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Origin and Evolution of Lunettes on the High Plains of Texas and New Mexico

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Lunettes—isolated dunes on the lee side of playa basins—are common landforms on the Southern High Plains of northwest Texas and eastern New Mexico. The dunes contain calcareous (15–40% $CaCO_3$) sandy loam or loamy sand, with minor amounts of sepiolite, deposited 25,000–8000 ^{14}C yr B.P. and derived by deflation of lacustrine carbonate in the basins. The dunes also contain low carbonate (0–15% $CaCO_3$) sand or loamy sand that was deposited 25,000–15,000 yr B.P. and 8000–5000 yr B.P. and was derived by deflation that created the basins or deflated from sand deposited in the basins. Buried soils are common in the lunettes: A-Bk profiles characterize soils formed in the calcareous sandy loam; the sandy low-carbonate sediments contain A-Bt profiles in the oldest sand of some dunes, and A-Bw, A-Bt, or A-Btk in the early and middle Holocene sand. The dune stratigraphy, combined with carbon isotope data (derived from dated A-horizons in lunettes), suggests the following scenario for the Southern High Plains. The lunettes began forming as low-carbonate sand dunes in the late Pleistocene as playa basins were formed or deepened by wind erosion. The erosion repeatedly alternated with stability. The environment probably was cool and dry, but one or more cool and wet intervals 25,000–15,000 yr B.P. resulted in a rise in the water table and deposition of lacustrine carbonate in the deepest basins. There may have been short departures toward warmer (and probably toward drier) conditions throughout this time. Episodically dry conditions 15,000–8,000 yr B.P. resulted in deflation of the carbonate and further dune construction by repeated accretion of calcareous sandy loam or loamy sand. The low carbonate sand was deposited during widespread drought and deflation 8000–5000 yr B.P. The dunes have been largely stable in the late Holocene.

INTRODUCTION

The geomorphic and sedimentologic records of the Southern High Plains are dominated by eolian processes. The bulk of the Quaternary deposits are wind-derived and most of the landscape was created or modified by wind (Holliday, 1987, 1991). One of the locally common but minimally studied results of this eolian activity is the lunette, an isolated dune formed on the leeward side of small playa-lake basins. Lunettes, first named by Hills (1940), have been studied in Africa, Australia, and North America (Chen, 1995; Goudie and Wells, 1995, Table 5; Marker and Holmes, 1995), but of all of the sites of late Quaternary deposition on the Southern High Plains (valleys, playa-lake basins, sand dunes, and lunettes), lunettes have received the least attention. Previous investigations showed that these dunes contain buried soils and dateable materials (Judson, 1950; Holliday, 1985), suggesting that they contain stratigraphic records spanning the past 30,000 years or more.

This paper discusses recent investigations of the lithostratigraphy, pedostratigraphy, geomorphic evolution, and paleoenvironmental implications of lunettes on the Southern High Plains. The stratigraphic, geomorphic, and paleoenvironmental records preserved in lunettes complement those available from valleys, playas, and dune fields (Gustavson *et al.*, 1995; Holliday, 1995a,b; Holliday *et al.*, 1996; Johnson, 1986; Johnson and Holliday, 1995; Reeves, 1990, 1991; Wendorf, 1961; Wendorf and Hester, 1975) thereby providing a broader view of the late Quaternary history of a substantial portion of interior North America. The genetic relation of lunettes and playas indicates that an understanding of the age and evolution of the dunes should provide clues to the origin and evolution of the ubiquitous basins which have been debated for over a century. Understanding playa genesis and development is significant because these basins contain late Quaternary stratigraphic records and because playas are important sources of recharge to the rapidly declining Ogallala aquifer (Nativ, 1988; Stone, 1990).

SETTING

The Southern High Plains or Llano Estacado (stockaded plains) of northwestern Texas and eastern New Mexico is a vast (130,000 km^2), level plateau (Fig. 1). The main Cenozoic deposits are the Ogallala Formation (Miocene–Pliocene); the overlying Blackwater Draw Formation (Pleistocene), which forms most of the High Plains surface (Reeves, 1976; Holliday, 1989, 1990); and more localized upper Cenozoic lacustrine sediments found below or intercalated with the Blackwater Draw Formation. The playa basins are inset into the Blackwater Draw Formation, older lake sediments, or the Ogallala ''Caprock,'' a thick pedogenic calcrete in the upper part of the Ogallala Formation. The lunettes rest on the Blackwater Draw Formation or on the lacustrine de-

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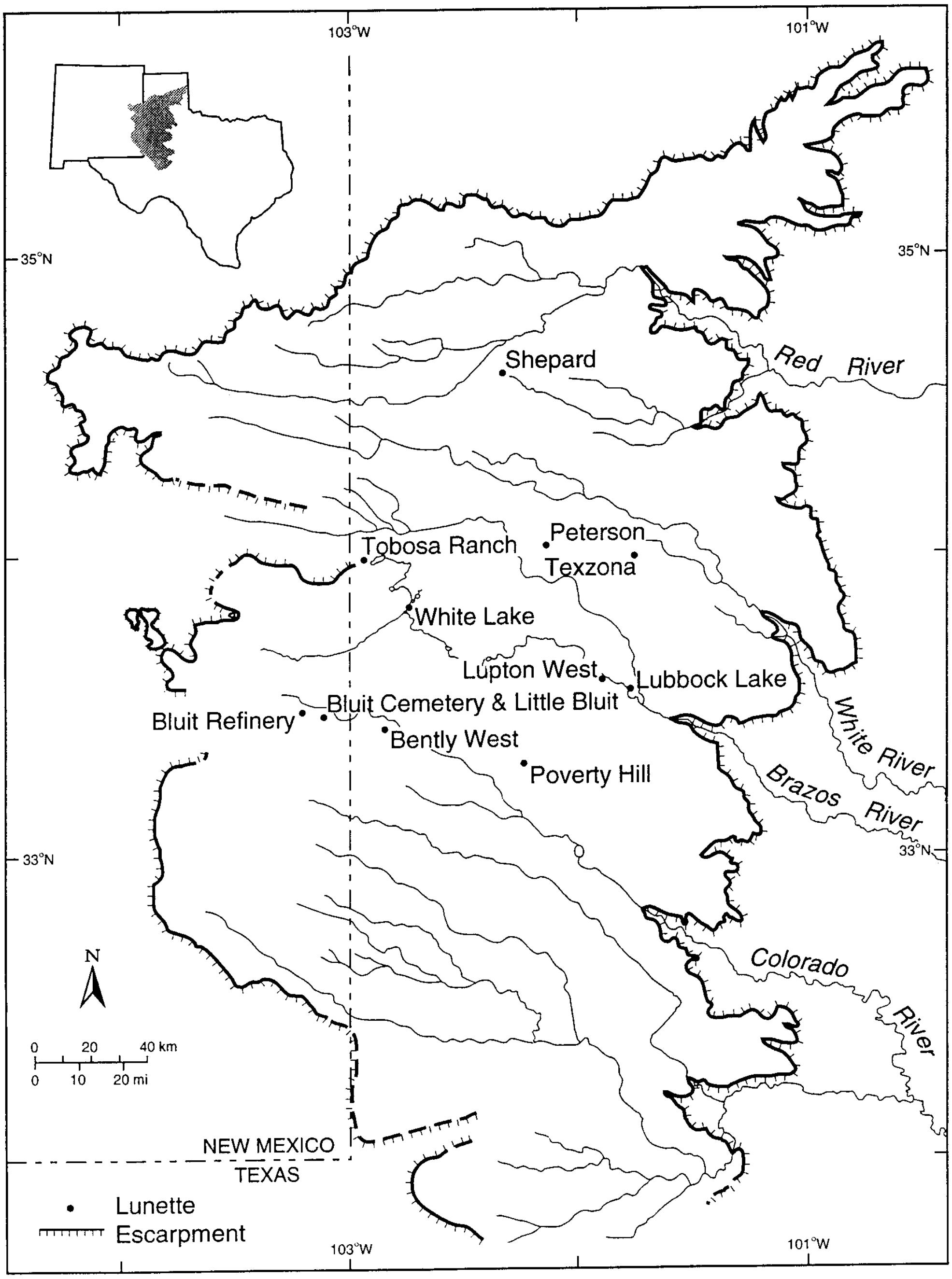

FIG. 1. The Southern High Plains, showing the locations of lunettes mentioned in the text and tables, major drainages, and White Lake. Inset shows location of Southern High Plains in Texas and New Mexico. Lubbock Lake is Cone playa in Holliday *et al.* (1996).

posits. Lunettes are associated with both large saline lake basins ($N \approx 40$, tens of km^2) and smaller playa-lake basins ($N \approx 25{,}000$, <5 km^2). Most lunette studies, including previous work on the Southern High Plains, focused on large dunes associated with large (usually $\geqslant 5$ km^2), often saline lake basins (e.g., Reeves, 1965; Goudie and Wells, 1995, p. 52, 53, 55). This paper, however, focuses exclusively on the lunettes associated with small playa basins.

