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Soil-geomorphic relations of lamellae in eolian sand on the High Plains of Texas and New Mexico

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Abstract

Clay lamellae are ubiquitous features in sands in a wide variety of settings around the world. Most studies of lamellae focus on: 1) a few or individual locales or on 2) formation by experimental methods in the laboratory. This study reports on lamellae from eight localities in three late-Quaternary dune fields on the Southern High Plains of northwest Texas and eastern New Mexico. Most lamellae observed are illuvial and they increase in number and thickness through time. A few (1–3) thin (1–2 mm) lamellae formed in Historic sediments. Lamellae are more numerous (3–12) and thicker (3–5 mm) in older late Holocene (< 1000 ^{14}C years BP) and middle Holocene (< 7600 ^{14}C years BP) sands. Soils that formed through the late Pleistocene and into the early Holocene (14,300–7600 ^{14}C years BP) or soils that formed throughout the Holocene can exhibit as many as 30 lamellae or lamellae of 10–12 mm thickness. The micromorphology of the lamellae shows that argillans on sand grains are thicker, more laminated, more continuous, and cap and link more grains through time. Other variables affect lamella morphology. Within individual dunes, the lamellae are best expressed where the sand is thickest; they decrease in number and thickness as sand thins. The lamellae also form only in clean, well-drained sand. Poor drainage and/or bioturbation result in formation of a continuous argillic horizon encasing lamellae.

Keywords: Lamellae; Clay band; Southern High Plains; Eolian sand; Soil geomorphology

1. Introduction

Lamellae are common features in sandy soils in a variety of environments (e.g., Dijkerman et al., 1967; Gray et al., 1976; Ahlbrandt and Freyberger, 1980; Larsen and Schuldenrein, 1990; Prusinkiewicz et al., 1998; Rawling, 2000). The origins of these thin, relatively clay-rich zones within a sandy parent material have been debated for decades, based both

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on field and experimental observations (summarized by Rawling, 2000). They are thought to originate via primary deposition, via pedogenesis or via pedogenesis controlled by sedimentary characteristics (Rawling, 2000 and references therein). Specific pedogenic mechanisms involved in lamella formation include sieving at pore discontinuities, flocculation where the pH is increased by either calcium carbonate or iron, reduction in the carrying capacity of soil water as the wetting front dries or clay precipitation when a maximum carrying capacity of the soil water is exceeded (Rawling, 2000 and references therein).

Despite the apparent interest in lamella genesis, data on rates of lamella formation and on their spatial variability are lacking. Only a few papers report direct age control (radiocarbon or archaeological) (Gray et al., 1976; Ahlbrandt et al., 1983; Berg, 1984; Larsen and Schuldenrein, 1990; Prusinkiewicz et al., 1998; Rawling, 2000). Likewise, most studies deal with one or a few profiles or focus on a small area. Understanding the rates of lamella formation and looking at these soils from a variety of settings in a regional context may provide clues regarding their genesis and help in evaluating the utility of lamellae as correlation tools and as age indicators in soil-stratigraphic and soil-geomorphic research.

This paper presents the results of research into the evolution of lamellae in late-Quaternary eolian sand on the Southern High Plains (Fig. 1). This research builds on the work of Gile (1979, 1981, 1985), who first discussed lamellae in the region in his classic 1979 paper. His work in the Muleshoe Dunes suggested that: 1) the number and thickness of lamellae appear to increase with age; 2) continuous Bt horizons evolve from lamellae; and 3) lamella morphology could be a useful tool for stratigraphic correlation throughout the dune field. Gile's data was from a small study area within the Muleshoe Dunes, however, and he had only limited age control. The data presented here are from throughout the Muleshoe Dunes as well as several other dune fields and sand sheets on the Southern High Plains. Moreover, many of the soils with lamellae are now dated by radiocarbon assays, archaeological artifacts whose age range is well constrained, and stratigraphic correlation. In addition to firmer age control, this paper also presents the results of thin-section analysis of the lamellae. The thin sections were used to better characterize the lamellae and to help confirm their genesis.

2. Setting and factors of soil formation

The Southern High Plains or Llano Estacado ("stockaded plains") is a broad plateau covering approximately 130,000 km^2 in northwestern Texas and eastern New Mexico (Fig. 1). The climate of the region is continental and semi-arid, dry steppe (Carr, 1967; Bailey, 1995). Precipitation ranges from almost 500 mm/year in the north to 280 mm/year in the southwest, and mean annual air temperature ranges from approximately 14 °C to 18 °C (Bomar, 1983). As a result of high evapotranspiration rates and limited precipitation most soils on the High Plains have aridic or torric moisture regimes. Frequent strong winds (> 11 m/s) and dust are also important components of the climate (Orgill and Sehmel, 1976; Holliday, 1987a).

The natural vegetation of the Llano Estacado is a mixed-prairie grassland (Blair, 1950; Lotspeich and Everhart, 1962). The dominant native plant community is short-grass (e.g., grama *Bouteloua* sp., and buffalo grass *Buchloe dactyloides*). The sandy soils of the dunes and sand sheets, however, are characterized by grasses as well as "shinnery oak" (*Quercus harvardii*), which can grow in dense stands. Native plant communities of the region occur in very few areas today, however, because most of the Southern High Plains is under cultivation, including significant areas of the Muleshoe Dunes, which are being leveled for center-pivot irrigation. On a geologic time scale, the Llano Estacado probably was a semi-arid grassland throughout the Holocene (Johnson, 1986, 1987; Holliday, 1987b, 1989, 1997a, 2000a, 2001).

Extensive Cenozoic deposits comprise most of the exposed sections on the Southern High Plains. The principal surficial deposit is the Blackwater Draw Formation (Reeves, 1976). This unit consists of early to late Pleistocene eolian deposits and buried soils (Holliday 1989, 1990; Gustavson, 1996; Gustavson and Holliday, 1999). Paleustolls and Paleustalfs formed in the top of the Blackwater Draw Formation are the principal soils of the High Plains surface (Holliday, 1990).

Slight topographic relief on the surface of the Southern High Plains is provided by thousands of

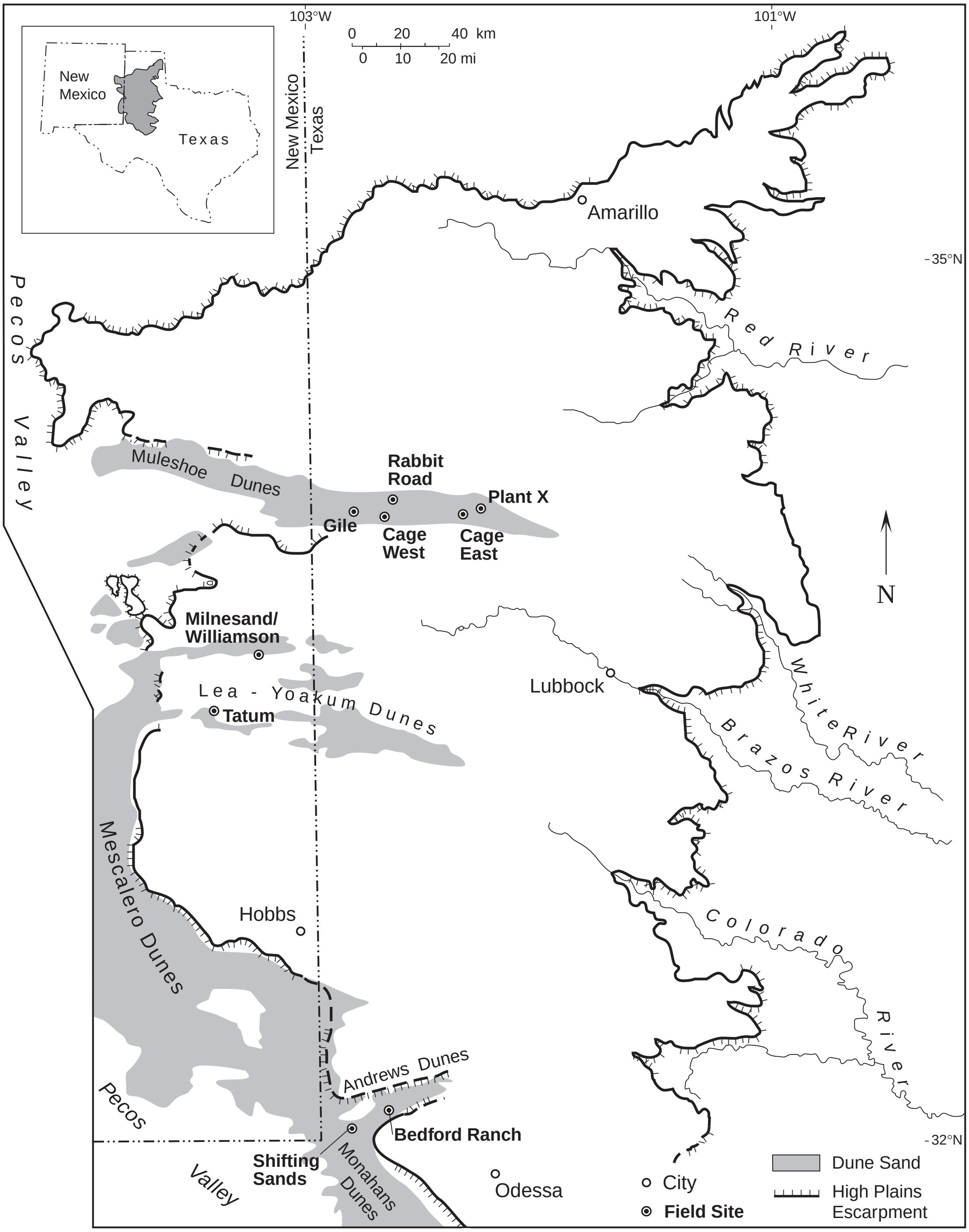

Fig. 1. The Southern High Plains of northwestern Texas and eastern New Mexico showing the location of dune fields mentioned in the text, selected physiographic features, and field sites discussed in the text. Inset shows the location of the Southern High Plains in Texas and New Mexico.

small lake basins or "playas", dry valleys or "draws", and dunes (Reeves, 1972; Hawley et al., 1976; Holliday, 1995a,b, 1997b) (Fig. 1). Dune fields mantle the Blackwater Draw Formation and began to accumulate in the late Pleistocene (Holliday, 2000a, 2001). They occupy ~5800 km^2 and are grouped into three west-to-east trending belts (Fig. 1). From north to south, these belts are: the Muleshoe Dunes (or "Sandhills"); the informally termed Lea-Yoakum Dunes (or "Bledsoe Dunes"); and the informally termed Andrews Dunes. An extensive belt of dunes is located in the Pecos Valley adjacent to the western escarpment of the High Plains (Fig. 1), called the "Mescalero Dunes" in New Mexico and the "Monahans Dunes" in Texas. Our study deals with soils in the Muleshoe, Lea-Yoakum, and Andrews dunes.

