastern Colorado with a basal age of ca. 4 cal. ka capped by the present soil indicates an episode of substantial aridity post 4 cal. ka (Blecker et al., 1997).

Recent evidence for eolian activity is visible on aerial photography as fresh-appearing compound parabolic dunes within ergs (Fort Morgan Dune Field; Fig. 2) of northeastern Colorado (Madole, 1994, 1995). Exposures of this latest dune sequence reveal at least two buried soils with A/C profiles, indicating < 1000 years of pedogenesis. Radiocarbon ages on disseminated organic matter from these buried soils yield ages of ca. 1400 and 900 cal. year (Forman et al., 1992b, 1995; Madole 1994, 1995), indicating two dune reactivation events in the past 1500 cal. year (Fig. 7B).

9. Wray Dune Field, Colorado and Nebraska

The Wray Dune Field straddles northeastern Colorado and southwestern Nebraska border and similar to other dune fields in eastern Colorado is dominated by northwesterly accreted compound parabolic and parabolic dunes (Fig. 1). The Hoover blowout site on the Nebraska side, provides 8 m of stratigraphic exposure and dateable material to constrain the activity of this dune field (Madole, 1995; Muhs et al., 1997a). A maximum limiting age on dune accretion is provided by a ^{14}C age of ca. 16 cal. ka on shells from paludal deposits that floor the blowout. Overlying the paludal sediments are > 2 m of eolian sand, indicating subsequent drying. A conspicuous compound buried soil developed in eolian sand is traced 100-m laterally in the blowout. Bulk organic matter from this buried soil developed in the top of the eolian sand yield a ^{14}C age of 8.7 cal. ka. These ages indicate that deposition of the lowermost eolian sand occurred sometime between ca. 8.7 and 16 cal. ka. Radiocarbon ages of 290 ± 60 ^{14}C years BP (CAMS-5301) and 360 ± 60 ^{14}C years BP (CAMS-3496) on two bison bones from eolian sand immediately above the buried soil indicate dune reaction during the past 500 years (Muhs et al., 1997a).

10. The Nebraska Sand Hills

The largest single erg in North America is the Nebraska Sand Hills (Fig. 1), where eolian sand deposits attain thickness up to 80 m (Swinehart, 1989). This mass of eolian sand is largely derived in the Pleistocene from eastward flowing rivers and streams like the Platte and Niobrara (Loope et al., 1995). A variety of eolian landforms exist in the Nebraska Sandhills, but crescentric and barchanoid forms are most common (Swinehart, 1989). A majority of dune orientation indicates paleowinds from north to northwest, similar to present prevailing winds (Ahlbrandt et al., 1983). Insights on Holocene eolian activity in the Nebraska Sand Hills is culled from stratigraphic studies of eolian sand sequences (Stokes and Swinehart, 1997; Muhs et al., 1997a) and from new understanding of dune-dammed lakes in southwestern Nebraska (Loope et al., 1995; Mason et al., 1997; Loope and Swinehart, 2000) (Fig. 8).

The history of reactivation of megabarchan dunes is investigated in the heart of the Nebraska Sand Hills, near Whitman, NE and at the Merritt reservoir (Figs. 2 and 8A), where there are 15- and 55-m-thick exposures of Holocene sediments, respectively (Stokes and Swinehart, 1997). Beneath the dune sequence are fluvial or lacustrine sediments that contained organic matter that provide a maximum constraining age on dune formation of ca. 9.8 cal. ka (Fig. 8A). Quartz sand grains from the lower part of a barchan dune yielded luminescence age of 5730 ± 710 cal. year BP (Oxod 884/1) placing initial dune accretion at ca. 6 cal. ka. Sands approximately 11 m from the dune base gave a luminescence age of 3810 ± 640 cal. year BP (Oxod 884/2). There remains uncertainty if dune accretion was continuous between ca. 5.7 and 3.8 cal. ka because of the presence of secondary clay immediately above the ca. 5.7 cal. ka luminescence age. However, deep translocation of secondary clay into porous sand may relate to a significantly later period of landscape stability (Gile, 1979), thus, the dune sequence may be conformable and reflect continuous deposition.

Barchan dunes exposed at the Whitman Reservoir were reactivated in the late Holocene indicated by a luminescence age on eolian sand of ca. 2.1 cal. ka, immediately overlying older ages (Fig. 8). Landscape stability followed indicated by a paleosol, which was subsequently buried by eolian sand; ^{14}C dating of the buried A horizon places dune reactivation sometime between ca. 2.0 and 1.4 cal. ka (Stokes and Swinehart, 1997). Higher in the section at Whitman Reservoir is a paleosol buried by 2 + -m eolian sand. Organic matter from the A horizon of this paleosol yielded a ^{14}C age of < 0.5 ka, and the sand overlying this A horizon gave luminescence ages of 450 to 210 cal. year BP (Fig. 8A).

Muhs et al. (1997a) provide insights into Holocene activity of megabarchan and barchanoid ridge dunes in the western Nebraska Sands Hills, flanking the Middle Loup River (Figs. 2 and 8B). Maximum constraining age on dune migration is provided by ^{14}C ages of ca. 2.8 cal. ka on organic matter from alluvial deposits subjacent to eolian sediments. The recency of dune migration is indicated by ^{14}C ages of ca. 700 to 200 years on collagen and carboxyl extracts from bison bones recovered from eolian sands with weak (A/C) paleosols. Data from disparate sections indicate that eolian sand deposition occurred at least twice in the past 3000 to possibly three times in the past 800 years.

Important insights on the magnitude and timing of dune migration in the western Nebraska Sandhills are culled from new understanding of the interactions of dune movement with the low-gradient Blue Creek (Loope et al., 1995; Mason et al., 1997). Large-scale dune migration results in a succession of dune dams of a drainage and subsequent rise in water table and formation of lakes. Radiocarbon dating of basal peat deposits formed in dune-dammed aquatic environments yield close constraining ages on dune migration. The blockage of Blue Creek Valley by migrating dunes formed Swan Lake between ca. 10.5 and 12 cal. ka ago. A second episode of dune blockage of this drainage, though not well dated, occurred in the middle Holocene (8–5 cal. ka). Eolian activity during the middle Holocene produced the latest set of dune dams, which eventually formed Crescent and Blue lakes by ca. 4000 years ago (Mason et al., 1997). The accumulation of gyttja in these lakes was mostly continuous for the past 4 to 3 ka. Relatively thin alternating beds of eolian sand and peat and gyttja at the top of the succession, possibly indicate brief periods of eolian activity at ca. 1.2, 0.7 and 0.6 ka (Loope et al., 1995; Mason et al., 1997).