The lunettes are relatively low, transverse dune ridges on the eastern to southeastern sides of playas (Fig. 2). They conform to descriptions of lunettes from other semiarid regions: typically crescentic with the horns pointing upwind, and asymmetric in cross section with the steepest face on the windward side (Hills, 1940; Bowler, 1973, 1983). Approximately 1100 playa basins have lunettes, mostly in the central one-third of the Llano Estacado (Sabin and Holliday, 1995). Most densities of lunettes are between 0 and 5 per 100 km^2; few regions have more than 10 per 100 km^2. Lu-

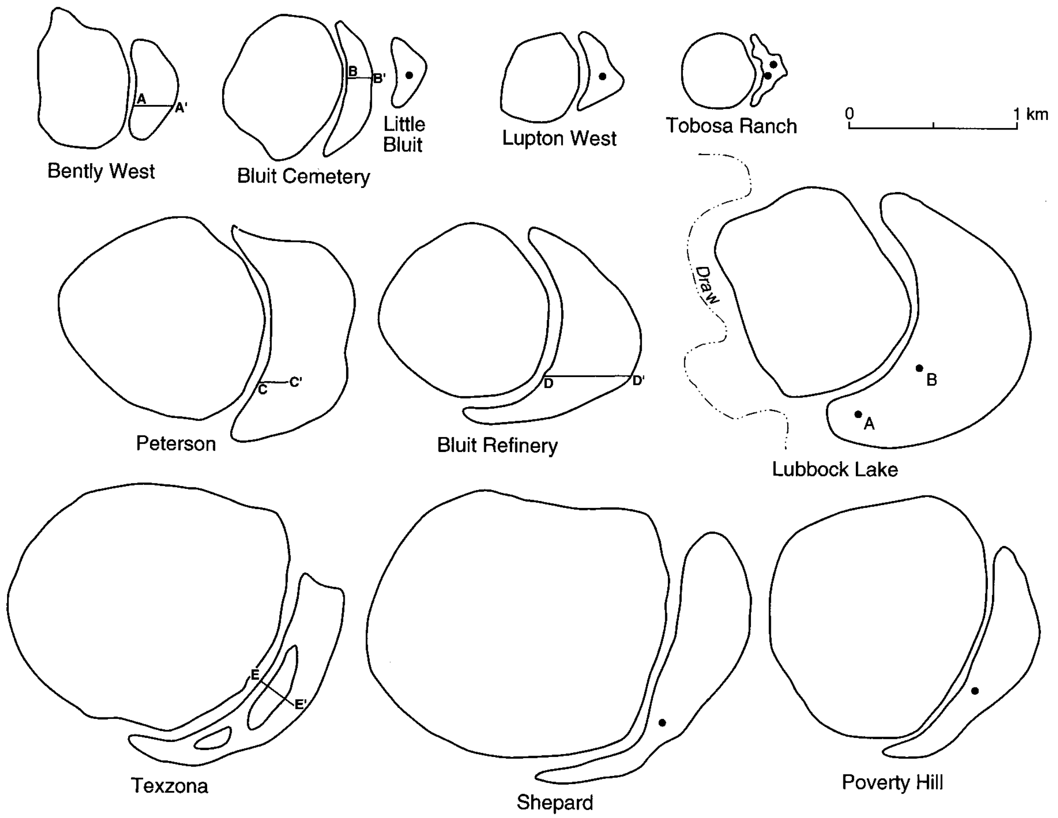

FIG. 2. Outlines of lunettes and adjacent playas, based on U.S. Geological Survey 7.5-min topographic maps. Locations of cross sections are shown for Fig. 3. Dots on lunettes are sections or cores shown in Fig. 4. The size and shape of the Tobosa Ranch playa is only an estimate because it is too shallow to appear on the 7.5′ maps. The Lubbock Lake playa is adjacent to Yellowhouse Draw. Texzona lunette has two crests, as shown.

nettes are associated almost exclusively with larger and deeper playas (Sabin and Holliday, 1995). Most playas are <1.5 km^2 and over half of them are ⩽0.1 km^2, but most lunettes are associated with playas that have an area of 0.3–0.8 km^2. Not all large or deep playas have lunettes, but few small playas do. Lunettes vary in size (Table 1), depending in part on the size of the adjacent playa. The large lunettes extend one-fourth to one-half the circumference of the associated playa and can be >10 m high (Table 1; Fig. 2), which are by far the highest natural landmarks in the region. Most lunettes have a single crest, but a few (<10%), mainly longer ones, have two (Fig. 2).

TABLE 1
Descriptive Statistics for Lunettes

Parameter (meters)	Minimum	Maximum	Mean	Standard deviation
Length[a]	168	2040	822	345
Width[a]	72	720	243	124
Height[a]	1.5	10.7	4.4	2.4
Height[b]	1.5	6.1	3.6	—

[a] $N = 129$.
[b] Height of second crest if present; $N = 9$.

METHODS

Field work focused on eleven lunettes (Figs. 1, 2). All exposures were measured, described (Table 2), and sampled. Samples were collected for sedimentologic and pedologic characterization (Table 3), radiocarbon dating (Table 4), and determination of stable-carbon isotope composition of buried A-horizons.

Most radiocarbon ages were determined on samples collected from the upper 5 cm of buried A-horizons. Studies in the region and elsewhere on the Great Plains show that soils can yield reliable results and that samples collected from the top of a buried A-horizon provide a maximum age for overlying sediments (Holliday *et al.,* 1983, 1985; Haas *et al.,* 1986; Holliday, 1995b; Martin and Johnson, 1995). Radiocarbon ages on A-horizons from weakly developed soils (A-C profiles) also provide a minimum age for their parent materials. For (1) samples or horizons with several radiocarbon ages, (2) situations where ages appear reversed, or (3) where two ages are available from a single sample

TABLE 2
Description of Soil Stratigraphy in the Texzona Lunette[a]

Depth (cm)	Facies[b]	Soil-stratigraphic description[c]
		Profile 1
0–120	LCS	A horizon, 0–30cm; S; gray (10YR 5/1 3/2m); wk sbk; gr bndy; Bw horizon, 30–87cm; LS; light brownish gray (10YR 6/2 5/1m); mod sbk; gr bndy; ABwb1, 87–120cm; LS; gray (10YR 6/1 5/1m); mod sbk/wk pr; cs bndy; LCS welded to underlying CSL by soil cumulization;
120–153	CSL	2Akb1, 120–140cm; SL; light brownish gray (10YR 6/2 5/1m); mod sbk/mod gr; v common carb thr & films; gr bndy (^{14}C); 2Bkb1, 140–153cm; SL; light gray (10YR 7/1 5/1m); mod sbk; few carb thr, films & concr; cs bndy.
153–200	CSL	2Akb2, 153–167cm; SL; light gray (10YR 7/2 5/2m); mod sbk; few carb thr, films & concr; cs bndy; 2Bkb2, 167–200cm; SL; white (10YR 8/1 7/2m); wk pr mod sbk; common carb thr & films; ab bndy.
		Profile 2
90–145	CSL	2Akb2, 90–105cm; SL: gray (10YR 5/1 4/1m); mod sbk; few carb thr, films & concr; cs bndy (^{14}C). 2Bkb2, 105–145cm; SL; white (10YR 8/1 7/2m); wk pr/mod sbk; common carb thr & films; ab bndy.
145–225	CSL	3Bkb3, 145–180cm; SiL; light gray (10YR 7/1 7/2m); mod pr/mod sbk; few carb thr & films; cs bndy; 3Btkb3, 180–225cm; SL; white (10 YR 8/1 7/1m); str pr/str sbk; common carb thr & films; ab bndy.
225–250	CSL	3Ab4, 225–235cm; SL; light gray (10YR 7/2 5Y6/2m); mod pr/mod sbk; cs bndy; 3Cb4, 235–250cm; SL; white (10YR 8/1 7/2m); wk sbk; cs bndy.
250–290	CSL	3Ab5, 250–260cm; SL; white (5Y 8/1 7/2m); mod pr/mod sbk; cs bndy; 3Cb5, 260–290cm; SL; light gray (10YR 7/2 6/2m); wk sbk; cs bndy.
290–408	CSL	3ABwb6, 290–360cm; SL; white (10YR 8/1 5YR 6/2m); str pr/str sbk; cs bndy. 3Bwb6, 360–408cm; SL; white (10YR 8/2 7/2m); v str pr/str sbk; cs bndy;
		Profile 4
250–365	LCS	4Ab7, 250–295cm; S; light gray (10YR 7/2 6/4m); w sbk; cs bndy; 4Cb7, 295–265cm; S; light gray (10YR 7/2 7/4m); v wk sbk; ab bndy.
365–435	LCS	4Btb8, 365–410cm; S; very pale brown (10YR 7/3 5/4m); mod sbk; cs bndy 4Bwb8, 410–435cm; S; pale brown (10YR 6/3 5/4m); mod sbk; cs bndy.
435–530	LCS	4Bt1b9, 435–500cm; LS; pale brown (10YR 6/3 4/3m); mod pr/mod sbk; cs bndy; 4Bt2b9, 500–530cm; LS; pale brown (10YR 6/3 4/4m); mod pr/mod sbk; cs bndy.
530–555	LCS	4ABtb10, 530–555cm; LS; light yellowish brown (10YR 6/4 4/4m); str sbk/gr; cs bndy; LCS welded to underlying CSL by soil cumulization;
555–565	CSL	5ABtkb10, 555–565cm; SL; pale brown (10YR 6/3 5/3m); str sbk; common carb films & thr.