The eolian sediments in the dunes and sand sheets are dominantly quartz fine sands (Gile, 1979, 1985; Holliday, 2001; Muhs and Holliday, 2001) and are moderately well sorted (Holliday, 2001). Mean particle size and clay content both decrease from west to east (Muhs and Holliday, 2001). The decrease in clay content probably is due to increased abrasion, releasing the clay coatings on sand grains into the atmosphere (Gillette and Walker, 1977; Muhs and Holliday, 2001). Greater distance of travel of the sand grains results in more abrasion of the sand and loss in clay. The same process probably accounts for an overall decrease in redness from dominantly 5YR hues in the west to 7.5YR hues in much of the central Muleshoe Dunes, to 10YR hues in the eastern end of the dune field (Muhs and Holliday, 2001). Most of the red coloration is in the clay coatings, that are lost downwind. The Muleshoe Dunes have some of the highest quartz contents of any dune field on the Great Plains (Muhs and Holliday, 2001). They have at most 2–3% $CaCO_3$ and typically are noncalcareous. Lunettes are dunes comprised of highly calcareous parent materials (Holliday, 1997b), but they are highly localized, found adjacent to a few playas.

Stratigraphic and geochronologic studies in the dune fields and sand sheets (Green, 1961; Haynes, 1975, 1995; Holliday, 2001) show that they accumulated episodically in the latest Pleistocene and Holocene. Periods of significant eolian sedimentation were between 11,000 and 8000 ^{14}C years BP, probably in several phases, episodically between 8000 and 4500 ^{14}C years BP, and in the late Holocene, < 4000 ^{14}C years BP and mostly < 1500 ^{14}C years BP.

One of the goals of our research is to evaluate rates of development of lamellae. Such studies are most easily carried out among soils that form a chronosequence (e.g., Birkeland, 1999). The soils of the dune fields and sand sheets on the Southern High Plains provide such an opportunity: they vary in age but most are otherwise similar with respect to the soil forming factors they experienced. Parent materials are similar and most of the study sections exposed soils in similar topographic settings. All of the soils probably formed under similar vegetation, and they formed during periods of landscape stability under similar climates in the middle and late Holocene.

3. Methods

Data were derived from field investigations of 48 natural and artificial exposures, and from laboratory analyses of selected sections (provided in Holliday, 2001; selected profile descriptions are presented in Table 1) (Holliday, 2001). The geochronology of individual sections and stratigraphic correlations between sections is based on radiocarbon dating and archaeology (Fig. 2) (Holliday, 2001).

The sediments and soils were described following standard pedologic and geologic nomenclature (AGI, 1982; Soil Survey Division Staff, 1993; Schoeneberger et al., 1998), with two exceptions. One modification was made regarding identification of buried soils: they were numbered with a suffix following the "b" according to their stratigraphic position below the surface (e.g., A–Bw–Ab1–Btb1–Cb1–Ab2–Btb2). The b1, b2, b3, etc., nomenclature also provides a convenient shorthand for referring to a specific buried soil.

A large literature exists on lamellae (see Rawling, 2000), but there are no satisfactory field designations. For horizons with lamellae that are clearly illuvial, the simple designation "Bt" is unsatisfactory because it does not convey the unique characteristics of thin, discrete zones of illuvial clay separated by clay-free or low-clay sands. The lamellae themselves clearly qualify as Bt but the interlamella zones often do not. USDA manuals for soil survey and description consider the interlamella zones as a type of E horizon

Table 1
Field description[a]

Thickness (cm)	Horizon	Color	d	m	Texture	Structure	Boundary	Lamellae		Remarks
								number	thickness (mm)	
Bedford Ranch										
100	C	10YR	6/6		fS	sg	cs			
20	Ab1	10YR	5/3	4/2	fS	sg	cs			
22	ACb1	10YR	6/3	4/3	fS	sg	ci			strongly bioturbated
33	CAb1	10YR	6/3	5/3	fS	sg	ci			strongly bioturbated
≤ 150	Cb1	10YR	7/2	6/3	fS	sg	ai	few	1–2	lamellae are locally common
100–200	Bt&C1b2	10YR	6/4	5/4	fS	sg	cs			upper half of horizon tends to be
	sand matrix	10YR	8/3	6/4						redder; lower half more pale
	Bt&C1b2 lamellae	10YR	5/4	4/4				30–35	3–15	5–15 mm thick, 3–5 cm apart, in upper section; 3–7 mm thick, 1–3 cm apart in lower
15	C2b2	10YR	7/4	5/4	fS	sg	as			
≤ 15	Bt&	10YR	6/4	5/4	SC	wk sbk	as			illuvial clay throughout with faint
	Btgb3	10YR	3/3	2/2						discont lamellae locally apparent
Shifting Sands sites										
Main Blowout										
200–400	C	10YR	7/4	6/4	fS	sg	a			
70	Bt&Cb1	10YR	7/4	5/4	fS	sg	cs			gley colors are localized in lower
	matrix	2.5Y	7/4	6/4						10–20 cm
	Bt&Cb1	7.5YR	6/6	4/6				25–30	5–15	upper lamellae are thickest, lower
	lamellae	2.5Y	6/4							lamellae are thinnest; gley colors are localized
30	Bwb2	10YR	6/4	5/3	fS	wk sbk	cs			
East Blowout, East Yardang	East Profile									
100–200	C	10YR	7/4	6/4	fS	sg	a			
120	Bt1b1	10YR	7/6	5/6		wk pr & wk sbk	cs			thin, discont clay films on ped faces
30	C&Bt2b1 sand matrix	10YR	7/4	5/4		m	a			lower boundary is lowest lamella
	C&Bt2b1 lamellae	10YR	6/6	4/6				8–10	3–5	lamellae are commonly discont
40	Cb1	10YR	8/4	5/4	fS	m	a			

East Blowout, East Yardang	West Profile									
100–200	C	10YR	7/4	6/4	fS	sg	a			
50	Bt1&Btb1 argillic matrix	10YR	6/6	5/6	fS	wk pr wk sbk	cs			thin, discont clay films on ped faces
	Bt1&Btb1 lamellae	10YR	6/6	4/6	fS			~6	3–5	
50	Bt2&Cb1 sand matrix	10YR	6/4	5/4	fS	m	cs			
	Bt2&Cb1 lamellae	10YR	6/6	4/6				25–30	3–5	upper lamellae are thinner, lower lamellae are thicker
60	Cgb1	2.5Y	7/4	6/4	fS	m				
East Blowout, West Yardang										
100–200	C	10YR	7/4	6/4	fS	sg	a			
25	Bt1b1	10YR	6/4	4/4	LfS	wk pr str sbk	cs			thin cont clay films on ped faces
20	Bt2b1	10YR	7/6	5/6	fS	v wk sbk	cs			thin patchy clay films on ped faces; few faint clay lamellae
40	Cb1	10YR	7/4	5/4	fS	m				few faint lamellae

Depth (cm)	Horizon	Color	d	m	Texture	Structure	Boundary	Lamellae		Remarks
								number	thickness (mm)	
Ted Williamson site										
0–60	C1	7.5YR	5/6	4/6	fS	sg	as			
60–130	C2	10YR	6/4	4/4	fS	sg	ai			cross bedded; lower 12 cm is reworked Ab1
130–163	A1b1	7.5YR	6/4	3/4	fS	m	cs			
163–188	A2b1	7.5YR	6/4	4/4	fS	m	g			
188–223	Eb1	7.5YR	5/6	4/6	fS	v wk sbk	cs			
223–333	C&Btb1 sand matrix	7.5YR	5/6	4/6	fS	m	cs			
	C&Btb1 lamellae	5YR	4/6					3–4 8–10	5–15 2–5	lamellae more common in upper 60 cm; thicker lamellae in the upper section; thinner lamellae below
333–373	Bwb1	7.5YR	5/6	4/6	fS	sg	a			slightly more yellow than above
Cage West site										
0–70	C1	10YR	6/6	3/6	fS	sg	g			
70–145	C2	10YR	6/6	4/6	fS	sg	cs			cross bedded
145–180	Ab1	10YR	6/6	3/4	fS	wk cse sbk	g			
180–210	Cb1 (E?)	10YR	6/6	4/4	fS	sg	cs			
210–260	C&Btb1 matrix	10YR	6/6	4/6	fS	m	cs			
	C&Btb1 lamellae	7.5YR	4/6	3/4				~8	1–2	

(continued on next page)

Table 1 (*continued*)

Depth (cm)	Horizon	Color d	m	Texture	Structure	Boundary	Lamellae		Remarks
							number	thickness (mm)	
Cage West site									
260–300	A&Btb2	10YR 6/4	4/4	fS	v wk sbk	g	1–2	2	
300–360	Cb2	10YR 6/6	4/6	fS	sg	g			
360–372	Bt&Btb3 matrix	10YR 5/8	4/6	fSL	wk pr & mod med abk	cs			cont thin clay films on ped faces
	Bt&Btb3 lamellae	10YR 5/6	4/5				2–3	5–8	upper 2 lamellae are thickest and cont; lowest lamella is thinnest and discont
372–379	Bt&C1b3 matrix	10YR 7/6	6/6	fS	sg	aw			lower boundary is lowest lamella
	Bt&C1b3 lamellae	10YR 5/6	4/5				2–3	4–5	discont; upper 2 lamellae are thickest, lowest is thinnest
379–434	C2b3	10YR 8/3	7/3	fS	sg	a vi	2 mm lamellae at ~390 cm; 2 discont 1 mm lamellae @ 400 and 405 cm		common limonite mottles in lower half
434–449	Btb4	10YR 6/6	5/6	fS	mod med sbk	cs			dense; bioturbated; thin cont clay films on ped faces; common limonite mottles
Rabbit Road sites									
NE Blowout									
0–300	C	10YR 6/6	6/4	fS	sg	cs			
300–340	Ab1	10YR 5/4	3/4	fS	wk sbk	cs			
340–440	C&Btb1 sand matrix	10YR 6/4	5/4	fS	sg	cs			
	C&Btb1 lamellae						2–3	4–5	lamellae are in lower 30 cm
440–500	A&Btb2 sand matrix	10YR 5/4	4/4	fS	wk sbk	cs			
	A&Btb2 lamellae						3–4	2–3	lamellae are faint
500–600	Cb2 sand matrix	10YR 6/6	5/6	fS	m	cs			cross bedded
	Cb2 lamellae						5–10	1–3	lamellae are in lower 100 cm, are faint and follow bedding planes
600–650	Ab3	10YR 5/4	4/4	fS	v wk sbk	cs			
650–700	Eb3	10YR 6/4	4/4	fS	sg	cs			
700–800	Bt&Btb3 argillic matrix	7.5YR 5/6	4/6	fS	wk sbk	cs			thin cont. clay films on ped faces