11. The Ferris Dune Field, Wyoming

The Ferris Dune Field occurs at ~2000 m asl in an intermontane basin in southeastern Wyoming, immediately west of the Great Plains. (Fig. 1). Eolian landforms are dominated by parabolic and blowout dunes of which approximately 85% are currently stabilized (Gaylord, 1982, 1987, 1990). The water table in the area is persistently close to the surface and ponds or wetlands have developed in interdune areas, where vegetation is concentrated. Dune morphology and sedimentary structures indicate that paleowind directions were predominantly from the west and southwest, which is similar to the current wind regime (Gaylord, 1987). The source of the dune sand is primarily the Battle Springs Formation, a fluvially derived Eocene unit immediately upwind from the Ferris Dune Field (Gaylord, 1982).

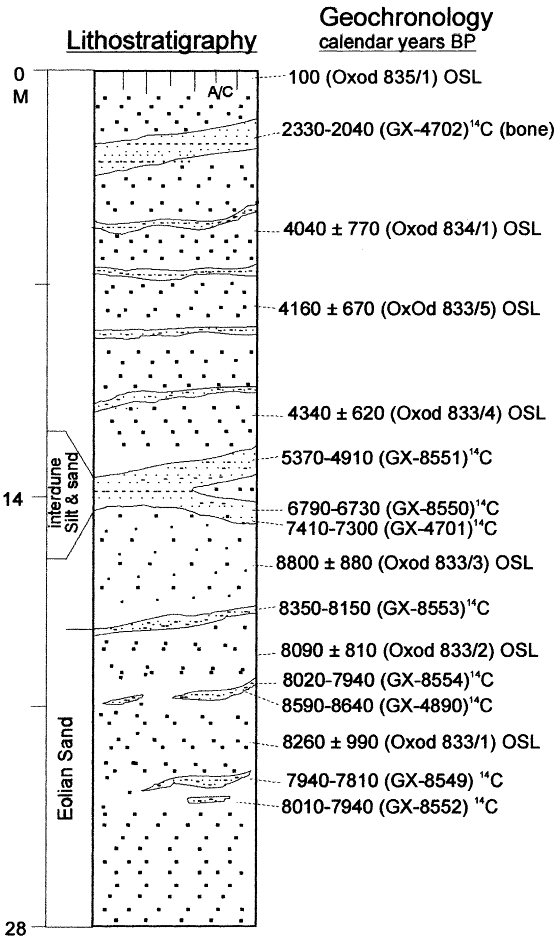

Fig. 9. Stratigraphy and ^{14}C and optically stimulated luminescence (OSL) ages on eolian deposition at Ferris Dune Field, Wyoming (Stokes and Gaylord, 1993). Sequence is composed of intercalated eolian sands and organic rich interdune silty sands.

The stratigraphy of the Ferris Dune Field is characterized by a nearly continuous sequence of eolian sand deposited during the past 10 ka (Gaylord, 1990; Stokes and Gaylord, 1993). Luminescence dating of eolian sands and ^{14}C dating of organic material from interdune layers show that ~13 m of eolian sediments were deposited between ca. 8.2 ka and 7.4 cal. ka (Fig. 9). The interdune layers are relatively thin and in places discontinuous, suggesting that the eolian activity proceeded without major interruptions during the early Holocene. These eolian sediments are overlain by ~1-m thickness of laterally continuous organic interdune silty-clay. This silty-clay layer contains wood, which yielded ages of ca. 7.4–6.7 cal. ka, and reflects wetter conditions, when eolian activity was limited. Above this interdune silt layer are alternating beds of interdune silty-sand and dune sand spanning from 5.2 to 4.0 ka, with a prominent eolian sand bed dated between 4.3 and 4.0 ka. Another organic-bearing interdune silt layer overlies the alternating beds and bone recovered from an interdune silt layer yields a ^{14}C age of ca. 2.2 cal. ka. Dune sands cap the sequence, representing eolian deposition that has occurred within the past 2 cal. ka (Stokes and Gaylord, 1993).

The record from the Ferris dune field shows that two major eolian episodes occurred from ca. 8.2 to 7.4 cal. ka and from ca. 4.3 to 4.0 cal. ka. There is evidence of sporadic eolian activity between ca. 6.5 and 5.5 cal. ka. Periods of relative landscape stability existed from ca. 7.4 to 6.7 cal. ka and from ca. 5.3 to 5.0 cal. ka. At least one episode of dune remobilization occurred after 2.0 cal. ka.

12. The Northern High Plains, US and Canada

Sand sheets and dune sands on the northern Great Plains are thinner and less extensive than counterparts on the southern and central Great Plains (Fig. 1). Eolian sands sheets and dunes in northern localities are mainly derived from glaciolacustrine and glaciofluvial sources and postdate the retreat of the Laurentide ice sheet at ca. 15 cal. ka (Wolfe et al., 1995; Muhs et al., 1997b). Stratigraphic studies document multiple weakly developed paleosols (A/C horizon) within an eolian sand sequence on the

Northern Plains spanning the past 4 ka (Muhs and Wolfe, 1999) (Figs. 10 and 11). ^{14}C dating of organic matter from buried A horizons, included bison bones, and optical dating of feldspar grains from eolian sand provides age constraint.

