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Middle Holocene aeolian activity on the High Plains of west-central Kansas

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Abstract: The uppermost surficial stratigraphic unit south of the Arkansas River in the Kansas High Plains is a previously unidentified middle Holocene or younger loess. The unit fits both a loess-thickness and a particle-size model for loess distribution with increasing distance from source. A soil immediately below this unit is radiocarbon dated 6000 to 6700 years BP. The radiocarbon ages indicate that the loess unit is younger than the commonly reported ranges for Bignell Loess in the Great Plains and demonstrate a need for re-examining Holocene loess stratigraphy of the Great Plains. In some locations closest to the Arkansas valley source, this middle Holocene unit is overlain by, or interfingers with, dune sands. The presence of these aeolian sands indicates that, following a period of relative landscape stability and soil development, a shift toward a middle-Holocene climate in which aeolian processes dominated occurred about 6000 years ago on the High Plains of west-central Kansas.

Key words: Loess, aeolian activity, palaeosol, radiocarbon dating, loess-distribution model, middle Holocene, High Plains, Kansas.

Introduction

In the High Plains of Kansas south of the Arkansas River and north of the Cimarron River, few detailed studies assess the character of the surficial sediments. Thorp and Smith (1952) provided the first comprehensive reconnaissance maps of this area, based in part on Smith's field work in the 1930s and 1940s. Some of the site data used to prepare the 1952 map are recorded in more detail in Smith (1940). The soil survey reports for Finney (Harner *et al.*, 1965), Gray (Tomasu and Roth, 1968), and Haskell (Hamilton *et al.*, 1968) Counties, Kansas, also provide background information on the soils and surficial sediments here. More recently the Kansas Geological Survey has provided a reconnaissance state map (Ross, 1991), and Johnson and Arbogast (1993) completed a surficial geologic map of Finney County. These studies describe the type of sediment present, but the source and distribution are not addressed. The objectives of the present study are: 1) to characterize the upper surficial stratigraphic units in order to compare these findings with the reconnaissance maps; and 2) to apply a loess-distribution model to the uppermost surficial unit in the study area to confirm its aeolian origin.

This study encompasses the region in west-central Kansas from the Arkansas River to the Cimarron River on the eastern edge of the High Plains. The High Plains is a nearly level largely undivided surface capped by the Pliocene Ogallala Formation overlain by thick unconsolidated surficial sediments of Quaternary age. Exposures in the surficial sediments, other than occasional borrow pits and railroad cuts, are rare. In our study area, coring provided the only method for subsurface stratigraphic investigation. The

surficial maps of Thorp and Smith (1952) and Ross (1991) show our study area as primarily loess-covered. Dune fields are shown adjacent to the Arkansas River and south of the Cimarron River. Thorp and Smith (1952) term the loess Wisconsinan estimate thicknesses of between 1.2 and 2.4 m (4–8 ft). Ross (1991) termed it 'thin undifferentiated Holocene and Pleistocene loess'. Figure 1, modified from Thorp and Smith (1952), illustrates the surface stratigraphy for the study area. From auger borings as deep as

Figure 1 Surficial geologic map of field area and locations of sample sites. Geology is modified from Thorp and Smith (1952).

21 m (70 ft), Simonett (1960) constructed a general stratigraphic section 27 km (17 miles) long, southward from the Arkansas River. Dune sand 1–18 m (3–60 ft) thick overlies 1–3 m (3–10 ft) of loess, which Simonett termed 'lower Peoria Loess' based on fossil evidence, over pre-Illinoian weathered sands and gravels. At a distance of 16 km (10 miles) from the Arkansas River, Simonett describes a second dune sand, 6 m (20 ft) thick, lying beneath the lower Peoria Loess and just above buried Wisconsinan and Illinoian terraces. We identified similar sequences of upper stratigraphic units, but did not penetrate the terrace sediments or weathered sand and gravel, as our coring was limited generally to depths of less than 6 m. Additionally, we identified a fine-grained deposit at the surface that seems to be stratigraphically equivalent to, or younger than, some of the dune sands augered by Simonett (1960). This uppermost, fairly continuous silty deposit, whose lower boundary is easily recognized in the field only when a palaeosol is present beneath, is the unit investigated in this study. Is it a loess or alluvium, and how does it relate to the Bignell Loess or other Holocene stratigraphic units? Prior evidence for Bignell Loess in this part of Kansas is lacking.