	Bt&Btb3	7.5YR 5/6 4/6				~12	7–8	upper lamellae
	lamellae						3–5	lower lamellae
800–830	Cb3	10YR 8/1	fS	sg				lamellae from Btb3 locally apparent
SW Blowout	North Side							
0–100	C	10YR 6/6 4/6	fS	sg	cs			
100–140	Ab1	10YR 5/4 3/6	fS	v wk sbk	cs			
140–200	C&Btb1 sand matrix	10YR 5/4 4/4	fS	sg	cs			
	C&Btb1 lamellae					2–3	1–2	
200–365	Bt&Cb2 sand matrix	10YR 7/4 5/4	fS	sg	cs			
	Bt&Cb2 lamellae	10YR 5/6 4/6				~25	5–15	
	South Side							
200–220	Ab2	10YR 5/4 3/4	fS	v wk sbk	g			
220–270	Btb2	10YR 5/6 4/6	LS	v wk pr & wk sbk	cs			thin patchy lamellae
270–290	Cb2	10YR 6/4 5/4	fS	sg	cs			
290–300	Cgb2	10YR 4/4 3/4	fS	m	ia			common krotovinas
300–325	Agb3	10YR 3/4 3/2	SC	mod sbk				dense; common Mn concretions; common krotovinas
Plant X								
0–100	C	10YR 6/4 5/4	fS	sg	cs			
100–120	Ab1	10YR 6/4 4/3	fS	v wk sbk	cs			
120–320	Cb1	10YR 6/4 5/4	fS	sg	cs			cross bedded
320–330	Ab2	10YR 5/4 3/3	LS	wk sbk	cs			
330–355	Cb2	10YR 6/4 4/3	fS	sg	cs			
355–400	C&Btb2 matrix	10YR 6/6 3/6	fS	v wk sbk	cw			
	C&Btb2 lamellae	10YR 5/6 3/6				6	1–2	
400–407	Ab3	10YR 5/4 4/4	fS	sg	cw			very faint
407–442	C&Btb3 matrix	10YR 5/6 4/4	fS	v wk sbk	ai			
	C&Btb3					1	1–2	top of horizon
	lamellae					1	5	bottom of horizon
442–	Ab4							

(continued on next page)

Table 1 (*continued*)

Depth (cm)	Horizon	Color d	m	Texture	Structure	Boundary	Lamellae number	thickness (mm)	Remarks
Milnesand site									
0–100	C	10YR 6/4	4/4	fS	sg	a			
100–140	Ab1	10YR 6/3	4/3	fS	w sbk	g			
140–190	Cb1	10YR 6/4	4/4	fS	sg	a			
190–110	Bt&Cb2 matrix	10YR 6/4	4/4	fS	sg	a			
	Bt&Cb2 lamellae	7.5YR 5/6	4/6				1 bifurcating to 12	25 1–2	lamellae separated by sand lenses 1–2 mm thick

Thickness (cm)	Horizon	Color d	m	Texture	Structure	Boundary	Lamellae number	thickness (mm)	Remarks
Cage East site									
≤ 500	C	7.5YR 7/8	6/8	fS	sg	cs			cross bedded
≤ 50	A1b1	10YR 5/4	4/4	fS	v w sbk	cs			
≤ 50	A2b1	10YR 6/6	5/6	fS	v w sbk	cs			
≤ 400	Cb1 matrix	7.5YR 7/8	6/8	fS	sg				
	Cb1 lamellae						12–15	1–2	lamellae are in lower 70 cm following bedding planes; a few cross cut bedding
Tatum site									
≤ 50	E	10YR 6/4	4/3	fS	sg	ci			locally common
300–500	C&Bt matrix	10YR 6/4	5/4	fS	sg	cs			E horizon locally common in upper 50 cm
	C&Bt lamellae	7.5YR 3/4		LfS	m		~6 1	3–8 5–10	thinner lamellae locally common in lower 1m; the single thick lamella is prominent at base of section

[a] Abbreviations for descriptive characteristics in all tables: Color (Munsell), d=dry, m=moist; Texture, fS=fine sand, LfS=loamy fine sand, LS=loamy sand, fSL=fine sandy loam, SC=sandy clay; Structure, sg=single grain; v wk=very weak, wk=weak, m=massive, mod med=moderate medium, sbk=subangular blocky, abk=angular blocky, pr=prismatic; boundary, g=gradual, cs=clear smooth, ci=clear irregular, a=abrupt, ai=abrupt irregular, a vi=abrupt very wavy, aw=abrupt wavy; Remarks, cont=continuous, discont=discontinuous.

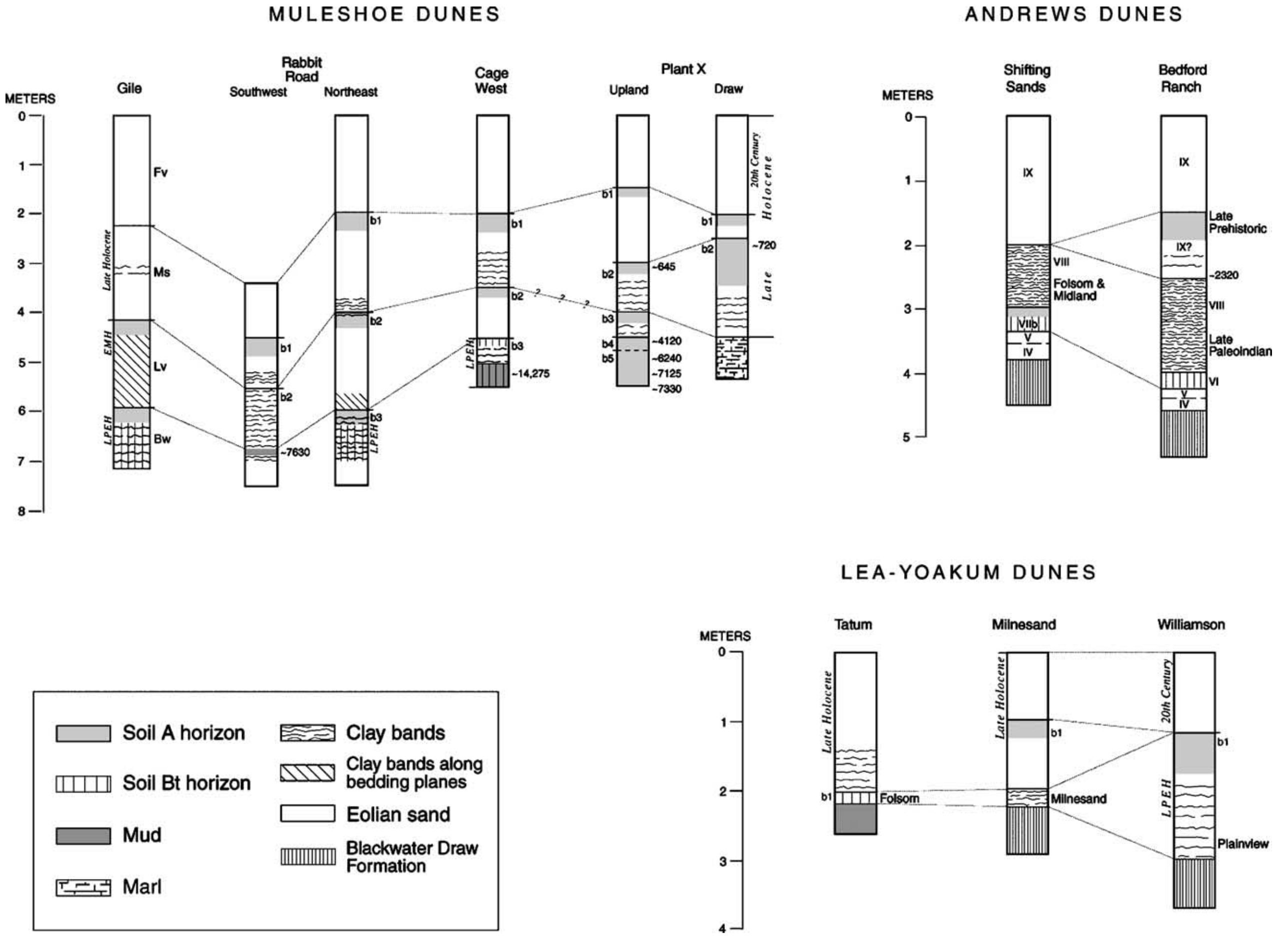

Fig. 2. Stratigraphic correlation of clay-band sequences in the Muleshoe Dunes, Andrews Dunes, and Lea-Yoakum Dunes investigated for this study (see Fig. 1 for locations). Sections modified from Holliday (2001, figs. 3,8,10).

and use "E and Bt" to designate lamellae in sand (Soil Survey Division Staff, 1993, p. 122; Schoeneberger et al., 1998, p. 2-2). An E horizon is characterized by loss of silicate clay (Soil Survey Division Staff, 1993, p. 119; Schoeneberger et al., 1998, p. 2-2), but the interlamella zones in our soils show no evidence for loss of clay relative to the parent material. They were zones of clay translocation, but not net loss. We can not demonstrate and will not presume that the interlamella zones are E horizons. These zones better qualify as a kind of C horizon, i.e., zones "little affected by pedogenic processes" (Soil Survey Division Staff, 1993, p. 120) or zones of "little or no pedogenic alteration" (Schoeneberger et al., 1998). Most of the lamella zones in our study, therefore, are a mix of Bt (lamella) and C (unaltered) horizons. These zones are referred to as C&Bt or Bt&C, depending on the dominant characteristics (following Gile, 1979, 1985). Zones with most lamellae following bedding were simply designated as C horizons. Continuous Bt or argillic horizons are referred to as continuous Bt horizons. In the case of a continuous Bt horizon with lamellae, the designation Bt&Bt is used.

Samples from 21 sites were selected for laboratory assessment of particle-size distribution (by sieving and pipet), organic-carbon content by wet combustion (Walkley–Black method), and calcium carbonate content by Chittick apparatus, following Singer and Janitzky (1986) (Table 2). Samples for analyses included individual lamellae. Many study sites were blow-outs in dunes where wind winnowed out the low-clay interlamella zones, leaving lamellae in relief along the exposures. They could then be collected individually using a trowel. Radiocarbon dating methods are discussed by Holliday (2001). All ages presented in this paper are in terms of uncalibrated radiocarbon years before present (^{14}C years BP).

Samples of lamellae from six sites were also collected for thin section analysis (Tables 3 and 4). The samples were oriented vertically in field collection and in cutting. Impregnation was with an epoxy resin under vacuum. Each slide was described following Fitzpatrick (1993), however these descriptions do not reflect morphological variability because lamellae form in sandy parent materials and are characterized by an increase of ~3–7% clay.

To compare lamella development among slides better, an index was devised, modified from Holliday (1988) and based on simple point counts of key characteristics. A 1 cm × 1 cm grid was drawn on each slide and for each cell four fields of view at 50× magnification were assessed for the number of grains coated in clay, argillan appearance, and distribution of argillans on sand grains (Tables 3 and 4). The number of grains coated with clay was estimated as few (0–2%), common (2–20%), abundant (20–50%), and many (> 50%). These estimates were then assigned values from 0 to 4 (Table 3), indicative of progressively stronger pedogenic development. Argillan appearance was noted as either microlaminated or non-microlaminated. Microlaminations have long been used as evidence of pedogenesis (e.g., Brewer and Haldane, 1957; Buol and Hole, 1961) and were assigned a value of 1, compared to non-microlaminated coatings assigned a value of 0. Microlaminations occur on sand grains in both pedogenic and depositional settings, but pedogenic clays will also preferentially coat the tops of sand grains and fill the bottom of pores (Bullock and Mackney, 1970). The distribution of argillans on sand grains was therefore noted as grain irregularities, grain caps, filled pore bottoms, and bridges, characteristics that are all indicative of pedogenesis (Bullock and Mackney, 1970). Higher distribution values were assigned to progressively more complex distribution patterns (e.g., grain irregularities were assigned a value of 0, whereas grain irregularities plus grain caps were assigned a value of 2) (Table 4). Argillan thickness was not measured in this study because of the uneven distribution of clay on the sand grains (e.g., as caps) and in pores (e.g., as pore-bottom fillings). Instead, argillan thickness (in lamellae only) was described qualitatively as thin, moderate, or thick and assigned values from 1 to 3 (Table 3A). The thin sections include both lamellae and interlamella zones, so data sets were gathered for both to provide another means of assessing degree of lamella expression (Table 3A,B).