Dune orientation in the Minot Field in North Dakota suggests paleowinds were from the northwest, similar to the current wind regimes (Muhs et al., 1997b). Radiocarbon dating of the organic matter from the lower most buried A horizon places the oldest recognized eolian event in the Minot Dune Field just prior to 1100–1300 cal. year (Fig. 10). Subsequently, eolian sand buries soils demarking two dune migration events at ca. 1000 and 600 cal. year ago and possibly a third in the past 400 years. The Sheyenne Delta Dune Field, east of the Minot

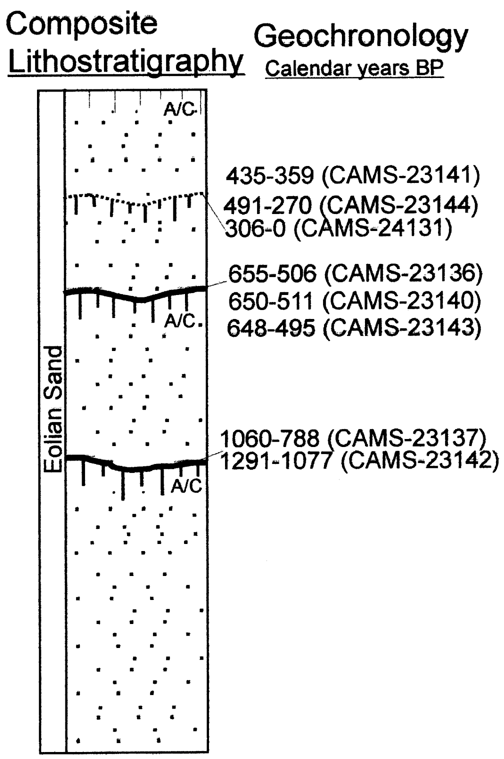

Fig. 10. Composite stratigraphy and ^{14}C ages on eolian sand deposition in the Minot Dune Field, North Dakota (Muhs et al., 1997b). A dark horizontal line with connected vertical lines indicates a buried soil. Dashed line indicates weak soil development. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

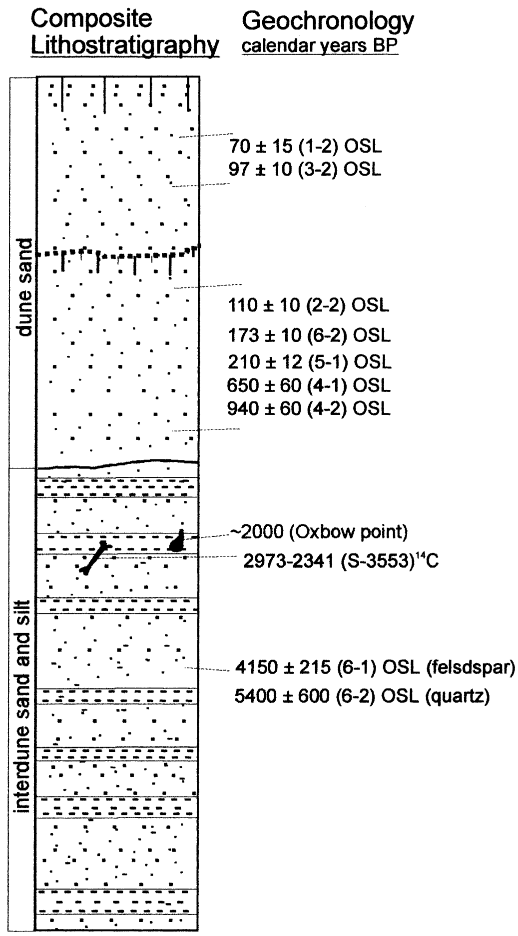

Fig. 11. Composite stratigraphy and feldspar optically stimulated luminescence ages on eolian sand deposited at the Great Sand Hills Dune Field, Saskatchewan, Canada (Wolfe et al., 1995; Muhs and Wolfe, in press). A dark horizontal line with connected vertical lines indicates a buried soil. Dashed line indicates weak soil development. The horizon development of buried soils is indicated by letter designations (Birkeland, 1999, p. 5).

system shows similar timing for eolian events (Muhs and Wolfe, 1999).

The Great Sand Hills in southwest Saskatchewan constitute the largest dune field on the Canadian Prairies (Fig. 1). The eolian deposits comprise parabolic dunes, blowout dunes and dune crevasses derived from underlying glacial sediments (Wolfe et al., 1995). Eolian sand is observed to unconformably overly a silty interdune deposit that gave a luminescence age of ca. 4.8 cal. ka (Fig. 11). Cultural material within interdune sediments range in age from ca. 4.0 to 2.0 cal. ka suggests a period of human occupation, and hence dune stability. Bison bones recovered from the same horizon yield ^{14}C age of 2973–2341 cal. year BP (S-3553). The stratified dune sands, which overlie the interdune deposits yield luminescence ages of ca. 940 ± 60 cal. year, and 650 ± 60 cal. year and four luminescence ages between 70 and 210 cal. year, indicating potentially three episodes of dune activity in the past 1000 years. Inferred periods of eolian deposition at the nearby Brandon Dune field, Manitoba are somewhat older at ca. 3.7, 2.2, 1.5 and 0.9 cal. ka (Wolfe and Muhs, 1999). A similar suite of eolian depositional events at ca. 3.5, 2.4 and 0.8 cal. ka is reconstructed for Pike Lake Dune Field in Saskatchewan (Muhs and Wolfe, 1999).

13. Lake Ann: Anoka Sand Plain, western Minnesota

Lake Ann is a closed basin situated downwind from a parabolic dune field on the Anoka Sand Plain in western Minnesota (Fig. 1). The dunes are up to 20-m high and indicate a predominantly northwesterly paleowind direction with later modification by winds from the east and west. The sediments contain in situ biogenic material, slope wash, littoral and eolian sand-grains from the adjacent dune field (Keen and Shane, 1990). Eolian sand has distinctive elevated magnetic susceptibility, reflecting the glacial outwash source, which is used to track eolian input through the record (Fig. 12). Chronologic control is limited to two ^{14}C ages of 4.9 and 8.1 cal. ka at 11.2 and 14.2 m, with a timescale generated by linear

