The Blackwater Draw Formation (Quaternary): A 1.4-plus–m.y. record of eolian sedimentation and soil formation on the Southern High Plains

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ABSTRACT

The Southern High Plains of northwestern Texas and eastern New Mexico are mantled by a vast (>100,000 km^2) sheet of Quaternary eolian sediment locally as much as 27 m thick and termed the "Blackwater Draw Formation." These sediments generally fine from southwest to northeast, exhibiting a linear relationship of decreasing sand content and sand size and increasing silt content with increasing distance, indicating the source area to be the Pecos River valley. As many as six well-developed buried soils (2.5YR to 5YR hues, Bt horizons 1–2 m thick, Stage II–III calcic horizons), similar to the regional Paleustalf and Paleustoll surface soils, occur in the formation. The buried soils indicate episodic sedimentation separated by long periods of landscape stability. Eolian sedimentation probably occurred during prolonged aridity, and stability and pedogenesis likely obtained during subhumid to semiarid conditions, similar to those of the late Quaternary. The presence of the 0.62-m.y. Lava Creek B Ash and the 1.4-m.y. Guaje Ash in the formation shows that the deposit accumulated throughout most of the Quaternary. Data from paleomagnetic, thermoluminescence, and radiocarbon studies suggest that each cycle of sedimentation-stability lasted for several hundred thousand years and that the last depositional event occurred at least several tens of thousands of years ago.

INTRODUCTION

This paper is a first approximation of the age, origin, and evolution of the Blackwater Draw Formation, expanding on a summary presented by Holliday and Gustavson (1989). The Blackwater Draw Formation, a sheet-like body of sandy to clayey sediment covering more than 100,000 km^2, is the principal surficial deposit of most of the Southern High Plains of northwestern Texas and eastern New Mexico (Fig. 1); its fertile soils support the lucrative agricultural industry of the region. There has been surprisingly little research concerning the history of the Blackwater Draw Formation, given its extent and economic importance, but the available data nevertheless demonstrate that it is more complex and spans much more time than previously believed.

The Southern High Plains, or Llano Estacado, are an extensive, semiarid plateau covering about 130,000 km^2. The region has a virtually featureless, constructional surface, formed by the eolian deposits of the Blackwater Draw Formation (Fig. 1). These eolian sediments rest on eolian and alluvial deposits of the Ogallala Formation (Miocene-Pliocene) and locally on lacustrine sediments of the Blanco Formation (Pliocene). The otherwise flat High Plains surface is locally interrupted by several dune fields, numerous small basins with ephemeral lakes (playas) in many cases associated with lunettes, and several northwest-southeast–trending dry valleys or draws, which are tributaries of the Red, Brazos, and Colorado Rivers (Holliday, 1985a). The dune fields and lunettes rest on the Blackwater Draw Formation, and the playas and draws are inset into it.

HISTORY OF INVESTIGATIONS

Frye and Leonard (1957, 1965) first described the Blackwater Draw Formation, using the informal term "cover sands," and considered the deposit to be of "Illinoian" age. Frye and Leonard, as well as Brown (1956), concluded that the "cover sands" were of eolian origin, probably derived from the Pecos River valley to the west and southwest. Frye and Leonard (1964, 1965) also recognized a strongly developed soil formed at the surface of the "cover sands" and considered it to be a "Sangamon Soil."

Reeves (1976) proposed the term "Blackwater Draw Formation" to replace "cover sands." Reeves also considered it an Illinoian deposit but noted that the term "Sangamon soil" should not be applied to the regional surface soil because of evidence of multiple periods of soil formation. Reeves (1976, p. 222) also identified a "thin cover of loess" overlying the Blackwater Draw Formation in the northeastern part of the Llano Estacado (Fig. 1).

Several other investigations provide data on the physical properties, age, and origin of the Blackwater Draw Formation. Well-developed buried soils were recognized in the sediments (Brown, 1956; Allen and Goss, 1974; Hawley and others, 1976; Holliday, 1988a; Holliday and Gustavson, 1989), indicating that the formation is composed of a number of individual layers, each deposited episodically. Limited numerical age control, discussed more fully in this paper,

TABLE 1. WEIGHTED MEANS OF ARGILLAN CHARACTERISTICS FROM Bt HORIZONS OF SOILS IN THE TYPE SECTION OF THE BLACKWATER DRAW FORMATION