[a] See Fig. 3 for stratigraphy and locations of the profiles.
[b] Facies: CSL = Calcareous sandy loam; LCS = Low-carbonate sand.
[c] Abbreviations: Texture, S, sand; LS, loamy sand; SL, sandy loam; SiL, silty loam: Color (Munsell), m, moist: Structure, v, very; wk, weak; mod, moderate; str, strong; gr, granular; sbk, subangular blocky; pr, prismatic: Carbonates (carb), thr, threads; concr, concretions: boundary (bndy), gr, gradual; cs, clear smooth; ab, abrupt.

(both residue and humate fractions), the oldest age is considered the closest approximation of the true age because younger contaminants are more commonly and more easily introduced into buried soils (Matthews, 1980; Head *et al.*, 1989; Hammond *et al.*, 1991). Contamination with dead carbon from groundwater, precipitated in calcium carbonate, is the only known, common means of yielding falsely old ages in the region. Calcium carbonate is removed during processing of samples, however. One radiocarbon age was determined on bone collagen using AMS following procedures described by Stafford *et al.* (1991).

The $\delta^{13}C$ (PDB) composition of soil organic matter was determined so inferences could be made regarding past vegetation and therefore the environment. The C_3 plants include cool season grasses, most aquatic plants, and all trees and are linked to cooler, more temperate settings. The C_4 plants are mainly warm-season grasses indicative of warm, semiarid environments and show more favorable physiological performance under warm and dry conditions than do C_3 plants (Kelly *et al.*, 1993; Nordt *et al.*, 1994). The samples were taken from those used to determine radiocarbon ages following removal of carbonates.

STRATIGRAPHY

Lithostratigraphy

The lunettes are composed mostly of eolian sediments, but some slopewash is locally apparent at or near the base

TABLE 3
Laboratory Data for the Texzona Lunette[a]

Horizon	Depth, cm	% of < 2 mm fraction[b] VCOS	COS	MS	FS	VFS	Sand	Silt	Clay	% $CaCO_3$	% Organic carbon
Profile 1											
A1	0–15	0	0	7	59	21	87	12	1	2	0.2
A2	15–30	0	0	7	58	21	86	13	1	5	0.3
Bw	30–87	0	0	7	51	26	84	15	1	0	0.2
ABwb1	87–120	1	1	4	43	29	78	20	1	10	0.2
2Akb1	120–140	0	0	2	21	31	54	43	3	20	0.4
2Bkb1	140–153	0	0	3	22	31	56	40	4	25	0.4
2Akb2	153–167	0	1	4	20	31	56	41	3	25	0.5
2Bkb2	167–200	2	5	8	21	23	59	34	7	38	0.2
Profile 2											
3Bkb3	145–180	0	4	3	15	25	46	50	3	33	0.1
3Btkb3	180–225	0	1	5	20	32	58	36	6	33	0.0
3Ab4	225–235	0	0	3	27	37	66	31	3	24	0.4
3Cb4	235–250	0	0	3	31	27	61	37	2	23	0.5
3Ab5	250–260	0	0	4	36	26	65	32	3	24	0.4
3Cb5	260–290	0	0	4	35	27	66	32	2	15	0.6
3ABwb6	290–360	0	0	3	24	29	57	42	2	21	0.6
3Bwb6	360–408	0	0	3	35	31	70	27	3	21	0.5
Profile 4											
4Ab7	250–295	0	0	11	67	15	93	6	1	6	0.3
4Cb7	295–365	0	0	8	67	19	94	6	0	2	0.4
4Btb8	365–410	0	0	8	59	24	91	8	1	0	0.4
4Bwb8	410–435	1	2	4	60	19	86	12	2	5	0.5
4Bt1b9	435–500	0	1	8	46	27	82	15	2	1	0.7
4Bt2b9	500–530	0	2	7	43	26	78	18	4	6	0.8
4ABtb10	530–555	0	4	9	41	26	80	16	4	7	1.1
5ABtkb10	555–565	0	4	14	35	22	75	18	7	16	0.3

[a] Methods follow Singer and Janitzky (1986).
[b] Abbreviations: VCOS, very coarse sand; COS, coarse sand; MS, medium sand; FS, fine sand; VFS, very fine sand.

of steeper slopes (Fig. 3). The dunes rest unconformably on the Blackwater Draw Formation, but the nature of the unconformity varies. Under small lunettes and beneath the leeward (eastern) edge of larger lunettes, the contact is disconformable, with little evidence for significant erosion prior to dune formation. Under the windward (western) edge of the larger lunettes, however, the contact is an erosional unconformity marking the edge of the adjacent lake basin.

The stratigraphy preserved in lunettes varies from simple in small dunes to very complex in larger ones (Figs. 3, 4). The smallest lunettes are composed of horizontal layers of eolian sediment (Fig. 4). The slightly larger lunettes contain horizontal to gently east-dipping (1°–2°) beds (Bluit Cemetery and Bently West) (Fig. 3). The oldest beds are horizontal, but the upper boundaries of successively younger layers have progressively increasing dips (3°–5°) to the east. The west (upwind) end of the dipping beds is truncated. The largest dunes have more complex stratigraphy, with cores of older, horizontally bedded deposits and overlying sets of both east-dipping and west-dipping strata (Bluit Refinery, Texzona, and Peterson) (Fig. 3). Bluit Refinery has no ''core'' of horizontal beds, but unconformities in the exposure and the irregular surface topography suggest that the south end of this lunette underwent repeated erosion that may have removed much of the stratigraphic record. The apparent stratigraphic simplicity in the large Shepard and Lubbock Lake lunettes (Fig. 4) is probably a function of relatively small exposures at the far south end of the dunes. These two lunettes, though not providing good cross sections, show that the limbs of some dunes have simple horizontal bedding.