Materials and methods

Two major traverses were sampled between the Arkansas and the Cimarron Rivers. Nine sites were on an east-west traverse along the main divide between the Arkansas and Cimarron Rivers from about 21 km (13 miles) south of Dodge City, Kansas, to about 19 km (12 miles) northwest of Sublette, Kansas (Figure 1). Eight sites were sampled in a north-south traverse at about the 101°W longitude, beginning near Garden City to 12.9 km (8 miles) north of Satanta, Kansas. With the exception of three sites on the north-south traverse, all sites were located approximately 8 km (5 miles) apart. Two sets of cores were extracted from each site with a Giddings hydraulic soil probe, and continuous cores were sampled and described according to methods in the Soil Survey Manual (Soil Survey Staff, 1951; 1993). Stratigraphy at each site was documented along with the soil descriptions and correlated among sites by field descriptions and later confirmed by analyses of particle-size separates. Laboratory analyses were completed following the standard methods of the Natural Resources Conservation Service (Soil Survey Laboratory Staff, 1992). The upper, most widely distributed stratigraphic unit was used to test the loess-distribution model. Particle size, calculated on clay-free basis, was used for determinations in the loess-distribution model. Weighted-average values were calculated for the very fine sand, coarse-silt, and fine-silt fractions. These values were plotted against distance from a projected valley source area. Radiocarbon analyses of whole soil were determined by accelerator mass spectrometry (AMS) through Beta Analytic, Inc. Ages referred to in this study are in radiocarbon years.

Results and discussion

Loess-distribution model

Loess may be defined simply as windblown silt. Loess deposits and their distribution have unique characteristics that distinguish them from other silty deposits such as alluvium. Among the characteristics are the consistent relationships between the source, the distribution, and thickness, which compose parts of a loess-distribution model.

Loess-distribution models have been developed for the thick loess units of the mid-continent USA. Among the more widely cited are those of Smith (1942) in Illinois and Ruhe (1969) in Iowa. Olson and Ruhe (1979) presented a similar model for southwestern Indiana. Ruhe (1973) comprehensively reviewed the

literature relevant to loess dispersion for the upper Mississippi Valley. Handy (1976) presented a theoretical mathematical treatment for loess distribution by variable winds in Iowa. To the west on the Great Plains, Frye and Fent (1947), Swineford and Frye (1951), and Frye and Leonard (1951; 1952) provided background on loess in Kansas but did not employ specific models to describe its distribution. In Texas, Seidlheko (1975) describes particle-size distribution of surficial sediments from a Pecos River valley source.

The first step in this study was to separate the uppermost stratigraphic unit from the underlying units. In this region where multiple loess units are present (Frye and Fent, 1947; Frye and Leonard, 1951; 1952), separation of Late Wisconsinan loesses from Holocene loess units has been limited to those locations where a palaeosol is present. This limitation has restricted recognition of these individual loess units to specific sites or extremely small areas. In Kansas, separation of loess units is complicated by the probability that many Holocene units, including the Bignell Loess, are reworked and derived from older materials of the same composition, principally the Late Wisconsinan Peoria Loess (Feng, 1991; Johnson, 1993). Without the presence of a palaeosol at the contact of these units, separation of younger, Holocene loess units from older, Peoria Loess is extremely difficult.

In this study area, palaeosols were described at seven sites beneath the Holocene unit. At the remainder of the sites, palaeosols either were not described or were not located in the proper stratigraphic position for comparison. At many sites, the base of the Holocene unit could not be determined from field evidence. The only field clue was that measured thicknesses for the Holocene unit were excessive when compared with sites where underlying palaeosols were present. A more reliable means of identifying the surficial Holocene unit was needed.

The most effective way found to separate stratigraphic units in this study without the benefit of stratigraphically continuous palaeosols was to calculate the particle size on a clay-free basis. The fine silt, coarse silt, very fine sand, and fine sand distributions were examined for each sample site. Where the difference in particle-size percentage between samples from adjacent depth intervals was greater than 3 or 4% for each fraction or were increased or reduced abruptly by two- or threefold, a stratigraphic break was inferred to be present. For example, Table 2 shows the depths and particle size calculated on a clay-free basis for the first 3 m at site 5. The first stratigraphic break was determined at a depth of 127 cm. Note that where the profile distributions of very fine sand and fine silt change significantly, the very fine sand decreases and the fine silt increases abruptly. The fine sands are reduced by nearly one-half and the coarse silts increased only by a few %. The 127-cm value represents the thickness of the uppermost stratigraphic unit for site 5. The thickness of the uppermost stratigraphic unit was determined for each sample location in the same manner. Thicknesses thus obtained were then checked against field textures and descriptions to ensure that the stratigraphic breaks were reliably interpreted.