An exercise in designing a lamella development index (CB-I) was also devised to express lamella development in thin section. The CB-I was modeled after indices for expressing pedogenic development semi-quantitatively on the basis of soil macromorphology (e.g., Bilzi and Ciolkosz, 1977; Harden, 1982; Langley Turnbaugh and Evans, 1993). The mean values for % grain coats, argillan appearance,

Table 2
Laboratory data[a]

Horizon	% of < 2 mm fraction								%CaCO$_3$	%OC
	vcos	Cos	ms	fs	vfs	Sand	Silt	Clay		
Bedford Ranch										
C	0	0	21	70	8	99	0	1	0	0.00
Ab1	0	2	41	53	2	98	1	1	0	0.11
ACb1	0	1	42	51	3	97	2	1	0	0.00
CAb1	0	0	38	56	2	96	3	1	0	0.00
Cb1	0	1	45	48	1	95	5	0	0	0.11
Bt&C1b2 matrix	0	0	43	54	2	99	1	0	0	0.09
Bt&C1b2 lamella	0	0	46	46	2	94	2	4	0	0.13
C2b2	0	1	33	62	2	98	0	2	0	0.00
Bt&Btgb3	0	1	30	46	5	82	5	13	0	0.00
Shifting Sands sites										
Main Blowout										
C	0	0	50	46	1	97	2	1	0	0.04
Bt&Cb1 matrix	0	0	18	70	3	91	8	1	0	0.05
Bt&Cb1 lamellae	0	0	24	62	3	89	6	5	0	0.00
East Yardang East Profile										
Btb1	0	0	26	67	3	96	3	1	nd	nd
East Yardang West profile										
Bt1&Btb1 matrix	0	0	24	55	16	95	4	1	nd	nd
West Yardang										
Bt1b1	0	0	32	54	2	89	2	9	nd	nd
Bt2b1	0	0	38	57	2	96	2	2	nd	nd
Cb1	0	0	21	74	2	97	2	1	nd	nd

Horizon	Depth (cm)	% of < 2 mm fraction								%CaCO$_3$	%OC
		vcos	cos	ms	fs	vfs	Sand	Silt	Clay		
Ted Williamson site											
C1	0–60	0	0	16	65	14	95	1	4	1	0.05
C2	60–130	0	0	10	71	16	97	1	2	1	0.00
A1b1	130–163	0	0	15	63	17	95	2	3	1	0.05
A2b1	163–188	0	0	15	66	15	96	1	3	0	0.05
Eb1	188–223	0	0	17	64	15	96	1	3	0	0.00
C&Btb1 matrix	223–333	0	0	15	62	15	92	3	5	1	0.47
C&Btb1 lamellae		0	0	15	63	12	90	7	3	0	0.05
Cage West site											
C1	0–70	0	3	24	63	9	99	1	0	0	0.00
C2	70–145	0	5	37	50	6	98	1	1	0	0.00
Ab1	145–180	0	3	30	46	16	95	5	0	0	0.13
Cb1	180–210	0	2	33	58	7	100	0	0	1	0.21
C&Btb1 matrix	210–260	0	1	21	65	12	99	1	0	0	0.00
C&Btb1 lamella		0	4	28	43	7	82	5	13	0	0.00
Ab2	260–300	0	3	29	54	11	97	2	1	0	0.10
Cb2	300–360	0	1	25	57	15	98	1	1	0	0.03
B&Btb3 matrix	360–373	0	2	29	50	8	89	4	7	0	0.19
Bt&Btb3 lamella	360–373	0	1	19	41	9	70	11	19	0	1.63
Bt&C1b3 lamella	373–379	0	3	25	49	8	85	4	11	0	1.05
C2b3	379–434	0	1	25	57	15	98	1	1	0	0.03
Btb4	434–449	0	3	34	49	6	92	1	7	0	0.00

(continued on next page)

Table 2 (*continued*)

Horizon	% of < 2 mm fraction								$\%CaCO_3$	%OC
	vcos	cos	ms	fs	vfs	Sand	Silt	Clay		
Rabbit Road sites										
NE Blowout										
Ab1	0	3	42	47	4	96	2	2	1	0.14
C&Btb1 matrix	0	3	52	39	4	98	0	2	2	0.06
ABtb2	0	3	42	48	4	97	1	2	1	0.15
Cb2	0	4	58	32	4	98	0	2	1	0.06
Ab3	0	3	40	45	7	95	3	2	1	0.06
Eb3	0	7	57	30	3	95	0	5	0	0.06
Bt&Btb3 matrix	0	4	43	42	5	94	3	3	2	0.05
Bt&Btb3 lamella	0	3	42	42	5	92	3	5	2	0.05
SW Blowout[b]										
C	0	3	49	41	3	97	1	2	0	0.00
Ab1	0	4	44	43	5	97	1	2	0	0.16
C&Btb1	0	3	37	49	8	97	1	2	0	0.06
Bt&Cb2										
Cb2[b]	0	4	46	41	4	95	3	2	1	0.00

Horizon	Depth	% of < 2 mm fraction								$\%CaCO_3$	%OC
		vcos	cos	ms	fs	vfs	Sand	Silt	Clay		
Plant X site											
C	0–100	0	0	36	58	3	97	2	1	0	nd
Ab1	100–120	0	0	28	54	13	95	4	1	0	0.20
Cb1	120–320	0	0	30	61	7	98	0	2	0	0.27
Ab2	320–330	0	0	18	42	26	86	10	4	0	0.20
Cb2	330–355	0	0	20	64	11	95	3	2	0	0.16
C&Btb2 matrix	355–400	0	0	23	62	10	95	1	4	0	nd
C&Btb2 lamella		0	0	21	63	7	91	3	6	0	nd
Milnesand site											
C	0–100	0	0	3	64	26	93	3	4	1	0.51
Ab1	100–140	0	0	15	64	16	95	2	3	1	0.98
Cb1	140–190	0	0	17	61	16	94	2	4	1	0.59

Horizon	% of< 2 mm fraction								$\%CaCO_3$	%OC
	vcos	cos	ms	fs	vfs	Sand	Silt	Clay		
Cage East site										
A1b1	0	1	33	55	6	95	4	1	nd	nd
A2b1	0	0	31	43	4	76	23	1	nd	nd
Cb1 matrix	0	1	49	36	2	88	10	2	nd	nd
Cb1 lamella	0	2	26	51	10	89	8	3	nd	nd

Horizon	Depth	% of < 2 mm fraction								$\%CaCO_3$	%OC
		vcos	cos	ms	fs	vfs	Sand	Silt	Clay		
Tatum site											
E	0–50	0	0	18	78	4	100	0	0	nd	nd
C&Bt matrix	50–300	0	0	30	64	4	98	1	1	nd	nd
C&Bt lamella	300–310	0	0	21	63	4	88	0	12	nd	nd

[a] Abbreviations for lab data: vcos = very coarse sand, cos = coarse sand, ms = medium sand, fs = fine sand, vfs = very fine sand; $\%CaCO_3$ = percent calcium carbonate equivalent; %OC = percent organic carbon.

[b] South side of blowout.

Table 3

A. Micromorphological characteristics of lamellae

Site	Horizon	Thickness[a]	Grain coat[b]	Appearance[c]	Distribution[d]	Cell sum	Normalized
Cage East	Cb1	1.1	3.3 ± 0.4	0.0	0.5	3.8	0.35
Rabbit Rd SW	Bt&Cb2	1.1	2.9 ± 0.1	0.2	0.3	3.4	0.31
Bedford Ranch	Bt&Cb2	2.7	3.7 ± 0.5	1.0	5.4	5.1	0.92
T. Williamson	C&Btb1	2.2	3.3 ± 0.4	1.0	5.1	9.3	0.85
Shifting Sands	Bt&Cb1	1.5	3.7 ± 0.5	1.0	4.1	8.8	0.80
Rabbit Rd NE	Bt&Btb3	2.2	3.6 ± 0.5	0.6	3.5	7.7	0.70

B. Micromorphological characteristics of interlamellae

Site	Horizon	Grain coat	Appearance	Distribution	Cell sum	Normalized
Cage East	Cb1	2.0 ± 0.0	0.0	0.0	2.0	0.19
Rabbit Rd SW	Bt&Cb2	2.0 ± 0.0	0.0	0.0	2.0	0.18
Bedford Ranch	Bt&Cb2	0.5 ± 0.8	0.1	0.3	0.9	0.08
T. Williamson	C&Btb1	1.8 ± 0.4	1.0	2.1	4.9	0.45
Shifting Sands	Bt&Cb1	1.9 ± 0.3	1.0	3.6	6.5	0.60
Rabbit Rd NE	Bt&Btb3	1.8 ± 0.5	0.3	1.5	3.5	0.32

[a] Thickness values: 1 = thin, 2 = moderate, 3 = thick.

[b] Grain coat: (mean + 1σ) 0 = none, 2 = few, 3 = abundant, 4 = many.

[c] Appearance: 0 = nonlaminated, 1 = laminated.

[d] Distribution: see Table 4.

and distribution in both the lamella zone and interlamella zone in each slide were summed and normalized to the highest value possible to come up with a lamella index (CB-I) value following Birkeland (1999, p. 360–367).

Table 4

A. Argillan distribution characteristics, lamellae

Site	0	2	4	6
Cage East	78	19	4	0
Rabbit Rd SW	84	16	0	0
Bedford Ranch	0	11	6	82
T. Williamson	0	17	12	71
Shifting Sands	0	0	94	6
Rabbit Rd NE	40	3	0	57

B. Argillan distribution characteristics, interlamellae

Site	0	2	4	6
Cage East	98	2	0	0
Rabbit Rd SW	100	0	0	0
Bedford Ranch	64	30	4	2
T. Williamson	32	47	4	16
Shifting Sands	0	36	45	2
Rabbit Rd NE	75	0	0	25

0 = grain irregularities; 2 = grain irregularities + grain caps; 4 = grain irregularities + grain caps + pore bottom infillings; 6 = grain irregularities + grain caps + pore bottom infillings + bridges.

4. Macromorphology of the lamellae soils

Soils with lamellae in the eolian sands of the Southern High Plains all share some common physical characteristics. The non-lamella zones of all soils are fine sand to loamy fine sand in texture (Tables 1 and 2). Colors in the non-lamella zones typically have 10YR hues (Tables 1 and 2). The lamellae likewise are fine sand to loamy fine sand, but of course are higher in clay content. The clay-free particle size of the lamellae is generally similar to the non-lamellae zones. Colors of the lamellae vary, but they always have a higher chroma and usually a redder hue than the surrounding matrix (Tables 1 and 2; also Gile, 1979, 1985), characteristics also reported from other areas (e.g., Folks and Riecken, 1956; Wurman et al., 1959; Robinson and Rich, 1960; Kemp and McIntosh, 1989; Cooper and Crellin, 1996).