Bedding is locally preserved in some lunettes, but most of the dune strata underwent pedogenic modification that destroyed sedimentary structures. The bedding typically is fine planar, usually in the older ''core'' deposits or in sediments deposited along the present basin-margin and inset against the older dune core (the western end of the Bluit Refinery, Bluit Cemetery, Peterson, and Texzona exposures) (Fig. 3). Slopewash with

TABLE 4
Radiocarbon Ages and Stable-C Isotopes from Buried Soils in Lunettes

Lunette	Age in ^{14}C yrs B.P.[a]	Lab No.	δ^{13}C (‰)	Material dated[b]
Bently West	7965 ± 170	A-7868	−21.1	Residue
	7250 ± 50	A-7868.1		AMS (CAMS-18062); humate fraction of A-7868
	19,340 + 825/−745	A-7867	−16.9	Residue
Bluit Cemetery	7880 + 185/−180	A-6904	−17.9	Residue
	21,865 ± 305	A-6903	−12.3	Residue
Bluit Refinery	13,730 ± 130	A-6454	−8.4	Residue
	14,740 ± 120	A-6453	−7.3	Residue
	15,150 ± 150	A-6455	−16.6	Residue
	16,210 ± 510/−480	A-6910	−18.0	Residue
	21,540 ± 220	A-6456	−16.2	Residue
Little Bluit	10,660 + 245/−235	A-6916	−10.5	Residue
Lubbock Lake	1335 ± 75	SI-4939	—	Residue
	6115 ± 190	SI-4169	—	Residue
	6980 ± 215	SI-5168	—	Residue
	8855 ± 100[c]	SI-4977	—	Residue; unreliable
	12,080 ± 200	SI-4941	—	Residue
	29,080 ± 1030	SI-4978	—	Residue
	33,750 ± 3600	SI-4979	—	Residue
	6695 ± 80	SI-4586	—	Residue
	8320 ± 90	SI-4587	—	Residue
Lupton West	24,410 + 1280/−1100	A-6911	−9.5	Residue
Peterson	1000 ± 85	A-6908	−14.1	Residue
	19,320 + 750/−690	A-6909	−15.7	Residue
Poverty Hill	13,800 ± 90	A-6457	−19.7	Residue, AMS (AA-9015)
Shepard	3110 ± 45	A-6445	−14.4	Residue
	5500 ± 65	A-6446	−16.1	Residue
	15,040 ± 200	A-6447	−22.2	Residue
Texzona	2500 ± 35[c]	A-6450	−17.8	Residue; unreliable
	3580 + 120/−115[c]	A-6902	−16.8	Residue; unreliable
	8030 ± 65	A-6448	−16.3	Residue
	8565 ± 80[c]	A-6451	−22.2	Residue; unreliable
	9470 ± 70	A-6452	−20.6	Residue
	11,670 ± 80	A-6449	−14.2	Residue
Tobosa Ranch	450 ± 30	A-6913	−17.0	Residue
	755 ± 35	A-6912	−17.8	Residue
	1000 ± 60	CAMS-16031	—	Bone, AMS
	14,940 ± 240	A-6914	−13.0	Residue

[a] Based on a radiocarbon half-life of 5568 yr; corrected for δ^{13}C fractionation, but not tree-ring calibrated.
[b] Residue is the NaOH-insoluble fraction; humate is the NaOH-soluble fraction.
[c] Age considered unreliable because sample is from or below a zone that yielded an older radiocarbon age.

laminated beds also is apparent in some exposures near the base of the windward side of the dune.

The dune sediments grade between two lithologies. The most common sediments are calcareous (15–40% $CaCO_3$) sandy loams and loamy sands. An unusual characteristic of these deposits is the presence of sepiolite, a clay mineral sometimes found in calcareous lacustrine sediments in semiarid regions, including small playas on the Southern High Plains (Parry and Reeves, 1968; Bigham *et al.*, 1980; Singer, 1989; Holliday *et al.*, 1996). The other common dune deposit is very low in carbonate (0–15% $CaCO_3$) and usually is a sand or loamy sand.

Soil Stratigraphy

Soils are the most obvious stratigraphic markers in the lunettes (Fig. 5). Four soil morphologies are typical. A-Bk profiles are characteristic of soils formed in the calcareous sandy loam deposits (Fig. 5B). The calcic horizons consist of nodules of carbonate set in a massive, finely divided carbonate matrix. Some of the finely divided carbonate in the calcic horizons probably is illuvial, as judged from the higher carbonate content of these horizons compared to the C horizons below. The buried A-Bk soils typically are the most prominent because the calcic horizons have coarse pris-

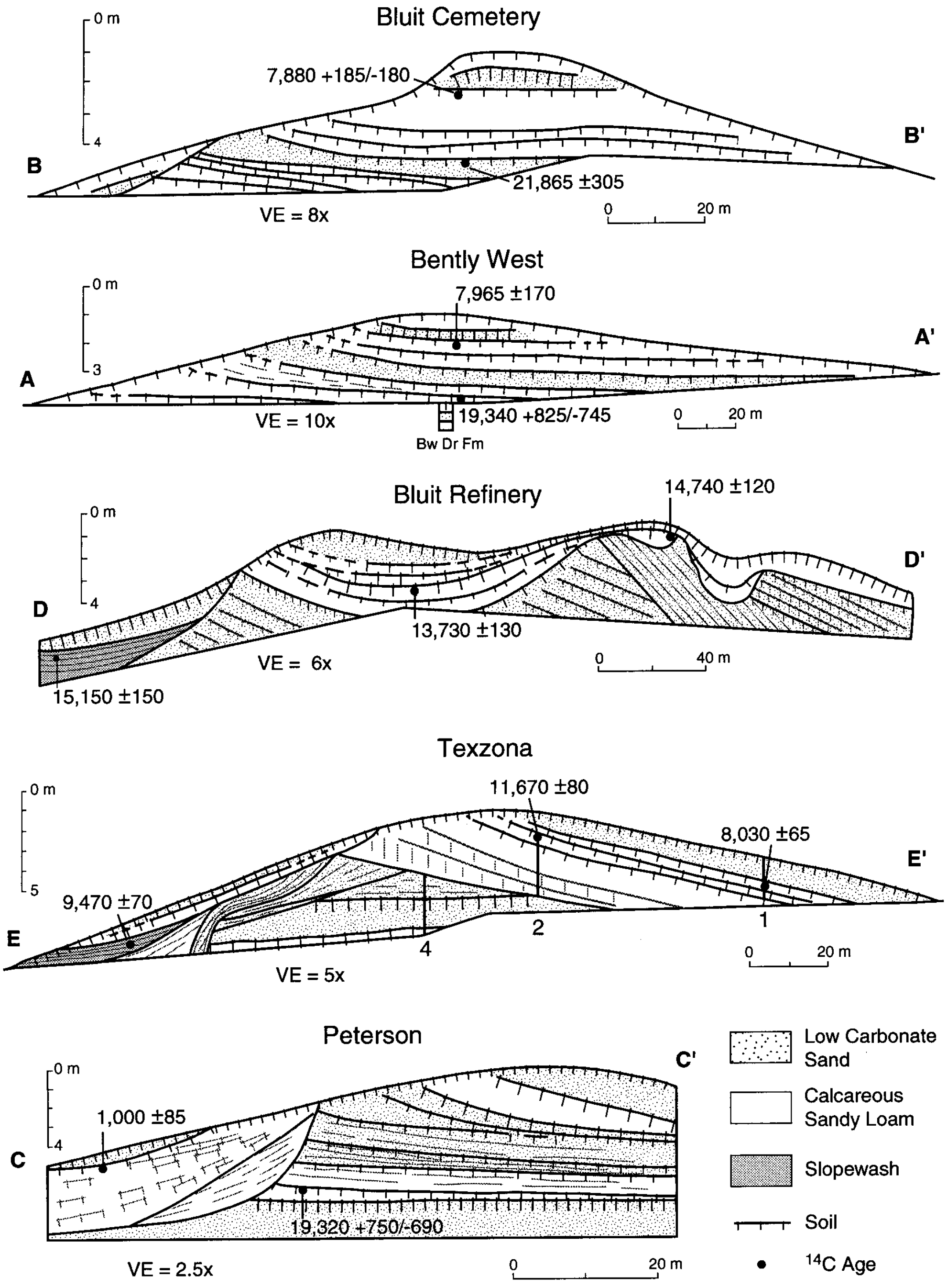

FIG. 3. Lunette stratigraphy and radiocarbon ages in the exposures at Bently West, Bluit Cemetery, Bluit Refinery, Texzona, and Peterson. For soils, more closely spaced lines represent stronger development. Texzona section shows location of profiles 1, 2, and 4 (Tables 2 and 3, Fig. 5B).

matic structure and are ledge-formers and because the dark A-horizons contrast with the light gray or white carbonate-rich zones (Fig. 5). In the sandy low-carbonate sediments three soil morphologies are apparent. The older sands at the core of some lunettes (Bluit Refinery, Peterson, Texzona) (Fig. 3) exhibit soils with multiple A-C horizon sequences similar to those of Fluvents on floodplains. Below these A-C sequences in the core of the Texzona and Peterson lunettes and in the low-carbonate sands at or near the top of most exposures are soils with A-Bw or weakly expressed A-Bt profiles, characterized by slightly stronger values and brighter chromas (6/3, compared to 7/2 in the unweathered sands), moderate subangular-blocky and prismatic structure, and thin, patchy clay films on ped faces and sand grains. Btk horizons with small carbonate nodules and films and threads of carbonate on ped faces are locally common.