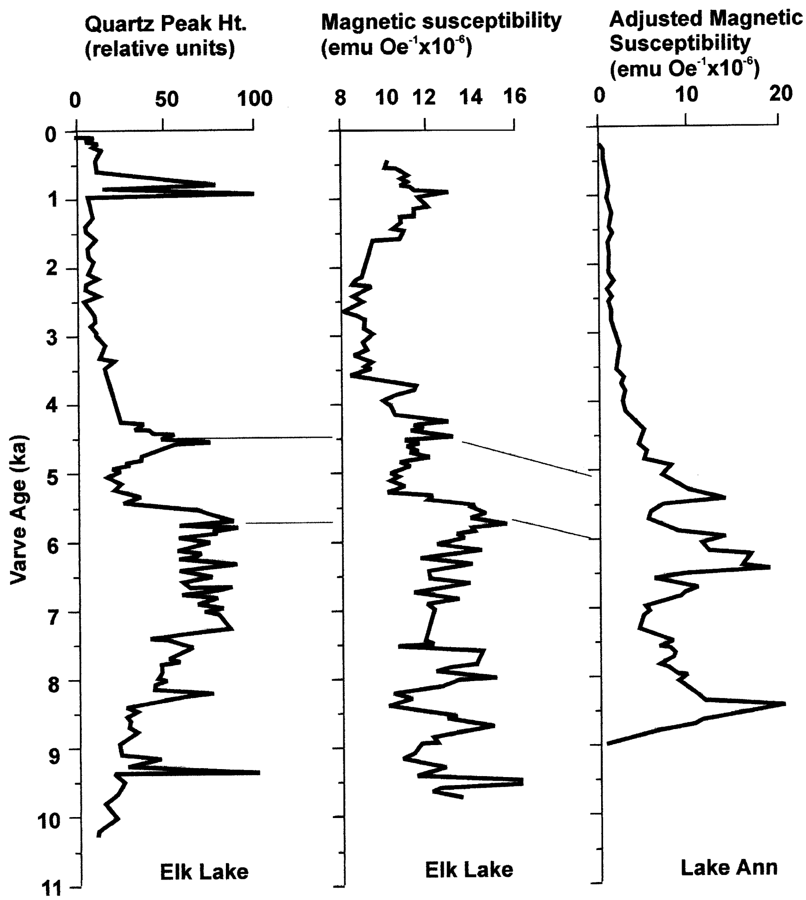

Fig. 12. Quartz peak height (by X-ray diffraction) and magnetic susceptibility for sediment records from Lake Ann and Elk Lake, Minnesota (Dean et al., 1996). Elevated values are associated with increased clastic input, associated with general drying and eolian activity.

interpolation and extrapolation from these ages (Fig. 12).

Near Lake Ann at ca. 10 cal. ka, a coniferous forest gave way to prairie vegetation reflecting a decline in precipitation and an increase in temperature. An increase in coarse silt and sand between 8.7 and 4.0 cal. ka, heralded by elevated magnetic susceptibility levels is clear evidence for enhanced eolian deposition into Lake Ann (Fig. 12). There are three distinctive peaks in eolian sand at ca. 8.0, 6.8 and 5.2 cal. ka, concurrent with reductions in lake organic matter, and increase in non-arboreal pollen. A 15% to 40% depression in precipitation from the current mean (72 cm) is inferred from pollen data and is associated with maximum eolian activity for the early to middle Holocene (Keen and Shane, 1990).

14. Elk Lake, northwestern Minnesota

Elk Lake at the northeastern margin of the Great Plains provides a subdecadal-scale sedimentary record of environmental changes since retreat of the Laurentide ice sheet (Bradbury and Dean, 1993). This record contains millimeter-scale varves spanning the past 11 ka and is composed of biogenic and autochthonous manganese oxyhydroxides and iron phosphate and allochthonous siliciclastic grains (Dean, 1997). Quartz content, magnetic susceptibility properties and elemental analysis identify periods of detrital influx associated with regional aridity (Dean et al., 1996; Dean, 1997) (Fig. 12).

Early Holocene pollen assemblages from Elk Lake show the transition from Spruce to Jack and Red Pine forest reflecting increasing summer temperatures and annual precipitation (Whitlock et al., 1993; Bradbury et al., 1993; Dean, 1993). A short dry episode occurred between ca. 9.5 and 9.1 cal. ka indicated by an increase in clastic sedimentation and birch pollen and a decrease in Pine pollen. Pine forests are greatly reduced and prairie grasses and sagebrush dominate the pollen taxa between 9.0 and 8.0 cal. ka, reflecting the eastward expansion of prairie environments. Ostracod and pollen assemblages and enriched $\delta^{18}O$ values for authigenic carbonate indicate cold and dry conditions between 8.0 and 7.0 cal. ka. Extreme arid conditions ensued between 7.0 and 5.8 cal. ka indicated by elevated Na, quartz, and plagioclase content, and maxima in magnetic susceptibility and varve thickness reflecting increased flux of eolian sediments. Concordant with an increase in eolian grains is the presence of aragonite needles, the heaviest ostracod $\delta^{18}O$ and an abundance of halophillic ostracod taxa, which indicates evaporative enrichment. Pollen data suggest that lake level fell to an all time low, responding to both warm summer and winter air temperatures.

Elk Lake freshened between 5.4 and 4.8 cal. ka as indicated by a reduction in clastics, a shift in ostracod taxa, and a decrease of sagebrush pollen with a concomitant increase in birch spores. Subsequent drying occurred between ca. 4.8 ka and 4.3 cal. ka with an increase in eolian clastic input, similar in magnitude to earlier in the Holocene. Decreasing quartz content and magnetic susceptibility between 4.0 and 1.0 cal. ka, parallel with succession from birch, oak and hornbeam forests to pine forests reflecting progressive increase in precipitation. At least three peaks of detrital (eolian) quartz occur in the past 1500 years at ca. 1300 to 1000, 900 to 600, 400 to 200 years, indicating subsequent late Holocene aridity (Fig. 12).

15. Temporal and spatial pattern of Holocene eolian activity on the Great Plains

Not one archive of eolian deposition on the Great Plains captures the total variability of the record. The apparent incompleteness of individual records reflects vagaries of preservation and erosion associated with the eolian stratigraphic and geomorphic record. For example, Madole (1995) reports details of late Holocene activity for eastern Colorado, whereas Forman et al. (1995) presents the early to middle Holocene record for a similar area; together these studies provide a more complete chronology of eolian activity. Assessing the age of eolian events and regional correlation is difficult because of outstanding uncertainties in accuracy and precision of ^{14}C dating of organic matter from buried soils developed in porous eolian sand. Organic matter preserved in a paleosol is not a closed system, but reflects complex processes of carbon storage, degradation, and translocation that lower the veracity of ^{14}C ages. This analysis underscores the need for multiple field assessments to more completely characterize the Holocene activity of dune fields. There is also a clear need for a more accurate and precise chronometer for eolian systems, which luminescence dating is poised to provide (Stokes, 1999). However, despite the acknowledged limitations in uniting records of eolian activity there is evidence for a sustained period of dune activity in the early to middle Holocene (10–5 cal. ka), parallel with regional loess deposition in eastern Colorado (Blecker et al., 1997), Kansas (Olson et al., 1997), and Nebraska (Martin, 1993; Maat and Johnson, 1996). Whereas, in the last 2000 years, there are numerous discrete submillennial to subdecadal scale arid events. This pattern of eolian activity indicates ca. 10 to 5 cal. ka directional climate change, from generally wet to dry conditions with variability, whereas the late Holocene shows solely high variability (cf. Laird et al., 1998).

