Late-Quaternary Landscape Response to Environmental Change in South-Central Kansas

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The central Great Plains is an excellent place to study late-Quaternary geomorphic responses to climatic fluctuations because the landscape is easily disturbed and deposits contain abundant paleoenvironmental information. Although much research has already been conducted, studies are needed that correlate a variety of geomorphic responses to environmental change at specific sites. This paper presents a paleoenvironmental and geomorphic reconstruction for the Great Bend Sand Prairie, a mosaic of sand sheets and dune fields in south-central Kansas. Results indicate that two stratigraphic units dominate the upland geology. Late-Wisconsin deposits consist of poorly sorted sand, silt, and clay that probably accumulated in a low-energy fluvial environment. Eolian deposition of loess also occurred, but most silt was integrated with the alluvium. Intact deposits of loess are widely scattered. All sediments contain well developed soils, indicating extended surface stability. Macrofossil and isotopic ($\delta^{13}C$) evidence suggest a mesic environment. Where eolian sedimentation did occur, northwest winds were responsible for mobilization. Although late-Wisconsin strata crop out intermittently, eolian sand is the common surficial deposit. Radiocarbon dating indicates that most dunes are Holocene landforms. In comparison to late-Wisconsin deposits, dune sands are well sorted, $\delta^{13}C$ values infer a relatively warm climate, and the orientation of parabolic dunes indicate mobilizing southwesterly winds. Dunes usually contain one or two weakly developed buried soils, indicating episodic mobilization of eolian sand in the latest Holocene. Surface soils are generally poorly developed, suggesting that dunes can easily be mobilized if vegetation is reduced, perhaps due to $C0_2$ warming. *Key Words: alluvium, central Great Plains, eolian sand, Holocene, late-Wisconsin.*

A region of North America receiving increased attention from geomorphologists is the central Great Plains (Figure 1). Given the semiarid to subhumid climate, the landscape is sensitive to disturbance, which can be rapid and dramatic (e.g., Dust Bowl, 1993 Flood). Thus the central Great Plains is an excellent laboratory for the observation and measurement of geomorphic responses to climatic fluctuations. In alluvial settings, for example, cycles of cutting and filling have been linked to climate change, with a variety of terraces being preserved in most stream valleys (e.g., Hall 1990; Johnson and Martin 1987; May 1992; Arbogast and Johnson 1994). When more arid conditions transpire, eolian processes dominate, with widespread mobilization of loess (e.g., Frye and Leonard 1951; Johnson et al. 1990, 1993; Feng et al. 1994) and eolian sand (e.g., Ahlbrandt et al. 1983; Muhs 1985; Holliday 1995a, 1995b; Madole 1995; Arbogast 1996a) being well documented. Landscapes consisting of unconsolidated sand are especially sensitive, with local reworking of dunes frequently occurring (e.g., Ahlbrandt et al. 1983; Madole 1995; Arbogast 1996a).

Given that relief over most of the central Great Plains is relatively low, and equilibrium can return quickly, much of the mobilized sediment is redistributed within the region. This is highly significant because thick deposits of loess (e.g., Frye and Leonard 1951; Johnson et al. 1990, 1993; Feng et al. 1994), alluvium (e.g., Schultz and Stout 1948; Hall 1990; Johnson and Logan 1990; May 1992; Arbogast and Johnson 1994) and other valley fill (Holliday 1995c), and eolian sand (e.g., Ahlbrandt et al. 1983; Muhs 1985; Muhs et al., 1996; Holliday 1995a, 1995b; Madole 1995) mantle much of the area. Most important, these deposits chronologically span significant portions of the Quaternary period

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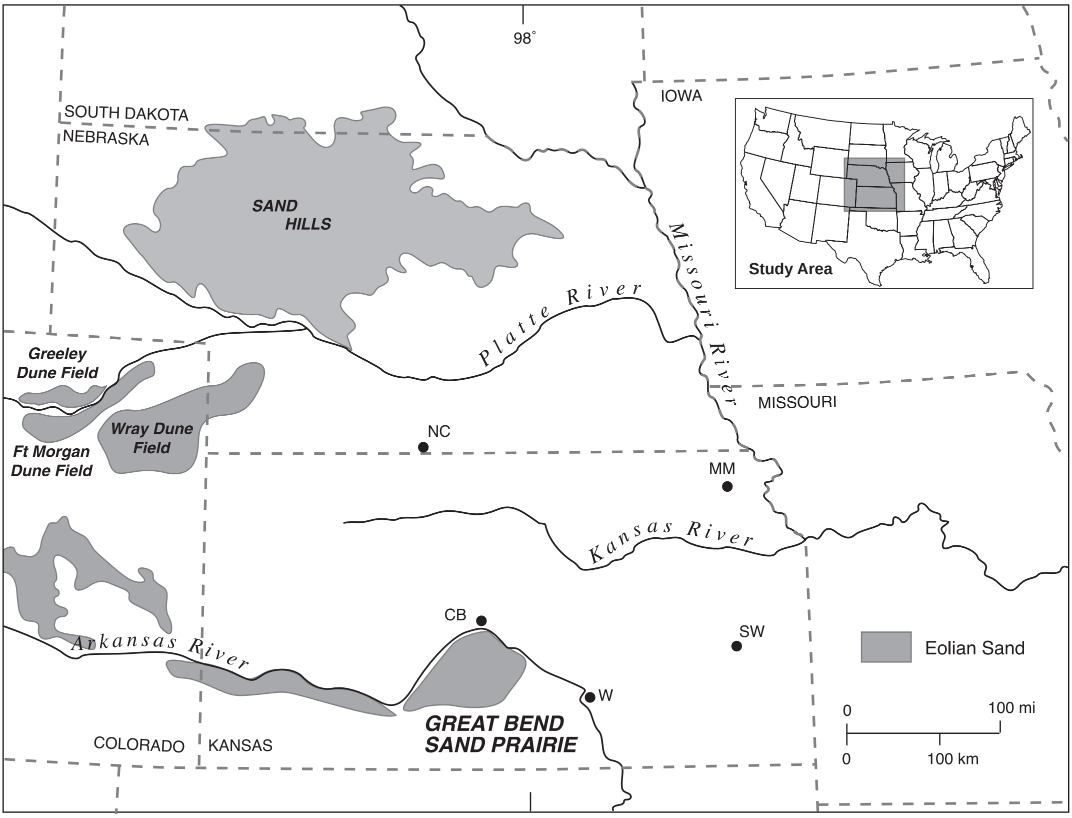

Figure 1. The central Great Plains in North America with location of study sites (CB = Cheyenne Bottoms; NC = North Cove; MM = Muscotah Marsh; SW = Sanders's Well; W = Wichita. Source: modified from Fredlund and Jaumann (1987) and Swinehart (1990).

(<1.65 million years), with late-Wisconsin and Holocene sediments being especially well preserved. Many of these sediments contain abundant information (e.g., sedimentological, pollen, snails, isotopic data, buried soils) that can be used to reconstruct regional paleoenvironmental and geomorphic histories. By synthesizing and integrating this data, paleoclimatologists and geomorphologists are illustrating the range of past changes, which, in turn, can be used to predict future change. This ability is critical if increased warming, such as modeled in many greenhouse scenarios (Hansen et al. 1988; Wetherald and Manabe 1988; Schlesinger 1989), occurs.

Although much is known about late-Quaternary paleoenvironmental conditions in the central Great Plains, significant gaps remain. Of the sites that have yielded data, for example, none have integrated environmental change and a suite of geomorphic processes from the late Wisconsin through the Holocene. In fact, geomorphic studies have focused largely on sites where either eolian (e.g., Ahlbrandt et al. 1983; Muhs 1985; Johnson et al. 1993; Feng et al. 1994) or alluvial systems (e.g., Hall 1990; May 1992; Arbogast and Johnson 1994) dominated. An important area that has received little attention, located within the core of the central Great Plains, is the Great Bend Sand Prairie in south-central Kansas (Figures 1, 2). In this region, late-Quaternary deposits are a complicated assemblage of unconsolidated alluvium, loess, and eolian sand. Theoretically, the paleoenvironmental and geomorphic history is related to many variables associated with climate change, including insolation variability, atmospheric circulation, alluviation, and eolian sedimentation. Thus this region represents a rare opportunity to reconstruct and integrate a wide range of environmental fluctuations and geomorphic processes through much of the past 20,000 years. This is significant within the context of global change because detailed chronologies are necessary to