4.1. Stratigraphic position and horizonation

Soils with lamella are in both buried and unburied settings; the buried ones are most common. The sola of the lamella soils typically are 1–2 m thick, though some buried soils were eroded prior to burial. Where the A horizon is preserved, depth to the top of the lamella zone varies from 20 cm to 400 cm, though 50–100 cm is typical.

The lamellae are usually below the A horizon and associated with clean sand (Figs. 3A and 4A), but in a few exposures lamellae were in buried A horizons or in a typical, continuous Bt horizon. Lamellae were observed in A horizons at two exposures in the Muleshoe Dunes: the A&Btb2 horizon at the Cage West site (Fig. 4B) and A&Btb2 horizon at Rabbit Road NE (Fig. 5A). Each horizon exhibited a few (1–2, 3–4, respectively) thin (1–3 mm) lamellae. Lamellae are associated with continuous Bt horizons at several localities. The b3 soil at both the Cage West (Fig. 4C) and Rabbit Road NE (Fig. 5C) sites in the Muleshoe Dunes, and Bedford Ranch (Fig. 5B) in the Andrews Dunes exhibit lamellae within continuous Bt horizons. The paleotopographic settings of these sections as well as weathering characteristics such as mottling and iron-oxidation are indicative of lowland settings with fluctuating water tables. In a similar setting in the Andrews Dunes, the East Yardang at Shifting Sands exposed a paleodune with a continuous Bt just above and overlapping with a well-expressed lamella horizon (Fig. 3B; Table 1; see below).

4.2. Number, thickness and morphology of lamellae

The number and thickness of lamellae in a single horizon or stratigraphic unit varies significantly. The

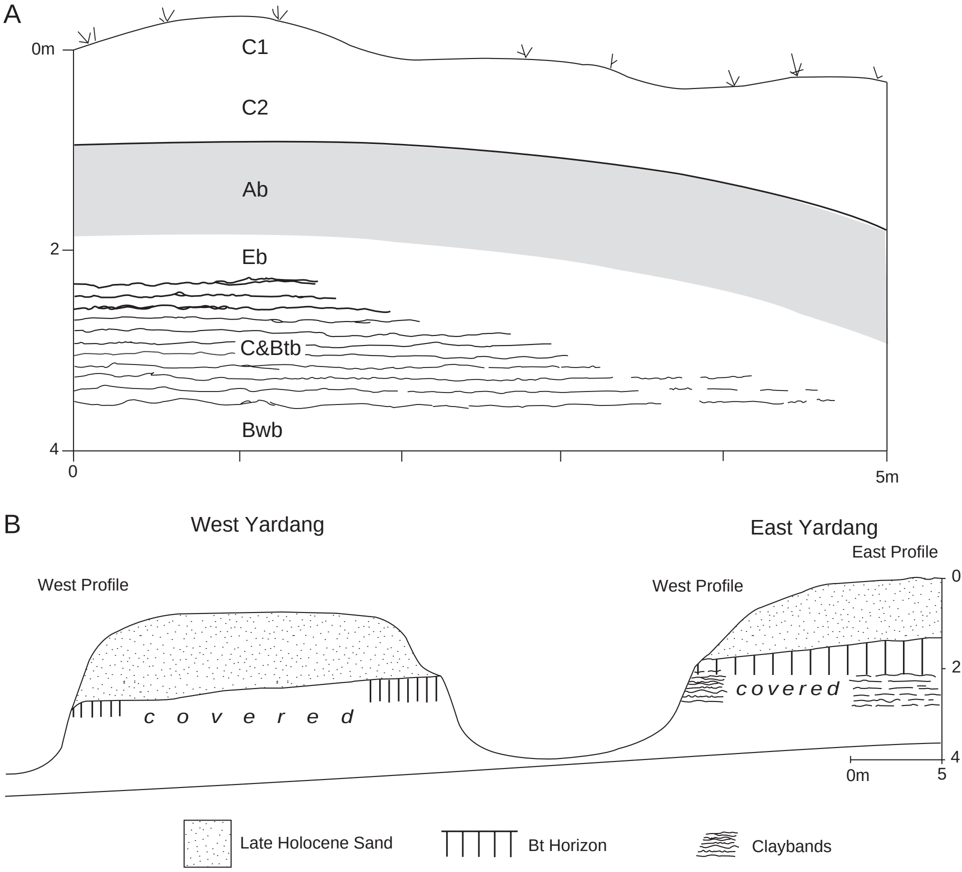

Fig. 3. A) Schematic soil-stratigraphic and soil-geomorphic relations of the buried clay-band soil at the Ted Williamson site. As the soil thins, the number and thickness of clay bands decreases (see Fig. 6A for photomicrograph of lamellae). B) Schematic soil-stratigraphic and soil-geomorphic relations of the buried clay-band soil exposed in yardangs at the Shifting Sands site. As the soil thins, the clay bands and a typical argilic horizon merge and the clay bands eventually disappear.

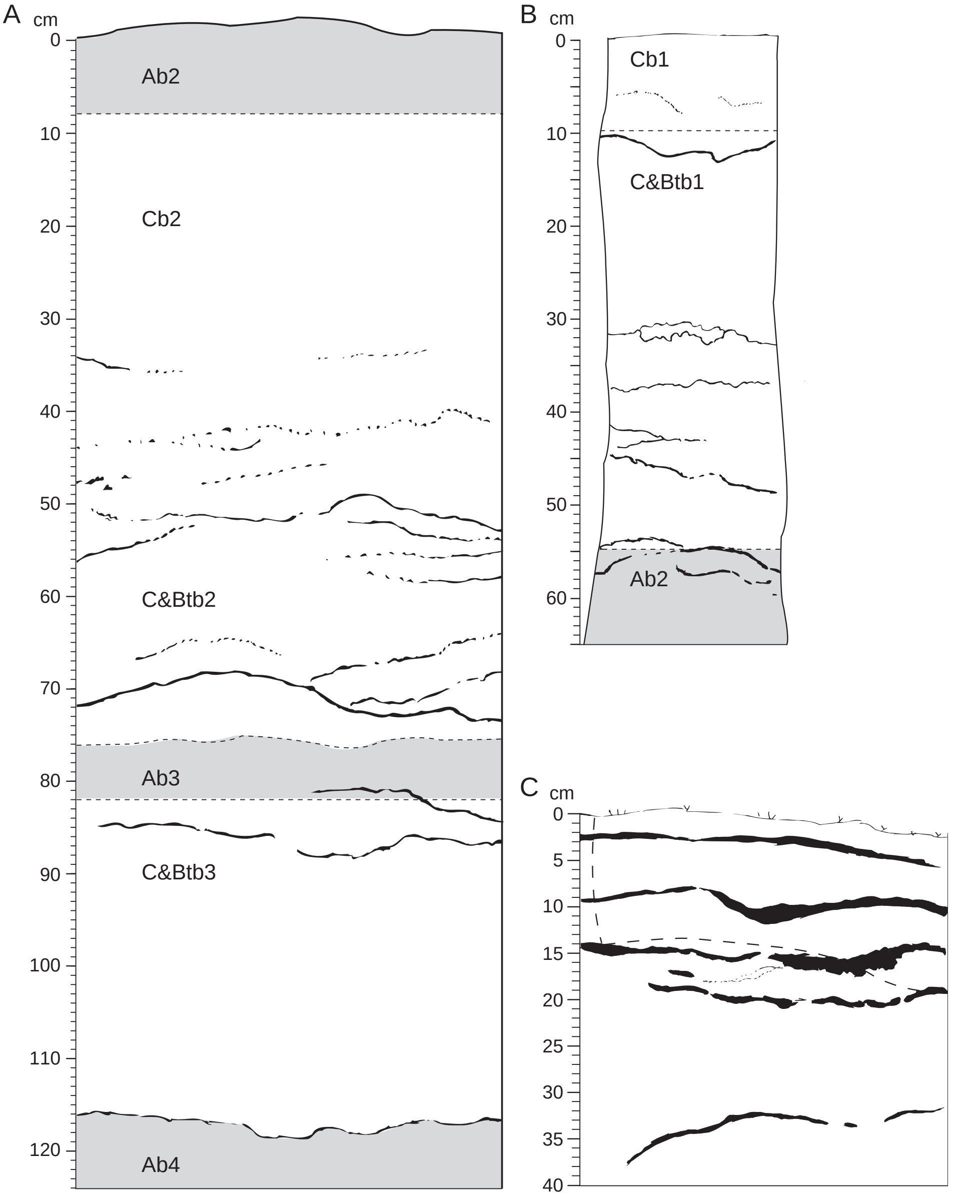

Fig. 4. A) Buried soils with clay bands at the Plant X site (see Fig. 2 for radiocarbon dates from this section). Note presence of clay bands in the Ab3 horizon and at the b3/b4 boundary. B) The younger buried clay-band soils at the Cage West site. Note clay bands in the lower C&Btb1 horizon welded to the Ab2 horizon. C) The older buried clay bands at the Cage West site within a continous Bt horizon, producing a compound Bt&Btb3 soil (see Fig. 2 for radiocarbon dates from this section).

typical number of lamellae ranges from 3 to 12, but as few as 1 to as many as 30 were seen. As described below, some lamellae bifurcate, explaining why the number can vary over a short horizontal distance (few centimeters).

Most lamellae are 2–10 mm thick. Thin lamellae (1–2 mm) tend to be discontinuous. A few lamellae are thicker than 10 mm, up to 15 mm at the Bedford Ranch and Shifting Sands sites in the Andrews Dunes (Table 1; Fig. 5B). The lamellae