Buried A horizons are well preserved and few of the buried soils exhibit evidence for erosion prior to burial. Older

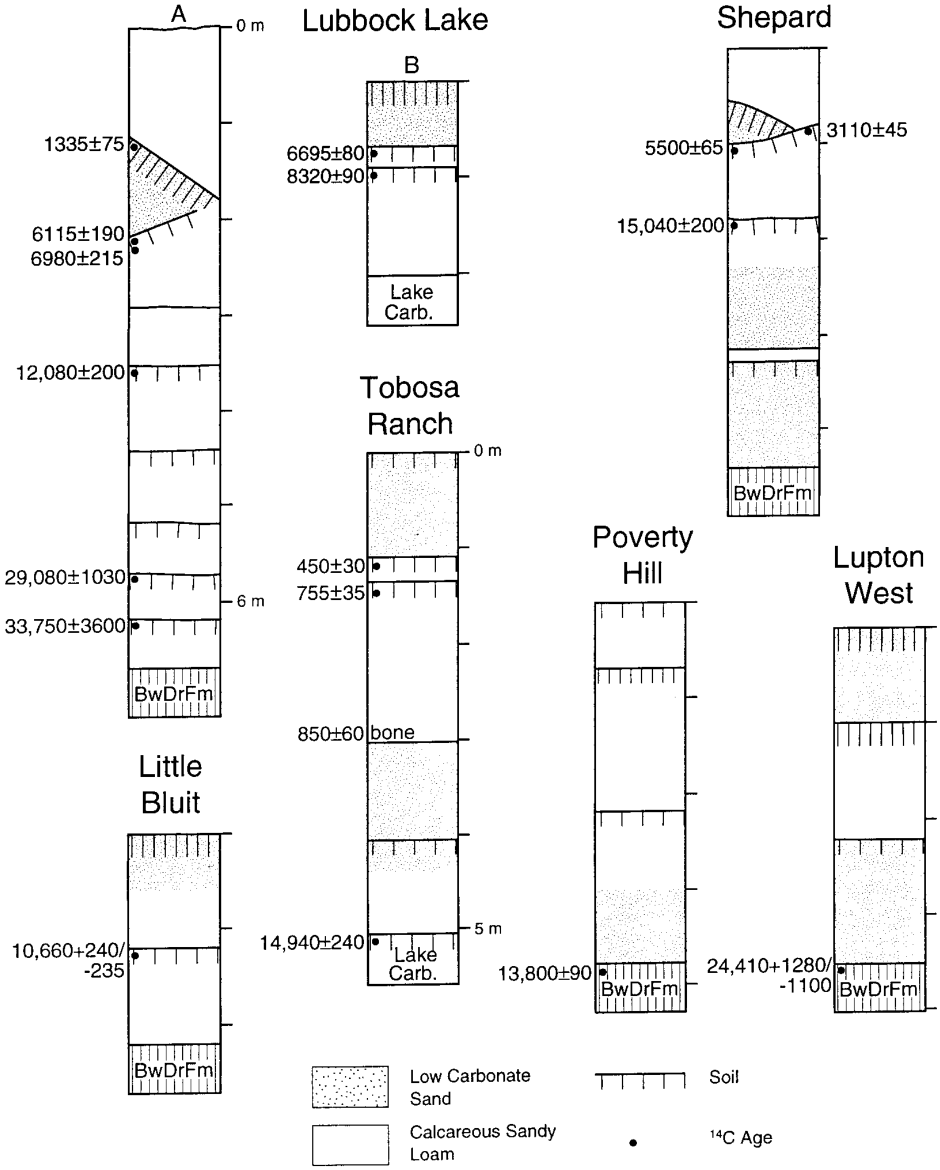

FIG. 4. Lunette stratigraphy and radiocarbon ages from cores or small sections. For soils, more closely spaced lines represent stronger development.

buried A horizons are rarely as prominent as younger ones, but this may be due to more subdued values and chromas (probably from post-burial alteration) rather than truncation. The buried soils commonly are welded together by translocated carbonate. The welding is particularly common among soils developed in the calcareous parent material. Nodules, films, and threads of $CaCO_3$ from overlying calcareous soils form in the underlying Ab horizons.

Chronostratigraphy

Thirty-two radiocarbon ages from 11 lunettes provide a chronology of eolian deposition and dune construction (Table 4). Four other ages were rejected as unreliable because they are much younger than stratigraphically higher samples (Table 4). All but one of the 32 assays were determined on organic carbon from the upper 5 cm of buried A horizons, thereby providing a maximum estimate of the age of burial of the soil and the beginning of a successive phase of eolian deposition and a minimum estimate for the age of the parent material.

Dating also was facilitated by soil correlation. The strong similarities in both soil stratigraphy and lithostratigraphy suggest that the older sands at Texzona and Peterson (Fig. 3) are correlative and, therefore, that they both date to ca. 19,000 yr B.P. The low-carbonate sands at or near the top of many lunette sections have very similar soil morphologies (A-Bw or weak A-Bt horizonation) which, combined with a few radiocarbon ages, indicate that these sands are early

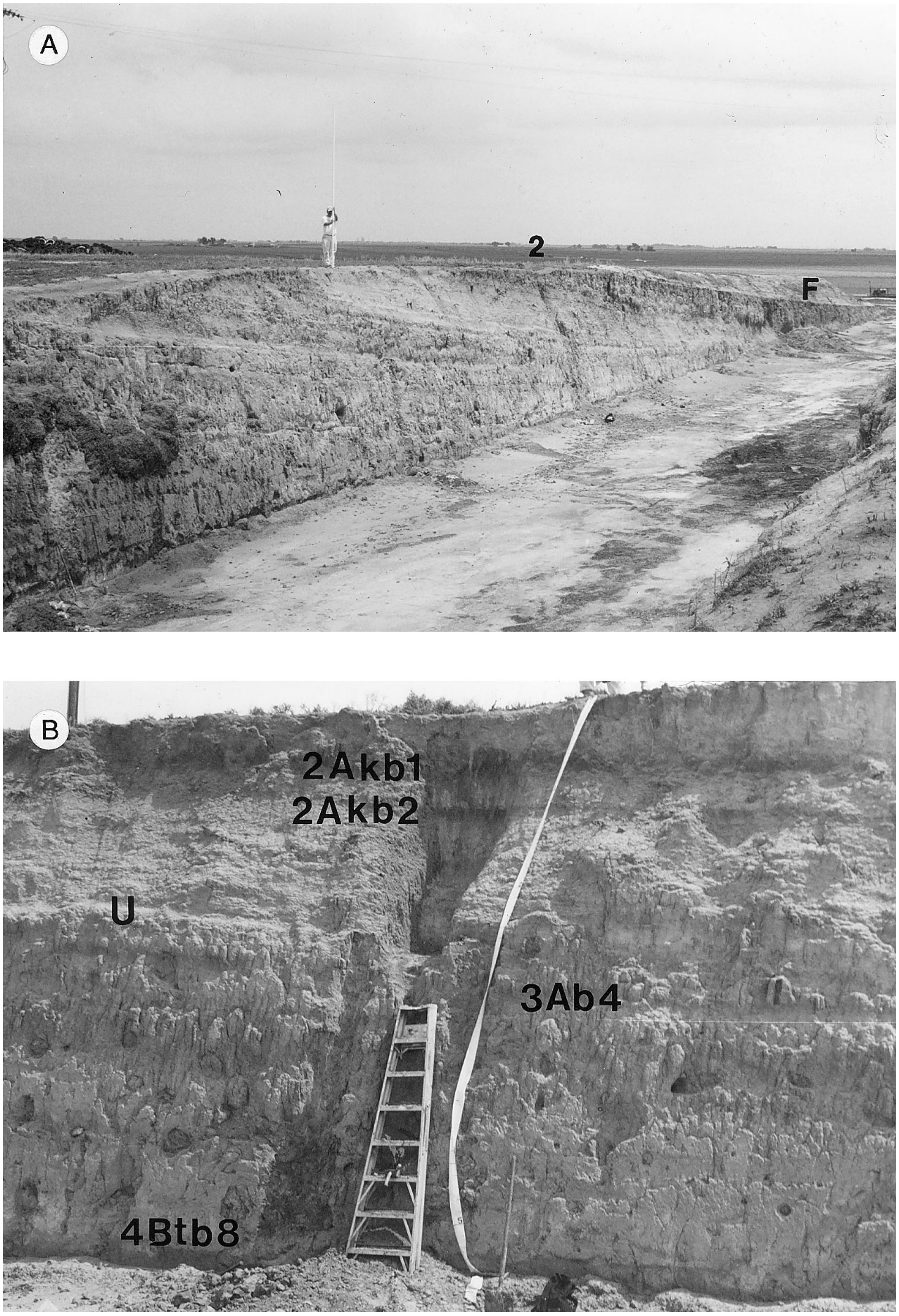

FIG. 5. The exposure in the Texzona lunette. (A) View east across east end of the cut showing the prominent east-dipping beds (2, location of Profile 2, Fig. 3; F, fill from excavation of the cut) and, at lower left, the more weathered (and resistant) horizontal beds of the old ''core'' sediments of the lunette. (B) Profile 2, located on the photo in (A), showing the prominent buried A horizons in the upper section (soils b1 and b2; the 2Akb2 horizon in this section is dated to 11,670 $\pm$ 80 yrs B.P.), and the unconformity between the younger, less weathered east dipping beds and the older, more weathered horizontal beds at the core of the lunette (e.g., 3Ab4 and 4Btb8 horizons). The coarse prismatic structure of the soils in the older beds, such as b4, is well expressed.