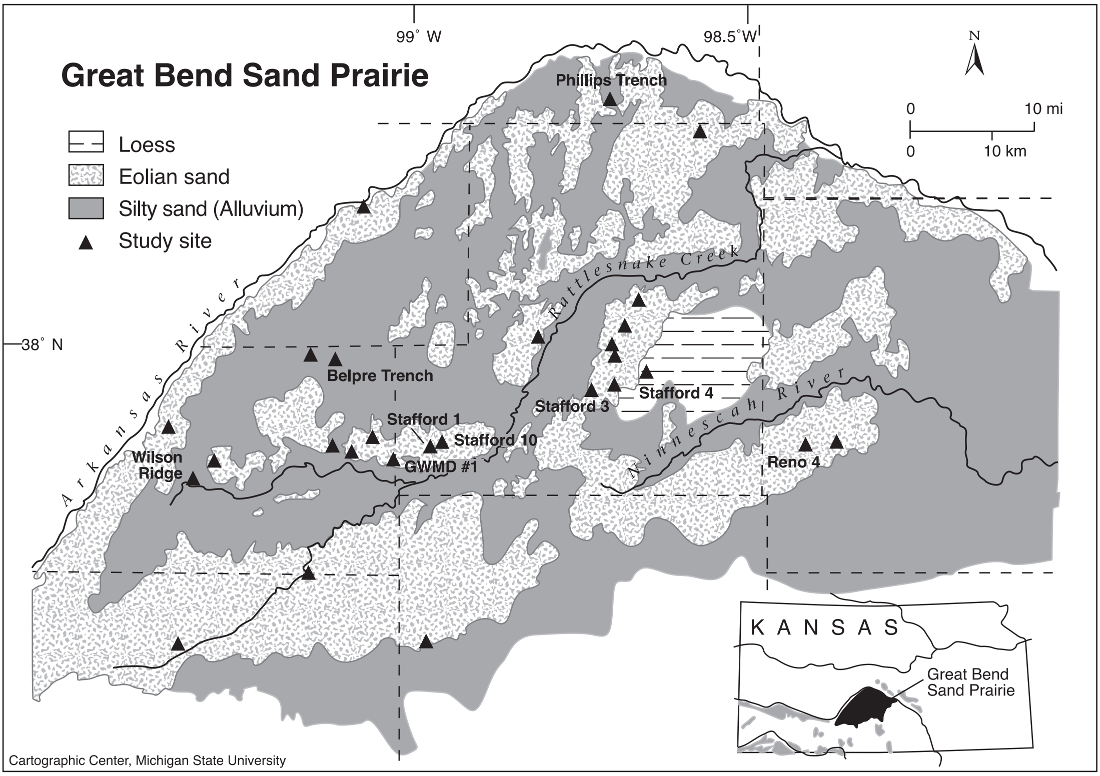

Figure 2. Surficial geology on uplands, study sites, and major tributaries on the Great Bend Sand Prairie, Kansas.

test and refine hypotheses derived from previously constructed models (e.g., Fredlund and Jaumann 1987; Kutzbach 1987; Wells and Stewart 1987; COHMAP 1988; Kutzbach et al. 1993) and to fully show the range of potential responses should future climate change occur. In that context, the goal of this study is to fully reconstruct the late-Quaternary paleoenvironmental and geomorphic history of the region. The primary focus is the chronologic, stratigraphic, and sedimentary differences that exist between late-Quaternary deposits on upland sites.

Late-Quaternary Environmental History in the Central Great Plains

Late Wisconsin (ca. 21–10 ka)

Proxy climate data derived from late-Wisconsin deposits generally infer a more mesic environment, with cooler temperatures, more effective moisture, and less seasonality than present. Climatic modeling, for example, suggests that the jet stream was split into northern and southern branches by the Laurentide ice sheet during the peak of the last glacial period around 18,000 yrs B.P. (e.g., COHMAP 1988; Kutzbach 1987; Kutzbach et al., 1993). Delcourt (1979) and Delcourt and Delcourt (1983) argued that the mean position of the polar front, which today is located in southern Canada, was at about 34° N at that time. As a result, mean annual surface temperatures in the central Great Plains were probably 2° to 4°C cooler than today (Kutzbach 1987). Mobilizing winds were northwesterly as indicated by the orientation of late-glacial eolian features (Wells 1983) and were perhaps 20–50 percent stronger than at present (Crowley and North 1991). As a result, immense quantities of loess were blown out of the Platte River valley in Nebraska and now mantle much of southern Nebraska (Frye and Leonard 1951; Johnson et al. 1990, 1993) and Kansas (Johnson 1993; Feng 1991; Feng et al. 1994). Faunal investigations in the Pleistocene biota of the central Great Plains indicate more complex and diverse biological communities, reflecting cooler summers and warmer winters than those of the Holocene (Martin 1984; Martin and Martin 1987).

In addition to decreased seasonality, the data generally indicate that higher levels of effective moisture were present in the central Great Plains during the late Wisconsin than present. The floral record, in particular, suggests a more mesic environment, reflecting a vegetational assemblage that is radically different from that found today in the region. According to Fredlund (1995), the pollen record at Cheyenne Bottoms, located in central Kansas (Figure 1), suggests a spruce parkland around 20,000 yrs B.P. In the Arkansas river floodplain, near Wichita, coniferous macro- and microfossils (e.g., spruce wood and needles, cone fragments) were recovered in peat that dated to about 19,000 yrs B.P. (Fredlund and Jaumann 1987). Wells and Stewart (1987) reported needle leaves of limber pine (*Pinus flexilis*) and white spruce (*Picea* cf. *glauca*) in charcoal that dated to about 14,500 yrs B.P. in south-central Nebraska. Data from Sanders's Well in eastern Kansas and from North Cove in south-central Nebraska imply that an aspen (*Populus*) parkland existed on uplands between 24,000 and 12,800 yrs B.P. (Fredlund and Jaumann 1987; Fredlund 1989). Isotopic data ($\delta^{13}C$ values derived from radiocarbon dates) from the Peoria loess also imply a cool and mesic environment (Johnson et al. 1993). In addition, grass phytoliths extracted from Peoria loess indicate deposition on a well vegetated surface, one consistent with high effective moisture (Fredlund et al. 1985).

Holocene (10,000 yrs B.P. - present)

The data derived from Holocene deposits generally suggests a warmer and more xeric environment in the past 10,000 years than during the late Wisconsin. During the very late Wisconsin and early Holocene, regional environmental change is modeled to have been associated with increased insolation and disintegration of the Laurentide ice sheet (COHMAP 1988). As the glacier wasted during the late Wisconsin and early Holocene, the steep north-south temperature gradient that had been present weakened, promoting zonal atmospheric flow (Knox 1983). Hence climate models (e.g., COHMAP 1988) suggest that seasonal temperature extremes began to increase. At Cheyenne Bottoms (Figure 1), Fredlund (1995) reported a dramatic increase in Chenopodeaceae-Amarathanceae (Cheno-Am) soon after 11,000 yrs B.P., reflecting sharp fluctuations in water levels within the basin as the climate became more variable. In northeastern Kansas, an abrupt decline in spruce began about 12,000 yrs B.P. at Muscotah Marsh and was concurrent with an increase in oak and elm. About 10,500 yrs B.P., spruce had been completely replaced by deciduous forest, and by 9000 yrs B.P., the region was dominated by grassland (Grüger 1973).

As the Holocene progressed, strengthened zonal flow triggered the generally warm dry conditions of the middle Holocene that prevailed in central North America from about 8 to 5 ka (Knox 1983; Kutzbach 1987; COHMAP 1988; Crowley and North 1991; Kutzbach et al. 1993). By approximately 6 ka, mean summer temperatures could have been 2° to 4°C higher than present (COHMAP 1988; Crowley and North 1991; Kutzbach et al. 1993). In addition, pollen data suggest that annual precipitation was potentially as much as 25 percent less than today (Bartlein et al. 1984; Kutzbach 1987). At Cheyenne Bottoms (Figure 1), this interval promoted stable but lower water levels, depressing Cheno-Ams (Fredlund 1995). In the neighboring Southern High Plains, increased aridity promoted widespread eolian sedimentation between 9000 and about 4500 yrs B.P., with the most intense interval occurring between around 5500 and 4500 yrs B.P. (Holliday 1995a, 1995b).

Following the middle-Holocene dry period, a period of increased moisture apparently occurred in the early part of the late Holocene. Evidence for this shift exists in northeastern Kansas where pollen data indicate that deciduous forest repopulated portions of the landscape briefly after 5000 yrs B.P. (Grüger 1973). Since that time, the climate has apparently fluctuated between relatively moist and dry. According to Fredlund (1995), Cheno-Ams were more common at Cheyenne Bottoms throughout the late Holocene, indicating variable water levels and periodic drying of the basin. As a result of these fluctuating climatic conditions, episodic mobilization of sand dunes occurred over much of the region, including Nebraska (Ahlbrandt et al. 1983; Swinehart 1990; Stokes and Swinehart forthcoming), Colorado (Muhs 1985; Madole 1995), northwestern Oklahoma (Olson et al. 1995), the neighboring Southern High Plains (Holliday 1995a, 1995b) and south-central Kansas (Arbogast 1996a).