In establishing potential source areas for testing the loess-distribution model in this study, a series of locations in the Arkansas and Cimarron River valleys were evaluated. Field estimates of textures from the top 64 cm (25 in) were examined along the two sampling traverses (Table 1). Surface textures for the dune-sand sites of the northern 48 km (30 miles) of the north-south traverse closest to the Arkansas River are coarse, gradually fining with distance away from the Arkansas River and toward the Cimarron River. Surface textures for all sites along the east-west traverse and for those along the southern 32 km (20 miles) of the north-south traverse are silt loam or silty-clay loam. Surface textures for the six sites closest to the Arkansas River on the north-south traverse are increasingly coarser to the north. If we accept the principles of aeolian sedimentation as described by Bagnold

Table 1 Surface textures measured in the field at each sample site; the upper 60–65 cm are tabulated with horizon designation and thickness

Site	Depth (cm)	Horizon [†]	Distance (km)	Surface texture* [‡]
15	0–13	Ap	135.3	sicl
	13–36	Bt1		sicl
	36–66	Bt2		sic
1	0–12	Ap	122.0	sil
	12–26	BA		sil
	26–44	Bt1		sicl
	44–60	Bt2		sicl
2	0–10	Ap	115.5	sil
	10–18	A		sil
	18–28	BA		sicl
	28–36	Bt1		sicl
	36–53	Bt2		sicl
	53–64	Bck		sicl
3	0–13	Ap	108.0	sil
	13–23	A		sil
	23–33	BA		sil
	33–46	Bt1		sicl
	46–66	Bt2		sicl
4	0–13	Ap1	99.0	sil
	13–23	Ap2		sic
	23–36	BA		sicl
	36–53	Bt1		sicl
	53–64	Bt2		sicl
5	0–15	Ap	89.3	sil
	15–36	Bt1		sicl
	36–48	Bt2		sicl
	48–58	Bt3		sicl
	58–64	Bt4		sicl
6	0–13	Ap	83.0	sicl
	13–25	Bw		sicl
	25–61	Bk		sicl
7	0–13	Ap	72.7	sil
	13–36	Bt		sicl
	36–46	Btk		sicl
	46–66	Btk		sicl
8	0–10	Ap1	64.1	sil
	10–18	Ap2		sil
	18–33	Bw		sil
	33–48	Bck		sil
	48–69	C1		sil
9	0–10	Ap1	61.9	sil
	10–23	Ap2		sicl
	23–30	Bt1		sicl
	30–38	Bt2		sicl
	38–61	Btk		sil
10	0–15	Ap	57.5	sil
	15–30	Bw		sil
	30–56	BC		sil
	56–64	C		sil
11	0–10	A	53.2	fsl
	10–33	Bt		scl
	33–61	2Btkb		sicl
16	0–20	A	52.6	ls
	20–38	AC		ls
	38–64	C1		s
17	0–13	A	53.0	vfsf
	13–25	AC		vfsf
	25–51	C1		vfsf
	51–64	C2		ls
12	0–10	A	50.0	lfs
	10–28	AC		fs
	28–64	C1		fs
13	0–15	A	47.6	lfs
	15–28	AC		fs
	28–64	C1		fs
14	0–13	A	47.6	lfs
	13–61	C1		fs

[†]Horizon nomenclature and textural abbreviations are from Soil Survey Staff (1951)

*Field measurements

Table 2 Particle-size distribution on clay-free basis for the top 3 m at site 5

Depth (cm)	Sands (%)		Silts (%)	
	Fine	Very fine	Coarse	Fine
0–15	2	25	48	23
15–36	2	30	46	21
36–48	2	32	48	17
48–58	2	40	44	13
58–89	2	39	41	18
89–109	4	38	39	18
109–127	2	34	46	17
127–157	1	10	50	37
157–178	tr	8	49	42
178–208	tr	10	47	42
208–229	tr	10	50	40
229–264	1	11	49	39
264–290	tr	12	49	38
290–312	1	16	47	36

(1941), these surface textures indicate a source in the Arkansas River valley rather than the Cimarron River valley. Our results also support the findings of earlier investigators (Welch and Hale, 1987; Smith, 1940), who suggested that sources for sedimentation in this part of Kansas are predominantly from the north and northwest.