Soil	% of grains w/argillans	% perimeter coated w/argillans	Thickness (microns)
Surface	55	42	1.7
b1	80	65	2.8
b2	80	65	2.0
b3	85	55	1.9
b4	80	40	2.3

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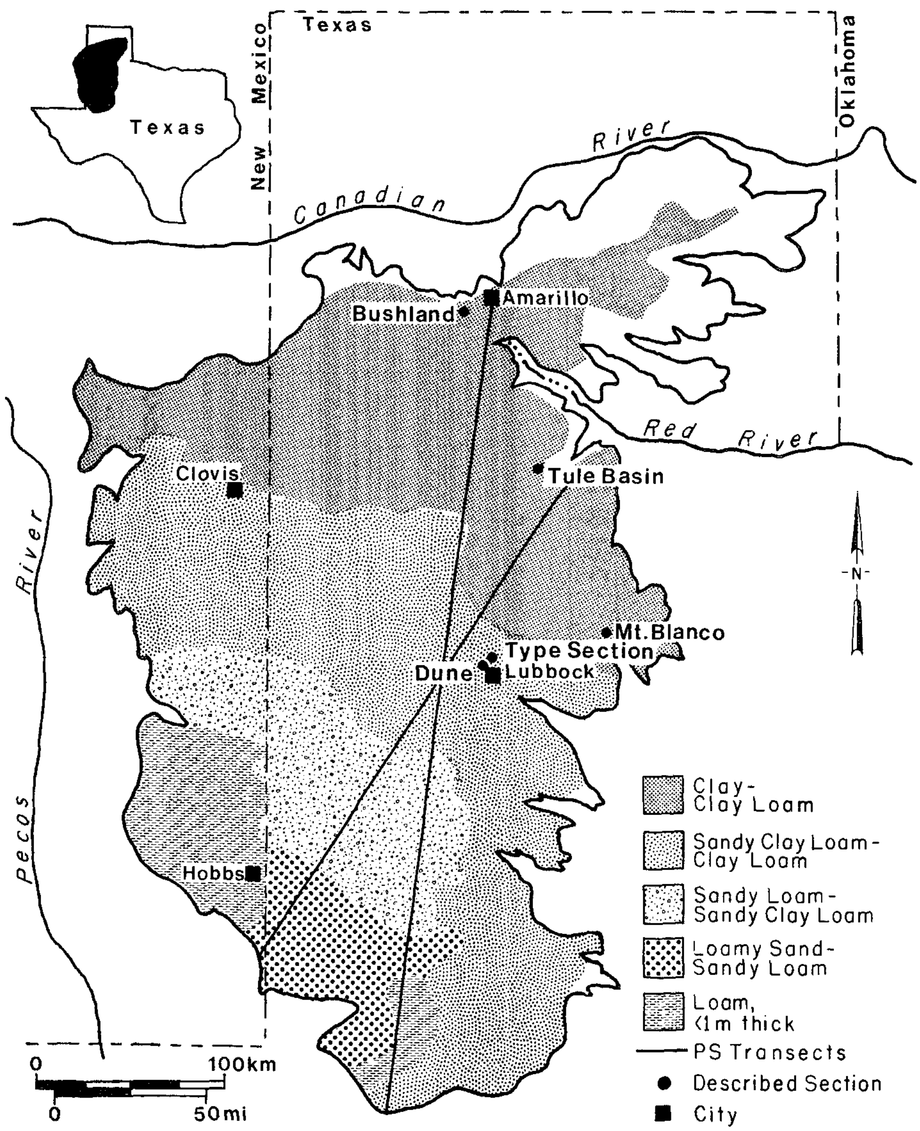

Figure 1. Map of the Southern High Plains, showing the distribution of the Blackwater Draw Formation and progressive fining of surface soils to the northeast. Also shown are all localities mentioned in the text, the south-north and southwest-northeast transects of particle size (PS) by Seitlheko (1975), and selected rivers and cities. The area of clay loam to clay soils is the area of "loess" defined by Reeves (1976, Fig. 1).

suggests that deposition took place throughout much of the Pleistocene (Holliday, 1984, 1988a; Machenberg and others, 1985; Patterson and others, 1988).

Seitlheko (1975) provided quantitative data on textural variation of the surface layer of the Blackwater Draw Formation. He demonstrated that the upper bed fines from southwest to northeast, supporting the hypothesis of eolian origin from the Pecos Valley (Fig. 1; see Sedimentology discussion below). Furthermore, Seitlheko showed that the silty and clayey surficial sediments in the northeastern portion of the area are the result of this downwind fining and are not a separate "loess cover."