Great Bend Sand Prairie

The Great Bend Sand Prairie is a mosaic of sand sheets and dune fields, about 4500 km^2, located within the “great bend” of the Arkansas River. At this point, the Arkansas river is a braided stream, owing to its sandy load, with discharge that fluctuates seasonally. In 1995, for example, discharge was low (< 10 cms) for most of the year, but peaked at 2750 cms in June (http://www-ks.cr.usgs.gov/Kansas/rt/html/07141300.desc.html). This dramatic increase was associated with spring snowmelt in the Rocky Mountain headwaters. Major tributaries to the Arkansas River are the North Fork Ninnescah River, which flows generally to the southeast, and Rattlesnake Creek, a northeasterly trending stream that bisects the study area (Figure 2). Although mean discharge fluctuates seasonally in each of these streams, it is generally low (< 30 cms) throughout the year (http://www-ks.cr.usgs.gov/Kansas/rt/.html).

The present climate of the region is semiarid to subhumid and strongly continental, characterized by extreme diurnal and annual variations in temperature. Average annual precipitation reflects the position of the Great Bend Sand Prairie on the boundary between the dry portion of western Kansas that is in the rain shadow of the Rocky Mountains and eastern Kansas, influenced by more humid air from the Gulf of Mexico. Although yearly precipitation may vary widely given the characteristics of the dominating air mass, annual precipitation on the western border (57 cm) is significantly less than average yearly rainfall on the eastern margin of the study area (80 cm) (Fader and Stullken 1978). At present, precipitation is sufficient to support a stabilizing cover of bunch grass on sand dunes, with the potential natural vegetation including sand bluestem (*Andropogon hallii*), little bluestem (*Andropogon scoparius*), sand lovegrass (*Eragrostis trichodes*), and switchgrass (*Panicum virgatum*; Kuchler 1974).

The upland geology consists of unconsolidated Quaternary deposits derived mostly from the Rocky Mountains. In general, they have a maximum thickness of about 100 m and contain five lithostratigraphic units. The upper pair of strata are central to this study, and were qualitatively characterized by Rosner (1988) as being very distinct from each other. The older deposit is a widespread, near-surface to outcropping unit of sand and silt, with locally high percentages of clay. The youngest sediments, in contrast, consist of scattered deposits of surficial eolian sand (Figure 2).

Although Arbogast (1996a) proved that most of the surficial sands are in the form of late-Holocene dunes, the origin, age, and actual extent of the near-surface deposit was unknown prior to this study. Thus the regional environmental and geomorphic change implied by these contrasting units could not be confidently reconstructed. Because the silty sands are massive and poorly sorted, most previous investigaters (e.g., Horsch et al. 1968; Roth 1973; Dodge et al. 1978) referred to them as “old alluvium.” This interpretation suggests a relatively moist environment, compared to that in which the dunes formed, at the time of deposition. The first radiocarbon ages were derived from these sediments in a preliminary study by Johnson (1991), who subsequently indicated that the deposits were likely late Wisconsin in age. Although no textural data was obtained, Johnson (1991) suggested that the strata consisted mostly of wind-blown silt (i.e, Peoria loess). In this scenario, the regional depositional environment would have been distinctly different than if alluviation had dominated. Given the limited data, we tested the hypothesis that the deposits are late-Wisconsin alluvial sediments.

Methods

In order to establish the spatial relations of the principal stratigraphic units, we mapped surficial geology on 1:24,000 topographic maps through field reconnaissance and by consulting published geologic maps and soil surveys. Dunes were classified by the genetic term “eolian sand,” which accurately reflects their wind-blown origin (Arbogast 1996a). In contrast, the nongenetic term “silty sand” was initially assigned to Rosner’s (1988) near-surface deposit because its origin was unknown. During the reconnaissance, the qualitative stratigraphic associations were explored at 126 widely-scattered localities by bucket augering. Based upon these results, twenty-six sites (Figure 2) were selected for intensive and systematic study so that stratigraphic variability among and within localities could be fully characterized. At each of these localities, stratigraphic units were differentiated through field and laboratory evidence, and pedologic horizons contained within the strata were described according to Soil

Conservation Service standards (USDASCS 1987).

A variety of laboratory procedures were employed to distinguish the physical and chemical characteristics of the stratigraphic units and soils. We quantified sediment texture by the pipette method (Day 1965), and used Krumbein's (1934) logarithmic transformation (ϕ scale) of the Udden-Wentworth (Wentworth 1922) grade scale to graphically plot the results. Subsequently, graphical statistics of the textural data, including the mean, median, sorting, skewness, and kurtosis (as defined by Folk and Ward 1957) were calculated with software by Prante (1990). In an effort to characterize the depositional history of the units, we conducted scatterplot analyses of textural variables (e.g., Folk and Ward 1957; Friedman 1967) on a total of 140 samples collected from the twelve sites where both silty sands and eolian sand were well expressed (see Arbogast 1995 for details).

After assessing the physical character of the sediments, we reconstructed the geomorphic and paleoenvironmental chronology from radiocarbon ages obtained from the prehistoric humus (total humate fraction) contained in the bulk samples ($\geq$ 4 kg) collected from the upper and/or lower 5 cm of buried soils. Although questions persist regarding the use of soil humates for detailed reconstructions of this kind (e.g., Martin and Johnson 1995; Wang et al. 1996), research in the Great Plains (e.g., Arbogast and Johnson 1994; Holliday 1995a, 1995b, 1995c, 1997; Madole 1995) indicates the method is reliable in the nonleaching environment of the region because the turnover of organic-material is very slow. Radiocarbon ages from the lower part of the soils provide the minimum-limiting ages for the host deposit, whereas those from the upper part of the soils estimate the maximum-limiting ages for overlying units. In order to reduce the chance that the samples contained material that could have contaminated the ages (e.g., by providing artificially young estimates), modern rootlets and other detrital plant material were extracted by flotation, and treatment with hydrochloric acid was performed to eliminate carbonates (Johnson and Valastro 1994). After the sand fraction was removed through decantation, the samples were oven-dried, pulverized, and sent to the Radiocarbon Laboratory at the University of Texas (Austin) so the ages could be determined. To ensure that the estimates were conservative, all ages were calculated at 2 standard deviations, corrected for isotopic ($\delta^{13}C$) fractionation because some plants preferentially incorporate ^{14}C over ^{12}C (thereby producing artificially young estimates; Stuiver and Polach 1977), and calibrated to the tree-ring and marine (coral) curves to approximate linear rather than radiocarbon time (Stuiver and Reimer 1993).

In an effort to characterize the paleoenvironmental conditions of the region, we collected and identified prehistoric faunal and floral remains. Additional paleofloral evidence was provided from isotopic ($\delta^{13}C$ values) data obtained from buried soils in the sediments. Data of this kind, calculated from the samples from which the radiocarbon ages were derived, may be used to infer paleoenvironmental conditions at the time of soil formation (e.g., Krishnamurthy et al. 1982; Delaune 1986). Warm-season (C_4) prairie grasses such as big bluestem (*Andropogon gerardii*) and switch grass (*Panicum virgatum*), for example, typically have mean $\delta^{13}C$ values of -12‰. In contrast, cool-season (C_3) prairie grasses such as Canada wildrye (*Elymus canadensis*) and western wheatgrass (*Agropyron smithii*) have average $\delta^{13}C$ values of -27‰ (Deines 1980; Krishnamurthy et al. 1982; Cerling and Quade 1993; Nordt et al. 1994). Given the regional climate record and a hypothetical late-Wisconsin age for the silty sands, we expected buried soils contained within those sediments to have more negative $\delta^{13}C$ values than those obtained from buried soils in late-Holocene dunes.

Results

Stratigraphy, Surficial Geology, and Sedimentology

During mapping and reconnaissance, a primary objective was to determine the spatial extent of silty sands on uplands. This was important because previous studies (Rosner 1988; Johnson 1991) indicated that the deposit was widespread and quite distinct from the surficial eolian sands. Thus the unit was clearly significant from a regional geomorphic and paleoenvironmental perspective. We identified the strata at one hundred eleven (77 percent) of all sites tested (by augering and backhoe), indicating that it is pervasive. The depth to the top of the unit varies considerably, however, depending on the presence and/or thickness of the surficial sands (e.g., Figures 3, 4).

Where silty sands are mapped, the deposit either crops out or is covered by a very thin layer of eolian sand, and very little relief (< 2 m) exists. The silty-sand unit is buried much deeper where eolian sand is mapped (Figure 2). In these areas, local relief is relatively high, with dunes ranging from 3 to 10 m in height. In addition to the primary map units, deposits of massive silt were also recognized as a surficial deposit. Clearly loess, these deposits were identified at several sites. Loess is a minor component of the overall surficial geology, however, with the only extensive and mappable outcrop located in the east-central part of the region (Figure 2). In this area, the topography is very similar to the places where silty sands are the surficial unit, with very little local relief (< 2 m).