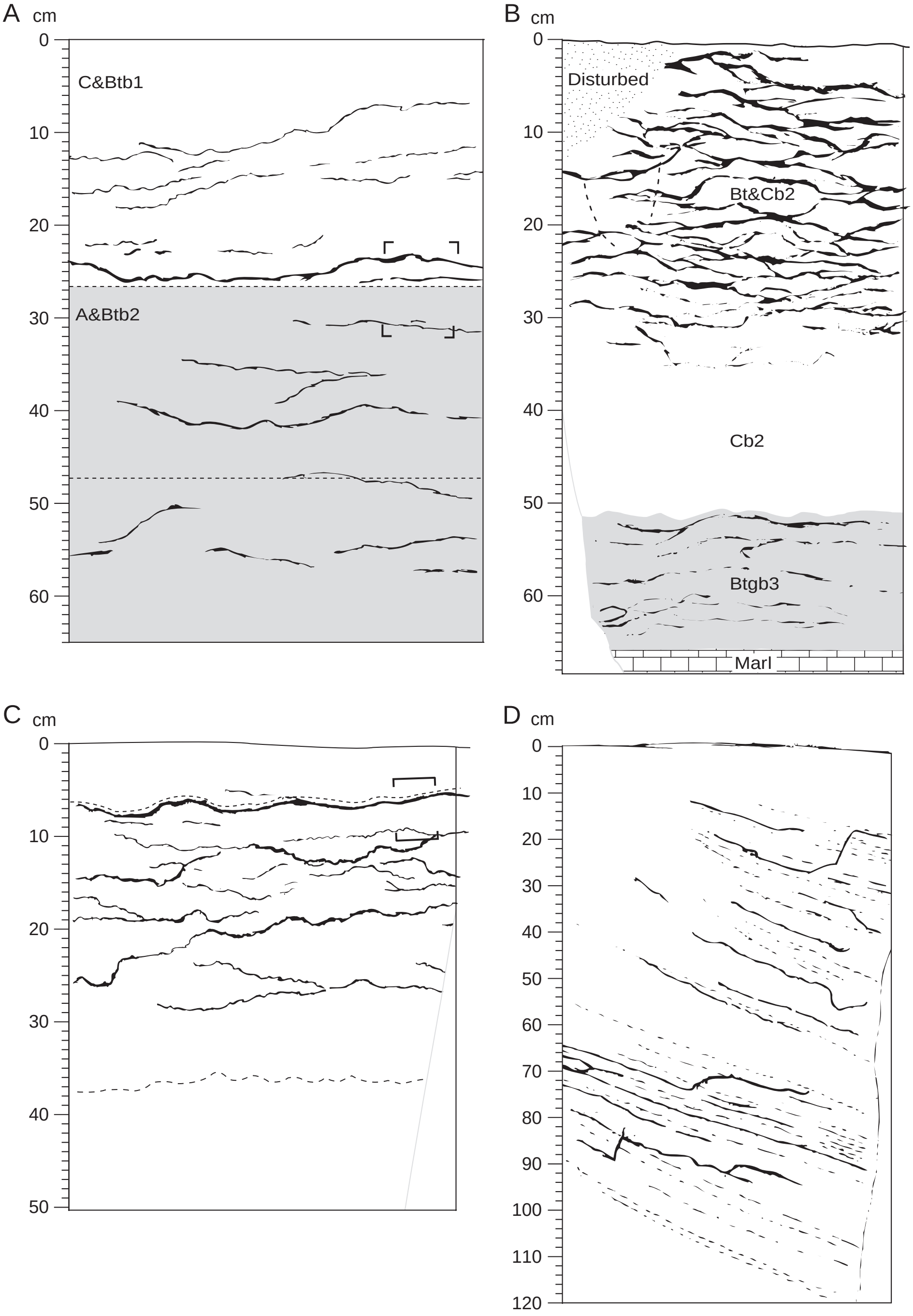

Fig. 5. A) The younger buried clay-band soils at the Rabbit Road Northeast site showing multiple clay bands in the lower b1 and buried A horizon of the b2 soil. B) The multiple clay bands and buried Bt&Btg soil at the Bedford Ranch site. Note that in the thick section of clay bands, the upper bands are thicker than the lower bands. Artifacts dating to ~8000 years BP were found among the multiple clay bands. C) The older buried clay bands at the Rabbit Road Northeast site, showing the compound Bt&Btb3 soil (see Fig. 2 for radiocarbon correlation for this section). D) Multiple clay bands following bedding planes at the Cage East site. Some bands were translocated or were connected by post-burial processes (see Fig. 6B for photomicrograph of lamellae).

are usually subhorizontal and tend to be wavy (e.g., Figs. 4A and 5A,B,C). In soils with thicker and more numerous lamellae, some variation with depth in lamella morphology, thickness, and spacing is apparent. At Bedford Ranch, the upper lamellae are 5–12 mm thick, spaced 4–5 cm apart, but the lower lamellae are 3–7 mm thick, spaced 1–3 cm apart (Fig. 5B). A similar morphology was observed in the main blowout at Shifting Sands, but the b1 soil in the east blowout exhibited the opposite relationship (i.e., the lamellae are thicker with depth) (Table 1). At the Ted Williamson site in the Lea-Yoakum Dunes, the upper 3 to 4 lamellae are 5–15 mm thick but the 8 to 10 lamellae below are in the 2–5 mm range (Table 1). In the Muleshoe Dunes at the Cage West site (Bt&Cb3 horizon; Table 1) and at Rabbit Road NE (Bt&Btb3 horizon; Table 1) the upper lamellae also are thicker than the lower lamellae (Figs. 4C and 5C). Rabbit Road SW (Bt&Cb2 horizon; Table 1), however, exhibits ~25 lamellae, but no systematic variation with depth. Gile (1985, p. 205) describes a similar situation for lamellae soils of his “Birdwell surface.” Locally, thicker lamellae bifurcate into two or more thin lamellae. At Bedford Ranch, lamellae 10–15 mm thick subdivide into lamellae 1–3 mm thick (Fig. 5B). At the Milnesand site, one lamella 25 mm thick, bifurcates into ~12 lamellae 1–2 mm thick (Table 1).

Lamellae usually are found along bedding planes in sections where bedding is well-preserved, which is usually in fresh or minimally weathered surface layers of sand. At Cage East, the lamellae that follow bedding are 1–3 mm thick, usually continuous, and in sets of perhaps 10–20 lamellae (Fig. 5D; Table 1). In sections where lamellae formed along bedding planes the lower part of these zones locally exhibit lamellae that are wavy and cross cut bedding (Fig. 5D) (see also Gile (1985, pp. 103–106).

Despite their easy recognition in the field, most of the lamellae display relatively little increase in clay content compared to adjacent horizons, a characteristic of the Muleshoe Dunes noted by Gile (1979, 1985). An increase of 2–4% is typical (Table 2; also indicated by Gile, 1979, 1985) although a thick lamella at the Tatum site had 11% more clay than the overlying sand (Table 2).

4.3. Variability of lamellae through dunes

Lateral variability of lamella morphology across a dune was documented at four sites. Gile (1985, pp. 99–109, 205) describes and discusses lamella variability down the side of a dune. He reports an increasing number of lamellae and thickening of lamellae down slope. The lamellae are in stratified sands and the down-slope increase in lamella development is attributed to lateral water movement along bedding planes just below the surface of the dune. Down slope variability in lamellae morphology was not observed in the present study.

Parent material thickness or position below a sloping surface or both affected B horizon morphology at two sites. At Rabbit Road SW, on the north side of an exposure, sand 165 cm thick contains ~25 lamellae, 5–15 mm thick, but to the south where the sand layer is only 70 cm thick, the soil contains an A–Bt profile with continuous argillic horizon. This contrasts with a buried soil at the Ted Williamson site (Fig. 3A). At its thickest, the soil with the lamellae is ~2.5 m. The lamella zone is ~110 cm thick with 10–14 lamellae, 2–15 mm thick. Toward the margin of the dune (over a lateral distance of ~5 m), 1) the lower 4 or 5 lamellae thin to 3–5 mm, then 2) the upper 3 or 4 lamellae disappear and the lower lamellae thin to 2–3 mm, then 3) there are 1–2 lower lamellae, 1–2 mm thick, and then 4) the lamellae disappear in a Bw horizon. The lamellae are subhorizontal throughout the exposure.

At the Shifting Sands site (Fig. 3B; Table 1) a buried dune contains a soil with both a continuous Bt horizon and a lamella soil. At the highest part of the buried dune is a continuous Btb (120 cm thick), over a lamella zone 30 cm thick with ~12 lamellae (many discontinuous), 1–2 mm thick. Downslope the continuous Bt thins to 50 cm and also exhibits 6 lamellae 3–5 mm thick (becoming a Bt1&Btb1 horizon), the lamella zone thickens to 50 cm, and the number of lamellae increases to ~25–30, 3–5 mm thick. At the lowest end of the section, the soil is a strongly expressed Bt horizon including a Bt1 25 cm thick. The overall impression is of the lamellae and a continuous Bt horizon merging or welding downslope to form a thinner but more strongly expressed Bt horizon.

5. Micromorphology of the lamellae

The lamellae and argillans in the interlamella zones express similar micromorphological features in all thin sections. The samples are sandy with irregular pores. They have a bridge to coat-and-bridge structure, and the argillans are commonly microlaminated, especially when bridging grains and filling pore bottoms (Fig. 6A, B). Argillans cover more sand grains within lamella zones, but argillans are found outside the lamellae. Considerable variability is apparent in the expression of the argillans, however. Lamellae in all of the slides express generally common grain coats, with the older soils (those with more time to form) exhibiting somewhat higher values in percent grain coats (Table 3). Grain coats are abundant in the Cage East and Rabbit Road SW lamellae, but abundant to many in all other (and older) soils. Lamella appearance is considerably more variable. Argillans are thin and non-laminated in the latest Holocene lamellae at Cage East (Fig. 6B). Argillans in the middle to late Holocene lamellae at Rabbit Road SW are also thin and exhibit some microlaminations, but are largely unlaminated. The argillans are thicker and almost entirely laminated in the older soils (Fig. 6A).

The greatest variation in the micromorphology of argillan development can be seen in the distribution characteristics of the lamellae (Table 3A). The younger soils exhibit only grain irregularities and some grain caps. The argillans are much more complex in the older soils (Table 4). The lamellae at Shifting Sands, Ted Williamson, and Bedford Ranch all exhibit grain irregularities, grain caps, pore-bottom infillings, and bridges between grains. The distribution of lamellae in the Bt&Btb3 horizon at Rabbit Road NE is somewhat unusual relative to the distribution in the other slides (Table 4). The

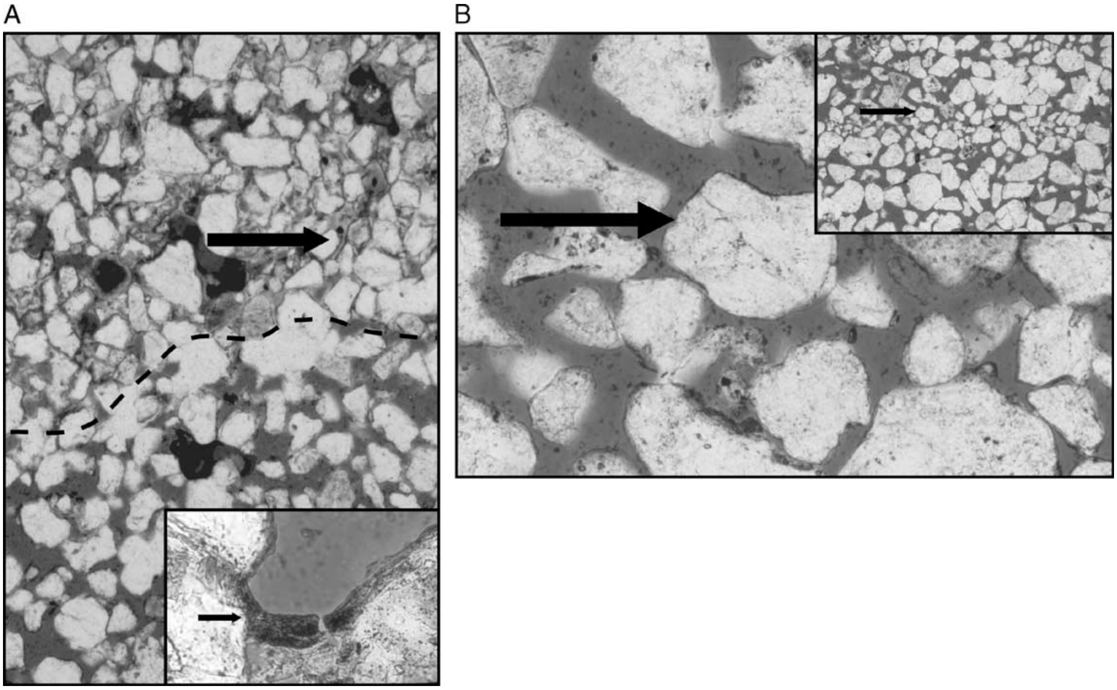

Fig. 6. Photomicrographs of clay bands. A) Typical characteristics of illuvial clay comprising clay bands, in this case at the Ted Williamson site (see Fig. 3A for macromorphology). The clay band is above the dashed line, and the interband is below. Large arrow (0.6 mm) points to a grain that has thick clay coats on it. The inset shows a strongly microlaminated and thick pore filling, arrow 0.03 mm. B) A youthful clay band along a bedding plane at Cage East (see Fig. 5D for macromorphology). Thin clay coats are concentrated in a bedding plane. Inset shows that the clay is concentrated in the upper portion of a lens of very fine sand. Arrows point to same grain capped with clay at high and low magnification. The large arrow is 0.2 mm long and the small arrow is 0.6 mm long.

characteristics are bimodal, with either simple grain irregularities (40% of grains) or the full suite of argillan characteristics (57%).