to middle Holocene (8000–5000 yr B.P.). At the top of some lunette sections is a layer of the calcareous sandy loam with an A-C profile. The soil morphology, stratigraphic position above the moderately developed soil in the early–middle Holocene sands, and two radiocarbon ages show that this deposit is late Holocene ($<$3000 yr B.P.).

Correlation among the lunettes (Fig. 6) suggests broad trends in the timing of deposition of the two different litholo-

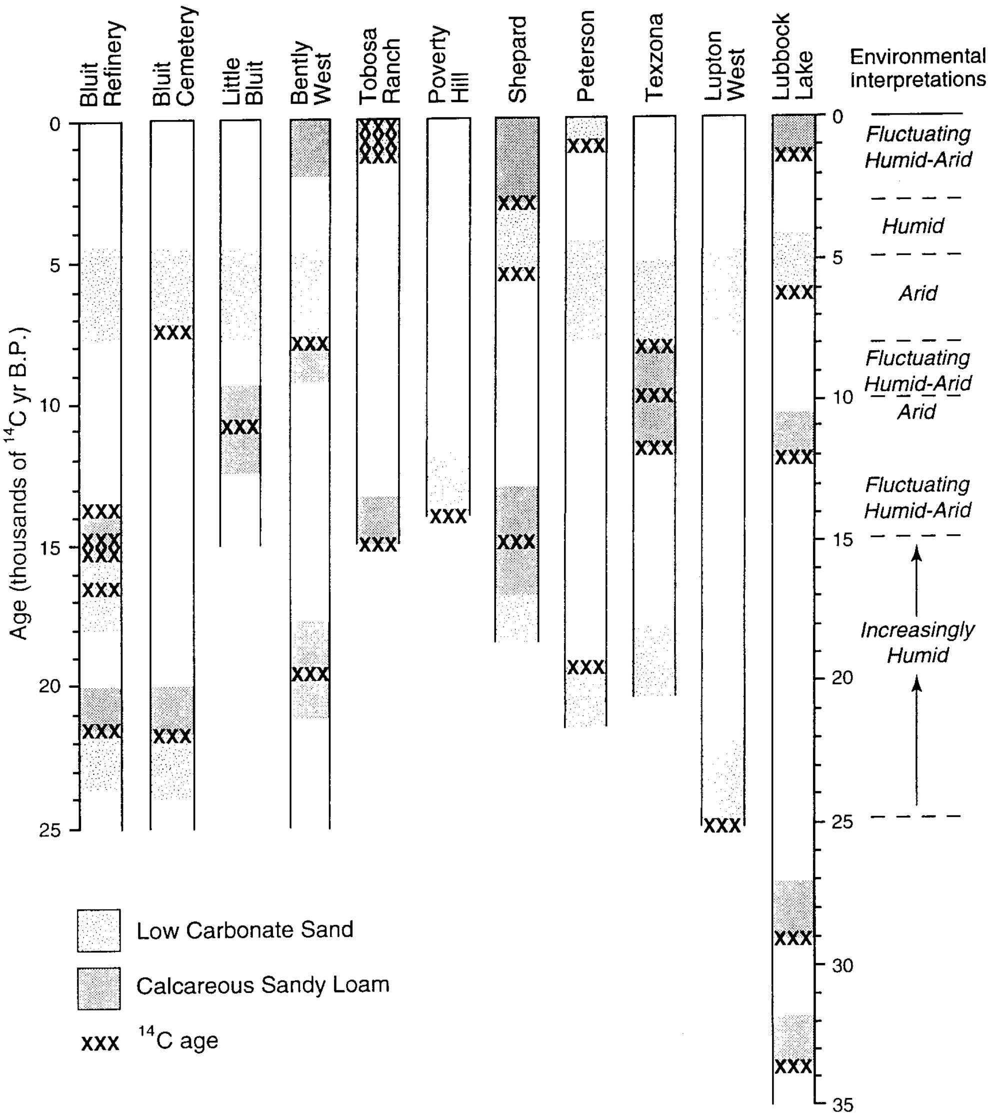

FIG. 6. Summary chronostratigraphy and lithostratigraphy of the lunettes. Only deposits with some age control (based on radiocarbon dating or soil-stratigraphic correlation) are illustrated. Blank areas in the columns are undated sections. The ''Environmental Interpretations'' are relative to modern conditions.

gies. Most of the low-carbonate sands at the cores of the lunettes date to between 25,000 and 15,000 yr B.P. Some calcareous sandy loam also accumulated during this time. Between 15,000 and 8,000 yr B.P., however, virtually all deposition in the lunettes was from accumulation of calcareous sandy loam. In contrast, low carbonate sand prevailed thereafter, into the middle Holocene. The degree of soil development in the middle Holocene sands suggests that many lunettes were stabilized by about 5000 yr B.P. and subjected to pedogenesis through most of the rest of the Holocene. Subsequent sedimentation was relatively localized, occurred in the past 3000 years, and included deposition of both lithologies. The late Holocene, noncalcareous sands at Tobosa Ranch probably were derived from the adjacent, largely carbonate-free dunes of the Muleshoe Sand Hills.

STABLE ISOTOPES

Only broad trends are apparent in the C-isotope data from the lunettes (Fig. 7). There is a gradual shift toward lighter isotope values from 25,000 to 15,000 yr B.P., indicative of an increase in plants favoring cooler, temperate environments. Isotope values for the period 15,000–8000 yr B.P., however, are highly variable, including both heavier and lighter values 15,000–13,000 yr B.P., a shift to heavier values 13,000–10,000 yr B.P. (based on just a few data points), and a shift

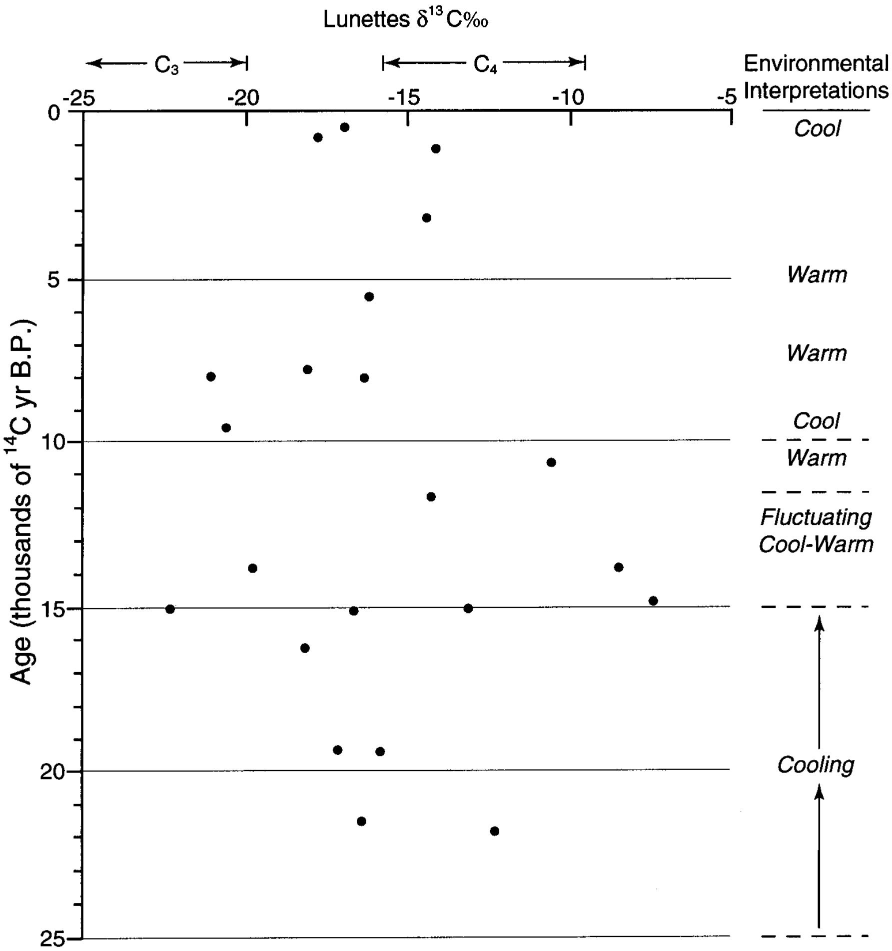

FIG. 7. Stable-carbon isotope trends for buried A horizons in lunettes. Range in $\delta^{13}C$ (PDB) composition for C_3 and C_4 plants is also indicated. ''Environmental Interpretations'' are relative to modern conditions.

back to lighter values 10,000–8000 yr B.P. (also based on a few data points). At ca. 8000 yr B.P. there is another shift to relatively heavier values until within the last millennia of the Holocene. Whether these apparent abrupt shifts reflect changes in vegetation composition on a regional scale will require additional data.