Simonett (1960), studying sand movement, investigated dune alignment south of the Arkansas River between Syracuse, Garden City, and Dodge City. He concluded that there is a weak tendency toward a south-southwest to north-northeast alignment of dunes, indicating winds blowing from the north. In addition, he showed that wind data from recording stations at Garden City and Dodge City had resultant sand movement vectors of 143° for Garden City and 110° for Dodge City. The 35° difference was attributed to the short duration of both records, whose periods of record overlapped only partially. He concludes that winds had the greatest transport capabilities and thus dune-building capacity when blowing out of the north-northwest. This too, suggests an Arkansas River valley source. Information from wind-direction data, previous references, location of dune fields, configuration of the river valleys, and surface textures point to the Arkansas valley as the most likely source for loess between the Cimarron and Arkansas Rivers. A line was drawn transverse to the Arkansas River source on the southeast side of the channel near the town of Sutton, and the distance to each sample site measured. Thickness of the upper surficial unit was calculated as described earlier. A linear relation between thickness and log distance from source resulted (Figure 2). The log function describing this thickness distribution is:

$$Y = 899.19 - 400.78 \log X \quad r^2 = 0.59$$

where Y is the thickness of the loess in cm and X is the distance from source in km. This relation, expressed by the general equation format, $y = b - a \log x$, is common for windblown silts or loess units (Olson and Ruhe, 1979; Ruhe, 1969; Smith, 1942) and fulfils one of the criteria for testing the validity of using the loess-distribution model. Handy (1976) suggests that this type of relation is the result of variable wind directions rather than prevailing winds. He also states that a moderate prevailing wind tends to preserve variable wind-induced semilog thickness relations on the downwind side of the source. Skidmore *et al.* (1994) demonstrate that the winds having the greatest capacity to move and redistribute material may not necessarily be the prevailing winds. From Simonett's (1960) vector diagrams, the present-day dune alignment throughout the area, and modern wind-direction data that show decided seasonal modality, it is likely that the

Figure 2 Loess thickness distribution with distance from the Arkansas River valley source.

winds producing these deposits were variable with erosive winds blowing commonly from the north.

The second test of the loess-distribution model is to examine particle-size distributions with distance from source. Figure 3 shows the distribution values for very fine sand, coarse silt, and fine silt plotted against distance. These data are more appropriately presented on a clay-free basis (Figure 3a) because the particle-size distribution of this stratigraphic unit as a whole is much coarser than loess units described to the east in Iowa, Illinois and Indiana, and because much of the unit is in the portion of the soil profile subject to pedogenic clay formation. However, the results for this particular study area do not differ greatly from those that include clay (Figure 3b), in part because clay illuviation is minimal. The lack of clay translocation seems to be a regional occurrence. We found few clay films in soils of similar age in nearby Morton County other than stress cutans. Fraser and Ransom (1989) also found little evidence of translocated clay in similar soils of western Kansas. In microscopic examination of clay films, Ransom *et al.* (unpublished data) suggest a stress (shrink and swell) rather than an illuvial origin for the clay films of soils in this region.

Particle-size distributions show a linear relation with distance from source: the very fine sand content decreases and the fine and coarse silt contents increase. The sites closest to the river do not seem to fit the model. At these sites, the upper surficial silty unit interfingers with dune sands and is eventually buried by these sands at sites nearest the river. Increasing amounts of very fine and coarser sands are present at these sites (Table 1). Because sands move by saltation rather than in suspension for any distance, sites having significant sand content cannot be described by the model developed for loess.

The thickness and particle-size distributions with distance from source have patterns approximating those that are known for loess, so the uppermost surficial unit in this study is considered to be loess. The correlation coefficients may seem somewhat low, in part because the loess is much coarser than that found in the Midwest, where many of these relations were first developed, and in part because the regressed values include those near the source. In addition, reworking of materials by variable winds from the south and southwest (Skidmore *et al.*, 1994) may have perturbed slightly the sediment distribution with distance from source.

Figure 3 Particle-size distribution plotted against distance from the Arkansas River valley source: (a) clay-free basis and (b) total < 2 mm-size basis.