The interlamella zones contain illuvial clay and these argillans express developmental trends generally similar to the lamella zones (Table 3B). The characteristics of the grain coats are almost uniformly more poorly expressed and have lower values than the lamella counterpart in each slide, however. Grain coats are generally common in most soils; an exception being Bedford Ranch, which had few grain coats. Most of the soils have largely non-laminated argillans. In contrast are two exceptions among the older soils–Ted Williamson and Shifting Sands–which exhibit argillans that are entirely laminated. The values for distribution are lower in the younger soils; higher in the older ones (Table 4). And similar to the characteristics of the lamella zone, the interlamellae of the Bt&Btb3 at Rabbit Road NE exhibit a bimodal distribution. Most (75%) are simple grain irregularities.

6. Stratigraphy and geochronology

The late Quaternary eolian sands of the Southern High Plains are composed of multiple layers of sand, separated by buried soils. Most of the soils with lamellae are buried. The following discussion of late Quaternary stratigraphy and dating of the dune fields and sand sheets (including all radiocarbon ages) is summarized from Holliday (2001).

6.1. Muleshoe Dunes

The Muleshoe Dunes are composed of a late Pleistocene/early Holocene layer (locally divisible into two or three distinct subunits), an early-to-middle Holocene layer, and late Holocene deposits (up to three individual layers in any one section, but probably more based on dating) (Fig. 2) (Holliday, 2001). Correlations with the work of Gile (1979, 1981, 1985) are presented in Fig. 2.

The oldest soils with lamellae in the Muleshoe Dunes vary in degree of development, in part depending on whether or not they were buried. In buried positions (b3 soil at both Cage West and Rabbit Road NE sites; Figs. 2, 4C, and 5C) the soil exhibits lamellae within a continuous Bt horizon (~12 lamellae, 3–8 mm thick at Rabbit Road NE; up to 5 lamellae 4–8 mm thick at Cage West; Table 1). At the Cage West site a sand sheet with the b3 soil (Fig. 2) rests on lake muds deposited ca. 14,300 ^{14}C years BP and subsequently altered by soil formation. The sand sheet was altered by some pedogenesis (formation of both lamellae and a continuous Bt horizon in the b3 soil; Fig. 4C; Table 1). At the Rabbit Road localities the b3 soil was buried below muds dated to ca. 7600 ^{14}C years BP (b3 in Fig. 2; Table 1). The b3 soil formed in the sands at Cage West and Rabbit Road (Fig. 5C) thus had about 7000 ^{14}C years to form. The unburied sheet sand, exposed at the Mitchell locality of the Clovis site (Fig. 1), is < 1 m thick with stronger continuous Bt expression but no lamellae. This deposit yielded an extensive assemblage of Folsom artifacts (11,000–10,000 ^{14}C years BP; Boldurian, 1990; Holliday, 1997a, 2000b). The sand sheet, therefore, was in place by 11,000 ^{14}C years BP and stabilized before ca 7600 ^{14}C years BP. For this oldest soil in the Muleshoe Dunes, pedogenesis must have begun prior to ca. 7600 ^{14}C years BP, perhaps as early as 11,000 ^{14}C years BP, and continued through the Holocene. This confirms Gile's (1985, pp. 60, 62) estimated the age of 13,000–7000 ^{14}C years BP.

The next younger soil in the Muleshoe Dunes is represented at only one site. The b2 soil at the Rabbit Road site SW locality (Fig. 2; Table 1) is 165 cm thick with ~25 continuous lamellae 5–15 mm thick, resting on lake muds dated to ca. 7600 ^{14}C years BP (confirming Gile's initial assessment of a middle Holocene age). The duration of soil formation is unclear, but it likely lasted through much of the Holocene, based on age estimates of < 1000 ^{14}C years BP for overlying sediments and soils (discussed below); allowing perhaps 6000 to 7000 radiocarbon years for pedogenesis.

Late Holocene deposits and soils are extensive throughout the Muleshoe Dunes (Fig. 2). A number of radiocarbon ages are available for these deposits, demonstrating at least three phases of eolian sedimentation between 5000 and 1000 ^{14}C years BP and three phases of eolian sedimentation since ca. 1000 ^{14}C years BP (Holliday, 2001). The surface layer of sand in all exposures is considered essentially modern (20th Century) because it exhibits little to no evidence of pedogenesis or weathering and because locally it buries modern artifacts and structures (see also Gile, 1985, p. 52). The buried soils exhibit simple A–C profiles or minimally expressed lamellae. Some of these soils buried by the 20th Century deposits (Fig. 2) probably formed in the active dunes reported in the 19th century (Muhs and Holliday, 1995). The late Holocene soils with lamellae are not directly dated by radiocarbon, but because sediments dating between 5000 and 1000 ^{14}C years BP are relatively rare and the deposits < 1000 ^{14}C years BP are ubiquitous (Holliday, 2001), most of the lamella soils probably formed in less than 1000 years, and some likely in a few hundred years.

6.2. Lea-Yoakum Dunes

The sands of the Lea-Yoakum Dunes are relatively thin and discontinuous (Holliday, 2001). Most of the eolian sediments are late Pleistocene/early Holocene or late Holocene in age, but only one traceable soil-stratigraphic unit with lamellae was identified: a late Pleistocene/early Holocene sheet sand commonly < 1 m thick. Most exposures exhibit a buried A–Bt or A–Bt–C profile with either continuous argillic-horizon morphology or lamellae (Milnesand and Williamson sites; Table 1). The buried soil at Milnesand is truncated but exhibits a lamella 25 mm thick that bifurcates into ~12 lamellae, 1–2 mm thick. The section at the Williamson site, as discussed above, is on the flank of a paleodune and therefore provides only a minimum figure for lamellae (~14, ranging from 2–15 mm thick) (Table 1). The lamella zone at the Milnesand and Williamson sites both produced large collections of artifacts that date the sediment to ca 10,000 ^{14}C years BP (Holliday, 1997a, 2000b). The soils at the two sites are buried by unweathered or minimally weathered sands, indicating that the lamella zone, at least at Williamson, formed through most of the Holocene. Lamella formation thus lasted ≥8000 radiocarbon years.

6.3. Andrews Dunes

The Andrews Dunes were first studied by Green (1961), who included them as part of the Monahans Dunes, which are located in the Pecos River valley to the west. Green (1961) identified nine stratigraphic units (Units I–IX). Unit VIII includes “thin darker colored” “argillaceous laminae” (Green, 1961, pp. 31, 32) following bedding planes. Green describes no other eolian sands with argillaceous laminae, however, so his Unit VIII is considered to include the prominent lamella zones at the Shifting Sands and Bedford Ranch sites (Fig. 5B; Table 1). This interpretation is supported by the stratigraphic relationship of the lamella soils at the two sites to eolian sand units otherwise identical to Green’s stratigraphic scheme. At the Shifting Sands and Bedford Ranch sites, Unit VIII is 1–2 m thick with dozens of lamellae 5–25 m thick (Table 1; Fig. 5B). Unit VIII at Bedford Ranch produced an extensive archaeological collection of Firstview artifacts (ca. 9400–8300 ^{14}C years BP) (Holliday, 2000b) and Shifting Sands yielded Folsom artifacts (ca. 10,900–10,000 ^{14}C years BP) (Hofman et al., 1990; Holliday, 1997a, 2000b). The lamella zone at Shifting Sands is covered by fresh, unweathered, probably Historic eolian sand, indicating that the lamellae had ~10,000 radiocarbon years to develop. Ash and charcoal were collected from the top of the lamella zone at Bedford Ranch and radiocarbon dated to ca. 2320 ^{14}C years BP (Holliday, 2001). This date provides an upper limit for lamella development because the burning post-dated formation of the lamellae. These data are indicative of ~7000 ^{14}C years for lamella development.

7. Discussion and conclusions

The data gathered for this study confirm some components of the evolutionary sequence for lamella development proposed by Gile (1979, 1985) for the central Muleshoe Dunes of the Southern High Plains. This study builds on that previous work by providing numerical age control on rates of soil development based on radiocarbon and archaeological dating, and a broader, regional perspective on lamella development based on work elsewhere in the Muleshoe Dunes as well as in two other major dune systems in the region. Moreover, this study provides additional insight into the broader issue of rates and mechanisms of lamella development.

Most of the lamellae in the study area are believed to be pedogenic for several reasons (modified from Gile (1979):1002). 1) They occur in the dunes in the same position as Bw and Bt horizons, i.e., in the upper part of the parent material below an A horizon and, under shinnery oak, below an E horizon. 2) They tend to parallel the surface and typically vary in morphology as the surface topography varies, i.e., they form a catena. 3) In exposures with well-preserved bedding the lamellae locally cross-cut these structures, i.e., they are post-depositional features or at least underwent post-depositional modification. 4) Their micromorphology is indicative of clay illuviation, although minimally in the youngest soils. Among some sets of lamellae, the lower ones are superimposed over buried A horizons; further indication of clay translocation.

The most likely source of the clay in the lamellae is probably aerosolic dust, which is abundant in the region (Orgill and Sehmel, 1976; Holliday, 1987a) and known to be important in soil genesis (Syers et al., 1969; Gile et al., 1981; Holliday, 1988; Reheis et al., 1995; Simonson, 1995; Mason and Jacobs, 1998). The clay likely enters the sand parent material via two mechanisms. One processes is that the sand is deposited first, then the clay is deposited as dust on the surface and subsequently translocated by water from precipitation. Our data from Cage East raises another possibility. The clay at Cage East is associated with thin lenses of very fine sand (Fig. 6B). The layers of clay may be primary deposits of dust accumulated as the sand accumulated; the dust representing the end of a fining-upward sequence of fine sand to very fine sand to clay (observed in young, unweathered sections such as Cage East), resulting from fluctuations in wind speed and wind energy. The clay is then in place for subsequent translocation. That is, rather than ending up along the bedding plane, the clay starts along a bedding plane and is then slowly translocated downward. Incipient movement of clay in the Cage East section supports this interpretation. Moreover, Cage East and other sections with multiple lamellae along bedding planes are very young (late Holocene if not Historic) and seem unlikely to contain abundant secondary clay. Schaetzl (1992) recognized an identical situation in a dune exposure in northwest Michigan and invoked an identical interpretation.