METHODS

Good exposures of the Blackwater Draw Formation are limited, but five were examined as part of this study. (1) The type locality for the Blackwater Draw Formation, established by Reeves (1976) near Lubbock, Texas (Fig. 1), was described because this was not done when the formation name was proposed and because there appeared to be several buried soils in the section. (2) A radiocarbon-dated lunette, the Dune site, on the north side of Lubbock (Fig. 1), was studied because it buries the surface of and provides minimum ages for the Blackwater Draw Formation (Holliday, 1985a). Sections (3) at Mount Blanco and (4) in the Tule Basin (Fig. 1) were examined because they contain dated volcanic ashes intercalated with buried soils. (5) A site near Bushland, Texas (Fig. 1), originally studied by Allen and Goss (1974), was re-examined because six buried soils are exposed and some pedologic data are already available. Sections were described using standard soil nomenclature (Soil Survey Staff, 1951, 1975; Guthrie and Witty, 1982) (Fig. 2; complete descriptions are presented by Allen and Goss, 1974; Gustavson and Holliday, 1988; and Holliday, 1988a). Stages of morphological development of horizons of carbonate accumulation follow the terminology of Gile and others (1966) as modified by Machette (1985). Reference to individual buried soils in this paper is based on their stratigraphic position below the surface, using their horizon designation postscripts (for example, b1 is the first buried soil, b2 is the second buried soil, and so on; Fig. 2).

Peds were collected from soil horizons at the Blackwater Draw Formation type section, the Blanco section, and the Tule Basin section for thin-section preparation and soil micromorphological characterization (following the terminology of Brewer, 1976). Illuvial clay and carbonate in thin sections from the type locality were further quantified using a technique developed by Holliday (1982, 1988b). Point counts, usually 200, were made for each thin section. Presence or absence of argillans (pedogenic clay films) around each counted quartz sand grain was recorded. When argillans were encountered, the percentage of grain perimeter coated was also estimated. Thickness of the argillans was determined by scanning the slide and measuring a random sample of 20 clay films. Weighted means were calculated for the percentages of the grains with argillans, the percentages of the grain perimeter coated with clay, and the clay film thicknesses for each soil (Table 1). Particles of pedogenic carbonate were also counted.

Seitlheko's (1975) data on textural variation in the Blackwater Draw Formation offer considerable insight into the source and sedimentary history of the deposit and therefore warrant further discussion and manipulation. The following discussion of methods is summarized from Seitlheko (1975, p. 13–18). Samples taken from two transects across the Southern High Plains (Fig. 1) were analyzed for particle size distribution. A south-to-north transect 438 km long included 27 sampling localities, and a southwest-to-northeast transect 392 km long