Holocene landscape evolution

Regional stratigraphic relations

The generalized Holocene sequence in southwestern Kansas from oldest to youngest consists of the Brady soil, the Bignell Loess, aeolian sands or fluvial deposits, and the modern ground soil. A ground soil is the soil presently at the surface. An accepted date for the Holocene-Pleistocene boundary is about 10 000 years (Hopkins, 1975). For west-central Kansas, this boundary is crossed by the Brady soil, a time-transgressive soil-stratigraphic unit (Schultz and Stout, 1948; Frye and Fent, 1947; Frye and Leonard, 1951).

The Brady soil is extensive only in northwestern and west-

central Kansas, but even there its occurrence is discontinuous (Frye and Leonard, 1951). Johnson (1993) states that 'without an overlying stratigraphic unit the Brady soil does not exist'. More likely the Brady soil is present but is welded to (Olson and Hupp, 1986; Ruhe and Olson, 1980), or is the ground soil, and thus it is difficult to distinguish as a unique soil-stratigraphic unit.

The Bignell Loess overlies the Brady soil. If the Bignell Loess is the uppermost stratigraphic unit, it also contains the ground soil in its upper part. According to published radiocarbon ages for the Brady soil, the Bignell Loess is generally less than 9000 years old. Throughout western Kansas, if the Bignell Loess is not the surface stratigraphic unit, the Brady soil is overlain generally by aeolian sands or fluvial deposits dating from 6000 years ago (Johnson and Arbogast, 1993; Johnson, 1993; Mandel, 1994; Porter *et al.*, 1995). Ground soils have developed in these deposits.

Local stratigraphic relations

From our data, the stratigraphy in much of the study area consists of an upper loess unit, overlying a palaeosol developed in sands. East of site 5, this same sequence consists of the upper loess unit overlying a palaeosol developed in silts that may be a second, lower loess unit. In coring, we did not penetrate the base of this underlying silt unit, so no determinations of its origin or boundaries could be made. In the immediate vicinity of the Arkansas River, the uppermost stratigraphic unit is dune sand rather than the loess unit. These dune sands are the same surficial sands described by Simonett (1960).

Buried soils were identified at several sample sites. At four sites, whole soil samples were collected for radiocarbon analysis from the palaeosol subjacent to the loess unit (Table 3). During field sampling, these buried soils were assumed to be the Brady soil. Johnson (1993) reports ages for the Brady soil in Kansas to be 10 000 to 8000 BP. At site 16, the Ab horizon is dated at 6760 ± 70 BP and is overlain by dunes. Nearby, at sites 17 and 13, the dates obtained from the Bt horizons of buried truncated profiles are 6085 ± 70 and 6220 ± 75 BP, respectively. The A horizons have been eroded from both profiles. These two sites are now overlain by dune sand. Site 5 is significantly further both from the other three sites and from the river than the other sites, and the palaeosol is buried by silts rather than by dune sand. The date obtained here from the truncated Bt horizon is 6220 ± 70 BP. The palaeosols in this study are 3000 to 4000 years younger than the ranges reported for the Brady soil anywhere else, including the type location along the Platte River (Dreeszen, 1970; Johnson, 1993) and sites along the Republican River (Souders and Kuzila, 1990) in Nebraska, both north of this study area.

Simonett (1960) described a palaeosol that he called Brady in a boring south of Holcomb, Kansas, very close to our sites 13,

16, and 17. Without the availability of any radiocarbon dates, he noted, however, that the palaeosol appeared less developed than the typical Brady soil of northeastern and northern west-central Kansas as described by Thorp *et al.* (1951) and Frye and Leonard (1952). In all likelihood Simonett described the same soil we have dated here, rather than the Brady soil.