Detailed and systematic study of the twenty-six specific sites focused largely on the stratigraphic differences that exist between the deposits of silty sand and eolian sand. These investigations further revealed that each unit has distinct and dramatically different characteristics. The site that best demonstrates this contrast is Reno 4, located in a well-developed dune field in the southeastern corner of the region (Figure 2). At this site, 2.3 m of eolian sand (Unit III) overlies 1.8 m of silty sand (Units I and II; Figure 5). The silty sand is moderately gleyed, very cohesive, and contains a strongly developed, but truncated (Bt horizonation) buried soil that extends through the full thickness of the exposed unit. In contrast, the overlying dune sand consists of loosely compacted, single-grained sediments with horizontal lamination that contain a weakly developed buried soil with A/AC/C horizonation. Particle-size data from Reno 4 illustrate the textural character of the two deposits. In the upper and lower part of the silty sand, the texture is coarse, containing more than 60 percent sand. The unit fines in the middle, however, with about 60 percent silt and 25 percent clay present. A sharp stratigraphic contact exists in the middle of the exposure, with a shift to more than 90 percent sand in the overlying dune (Figure 5b).

When viewed in thin section, the contrast between the two deposits is clear (Figure 6). The silty-sand matrix generally consists of a fine-textured plasma (silt and clay; light gray in Figure 6a) that separates sand grains (dark gray and white in Figure 6a). Sand mineralogy is dominated by quartz, with lesser amounts of feldspar and miscellaneous rock fragments. In contrast, the dune sand (Figure 6b) consists of individual grains of sand. Mineralogy is again dominated by quartz, with some feldspar and miscellaneous rock fragments. Several of the grains are pitted and frosted. These features indicate that grains collided with one another during eolian transport.

Scatterplot distributions of summary statistics, derived from the twelve sites where both deposits occur, clearly illustrate the sedimentological differences that exist between the two units (Figure 7). The variables that best distinguish the deposits are mean particle size and sorting, with two nearly distinct groups resulting when the variables are plotted together. Mean grain size in the silty sand is coarse to fine silt, whereas average texture in eolian sands ranges from coarse silt to very fine sand. Sorting in the silty sand is poor to very poor (~ 3.0), while it is typically moderate (~ 1.0) in the dunes.

In contrast to the clear eolian origin of the surficial sands, the sedimentary character of the silty sands suggest that it is a fluvial deposit. In general, alluvial sediments are poorly sorted relative to eolian sands because fines, suspended in the denser fluid, are trapped between sand grains

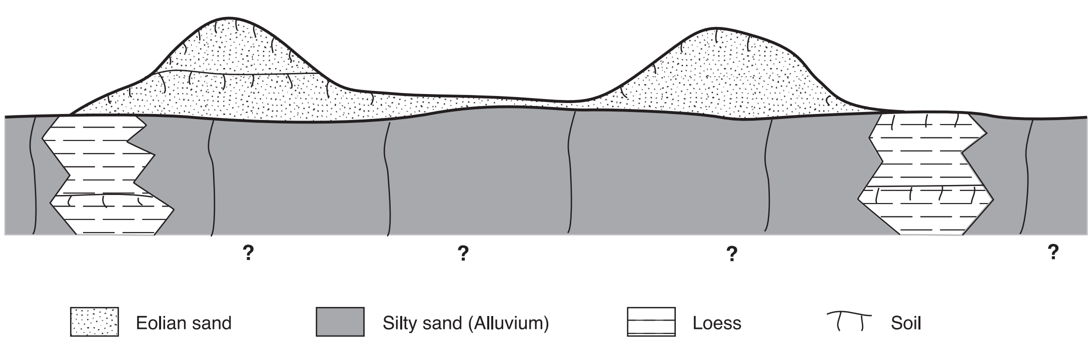

Figure 3. Schematic cross section of uplands on the Great Bend Sand Prairie, showing the pedostratigraphic, lithostratigraphic, and geomorphic relationships of late-Quaternary deposits.

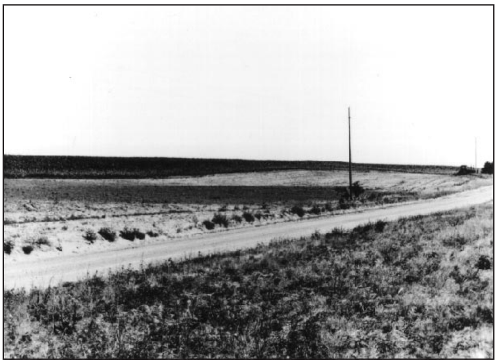

Figure 4. Site in the NW, NW, sec. 24, T26S., R15W, 6PM where silty sand (dark area in the center of the photograph) crops out within a dune field. In all probability, the deposit has been buried and uncovered several times whenever eolian sand in the area mobilized.

or are deposited with them when discharge diminishes (Blatt et al. 1980). Although poorly sorted eolian deposits (e.g., "loamy coversand," "sandloess") have been recognized in Alaska (Lea and Waythomas 1990) and Europe (Koster 1988; Schwan 1988), they are well stratified. Unfortunately, no primary sedimentary structures are preserved in the silty sands that could reflect the genesis of the unit on the Great Bend Sand Prairie. In all probability, such evidence was destroyed, in part, by intensive bioturbation. Such internal reorganization of the sediments could easily have occurred in periodically flooded wetlands where biologic activity is high. Moreover, the upper part of the soil was sharply and irregularly truncated at several sites, far from modern streams, where it was overlain by eolian sand. This is provocative because it demonstrates that flowing water was present on modern upland sites sometime before burial by eolian sand.

In addition to its poorly sorted nature, lack of stratification, and nature of truncation in places, additional evidence suggests that the silty sands are alluvial deposits. Specifically, the unit varies considerably in texture within and between sites. At some localities, the silty sand is 60 percent sand, whereas it contains as much as 80 percent silt or 40 percent clay at others. Moreover, the deposit contains at least one, and as many as three, fining upward sequences at each site studied (e.g., Reno 4; Figures 2, 5b). This pattern contrasts with the Blackwater Draw Formation, also a poorly sorted upland deposit in the nearby Southern High Plains (Holliday 1989). According to Holliday (1989), the Blackwater Draw

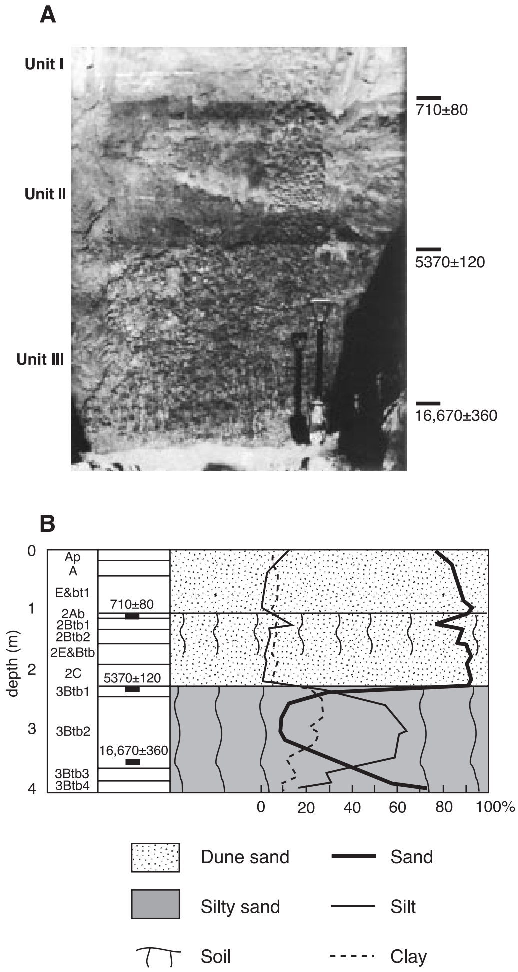

Figure 5. (a) Reno 4 (4.0-m high) with stratigraphic units (Units I and II are eolian sand; Unit III is silty sand) and radiocarbon ages. At this site, approximately 2.27 m of dune sand overlies silty sand. An extremely well-developed buried soil is formed throughout the silty sand, whereas, the dune sand contains a weakly developed soil. (b) Soil stratigraphy, texture, and radiocarbon ages at Reno 4. Note the fining-upward sequence within the alluvium and the well-defined stratigraphic contact with the overlying dune sand, i.e., the sharp increase in sand.