The response of eolian systems on the Great Plains during the Pleistocene–Holocene transition was variable reflecting a steeper north–south temperature gradient in response to reducing presence of the Laurentide ice sheet (Kutzbach et al., 1998). On the Southern High Plains, temporal discrete eolian deposition occurred ca. 12 to 11 cal. ka and possibly other intervals between 13 and 10 cal. ka (Holliday, 1995, 2000). This inferred drying is recently associated with loess deposition in eastern Colorado and potentially western Nebraska between 13 and 11 cal. ka (Muhs et al., 1999). In central Kansas, grasslands had fully developed by ca. 12 cal. ka, with sharp fluctuations in water table into the early Holocene (Fredlund, 1995). Pollen time series from the eastern and northern areas of the Great Plains document a diachronous vegetation transition from boreal forest to prairie-grasslands starting at ca. 11 to 9 cal. ka with maximum eastward extension of prairies at ca. 6.5 cal. ka (Webb et al., 1993). However, peak drying occurs later further eastward in Iowa between 6.0 and 3.5 cal. ka (Baker et al., 1992).

Dune fields on the Great Plains were sporadically active between 10 and 9 cal. ka (Fig. 13). However, deposition of the Bignell Loess in southern Nebraska began by 10 cal. ka; the source of this loess is either nearby rivers or disturbed surfaces or hill slopes upwind. In eastern Colorado, a paleosol enriched with eolian additions (Forman et al., 1995), is consistent with loess deposition on interfluves (Blecker et al., 1997), reflecting regional drying. A number of lake systems in Minnesota and North and South Dakota between 10 and 9 cal. ka show falling lake levels or other hydrologic changes consistent with drying (Keen and Shane, 1990; Dean et al., 1996; Haskell et al., 1996; Laird et al., 1998).

Many dune fields on the Great Plains show evidence of large-scale dune migration or maxima in accumulation of eolian sediment between 9 and 5 ka (Fig. 13). Activation of the largest dune fields on the High Plains, the Nebraska Sand Hills, Great Bend Sand Prairie in Kansas and ergs of eastern Colorado is registered between 7 and 5 cal. ka. Accretion of cover sands and activation of lunette dunes commenced by 8.5 cal. ka on the Southern High Plains, with distinct events starting at ca. 7 and 5 cal. ka. (Holliday, 1989, 1995). The Lake Ann and Elk Lake records from Minnesota show a sharp increase in clastic sedimentation after 9.0 cal. ka with peak clastic input registered between 7.5 and 5.5 cal. ka associated with reactivation of nearby dunes (Dean et al., 1996). However, dune reactivation, with the sedimentation of ~13 m of eolian sand, at the Ferris Dune Field, Wyoming occurred earlier between 8.2 and 7.4 cal. ka (Stokes and Gaylord, 1993). Some lacustrine paleoenvironmental time series also indicate that peak aridity occurred earlier at ca. 9–8 cal. ka particularly in the western part of Great Plains (Fritz et al., 1991; Yansa, 1998).

Uncertainty remains whether dune fields exhibited continuous activity through the early to middle Holocene; a number of studies infer arrests in eolian activity, some associated with pedogenesis, between 7.5 and 5 cal. ka (Fig. 13). However, the accumulation of the loess (Bignell) between ca. 10 and 4 cal. ka in southern Nebraska, northern Kansas, and eastern Colorado reflects landscape drying and supports the dominance of arid conditions for this interval (Martin, 1993; Maat and Johnson 1996; Blecker et al., 1997; Olson et al., 1997). A succession of plant macrofossils from southeastern Nebraska dated between ca. 9500 and 6800 cal. ka indicates disappearance of upland trees and sparse riparian environments and high variability in grass and weed taxa associated with peak warmth and dry conditions for the Holocene (Baker, 2000). A number of lacustrine records from the northern and eastern margin of the