Can we discount contamination as a factor in the age determinations of the buried soils reported here? Younger carbon contamination can be mechanical, such as rootlet intrusion, or chemical, from the leaching of acids or bases. The impact of a given amount of contamination with modern carbon becomes twice as great for each half-life of range extension (Bradley, 1994). In this study, the radiocarbon ages were slightly more than one half-life. In addition, the relative amount of contamination affects the error in reporting ages. Bradley (1994) shows that for 5% contamination by younger carbon, the error in radiocarbon years is <500 years; for <10% contamination, it is less than 900 years. AMS, the technique used in this study, is less prone to contamination. Smaller samples are used than in conventional ^{14}C techniques. Given these generally inherent factors, contamination risk is low for our samples. In addition, the properties of the samples themselves preclude much possibility for contamination. As discussed earlier, clay translocation is minimal, indicating that little leaching has occurred. The organic carbon profiles above, in, and below the sampled horizons are low, generally <0.3%. Carbonates are present in or above only the sample from site 5. For the other three sites, the pH values for the samples are between 7.3 and 8.1 (1:1 soil to water paste) suggesting that Ca^{++} and Mg^{++} dominate the exchange complex of the soil profiles. Under these conditions, organic carbon is considered complexed and nonmobile (Jenny, 1980: 132; Stevenson, 1994: 367). Schaetzl and Sorenson (1987) show that postburial enrichment of organic matter from bases, including carbonate, is minimal below depths of 1.0 m. All sites in this study were sampled at depths below 1.0 m. The reported radiocarbon ages are similar regardless of the textures of the overlying horizons. All these factors provide little evidence for contamination.

Sites 16 and 17 represent the best arguments for possible contamination. Both sites are geographically closer to each other than to any of the other sites and should have the most similar ages. Site 17 is a truncated version of the complete buried profile found at site 16. The age for the Ab horizon at site 16 is 6760 ± 70 BP and that for the Btb horizon of the truncated profile is 6085 ± 70 BP. Assuming the proximity of these two sites allows us to examine these as a solum sequence, hypothetically the A and B horizons of the same soil, the radiocarbon ages show the B horizon to be approximately 700 years younger than the A horizon, an unlikely occurrence. This difference could be attributed to contamination of the B horizon by younger carbon either before or after truncation. Interpolations from the graphs provided in Bradley (1994) show that younger carbon contamination could be as much as 7%. If younger carbon contamination is related to truncation, the Btb horizon ages from the three sites 5, 13 and 17, once corrected, would have ages more similar to that of site 16. If contamination is not related to truncation, then the relative differences in ^{14}C ages between sites remain about the same but approximately 700 years older than those ages reported in Table 3. The range in ages of the buried soils reported here and discussed below are still too recent for an age range associated with the Brady soil, whether one accepts the possibility of contamination or not. These ages for the buried soil do represent a middle-Holocene period of soil development and landscape stability.

From the evidence presented here, the uppermost stratigraphic unit in the study area is a loess unit. Whether it is the Bignell Loess or some younger unit is less clear. Johnson (1993) postulates that Bignell Loess deposition occurred from about 9000 or 8000 years ago to about 5500 years ago. A second problem is that

Table 3 Radiocarbon dates from four sample sites south of the Arkansas River

Site	Depth (cm)	Horizon	^{14}C years $\pm 1 \sigma^*$	Laboratory number
5	127–157	2Btkb	6220 ± 70 BP	Beta - 48107
13	279–305	2Btb	6220 ± 75 BP	Beta - 48108
16	191–201	2Ab	6760 ± 70 BP	Beta - 48109
17	249–274	2Btb	6085 ± 70 BP	Beta - 48110

*These samples were analysed by AMS. σ is one standard deviation representing a 68% probability. $\delta^{13}\text{C}$ values are not given because reported values have been adjusted by ^{13}C for total isotope effects generated in both nature and during physical and chemical laboratory procedures. These effects cannot be decoupled. Reported values are corrected for all fractionation effects. Adjusted ages are normalized to -25 per mil $\delta^{13}\text{C}$.

the Bignell Loess as defined lacks any palaeosols. The palaeosols described and dated in this study would necessarily have to be included if the loess unit is equivalent to Bignell Loess.

Climatic implications

Little has been written about periods of landscape stability during the middle Holocene in west-central Kansas. Early- and middle-Holocene erosion and removal of sediment in small and medium-sized river valleys has been reported across much of the Midwestern United States (Bettis *et al.*, 1984; Knox, 1983). Periods of soil development both earlier and later than middle Holocene have been documented in valleys of central and northern Kansas in concert with incision and sediment removal. These periods are all in phase with those in the Midwest (Mandel, 1994; Arbogast and Johnson, 1994; Johnson, 1993). However, Arbogast and Johnson (1994) describe an interval of soil formation occurring about 6800 BP, referring to it as a 'yet poorly documented period of soil stability'. Mandel (1994) states that Holocene valley fills in the Pawnee River alluvial valley of Kansas are devoid of any indications of soil development from 7000 to 5000 BP. This hiatus in soil development is in the precise interval occupied by the soils dated in this study. The apparent out-of-phase chronology might be expected given that the soils dated in the Pawnee valley system are primarily on alluvial surfaces, whereas the soils dated in this study are on the High Plains surface, well away from the valley.