Formation fines from southwest to northeast, but is texturally similar at a given locality. Thus it is believed to be an eolian deposit that was mobilized by southwesterly winds. On the Great Bend Sand Prairie, textural variability in the silty sands does not follow a consistent regional trend; in fact, it is random. Moreover, the fining-upward sequences are suggestive of alluvial deposition

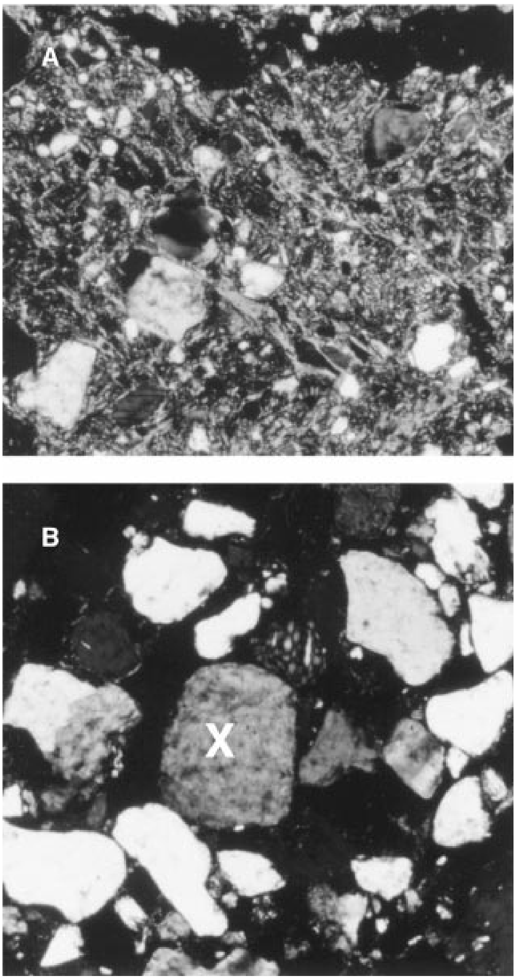

Figure 6. (a) Thin section (FOV - 1.85 × 2.69 mm) of silty sand. Note the light gray filaments (silt and clay) that separate sand grains. Black areas are voids. (b) Thin section (FOV = 1.85 × 2.69 mm) of eolian sand. In contrast to Figure 6a, note the lack of silt and clay. The sand grain in the center of the image (X) is extensively pitted, indicating eolian transport.

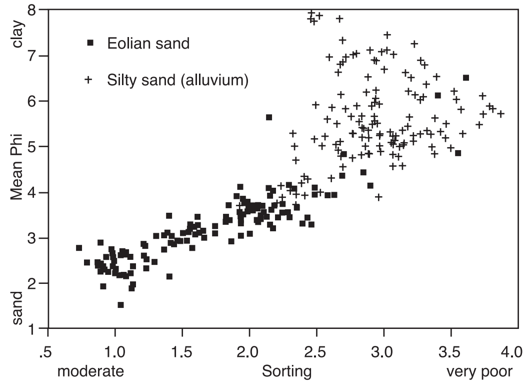

Figure 7. Scatterplot of mean phi and sorting from all sites studied on the Great Bend Sand Prairie. Note the clear separation that exists between alluvium and eolian sand, suggesting that alluvium accumulated in a poorly sorted alluvial environment in contrast to the dunes.

rather than eolian sedimentation. In this scenario, coarse- and fine-textured sediments would have accumulated when discharge was relatively high and low, respectively.

Overall, the combined textural, sedimentary, stratigraphic, and geomorphic evidence leads to the conclusion that the silty sands are fluvial deposits. Given the tremendous textural variability observed in the silty sands between and within sites, alluviation on the Great Bend Sand Prairie could have occurred in a variety of depositional environments, including main channel, secondary channel, and lacustrine. Although it is impossible to determine with present data, the entire region may have contained a series of wetlands that were interconnected by stream channels. Alternatively, the silty sands may be related directly to flooding in the Arkansas River valley. At present, there is conflicting evidence as to the morphology of the ancestral Arkansas River. According to Johnson and Dort (1988), the geometry of prehistoric meanders in western Kansas (west of the Great Bend Sand Prairie) suggests that the stream was narrow, sinuous, and deep sometime during the late Wisconsin. This is consistent with a stream that carried abundant fine-textured material, which could account for much of the silt and clay in the alluvium downstream. The system was probably a braided meltwater stream at other times (Schumm and Brackenridge 1987), however, with highly variable discharge as alpine glaciers in the Rocky Mountain headwaters fluctuated. The gradient of the river declines sharply in the vicinity of the Great Bend Sand Prairie (Fent 1950). As a result, the Arkansas River probably flooded the study area regularly and could have deposited its alluvium over a broad area given the low relief of the region.

Although silty-sand alluvium and eolian sand are the dominant near-surface to surficial deposits, and were the focus of detailed investigations, we identified thick deposits of loess that we examined at three widely scattered sites: Belpre trench, Phillips trench, and Stafford 4 (Figures 2, 8). The stratigraphy at the Belpre and Phillips

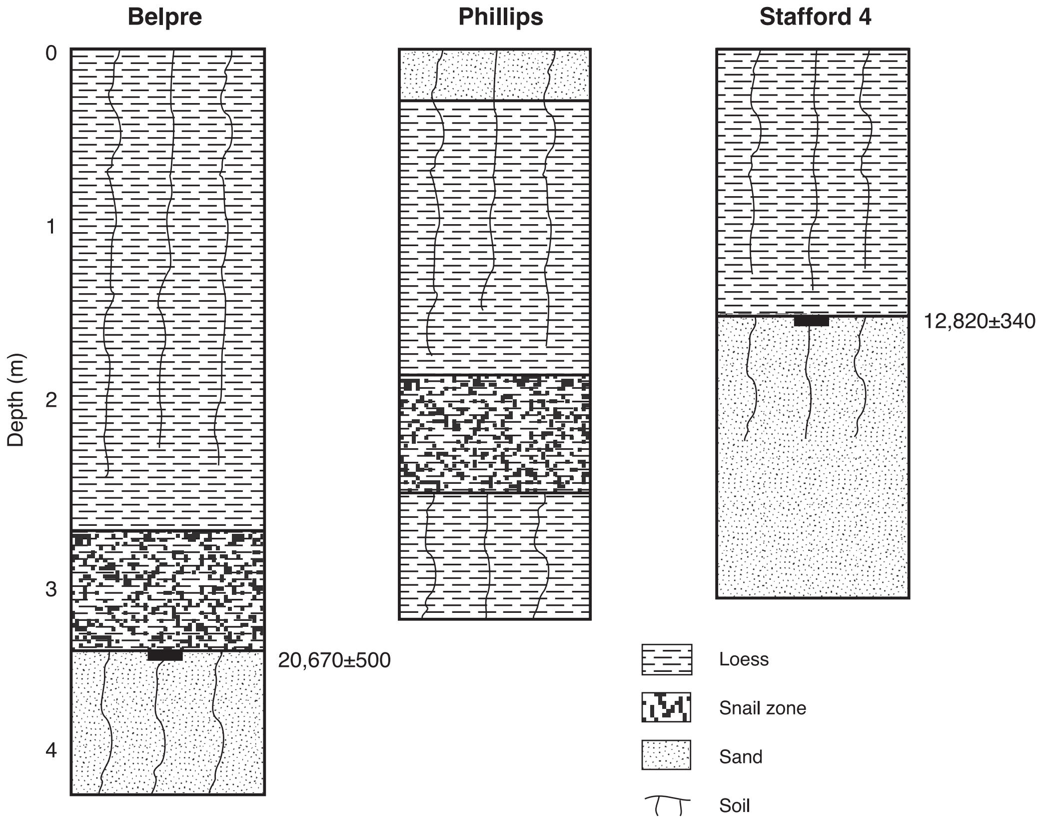

Figure 8. Stratigraphy at the Belpre and Phillips trenches, and at Stafford 4.

trenches is generally similar, with about 3 m of fossiliferous (gastropods), pale-brown (10YR6/3) silt overlying a well-developed buried soil (Bt horizonation). At Stafford 4, the deposit is approximately 1.7 m thick and overlies another well developed but truncated soil (Btb horizonation). In contrast to the pale-brown silt at the Belpre and Phillips trenches, the silt at Stafford 4 is dark grayish brown (10YR3/2) to dark brown (10YR3/3; Figure 8).

Radiocarbon Dating

Forty-eight $\delta^{13}C$-corrected radiocarbon ages, obtained from backhoe trenches, roadcut exposures, and quarries, establish a generalized chronology of deposition and landscape stability for late-Quaternary deposits on the Great Bend Sand Prairie. The majority (46) of the ages were derived from three stratigraphic positions: (1) the lower part of alluvial deposits (i.e., 2–4 m below the top of the unit), (2) the upper part of alluvial deposits (i.e., upper 5 cm of the deposit) where the unit was buried by dunes, and (3) buried soils contained within the dunes. Ages from the lower part of the exposed deposits theoretically provide a maximum estimate for initiation of pedogenesis. In contrast, ages obtained from the upper portion of the alluvial units generally evaluate the mean residence time of humates at the top of the deposit and provide a maximum-limiting age for overlying dunes. Lastly, ages secured from buried soils in dunes (reported by Arbogast 1996a) provide maximum and minimum ages for overlying and underlying sand, respectively (see http://www.ssc.msu.edu/~geo/fac/arbogast/GB14C.html for details).