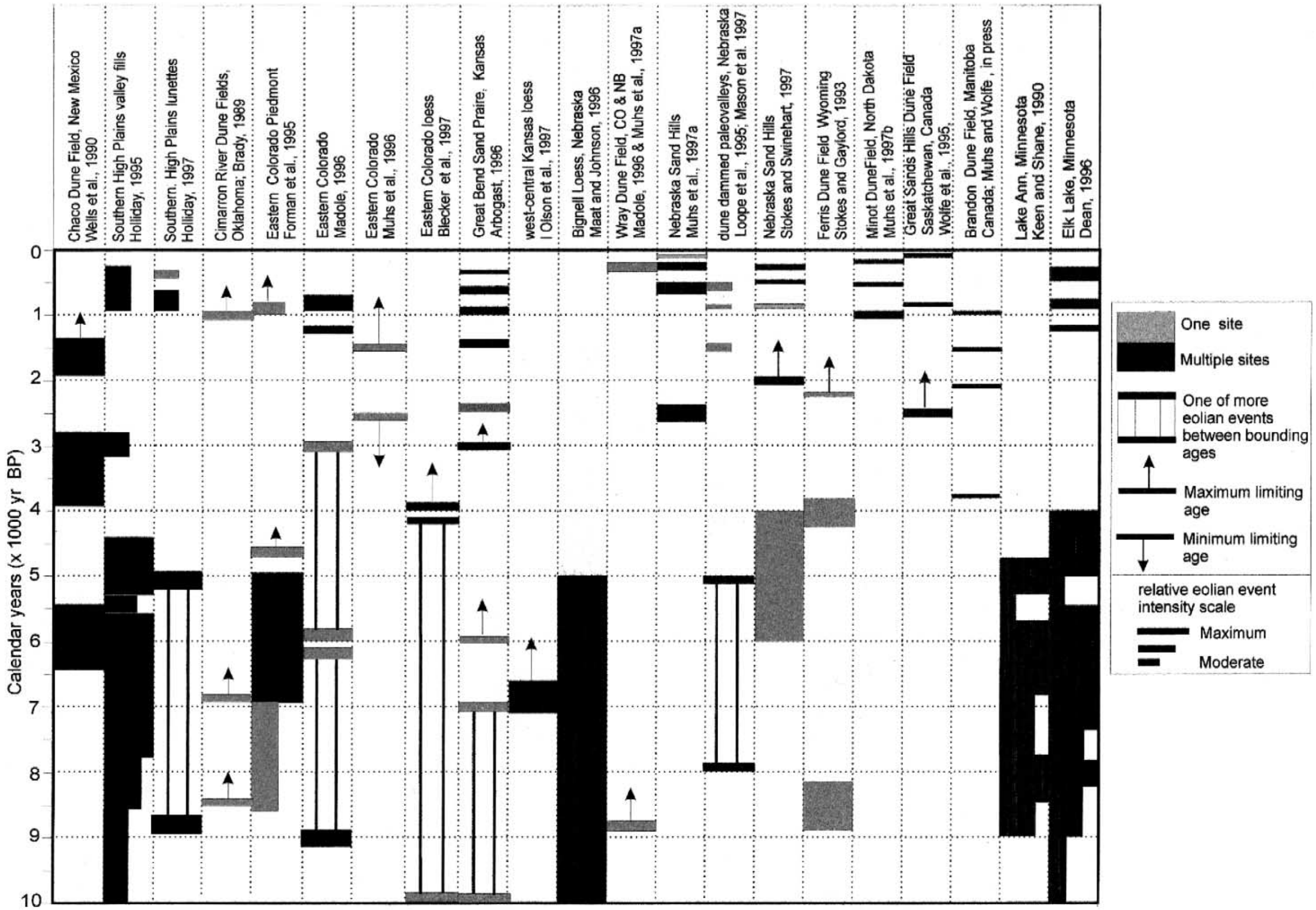

Fig. 13. Summary of dune field activity and associated loess deposition for the Great Plains, US. The terrestrial eolian record is also compared to eolian input record from Lake Ann and Elk Lake, Minnesota. Note that there is evidence for sustained aridity between 10 and 5 cal. ka and numerous discrete events in the past 2 cal. ka. Length of solid bar reflects duration of eolian events and inferred dating errors.

Great Plains also register aridity between ca. 9.0 and 5.0 ka with the driest interval between 7.5 and 5 cal. ka, associated with highest inferred salinity, heaviest oxygen isotopes and/or, occurrence of *Rupia* pollen or maximum in detrital input (Valero-Garces et al., 1995, 1997; Laird et al., 1996; Xia et al. 1997; Schwab and Dean, 1998). Pronounced dryness between 9 and 6 ka is also well expressed in lacustrine systems at lower altitudes in southwestern Canada (MacDonald 1989; Sauchyn, 1990; Sauchyn and Sauchyn, 1991; Vance et al. 1992, 1995; Last and Sauchyn, 1993) and may be associated with persistent zonal Pacific air flow (Edwards et al., 1996).

Eolian activity is apparently less prevalent across the Great Plains between 5 and 2 cal. ka (Fig. 13). However, studies in Wyoming (Stokes and Gaylord, 1993), Nebraska (Stokes and Swinehart, 1997) and Colorado (Forman et al., 1995) indicate potential reactivation of dune systems sometime between 5 and 4 ka. A 1+ m-thick loess deposit in eastern Colorado with a basal age of 4 cal. ka and capped by the present surface soil indicates an episode of substantial aridity post 4 ka (Blecker et al., 1997). Plant macrofossils from fluvial deposits 5.8 to 2.7 cal. ka old in southeastern Nebraska indicate generally moist conditions with intermittent drying similar to earlier in the Holocene (Baker, 2000). Elk Lake and Lake Ann in Minnesota show an increase in detrital flux between 4.8 and 4.3 cal. ka, also similar in magnitude to arid intervals earlier in the Holocene (Fig. 13). Arid interval(s) between 4 and 2 ka may have a more eastern representation with peak drying registered in lacustrine records from the Midwest (Baker et al., 1992) and southern Ontario, Canada, associated with weakened meridional flow off of the Gulf of Mexico (Yu et al., 1997). Eastern aridity is associated with predominance in cool season precipitation during a period of sustained drought (Denniston et al., 1999).

There is clear evidence for the reactivation of dune fields across the Great Plains in the past 2 cal. ka. Some studies identify a broad period post 1 to 2 cal. ka characterized by eolian activity (e.g. Wells et al., 1990; Forman et al., 1995). Other studies document up to five stratigraphically distinct episodes of eolian deposition separated by weakly developed paleosols (Arbogast, 1996). Dune reactivation is registered at three or more localities on the Great Plains at ca. 1.5–1.3, 1.0–0.8, 0.7–0.4 and > 0.4 ka. Uncertainty remains whether if late Holocene dune mobilization events reflect regional aridity or an endemic response. There is not a clear association of dune reactivation events with aridity indicators from lake records in the past 2000 years. The Elk Lake sediment record exhibits three broad periods of increased detrital input associated with regional aridity at 1300 to 1000, 900 to 600, and 400 to 200 years (Dean, 1997). Higher resolution lake records from North Dakota register up to 13 potential droughts in the past ca. 2000 years inferred from diatom taxa and ostracod Mg/Ca ratios (Yu and Ito, 1999; Fritz et al., 2000). Lacustrine systems also record an unknown range of variability in hydrologic conditions, whereas dune fields reactivate under extreme drought conditions. Thus, it is difficult to assess the magnitude of drought signature in proxy data from lakes (e.g. diatom and Cd/Ca) that has a correlative expression as reactivation of dune fields. The amplitude of diatom-based salinity estimates and Cd/Ca ratios for the 20th century is similar to century to millennial scale variations (e.g. Fritz et al., 2000) indicating a lack of sensitivity of certain proxies to capture extreme drought conditions.