DISCUSSION

The data presented above provide a basis for reconstructing the processes and chronology of lunette formation, and to a certain extent playa evolution, and allow for some observations to be drawn regarding regional landscape evolution and paleoenvironments. The lunettes appear to evolve through several stages, regardless of their age or the lithology of the individual layers (Fig. 8). The lunettes start as low relief dunes with horizontal or low-angle (downwind or east-dipping) layering. As the playa basin enlarges the windward side of the dune is eroded. As the lunette builds up and is subjected to windward erosion, the crest and/or lee-side continue to accumulate sediment. The eroded windward side can also accumulate sediment later from both eolian and slopewash deposition.

Variation over time in the lithology of sediments accumulating on the lunettes is indicative of the processes of basin formation and deflation (Fig. 9). There probably were three sources for the sediment in the dunes. The low-carbonate sand was likely derived from the Blackwater Draw Formation because no other source of sand is available in the area of the study sites. The sand was eroded (1) directly from the Blackwater Draw Formation during deflation of the playa basin (Fig. 9A) or (2) deflated from sandy sediment derived from erosion of the Blackwater Draw Formation along the basin margins and commonly found in playa basins (Fig. 9B) (Gustavson *et al.*, 1995; Holliday *et al.*, 1996). The low-carbonate sands in the lunettes are lower in clay and silt content than the Blackwater Draw Formation in the same region. However, wind erosion of the Blackwater Draw For-

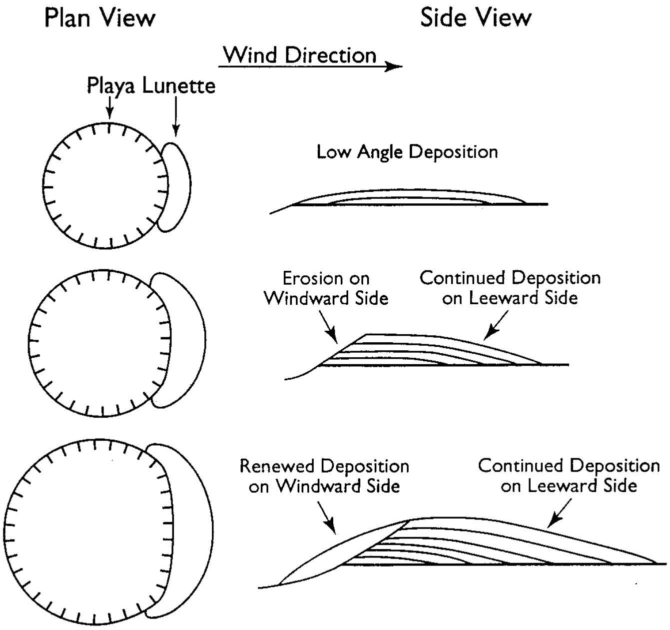

FIG. 8. Schematic diagram illustrating the proposed evolutionary relationship of playas and lunettes. The sequence begins (top) with a small dune with relatively simple stratigraphy adjacent to an intermediate size playa, and culminates (bottom) in a large lunette with complex stratigraphy next to a large playa.

mation quickly sorts the saltating sand grains from silt and clay by carrying off the fines as dust (Gillette and Walker, 1977). Low-carbonate sands are the oldest deposits at the core of over half of the study lunettes (Figs. 3, 4), suggesting that these sediments may represent the earliest sediment that was removed to form the adjacent playa basins, via deflation of the Blackwater Draw Formation.

The calcareous sandy loams were likely derived by deflation of the third source material for the dunes: marls from the playa basins adjacent to the lunettes. This conclusion is based on a comparison of the lithology and mineralogy of the lake sediment and lunette deposits. The carbonate probably precipitated by evaporation of water in the basins, but the clastic material (sand, silt, and clay) in the calcareous sandy loam likely was derived from the Blackwater Draw Formation by slopewash or wind deflation and mixed into the marl prior to deflation or it was mixed into the carbonate dust during deflation (Fig. 9C).

Deflation has been proposed as the principal mechanism for playa basin formation (e.g., Reeves, 1966; Gustavson *et al.*, 1995; Holliday *et al.*, 1996, Table 1), but this mechanism has been challenged in favor of a process of dissolution and subsidence (Osterkamp and Wood, 1987). The presence of old low-carbonate sands at the core of several lunettes provide the first direct evidence of eolian deposition due to wind erosion of the Blackwater Draw Formation during basin formation. However, if most or even some playas grow by means of eolian erosion, then why are lunettes so rare (<5% of small playa basin have lunettes)? One possibility is that the older low-carbonate sands were sealed in place only where there were calcareous sediments deflated from playa basins with lacustrine carbonates. When the calcareous sands are deflated from the basin and deposited next to it, they are easily stabilized by dissolution and reprecipitation of the carbonate, a process also noted for late Pleistocene lunettes in Australia (Bowler, 1973). Moreover, carbonates increase threshold shear velocity because they act as bonding agents and promote surface crusting (Gillette *et al.*, 1980, 1982; Nickling, 1984). Lacustrine carbonates are relatively rare playa-basin fills, however (Holliday *et al.*, 1996). Around most playas, sands deflated from the basins are never stabilized and are eventually transported far beyond the basin margins.

The presence of calcareous sands in a lunette demonstrates that the adjacent playa basin had formed and then accumulated lacustrine carbonate. Factors controlling the formation of the marls are not understood, but because lunettes are associated with deeper basins, marl formation may be related to groundwater phenomena (Sabin and Holliday, 1995; Holliday *et al.*, 1996). Fluctuations in the water table are linked to variations in effective precipitation; the groundwater rises quickly after times of higher precipitation (Cronin, 1964; Ashworth, 1991; Ashworth *et al.*, 1991). Marl formation, therefore, probably represents a rise in the water table to the

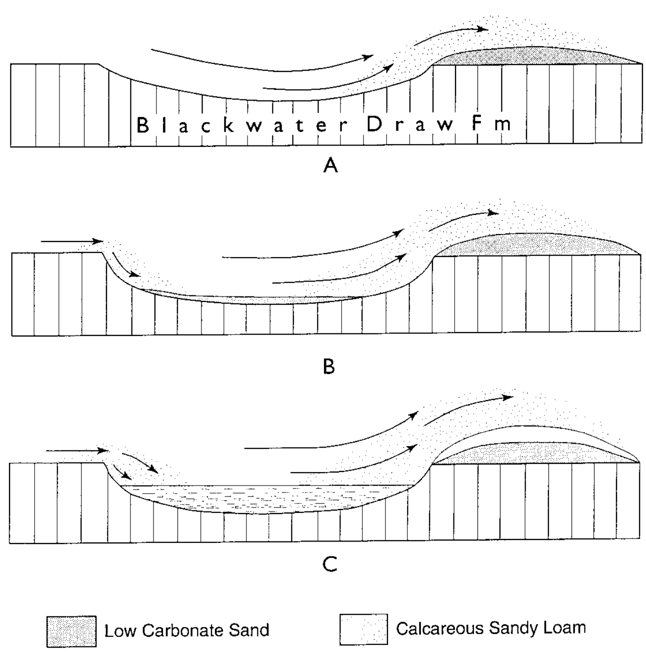

FIG. 9. Schematic view of three sources of sediment for construction of lunettes. Low-carbonate sand is derived from (A) direct deflation of the Blackwater Draw Formation or (B) from deflation of sand initially deposited in the playa basin by wind or slopewash erosion. (C) The calcareous sandy loam is derived by deflation of lacustrine carbonate (broken horizontal lines), which also contains clastic sediments eroded from the Blackwater Draw Formation.

basin floor. Deflation of the marls is indicative of a drop in the water table, probably linked to a drier climate, which exposes the carbonate to wind deflation.