The distribution of radiocarbon ages from alluvium and dunes illustrate a clear age-stratigraphic relationship, with the lower part of the exposed alluvium yielding late-Wisconsin to early-Holocene ages, ranging from approximately 20,000–8000 yrs B.P. Of the thirteen ages derived from sediments in this stratigraphic position, nine date to the late Wisconsin (Figure 9). At Reno 4, for example, the lower part of the exposed alluvium provided an age of 16,670 ± 360 yrs B.P.

(Figure 5). Overall, the distribution of ages derived from lower alluvium indicates that the stratum accumulated in the late Wisconsin.

Following deposition of the alluvium at any particular site, a significant period of stability occurred, resulting in the formation of a strongly developed soil. At this time, the duration of pedogenesis in the alluvium at specific localities is unknown, but radiocarbon ages from the upper part of the deposit suggest that the unit and its soils were buried episodically in time and space by eolian sand. Given the mobility of dunes, it is conceivable that the alluvium was locally buried, uncovered (e.g., Figure 4), and reburied many times. As a result, the upper part of the deposit conceivably contains humates that date to several periods. At three sites (GWMD5 #1, Stafford 1, Stafford 10; Figure 2), the top of the alluvium dated to the late Wisconsin, with ages of approximately 14,000, 17,000 and 20,000 yrs B.P., respectively. These ages indicate that the overlying eolian deposits are no older than late Wisconsin and may, in fact, be late Wisconsin in age.

At the majority of sites, however, the upper 5 cm of alluvium dates to the middle and late Holocene, with fourteen of the seventeen ages spanning the interval between approximately 7000 and 800 yrs B.P. (Figure 9). At Reno 4 the upper part of the alluvium gave an apparent age of 5370 ± 120 yrs B.P., indicating a late-Holocene age for the overlying dune sand (Figure 5). Because the vast majority of ages from the upper alluvium are middle-to-late Holocene, Arbogast (1996a) concluded that the overlying dune sediments are Holocene landforms. Radiocarbon dating of buried soils within the dunes indicated that evidence of late-Holocene activity is preserved. Of the fifteen ages derived from these positions, fourteen are less than 2500 yrs B.P., and ten fall within the past 1000 years (Figure 9). At Reno 4, for example, the weakly developed 2Ab horizon provided an age of 710 ± 80 yrs B.P. (Figure 5; Arbogast 1996a).

In addition to the radiocarbon ages derived from alluvium and dunes, buried soils were dated at two of the three sites, the Belpre trench and Stafford 4, where loess was identified. At the Belpre trench, the upper part of the buried soil provided an age of 20,670 ± 500 yrs B.P. Given the similarity in stratigraphy and the development of buried soils between the Belpre and Phillips trenches, it is assumed that the soil at the Phillips trench essentially dates to the same period. An additional age was obtained from the soil buried by dark brown loess at Stafford 4. At this site, the humates at the top of the soil yielded an age of 12,820 ± 340 yrs B.P. (Figure 8).

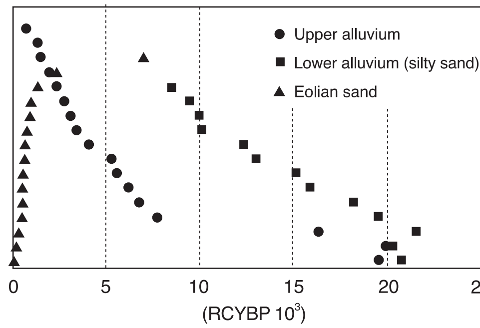

Figure 9. Radiocarbon age and stratigraphic position on the Great Bend Sand Prairie. In general, ages from the lower alluvium range from 20,000 to 10,000 yrs B.P., whereas the upper part of the deposit dates to the middle Holocene. Buried soils in dune sand are typically less than 2500 yrs B.P. in age, indicating that dunes are largely late-Holocene landforms.

Evidence For Late-Quaternary Paleoenvironmental Change

Floral and Faunal Remains

Prehistoric floral and faunal remains provide evidence for climate change in the region during the past 20,000 years. In general, evidence from late-Wisconsin deposits indicates a cooler and more mesic environment than during the Holocene. For example, a fragment of white spruce (*Picea* cf. *glauca*) charcoal, recovered from alluvium (ca. 2.0 m deep) at a site near the Belpre trench, dated to about 17,000 yrs B.P. (Johnson 1991). In addition, gastropods were collected from the loess at the Belpre and Phillips trenches (Figures 2, 8), where the underlying soils date to about 20,000 yrs B.P. The fauna includes the species *Discus cronkhitei, Helocodiscus singleyanus, Lymnea parva, Succinea avara,* and *Vertigo tridentata,* and an unidentified aquatic bivalve (see Arbogast 1995 for details). All of the identified species are presently extinct in the central Great Plains and are generally found in forested areas of North America where there are cooler temperatures and more effective moisture (Leonard 1952).

Stable Isotopes

This study analyzed detrital organic matter for stable-carbon isotopes for each sample that was dated by radiocarbon. Because the upper part of the alluvium potentially contains a mixture of relatively young and old humates, only the $\delta^{13}C$ values from the lower alluvium and dunes were used for the paleoenvironmental reconstruction. More negative $\delta^{13}C$ values correlate with late-Wisconsin radiocarbon ages in the lower alluvium, whereas less negative $\delta^{13}C$ values correspond with Holocene ages derived from dunes. Consequently, $\delta^{13}C$ values derived from the lower alluvium indicate the dominance of C_3 plants, at least within lowlands of the Great Bend Sand Prairie, during the late Wisconsin. Coupled with the snail and spruce macrofossils, this suggests a mesic environment in the region that was forested. Isotopic values obtained from late-Holocene dunes, in contrast, demonstrate the presence of a warm-season (C_4) grassland in the past 5000 years (Figure 10) because the region was more arid.

Sedimentology

Sedimentological data, coupled with radiocarbon ages obtained from alluvium and dunes, also provide evidence for late-Quaternary climate change. Given the disparity in sorting between the two deposits (Figure 7) and the regional extent of alluvium on uplands, we concluded that fluvial processes dominated in the late Wisconsin, whereas eolian sedimentation has prevailed during the Holocene. In conjunction with the biological and isotopic evidence, the sedimentological evidence indicates that the environmental conditions were more mesic between about 20,000 and 10,000 yrs B.P. than in the past 10,000 years.

Dune Orientations

The orientation of parabolic dunes reflects the direction of prevailing winds during deposition, with limbs pointed upwind. Dominant orientations on the Great Bend Sand Prairie are northwesterly and southwesterly, with the direction a function of age. The most prominent eolian feature containing significant late-Wisconsin deposits is Wilson Ridge, a lunette in the southwestern

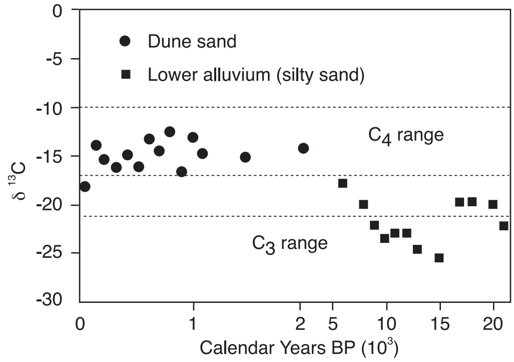

Figure 10. Distribution of $\delta^{13}C$ values, derived from lower alluvium and eolian sand, and radiocarbon age on the Great Bend Sand Prairie.

part of the study area (Figure 2). At this site, northwest winds episodically deflated the adjacent playa bed during the late Wisconsin, resulting in deposition on the southeastern margin of the basin and the development of a parabolic dune with northwesterly-oriented limbs (Arbogast 1996b). In contrast to Wilson Ridge, the orientation of Holocene dunes with a clear parabolic form is to the southwest, indicating southwesterly winds at the time of deposition (Arbogast 1996a; Figure 11).

Discussion

Integration of data collected from field reconnaissance, mapping, backhoe-trench investigations, roadcut exposures, quarries, and previous research has provided a chronology and understanding of late-Quaternary paleoenvironmental change and landscape evolution on the Great Bend Sand Prairie in south-central Kansas. This data is significant because it tests hypotheses regarding regional environmental change during the past 20,000 years. In addition, the data shows that a wide range of climatic variables and geomorphic responses are correlated.