Dendroclimatic and other proxy time series from North America provide needed insight on potential extreme droughts in the past ca. 2000 years (Woodhouse and Overpeck, 1998). These proxies show that droughts prior to the 16th century are of longer duration and greater spatial extent than 20th century events. A recent analysis of tree-ring time series further defines a “megadrought” that spanned the first half of the 16th century with clear expression across the North American continent (Stahle et al., 2000). Tree-ring time series from the western margin of the Canadian Prairies also reveal a prolonged 16th century drought, but the strongest drought signature in the past 500 years is in the late 18th century (Case and MacDonald, 1995). Lacustrine and tree-ring time series spanning the past 750 years from Yellowstone National Park, Wyoming identify three maxima in regional forest fires at ca. 1700, 1560 and 1440 AD, which may reflect prolong aridity (Millspaugh and Whitlock, 1995). At a number of localities on the Great Plains up to two-dune reactivation events are identified in the past 600 years (Fig. 13), however the direct association of these events to dendroclimatologic-determined drought is unclear.

16. Climate controls on North American aridity

Environmental changes in North America during the past 10 cal. ka are often ascribed to interaction between climatic effects of the waning Laurentide ice sheet and seasonal variations in insolation (Kutzbach and Guetter, 1986; Kutzbach, 1987; COHMAP, 1988; Kutzbach et al., 1994, 1998). Reactivation of the largest dune systems on the Great Plains between 9 and 5 cal. ka is parallel to elevated summer insolation values, compared to today, which predominated after 7.5 cal. ka with demise of the remnants of the Laurentide ice sheet (Bush, 1999). The reactivation of dune systems is associated with growing season droughts of greater duration and severity than recorded historically. These "mega-droughts" reflect the dominance of drought conditions for a decade or more with at least a 25% deficit in growing season precipitation (cf. Tomanek and Hulett, 1970; Keen and Shane, 1990; Mock, 1991). Numerous studies forward the correlation between solar forcing and centennial and decadal scale droughts, particularly for the past ca. 2 cal. ka in the northern Great Plains (Anderson, 1993; Laird et al., 1996; Dean, 1997; Yu and Ito, 1999). One mechanism specific to North America is the modulation of the Earth's geomagnetic field via increasing solar winds, which leads to compression at the 700-mbar height and subsequent increase in westerly arid zonal flow (Dean, 1997).

Paleoclimate modeling of Kutzbach and Guetter (1986) and subsequent refined simulations that are driven largely by insolation changes show a small ($<10\%$) reduction in moisture ca. 6 cal. ka ago compared to present for the midcontinental US (e.g. Kutzbach et al., 1994, 1998; Bartlein et al., 1998; Vettoretti et al., 1998). These results are inconsistent with proxy environmental data summarized in this paper that document droughts of sufficient magnitude to reactivate dune systems. Furthermore, the Paleoclimate Modeling Intercomparison Project (PMIP et al., 1999), an assessment of more than a dozen separate climate models focused on the middle Holocene monsoon responses in north Africa and south Asia, show that models consistently under-represent the hydrologic response in North American compared to proxy paleoenvironmental data. This model-data discordance for middle Holocene drought in North America suggests that there are a variety of external and internal climate controls besides insolation that could lead to persistent arid conditions.

A number of recent analyses demonstrate an instrumental-based relation between cooler Pacific sea-surface temperatures and central North American drought (Trenberth and Guillemot, 1996; Ting and Wang, 1997). A global statistical analysis utilizing the Palmer Drought Severity Index for the past century shows clear regional patterns of drought and wet conditions that are correlated with phases of the El Niño-Southern Oscillation (ENSO) (Dai et al., 1998). Of particular interest is the association of dry conditions across central North America and somewhat wetter conditions in North Africa during a La Niña phase (Palmer and Brankovic, 1988). An analysis of 130 years of instrumental and dendroclimatologic data also shows a relation between Pacific sea-surface temperatures and central North American hydrologic extremes (Cole and Cook, 1998). Modes of Pacific Ocean variability and relation to drought relation have changed, with La Niña-related droughts extending throughout most of the conterminous US in the late 19th century, whereas recent droughts are more restricted to the southwestern US. Given the modern and recent climate relation between equatorial Pacific sea surface temperatures (SSTs) and hydrologic extremes in central North America, prolong droughts on the Great Plains of North America during the Holocene may be related to the persistence of La Niña type conditions. Indeed, proxy ENSO records from localities in Ecuador (Rodbell et al., 1999) and Peru (Foutugne et al., 1999) indicate multidecade dominance of La Niña conditions between 10 and 6 cal. ka.

La Niña conditions would weaken the southwesterly flow of air in the mid-to-high troposphere and reduce moisture flux to the Great Plains. A relatively small amount of water is associated with southwesterly flow but this flux can enhance cyclogenesis by promoting the lift of low-level moisture off of the Gulf of Mexico with passage of storm systems (Oglesby, 1991). ENSO variability of the eastern tropical Pacific Ocean also has a downstream effect on tropical Atlantic Ocean, Gulf of Mexico and Caribbean SSTs (Hastenrath et al., 1987; Enfield and Mayer, 1997). Giannini et al. (2000) estimated the lag time between a warm or a cold ENSO event and a response in the tropical North Atlantic Ocean to be on the order of 2 to 4 months. Whereas Penland and Matrosova (1998) find that the northern tropical Atlantic and Caribbean SSTs anomalies can be skillfully predicted with about a 6-month phase lag of the El Niño sea surface temperature anomalies. These modern studies suggest that following the winter impacts of a La Niña Spring and Summer Caribbean SSTs can be expected to be anomalously cold. A cooler tropical sea surface would weaken the low level jet, a critical circulation element that funnels surface moisture northward from the Gulf of Mexico to central North America (Oglesby, 1991; Kroczynski et al., 1993; Higgins et al., 1997; Dirmeyer and Brubaker, 1999).

Regional aridity on the High Plains is principally controlled by variation in precipitation during the spring and summer growing seasons. Most thunderstorms that produce localized and frequently heavy precipitation over the High Plains originate as small storms over the Front Range of the Rocky Mountains, from differential heating of the mountain slopes providing the initial atmospheric lift. Systems of updraft and downdraft associated with these storms are maintained and enhanced by moist air at low levels as they drift eastward over the adjacent plains. If the low-level air is sufficiently moist and unstable, relatively weak storms can expand into massive, even severe supercell storms over the High Plains. The source of this moist air is the low level jet flowing inland off the backside of the Bermuda High, which moves air, conditioned by the Gulf of Mexico, to the north and west. More widespread occurrences of thunderstorms can occur when cool air near the surface lifts a similarly low-lying layer of warmer, moist air; this is enhanced by a southwesterly flow of dry air at mid-levels. These occurrences are frequently associated with a significant southerly shift and intensification of the subtropical Jet Stream (Kroczynski et al., 1993; Dirmeyer and Brubaker, 1999).