The multiple A-C soil profiles within the older low-carbonate sands suggest that early dune formation consisted of relatively brief phases of basin deflation and sediment accumulation, and similarly brief phases of basin and dune stability with soil formation on the dune. Deflation of the High Plains surface occurs when relatively warm and dry climates reduce the vegetation cover and soil moisture (Holliday, 1987; Muhs and Holliday, 1995). Basin formation and basin enlargement, therefore, likely reflect relatively arid conditions.

The above model for the evolution of lunettes on the Southern High Plains is not directly comparable to other models. Most were developed for large basins that have or had relatively deep standing water, fluctuating lake levels, and evaporite deposits (e.g., Bowler, 1983; Goudie and Wells, 1995, p. 52, 53, 55). The mode of formation of lunettes on the Southern High Plains appears to contrast with the formation processes reported from other regions. Aridity and deflation of basin floors appears to be a necessary step in lunette genesis on the Southern High Plains, whereas standing or fluctuating water levels are important in other regions (Price, 1963; Bowler, 1973, 1983; Marker and Holmes, 1995).

All of the lunettes began forming in the late Pleistocene (oxygen isotope stage 2) and, therefore, all associated playas are at least as old. Radiocarbon dating of fills in 19 playas that lack lunettes shows the same trend (Holliday *et al.*, 1996). Low-carbonate sands are the oldest deposits in many lunettes, dating 25,000 to 15,000 yr B.P., but the calcareous sandy loam lithology is the oldest sediment found in any lunette (>30,000 yr B.P. in the Lubbock Lake lunette). Through the late Pleistocene the calcareous sediment became an increasingly common component of the lunettes and was the dominant lithology deposited from 15,000 to 8,000 yr B.P. Much of this Pleistocene history—erosion of the High Plains surface to form the playa basin, coincident deposition of low-carbonate sands as a lunette, and subsequent lacustrine sedimentation in the basin—suggests a dry climate 25,000–15,000 yr B.P. followed by a rise in the water table from increased effective precipitation.

The soil-stratigraphic record for the period 15,000–8000 yr B.P. appears to be one of episodic accumulation of sediment deflated from marl and briefer intervals of nondeposition and soil formation, suggestive of relatively rapid fluctuations between wetter and drier conditions in the playa basins. The chronostratigraphy of the lunettes, therefore, supports the argument that the period 15,000–8000 yr B.P. began with higher effective precipitation, relative to the preceding millennia, which raised groundwater levels and resulted in deposition of lacustrine carbonate in some deeper basins. Although the duration of this lacustrine phase is unknown, much of the time 15,000–8000 yr B.P. is marked by episodic deflation of the marl and deposition on the lunettes. The period probably witnessed high environmental variability, therefore, including episodic drying.

Most of the Holocene is represented in the lunettes by deposition of nonbedded, low-carbonate sands 8000–5000 yr B.P. followed by formation of A-Bw or weak A-Bt soils in these sands. Deposits of both low-carbonate sands and calcareous sandy loams dating <3000 yr B.P. accumulated on a few lunettes in the late Holocene. The Holocene record is indicative of significant regional deflation and therefore drying in the middle Holocene, followed by longterm landscape stability and hence at least slightly more moist conditions, with episodic drying in the last few millennia of the Holocene.

The stable-C isotopes support the paleoenvironmental interpretations derived from the lithostratigraphy and soil stratigraphy (Fig. 7). The data show a gradual increase in biomass produced by temperate-climate plants, hence suggesting a trend toward cooler conditions 25,000–15,000 yr B.P. Limited pollen data led Hall and Valastro (1995) to propose that the area was a treeless *Artemesia* grassland ca. 20,000–18,000 yr B.P. The extreme isotopic variability for the period 15,000–8000 yr B.P. may be indicative of environmental fluctuations between cooler and warmer climates, consistent with the stratigraphic evidence for shifts between landscape stability and instability. The most dramatic shift is that toward heavier isotopic values 12,000–10,000 yr B.P., indicating a shift to warmer conditions. Though these data are sparse, stratigraphic evidence from other settings suggests a similar trend, as inferred from widespread formation of eolian sand sheets 11,000–10,000 yr B.P. (Holliday, 1995b, in press). Around 10,000–9000 yr B.P. there was a return to cooler conditions that lasted for several millennia, but the early Holocene was otherwise marked by large variability in temperature. The isotopic data from the lunettes also indicates a shift toward warmer conditions at ca. 8000 yr B.P. The few data points for the late Holocene suggest a shift back to cooler conditions.

The Holocene stratigraphy and isotopic trends in the lunettes are nearly identical to those found in the nearby draws (Holliday, 1995b) and share some broad similarities with the record reported from the nearby sand dune fields (Holliday, 1995a), from a large lunette associated with a salina (Reeves and Vincent, 1991), and from small playa basins (Holliday *et al.*, 1996). All of these settings provide strong evidence for regional, intense, and prolonged deflation of the High Plains surface in the middle Holocene (8000–5000 yr B.P.), indicative of a significant period of drought. Other records of middle Holocene drought on the Southern High Plains come from vertebrate and invertebrate paleontology (Johnson and Holliday, 1986; Neck, 1995; Winsborough, 1995) and archaeology (Meltzer, 1991). Evidence for regional, episodic late Holocene drying has also been obtained from paleontology (Hall, 1982; Johnson, 1987).

CONCLUSIONS

Initial construction of lunettes resulted from wind erosion of the Blackwater Draw Formation, a process which simultaneously created the adjacent playa basin. Subsequent deposition of calcareous sediments on the lunette, ultimately derived from lacustrine carbonate deposited in the basin during wetter periods, promoted cementation that maintained the lunettes.

The late Pleistocene of the Southern High Plains since ca. 25,000 yr B.P. is represented in the lunettes by episodic deposition with brief intervals of stability and soil formation, in contrast to accumulation of thicker deposits in the middle Holocene followed by a relatively long period of stability and soil formation. The Holocene depositional sequence in the lunettes is similar to those in the dune fields and draws of the region (Holliday, 1995a, 1995b).

Because the episodic, accretionary sedimentation of the late Pleistocene has not been reported from any Holocene locality in or near the Southern High Plains, the environment of initial lunette formation 25,000–15,000 yr B.P. is not analogous to any Holocene environment in the region. A similar conclusion was reached by Hall and Valastro (1995), based on pollen from White Lake (Fig. 1). The lunette data show a trend toward cooler temperatures and increased effective precipitation during and after the period 25,000–15,000 yr B.P., but also suggest repeated, short departures toward warmer temperatures and probably toward drier conditions throughout the late Pleistocene.

The lunettes of the Southern High Plains differ from lunettes elsewhere in lithology, stratigraphy, age range, and paleoenvironmental implications. Many lunettes in other regions (Australia, coastal south Texas, Algeria, West Africa) have a high clay content and are often referred to as ''clay dunes'' (e.g., Price, 1963; Bowler, 1973). Clays are a common component of playa fills on the Southern High Plains (Holliday *et al.,* 1996) but are rarely deflated, probably because they do not form the wind-erodible ''clay pelletal aggregates'' that are important in the formation of clay dunes (e.g., Bowler, 1973, 1983). Lunette accretion on the Southern High Plains is episodic, as indicated by buried soils. Studies in other regions suggest or hint that lunette formation is accretionary (e.g., Chen, 1995), but buried soils are rarely mentioned or described. The work reported here shows that lunettes formed both in the late Pleistocene as well as Holocene. The record is less clear in other areas, but Bowler (1973, 1983) suggests that some are fossil features and formed only in the late Pleistocene, whereas others are modern. Bowler (1983, p. 166) also proposes that the formation of many lunettes around the world depends largely on ''local hydrology rather than regional climates.'' Local hydrology clearly is a factor in playa sedimentation and lunette formation on the Southern High Plains, but local hydrological changes are significantly affected by regional climate fluctuations (Cronin, 1964; Ashworth, 1991; Ashworth *et al.,* 1991). Therefore, the processes of lunette construction on the Southern High Plains appear to have regional environmental significance.

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