Given the ages of materials presented here, the aeolian unit is either a late phase of Bignell-age deposition separated from earlier deposition by a palaeosol, or a younger unit entirely. Bignell Loess deposition must have decreased in the area prior to 6700 BP to allow soil development followed by a truncation phase some time after 6700 BP. This stratigraphic sequence indicates that an aeolian phase was activated some time after soil development around 6700 years ago.

A shift towards a warm, dry climate occurred from 8000 to 5000 BP (Deevey and Flint, 1957; Bryson *et al.*, 1970; Webb and Bryson, 1972; Kutzbach, 1987). Atmospheric circulation patterns changed from primarily meridional to zonal air flow, which restricted the incursion of moist tropical air into the Great Plains (Deevey and Flint, 1957; Knox, 1983; Jacobson *et al.*, 1987; Holliday, 1989). As the climate became drier, ecosystem zones shifted eastward. Trees were replaced by tall and mixed grasses and eventually by sparser short grasses. Reduced vegetation cover would tend to increase erosion, particularly from hillslopes, especially during seasonal rains or heavy cloudbursts. Broad, nearly level interfluvies associated with the High Plains surfaces would be among the least and last to be affected by backwearing of slopes as hillslopes eroded. A lag time between the interruption of soil-forming intervals on upper surfaces and that on surfaces within the valley is entirely possible. Thus ages of soils on upper surfaces would appear slightly out-of-phase with ages of soils on surfaces in valley alluvial systems. This concept is supported also by reports that palaeosols on Holocene alluvial fans debauching into large valleys of the upper Mississippi River valley system are dated around 6500 ± 600 BP (Bettis and Hoyer, 1986; Bettis *et al.*, 1984).

Following an interval of soil development, dune reactivation began some time after 6700 BP. Buried soils at the sites closest to the Arkansas River are overlain by sands, and those farther east and south are overlain by silts that fit a loess-distribution model. These sands are the stratigraphic equivalent of the loess unit. Younger dunes are also present and in places overlie both of these units. The time for reactivation in the study area compares well with a dune reactivation period reported at about 5570 BP in Morton County, Kansas, south of the Cimarron River (Porter *et al.*, 1995) and one at about 5670 BP near Great Bend, Kansas (Arbogast, 1993). Three to four intervals of dune reactivation have been reported during the Holocene on a regional basis (Ahlbrandt

et al., 1983; Holliday, 1989; Forman *et al.*, 1992; Madole, 1995). Holliday (1989) refers to two aeolian pulses in the middle Holocene from about 6300 to 5000 BP and from about 5000 to 4500 BP. Both the vertical and lateral distributions of surficial sediments in the study area clearly indicate alternating periods of aeolian activity and landscape stability from 7000 to 5000 years ago.

Conclusion

The results of this study agree well with the composition of the map units in the surficial geology maps prepared from investigations of previous workers in this region, but they do not agree with the ages of the surficial units. The uppermost stratigraphic unit examined at sites south of the Arkansas River is a loess unit that fits a loess-distribution model and therefore is of aeolian origin. Close to the Arkansas River, the loess is either overlain by or interfingers with dune sand. A soil immediately below this loess is radiocarbon dated as middle Holocene, having ages between 6000 and 6700 years. These ages have been shown to be appropriately defined. Possible contamination of the samples by younger carbon is precluded by the properties of the soils and depth of sampling. This dates the loess as middle Holocene or younger. The radiocarbon ages do not agree with those accepted for the development of the Brady soil and the deposition of Bignell Loess, the only Holocene loess unit recognized in the mid-continent. Additional investigation of Holocene stratigraphy in the Great Plains of the USA may be warranted.

A climatic shift in which aeolian processes dominate following a relative period of landscape stability is indicated by dune sands and loess deposits overlying palaeosols dated between 6000 and 6700 years BP. This shift has been reported from proxy data by several researchers in other areas of the southern Great Plains and may be significant in a regional context.

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Note

Mention of trade names or commercial products in this article does not constitute endorsement or recommendation for use.

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