Proxy climate data derived from late-Wisconsin deposits generally infer a more mesic environment than during the Holocene. Macrofloral evidence, in the form of dated white-spruce charcoal, indicates the presence of conifers around the peak of the last glacial period (Johnson 1991). In addition, faunal macrofossils (e.g., *Discus cronkhitei, Succinea avara,* an aquatic bivalve), and $\delta^{13}C$ data (Figure 10) also imply a forested landscape. This reconstructed environment com-

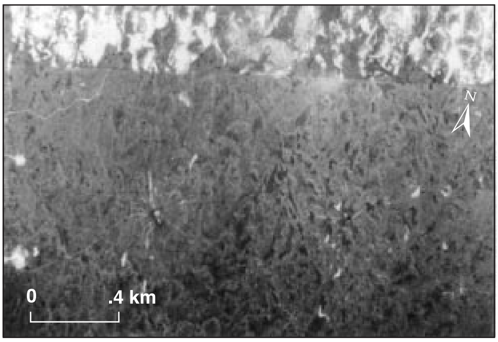

Figure 11. Aerial photograph of a parabolic dune field in sections 9 and 10, T.27S., R.20W. The sharp boundary near the top of the photo is the section line, one that separates grassland to the south from cultivated fields to the north. Note the well-defined, crescentic-shaped dunes with arms that point south to southwesterly, indicating prevailing winds from that direction, in the southwestern third of the photograph. Bright spots in the southern part of the photograph are blowouts, where sand is locally active. The large, bright circles at the top of the photograph are soils stripped of stabilizing vegetation through intensive circle-pivot irrigation (expanded from Arbogast 1996a).

pares favorably with that described downstream in the Arkansas River valley (Fredlund and Jaumann 1987), immediately (<20 km) to the north at Cheyenne Bottoms (Fredlund 1995), and elsewhere within the central Great Plains (e.g., Grüger 1973; Fredlund and Jaumann 1987; Fredlund 1989; Johnson et al. 1993; Wells and Stewart 1995). In addition, this correlation supports the hypothesis proposed by Fredlund and Jaumann (1987) that coniferous and hardwood species favored mesic river valleys during the late Wisconsin. Undoubtedly, this ultimately occurred because the Laurentide ice sheet covered much of North America at that time, and the mean position of the polar front was probably to the south of Kansas (about 34° N) (Delcourt 1979; Delcourt and Delcourt 1983).

Within this environmental context, alluviation dominated the geomorphic regime all over the Great Bend Sand Prairie throughout the late Wisconsin. Given that evaporation rates would have been relatively low in the cooler environment, and sediment texture would have promoted slow drainage, the landscape probably contained a series of interconnected shallow lakes and wetlands. A portion of this system's morphology may be preserved at the playa adjacent to Wilson Ridge, where late-Wisconsin sediments were documented by Arbogast (1996b).

This long-term pattern of saturation contrasts distinctly with the record at Cheyenne Bottoms, where Fredlund (1995) reported a major sedimentary gap that spans the latter part of the late Wisconsin. Fredlund (1995) hypothesized that this erosional interval occurred because climatic conditions became more arid and surface winds strengthened following the glacial maximum. It is possible that Fredlund's (1995) data is biased because it was obtained from only one core. If a major period of erosion transpired at Cheyenne Bottoms, however, it should have also happened on the Great Bend Sand Prairie, based on the proximity of the sites and their similar character (i.e., poorly drained lowlands). The primary difference between the two regions is their drainage. Cheyenne Bottoms is located within a closed basin (Latta 1950; Bayne 1977), whereas the Great Bend Sand Prairie is part of the Arkansas River system. This supports the conclusion that late-Wisconsin sedimentation on the Great Bend Sand Prairie was related in large part to flooding of the river. Given the Arkansas River's origin in the Rocky Mountains, massive alluviation within the Great Bend Sand Prairie may have occurred concurrently with intensive eolian deflation of Cheyenne Bottoms.

In addition to the extensive alluviation that occurred on the Great Bend Sand Prairie, some eolian sedimentation also transpired. Eolian mobilization of sand and silt occurred within the region during the late Wisconsin, probably on a local scale and due to northwest winds, with wind-blown sand and silt being preserved at Wilson Ridge (Arbogast 1996b) and perhaps in a few other dunes. This correlates with localized responses on the nearby Southern High Plains, where Holliday (1997) documented lunette formation adjacent to playas in the late Wisconsin. Pulses of eolian mobilization within the region likely correlate with more arid intervals and may be climatologically related to the erosional period described at Cheyenne Bottoms by Fredlund (1995).

Although eolian mobilization within the Great Bend Sand Prairie was likely of limited scale, evidence indicates that a large volume of loess may have blown into the region from distant sources. Specifically, late-Wisconsin deposits contain high percentages of silt at many sites. Some of this silt is likely Peoria loess, which accumulated over much of the central Great Plains after blowing out of the Platte River valley in Nebraska (Frye and Leonard 1952; Wells and

Stewart 1987; Johnson 1993; Johnson et al. 1993). Thick deposits of Peoria loess exist immediately north and south of the study area (Feng 1991; Feng et al. 1994), and deposition of eolian silt definitely occurred on the Great Bend Sand Prairie as well. Although the Peoria loess was probably integrated with the alluvial deposits at most sites through simultaneous deposition, it retained its distinctive character at the Belpre and Phillips trenches. At these sites (Figures 2, 8), the silt overlies a soil that dated to about 20,000 yrs B.P. This age correlates nicely to terminal ages from the Gilman Canyon Formation, which is a stratigraphic complex that immediately predates the Peoria loess in the central Great Plains (e.g., Johnson et al. 1990, 1993; Johnson 1993).

Regardless of the alluvial or eolian origin of the late-Wisconsin sediments on the Great Bend Sand Prairie, all have been altered by postdepositional processes. In particular, pedogenesis in the alluvium and loess resulted in strongly developed soils that spanned the entire thickness of the deposit at every site studied (e.g., Figure 5). Well-defined clay films, traceable in the soils over several meters, were commonly observed. Moreover, slickensides were also noted in places, suggesting that the soils have frequently expanded and contracted through time. Overall, this evidence indicates that periods of extended landscape stability and soil formation occurred in the alluvium throughout the region following its deposition. Unfortunately, pedogenesis probably contributed to destruction of diagnostic sedimentary structures in the alluvium, in conjunction with intensive bioturbation.

In contrast to the mesic conditions that transpired during the late Wisconsin, data derived from Holocene deposits suggests a warmer and probably more xeric environment in the past 10,000 years. Although most of the preserved strata date to the late Holocene, indirect evidence exists for early-to-middle Holocene environments. The youngest radiocarbon age from the lower part of the alluvium, for example, is about 8000 yrs B.P. (Figure 9), suggesting that the massive and widespread alluviation that occurred during the late Wisconsin ceased sometime during the late Wisconsin or very early Holocene. In addition, gastropods with a boreal affinity disappeared from the region, and $\delta^{13}C$ values (Figure 10) imply a higher proportion of C_4 grasses. This period of environmental change correlates nicely with the record at Cheyenne Bottoms (Fredlund 1995) and northeastern Kansas (Grüger 1973), and transpired in conjunction with increased insolation, disintegration of the Laurentide ice sheet (COHMAP 1988), and stronger zonal atmospheric flow (Knox 1983).

As the early-Holocene environments on the Great Bend Sand Prairie became warmer and widespread alluvial deposition ceased, the modern (largely ephemeral) drainage network probably originated, and eolian processes started to dominate. In all probability, deposits of eolian sand began to accumulate throughout the area. Hypothetically, the origin of these sands was the reach of the Arkansas River valley that bounds the northwestern part of the region (Figure 2). It is conceivable that the floodplain was deflated and eolian sand was transported to the south and east, across the lowland, as climate warmed during the early Holocene. Arbogast (1996b) demonstrated that the prevailing northwest winds of the late Wisconsin persisted into the early Holocene at Wilson Ridge, where an eolian unit accumulated on the north slope of the dune around 9000 yrs B.P. This supports model data (COHMAP 1988; Kutzbach et al. 1993) that strong northwest winds were present in the early Holocene, at least during the winter months. Middle-Holocene sedimentation by wind was documented at Stafford 3 (Figure 2), where a buried soil in dune sand dated to about 6000 yrs B.P.

Overall, early and middle-Holocene transport of eolian sand on the Great Bend Sand Prairie is logical within the context of other research. As atmospheric flow became increasingly zonal, warmer and drier conditions generally prevailed in the region during the middle Holocene (Knox 1983; Kutzbach 1987; COHMAP 1988; Crowley and North 1991; Kutzbach et al. 1993). This interval had a demonstrable effect near the Great Bend Sand Prairie. At Cheyenne Bottoms, Fredlund (1995) argued that stable but lower water levels were present. In northwestern Oklahoma, Brady (1989) reported that eolian sand was mobilized during the early and middle Holocene. Holliday (1995a, 1995b) demonstrated that eolian sedimentation occurred in the neighboring Southern High Plains between 9000 and 5500 yrs B.P. To the northwest, early- and middle-Holocene dune formation apparently occurred in northeastern Colorado (Forman and Maat 1990; Madole 1995).