Synoptic climate analysis indicates that relatively small changes in atmospheric circulation in the Northern Hemisphere can lead to widespread drought on the Great Plains (Palmer and Brankovic, 1988; Trenberth et al., 1988; Oglesby, 1991; Forman et al., 1995). Land regions, which absorb relatively more heat, develop a thermal surface low while adjacent relatively cooler oceans are subject to high pressure. A ridge aloft (700- to 300-mb level) accompanies this surface low-pressure, centered over the southwestern US. The positioning of this ridge aloft, relative to the Bermuda High is crucial. If the ridge is positioned slightly towards the west, southerly surface circulation will strengthen that enhances moisture transport from the Gulf. Conversely, if the ridge shifts to the east there is no enhancement of moisture flux to the High Plains. Shifts of the ridge aloft in the western US and the Bermuda High are recognized as important controlling factors in recent droughts and floods in the mid-continental US (Trenberth et al., 1988; Dirmeyer and Brubaker, 1999).

17. Landscape-climate links on the Great Plains

Reduced soil moisture during late winter and/or spring over midcontinental North America could help induce and amplify regional aridity during the summer by reduction of evaporative cooling and by changing atmospheric circulation patterns (Namias, 1991). Model studies found that reductions in soil moisture led to an increase in surface temperature, lower surface pressures, and reduced regional precipitation (Oglesby and Erickson, 1989; Oglesby, 1991; Dirmeyer and Brubaker, 1999). Synoptic scale changes with soil drying include increase ridging aloft, a northward shift of the jet stream, and a strong reduction in moisture transport from the Gulf of Mexico to the central US. Thus, droughts can be perpetuated by synoptic feedbacks associated with depleted soil moisture, particularly during the late spring (Oglesby, 1991; Atlas et al., 1993).

Dune reactivation on the Great Plains not only signifies a reduction in precipitation and soil moisture, but a widespread disturbance of vegetation. The immediate response to past droughts on the Great Plains would be an $>30\%$ drop in primary productivity of grasslands, exceeding the historic response to drought (Sala et al., 1988), particularly in the four state area of Colorado, Kansas, New Mexico and

Nebraska. This drop in grassland productivity would significantly reduce forage for >30 million bison that existed on the Great Plains prior to European contact (Dary, 1974, p. 29). The presence of bison tracks in Holocene eolian sequences indicates that large herds of bison may be a factor in landscape stability (Loope, 1986; Swinehart, 1989). Continued grazing by bison with a precipitation-driven drop in grassland productivity could lead to denudation and exposure of underlying soil with trampling (Schlesinger et al., 1989). Regional warming would be augmented by the loss of evapotranspiration cooling associated with less soil and vegetation coverage. The lack of soil cover would promote additional erosion with excessive rilling associated with periodic high rainfall events. The net effect of aridity is landscape heterogeneity, where grass cover is sparse and shrubs (e.g. yucca and sage) with deep root systems predominate (Schlesinger et al., 1989).

Uncertainty persists if dune fields on the Great Plains will reactivate with future droughts similar to earlier in the Holocene. Historic observations indicate limited local reactivation of dunes on the Great Plains for the 19th and 20th centuries droughts (Muhs and Holliday, 1995; Wolfe et al., 1995). An ecosystem model for western Nebraska that extends 1930s drought conditions for ~ 30 years shows a sharp reduction in above ground vegetation, but is an insufficient change for dune remobilization (Mangan et al., 1999). Other model experiments indicate that a severe, extended drought (ca. a $>30\%$ reduction in growing season moisture) could deplete vegetation sufficiently to initiate dune mobilization and that the impact of extreme drought on land cover is amplified by fire, grazing, and shifts to shrub-dominated communities. However, the current presence of widespread irrigation, the lack of open rangeland affected by bison herds, and the suppression of fires reduce landscape disturbance factors necessary to expose the underlying sand to eolian activity.

18. Conclusion

Periods of dune mobilization reflect the dominance of decade to century scale drought that exceeded 20th century events with a $>25\%$ deficit in growing season precipitation. Dunes formed or were remobilized across the Great Plains numerous times during the Holocene, with sustained eolian activity in the early to middle Holocene and numerous discrete events since 2 cal. ka ago. The largest dune fields, the Nebraska Sand Hills and ergs in eastern Colorado, Kansas and the Southern High Plains, show peak activity sometime between ca. 7 and 5 cal. ka, but prominent eolian deposition is also registered at ca. 9 to 8 cal. ka and 5 to 4 cal. ka for some fields. Regional loess deposition in eastern Colorado, Nebraska and Kansas between 10 and 4 cal. ka indicates widespread drying. Most dune fields exhibit evidence for one or more reactivation events sometime in the past 2 cal. ka. In the central and northern Great Plains, up to three events is registered post 1 cal. ka, the latest potentially after the 15th century. However, associating dune mobilization events to the 13 potential droughts identified in dendroclimatic and lacustrine records in the past 2000 years remains unresolved.

Periods of persistent drought are associated with a La Niña-dominated climate state, with immediate cooling of the tropical Pacific and later of the tropical Atlantic sea surface temperatures (SST), which weakens cyclogenesis into North America. Cooler SSTs in the Gulf of Mexico would significantly reduce the strength of the low-level jet to funnel moisture northward in the lower troposphere. As drought proceeds during the growing season, reduced soil moisture and vegetation cover would lessen evaporative cooling and increase surface temperatures. These surface changes enhance eastward expansion of a high-pressure ridge at the 700–300 mb level and northern shift of the jet stream, which further enhances continent-wide drought. It is uncertain whether dunes will reactivate in the future at a scale similar too earlier in the Holocene. The current and widespread use of irrigation, the lack of migratory bison herds, and the suppression of prairie fires enhance stabilization of dune fields on the Great Plains.

Acknowledgements

The impetus for this paper arose after a NOAA/NASA workshop in 1999 on North American Droughts and Land Cover Changes. This paper benefited significantly from the reviews of M. Waters, D. Loope, E.A. Bettis and an anonymous reviewer.

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