Gile (1979, p. 1002) suggested that lamellae formation was controlled, at least in part, by changes in particle size and also as a function of the wetting front (processes also noted and described by researchers working in other areas, e.g., Torrent et al., 1980; Schaetzl, 1992, among others). Data from the present study provide some support for this interpretation. Comparisons of the non-clay fractions in the lamellae and in the inter-lamellae zones shows that some fractions are slightly higher in the lamellae (e.g., Bedford Ranch, Bt&C1b2; Shifting Sands, main blowout, Bt&Cb1; and Cage West, C&Btb1) or that there is a significant difference in the sand content between the lamellae zones and non-lamellae zones (e.g., Cage East, Cb1). The wetting-front hypothesis could not be tested, but is a reasonable explanation in this semi-arid environment. During and after rainfall on the sand the water enters the parent material and carries clay in suspension through the solum. As the penetration slows and the water evaporates, the clays are left behind.

The lamella chronosequence for the Muleshoe Dunes proposed by Gile (1979, 1985) was partially confirmed, but also expanded upon and modified. Very generally, lamellae increase in number and thickness through time as the lamellae-forming processes are allowed to operate. Soils with minimally expressed lamellae (up to 6 or 8 lamellae no more than 2 mm thick and locally discontinuous) (b1 soil at Rabbit Road SW and NE, and Cage West, and b2 soil at Plant X, upland and lowland; and IX at Bedford Ranch) formed in sediments deposited within the past 1000 years and buried withing the past few hundred years. Sediments with no or minimal pedogenesis (i.e., simple A–C profiles or lamellae along bedding planes) were deposited in the 19th or 20th centuries. Soils that formed through much of the Holocene (i.e., for > 5000 to at least 8000 radiocarbon years) include the b2 soil at the Rabbit Road SW locality in the Muleshoe Dunes and the b1 soil at the Bedford Ranch and Shifting Sands sites in the Andrew Dunes. The lamellae in these soils are thicker and more numerous than those in the younger sands, some forming spectacular exposures (Fig. 5B). Micromorphologically, however, lamellae in the b2 at Rabbit Road SW, are significantly less well expressed and are much more similar to the late Holocene lamellae.

The soils at the Andrews Dunes localities represent another stage in lamella development with formation of twice the number of lamellae as observed anywhere in the Muleshoe Dunes, but within the early to middle Holocene. These soils may not be exactly comparable with the chronosequence in the Muleshoe Dunes because they are in a warmer, drier environment, but do provide an indication of the trend in soil development. They appear to represent a continuation of the evolutionary sequence of lamellae first proposed by Gile (1979, 1985). The lamella soils at Bedford Ranch and Shifting Sands have no equivalent in Gile's scheme.

The thin section data generally reflect the lamella chronosequence that is apparent macromorphologically. Argillans in the late and middle Holocene soils are more poorly expressed than those that formed through the early and middle Holocene. The thin section data do not fully convey degree of lamella development, however. The Bt&Cb2 horizon at Rabbit Road SW, developed for perhaps 6000–7000 radiocarbon years and has ~25 lamellae, but in thin section is no more developed than the lamellae that follow bedding planes in the latest Holocene soils at Cage East (Cb1 horizon). They have somewhat fewer grain coatings, mostly nonlaminated, and are composed largely of simple grain irregularities and some grain cappings. More clay is distributed through the older soil (i.e., there are more lamellae), but the characteristics of the argillans are not more strongly expressed. The soils that formed for 7000 to 8000 radiocarbon years during the latest Pleistocene (Rabbit Road NE, Bt&Bt horizon) or from the early into the late Holocene (Ted Williamson, C&Btb1 horizon; Shifting Sands, Bt&Cb1 horizon; Bedford Ranch, Bt&Cb2 horizon) all exhibit much stronger expression in argillans: more of them, mostly laminated, and much more complex.

Argillan development, at least in the Bt&Cb2 at Rabbit Rd SW, seems to be independent of the number or thickness of lamellae. The expression of clay-coat characteristics may be due to environmental factors as well as time. More arid conditions with increased frequency of thunderstorms in the middle and late Holocene (e.g., Knox, 1983) could result in flushing of clay to variable depths, but not allowing clays to be repeatedly concentrated in any one position. The latest Pleistocene and early Holocene apparently was characterized by more effective precipitation that was more evenly spread out. This may have allowed clays to be concentrated within particular zones, thereby enhancing development of argillans.

The similarities in field expression of the lamellae at Rabbit Road SW and at Bedford Ranch and Shifting Sands (i.e., several dozen lamellae of moderate thickness) raises another possibility. Lamella development may start as an increase in the number and perhaps thickness of the lamellae but not in stronger expression of argillans. Eventually, however, an internal pedogenic threshold (Muhs, 1984) is crossed whereby the grain coats act to impede downward soil–water movement and sieve out additional clay, building up the argillans; lamella development results in positive feedback for degree of lamella expression in thin section.

Neither hypothesis can be fully examined in this study, however, for two reasons. First, in the Muleshoe Dunes there is no well-dated early to middle Holocene or early to late Holocene soil with lamellae with which to compare the Rabbit Road SW lamellae. Second, and relatedly, the comparisons being made to propose both hypotheses are based on comparisons of soils in two different dune fields (Muleshoe and Andrews) ~200 km apart, each of which is in a somewhat different environment.

The Bt&Btb3 horizon at Rabbit Road NE exhibits a bimodal trend in argillan distribution. This may reflect the combination of illuvial clay in lamellae and illuvial clay in a continuous Bt horizon. The simple expression of clay distribution characterizes the clay in lamellae, whereas the more complex distribution is characteristic of the continuous argillic horizon.

The experimental lamella development index (CB-I) seems to provide a means of expressing lamella development micromorphologically. The soils with more strongly expressed clay illuviation in both macromorphology and micromorphology are those soils with a higher CB-I. As with any semi-quantitative development index, where a variety of characters are assigned a rating and then ultimately summed and expressed as a single value, there are problems of equifinality. That is, a group of characteristics could vary from soil to soil in degree of expression, but the sums of the resulting values could all be similar. Nevertheless, the way the CB-I and other rating systems are defined, they tend to yield higher values for more strongly expressed soils, and thus provide a simple means of comparing relative degree of soil development. We invite other investigators to apply and refine (or discard!) the CB-I.

Gile (1979, 1985) proposed that the next stage of lamella development following formation of thick, multiple lamellae was characterized by clay accumulation between the lamellae, forming a continuous Bt horizon with lamellae (i.e., soils of his Birdwell surface). The data from the current study indicates that in well drained settings the next stage of development is to more and thicker lamellae, but in more poorly drained settings the soils will develop continuous Bt horizons along with lamellae. Soils with a continuous Bt that contains a lamella zone almost certainly started as simple lamella soils. All other soils in this study as well as data from most other studies of lamella in sand clearly show that they form only in essentially clean sand and in well drained settings (e.g., Dijkerman et al., 1967; Gray et al., 1976; Bond, 1986; Schaetzl, 1992; Cooper and Crellin, 1996; Rawling, 2000). The argillic horizons most likely are superimposed on and post-date the lamellae. This change in pedogenic pathway from clay illuviation in discrete lamellae to a continuous Bt horizon probably represents a change in the pedogenic environment. Field observations suggest at least two different scenarios for this change and for the origin of these compound argillic horizons. The high water-table conditions associated with the b3 soils at Cage West and Rabbit Road NE (Figs. 4C and 5C) likely post-date lamella formation. One scenario for the origin of the Bt&Bt horizons is a two-step process whereby: 1) these sites were well drained during lamella genesis, but then 2) the water table rose, perhaps supporting heavier vegetation growth with concomitant bioturbation and formation of a continuous Bt horizon. Formation of the argillic horizons overlapping the lamella zones in the Muleshoe Dunes may signal a shift to heavier vegetation. In the Yardang exposure at Shifting Sands, the continuous argillic horizon clearly merges with the lamella zone (Fig. 3B). Most of the data for this study and others shows that lamellae tend to form at depth, suggesting that the b1 in the Yardang exposure was eroded, and perhaps more heavily vegetated, before the argillic horizon formed and partially engulfed the lamella zone.

Little evidence was found to indicate that lamellae “grow” into continuous argillic horizons. In all sections with lamellae embedded in an argillic horizon, the individual lamella are a few millimeters to a few centimeters thick and separated by a few centimeters. At the Tatum site, the C&Bt horizon contains a zone of illuvial clay up to 10 cm thick (and more clay than a typical lamella). Is this a thick, well developed lamella or a thin “typical” continuous argillic horizon? This section was the only one to provide any indication that some lamellae thicken to the extent that they become a more usual argillic horizon.

Topography and thickness of the parent material appear to have some influence on lamella expression. An overlap between a continuous Bt horizon and lamellae following beveling of a dune surface was noted above. At Rabbit Road SW, the thick lamella zone of the b2 is in the thickest part of the paleodune. As the dune thins the lamella zone becomes a continuous Bt horizon. In contrast, at Ted Williamson the lamella zone of the b1 was likewise best expressed in the thickest part of the paleo-dune, but as the dune thins the lamellae simply become thinner and fewer in number, probably due to decreased infiltration because of run-off on the sloping dune surface. At Ted Williamson, the weaker lamellae are in almost 2 m of sand and start at > 150 cm below the surface, whereas at Rabbit Road, the Bt horizon on the dune flanks is in 70 cm of sand.

Some post-burial alterations related to lamella development were observed in a few sections. Lamellae were observed within buried A horizons at some localities (Figs. 4A,B and 5A). These lamellae probably are related to lamella formation in the overlying soil, thus representing welding with the overlying soil, because 1) lamellae are absent in the horizon below the buried A, and 2) lamellae with similar morphologies are present in the immediately overlying soil. Gile (1985, pp. 103–106) also describes and illustrates lamellae in a layer of eolian sand penetrating an underlying soil.

In summary, several factors affect lamella morphology in the sand dunes of northwest Texas and eastern New Mexico, providing further evidence of pedogenic equifinality in their genesis (as discussed by Rawling, 2000). Processes of clay infiltration over time result in increasingly better expressed lamellae through time. This age relationship is apparent in terms of the number and thickness of lamellae and in the distribution and appearance of argillans in thin section. A lamella development index (CB-I) may be a useful means of expressing degree of argillan development. Very limited data suggests that the number and thickness of lamellae increases first (i.e., the macromorphology), followed by increasing development of argillan characteristics (i.e., micromorphology). The rates will be affected by the availability of aerosolic dust. Other factors are also important. Particle-size variation exerts some influence on where the lamellae form. Changes in particle-size, both subtle and dramatic, appear to cause clay to "hang up" and form a lamellae at down-profile textural changes. Seasonality and intensity of precipitation may play a role in lamella morphology. Position in a dune seems to be important, with the strongest expression of lamellae in the center of the dune, where sand is thickest and the ground surface is flat or most nearly level of any part of the dune surface. Lamellae can be useful age indicators, but like many pedogenic characteristics, in any given area or study, considerable data should be mustered regarding variability of soil morphology through time and space before a chronosequence is described.

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