In addition to the theorized mobilization of eolian sand during the early and middle Holocene, large-scale loess deposition definitely occurred over about a 100 km^2 area in the vicinity of Stafford 4 (Figure 2). At this site, dark brown, unweathered loess overlies a moderately developed soil dated to about 12,000 yrs B.P. (Figure 8). Given the age from the soil, the loess could be late-Pleistocene loess or early-Holocene loess (Frye et al. 1968). Empirically, the deposit closely resembles Bignell loess, an early-Holocene loess (Frye et al. 1968; Johnson and May 1992; Johnson 1993) which has been recognized immediately to the north and south of the study area (Feng 1991). If the deposit at Stafford 4 is Bignell loess, that indicates that eolian sedimentation occurred on the Great Bend Sand Prairie over a broad area during the early Holocene. Moreover, this area represents the largest expanse of the loess in the central Great Plains.

Although some early- and middle-Holocene eolian sediments are preserved on the Great Bend Sand Prairie, the vast majority of Holocene strata on uplands are contained within late-Holocene dunes. The best developed landforms are parabolic dunes (Figure 11) with southwesterly-oriented limbs. A variety of potential sources exist for the dunes. Some of the sand may have been derived from the floodplains of streams within the area. For example, Rattlesnake Creek flows through the core of a dune field in the southwestern part of the region (Figure 2). Thus it is conceivable that eolian sand is supplied from the channel to dunes in the immediate area during the dry season. Secondarily, outcrops of silty-sand alluvium were a probable source for some of the sand. This may account for the lack of A horizons in alluvial soils at many sites. On the other hand, the thick, massive, and cohesive nature of the sediments suggests that the deposit was not an important origin. In all probability, the primary source for the dunes is older dunes that were reworked. Assuming that eolian-sand deposits were present during the early and middle Holocene (e.g., Brady 1989; Forman and Maat 1990; Madole 1995; Holliday 1995a, 1995b), and are poorly preserved in the region today, this is the most logical conclusion.

From a paleoenvironmental perspective, values of $\delta^{13}C$ from buried soils within the dunes imply that a semiarid environment existed in the late Holocene (Figure 10). As a result, the dunes have evolved in cycles, with soils likely forming during moist intervals and mobilization occurring when conditions were relatively dry. The distribution of radiocarbon ages indicates significant activation of the dunes in the past 1000 years, and the orientation of the dunes indicates prevailing winds were southwesterly (Arbogast 1996a). At Reno 4 (Figure 2), two periods of sand mobilization occurred in the late Holocene, with an intervening period of stability around 700 yrs B.P. (Figure 5). Given that some surface soils in dunes are better developed (A/Bt/C horizonation) than others (A/AC/C horizonation), the mobilization of dunes must have varied spatially in the past. This is certainly the case today, as blowouts are common in otherwise stable dune fields. Blowouts are more numerous in the more arid part (west half) of the region (e.g., Figure 11), which suggests that dune fields in this area may easily destabilize if the climate becomes increasingly arid.

The late-Holocene record preserved in dunes correlates well with that reported elsewhere in the region. Episodic aridity within the semiarid environment has caused periodic mobilization of dunes throughout the central Great Plains in the late Holocene, with mobilization reported in Nebraska (Ahlbrandt et al. 1983; Swinehart 1990; Stokes and Swinehart forthcoming), Colorado (Muhs 1985; Forman and Maat 1990; Forman et al. 1992; Madole 1995), northwestern Oklahoma (Olson et al. 1995) and the neighboring Southern High Plains (Holliday 1995a, 1995b). In particular, Arbogast (1996a) demonstrated that periods of late-Holocene stability on the Great Bend Sand Prairie correlate well with the record derived from northeastern Colorado (Madole 1995). More buried soils of differing apparent age were documented on the Great Bend Sand Prairie (Arbogast 1996a), however, than were reported by Madole (1995). Arbogast (1996a) attributed this difference to the more humid location of south-central Kansas, which resulted in more soils forming in the dunes and/or better preservation because less erosion occurred. If more soils formed, that would imply more frequent climatic fluctuations (i.e., from wet to dry) in south-central Kansas than in northeastern Colorado. The sensitive nature of contemporary dunes is consistent with the accounts of early nineteenth-century explorers, who noted both active and inactive dunes along the Arkansas River valley (Muhs and Holliday 1995). Other research (Muhs and Maat 1993) has demonstrated that dunes in the central Great Plains are currently near their threshold for instabilty. In fact, they could increase one activity class (e.g., inactive to active crests) if the increase (4°C) in temperature that is modeled in many greenhouse scenarios (e.g., Hansen et al. 1988; Wetherald and Manabe 1988; Schlesinger 1989) occurs.

Conclusion

Within the context of global climate change, the central Great Plains is an excellent place to study geomorphic responses because landscapes are easily disturbed in the semiarid and subhumid climate. In addition, thick deposits of loess, alluvium, and eolian sand that contain abundant information about past environments are common. Thus geomorphologists are systematically analyzing these sediments in efforts to reconstruct the region's late-Quaternary paleoenvironmental and geomorphic history. Through these studies, relationships between sites are being established throughout the area. Although a regional picture has begun to emerge, however, significant temporal and spatial gaps remain. Moreover, little work has been conducted in areas where a variety of geomorphic processes can be correlated with climatic fluctuations.

In an effort to fill an important void in the late-Quaternary record of the central Great Plains, a systematic reconstruction of the paleoenvironmental and geomorphic history of the Great Bend Sand Prairie was presented here. The Great Bend Sand Prairie is a mosaic of sand sheets and dune fields that extends over a broad area in south-central Kansas, within the core of the central Great Plains. In contrast to previous studies in the central Great Plains, which focused largely on sites where eolian or alluvial processes dominated, the record from the Great Bend Sand Prairie indicates that a variety of late-Quaternary paleoenvironmental conditions and geomorphic processes occurred. Results from this study show that a number of variables are interrelated, including insolation, atmospheric circulation, alluviation, eolian sedimentation, and glaciation. This data can be used in future studies to test and refine hypotheses focusing on regional environmental change.

Proxy climatic data (i.e., floral, faunal, isotopic, dune orientations) demonstrates that late-Wisconsin and Holocene climates differed dramatically. Evidence derived from late-Wisconsin strata indicate relatively mesic conditions and prevailing northwest winds at the time of deposition. This occurred because the Laurentide ice sheet covered much of North America, and the mean position of the polar front was south of Kansas. The lowland was apparently forested, with coniferous species such as white spruce present. This reconstruction correlates with previous data and supports the hypothesis that boreal species forested riparian zones in the central Great Plains during the late Wisconsin. In contrast to late-Wisconsin conditions, Holocene environments were warmer and probably drier, and were caused by elevated insolation, disintegration of the Laurentide ice sheet, and increased zonal atmospheric flow. The data demonstrate that northwest winds caused eolian mobilization of sediment during the early Holocene, which verifies previously modeled wind directions. In the late Holocene, mobilizing winds have generally been southwesterly. In general, this correlates with the pattern observed elsewhere in the central Great Plains.

As a result of these contrasting climatic regimes, late-Wisconsin and Holocene landscapes evolved by different geomorphic processes. Late-Wisconsin deposits are a complicated assemblage of sand, silt, and clay. Although sedimentary structures are not preserved in these deposits, their poorly-sorted nature, numerous fining-upward sequences, random textural variability, and irregular truncation suggest deposition largely by alluviation. Eolian deposition of Peoria loess undoubtably occurred, but most loess was probably incorporated within the alluvial sediments through simultaneous deposition or reworking. Intact deposits of Peoria loess and perhaps some wind-blown sand are preserved, however, at scattered localities. Radiocarbon ages from the lower part of late-Wisconsin deposits range from about 20,000–8000, indicating that widespread sedimentation persisted through the late Wisconsin and perhaps into the Holocene. Given the major unconformity at Cheyenne Bottoms, this supports the conclusion that alluviation on the Great Bend Sand Prairie is related to intensive flooding in the Arkansas River valley. Conceivably, high discharge occurred whenever alpine glaciers melted significantly. This likely resulted in a series of interconnected wetlands. Following deposition, individual sites were stable for significant periods of time, causing strongly developed soils to form.

As the climate became more xeric in the early Holocene, widespread alluviation ceased and eolian processes probably began to dominate. An extensive deposit of loess accumulated in the east-central part of the region, and eolian sands were likely mobilized as well. Hypothetically, early-Holocene eolian sand was derived from the Arkansas River valley to the northwest. Most contemporary dunes are late-Holocene landforms and probably consist mostly of reworked early- and middle-Holocene dunes. Dunes usually contain one or two weakly developed buried soils, representing brief periods of landscape stability, that presumably developed during intervals of more effective moisture. Surface soils vary in development, indicating that mobilization has varied spatially. Today, dunes in the more arid part (western) of the region are the most active, suggesting that they may easily remobilize if future warming occurs.

Acknowledgments

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