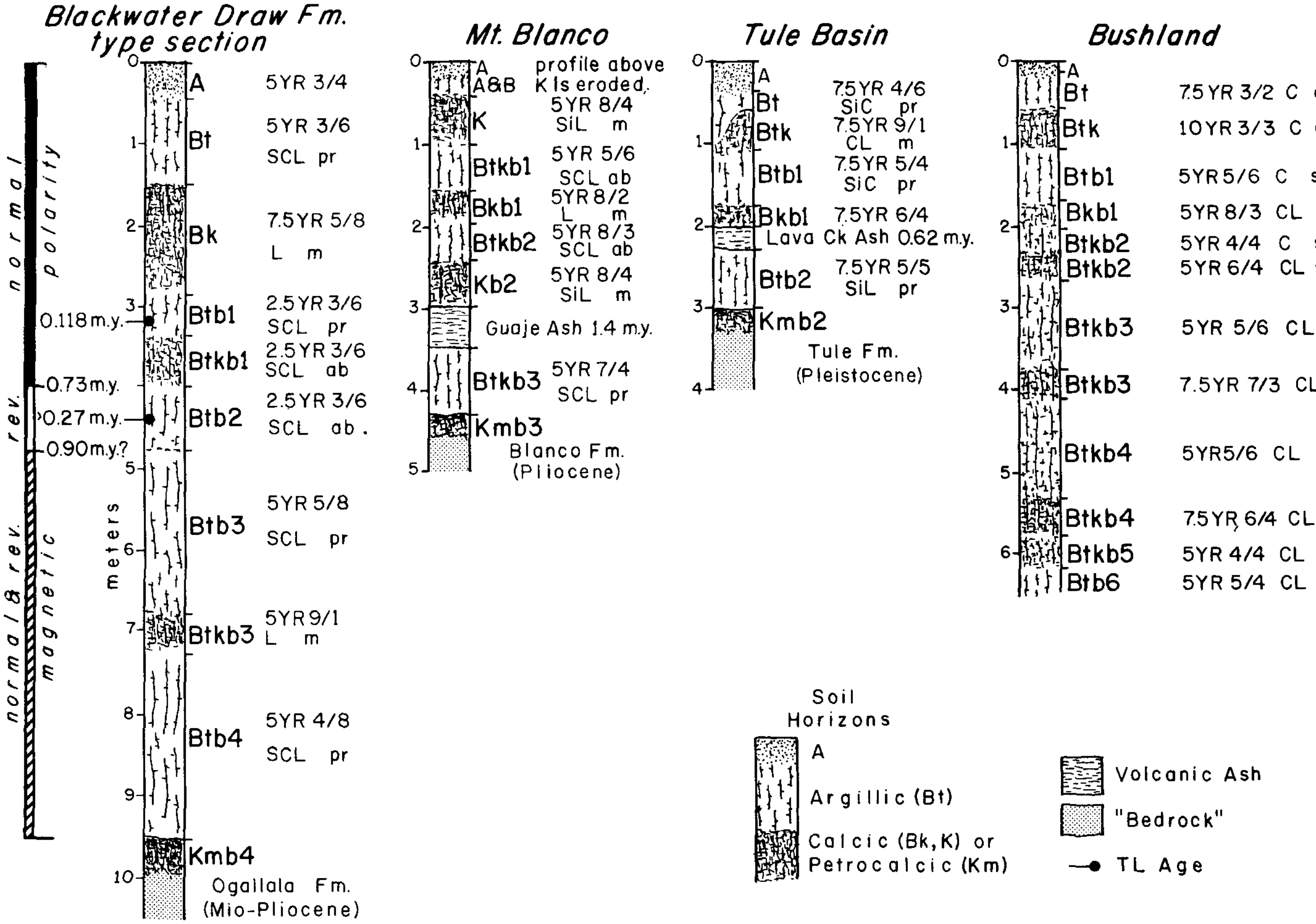

Figure 2. Generalized diagrams of the soil stratigraphy, soil horizonation, and selected soil morphological characteristics from the Blackwater Draw Formation type section, Mount Blanco, Tule Basin, and Bushland (based on descriptions by Allen and Goss, 1974; Gustavson and Holliday, 1988; and Holliday, 1988a). (Key: colors are dry Munsell. Textures are SCL, sandy clay loam; L, loam; SiL, silt loam; SiC, silty clay; CL, clay loam; C, clay. Structures are pr, prismatic; ab, angular blocky; sb, subangular blocky; m, massive.)

had 23 sampling localities. Samples were collected from a depth of approximately 15–25 cm in the upper B horizon of the surface soil. Samples with free $CaCO_3$ were treated with 10% HCl for carbonate removal. The sand fraction (2.0–0.5 mm) was determined by wet sieving, drying, and weighing, and the silt (0.5–0.002 mm) and clay (<0.002 mm) fractions were determined using the hydrometer method. Only the sand and coarse silt fractions were dealt with in Seitlheko's study because most horizons of all of the soils examined contained illuvial clay and possibly illuvial fine silt.

Seitlheko's transects began in the Pecos River valley and thus do not cross the Blackwater Draw Formation at their southern ends, based on geologic maps of the area (Eifler and Reeves, 1976; Eifler, 1976) and soil profile descriptions. These samples (the southernmost four from the south-north transect and the southernmost two from the southwest-northeast transect) are therefore not included in this study. Seitlheko regressed the log of distance from the Pecos River on mean sand size, calculated following Krumbein and Pettijohn (1938). These analyses were recalculated using the reduced data sets (Fig. 3), and several other regressions were performed: distance versus sand percent, log of distance versus sand percent, distance versus mean sand size, log of distance versus mean sand size, distance versus very fine sand (VFS)/silt, and log of distance versus VFS/silt (Table 2).

Samples for radiocarbon dating and thermoluminescence (TL) dating were taken at several sites. Radiocarbon samples were taken from the upper 10 cm of buried A horizons within a lunette that overlies the Blackwater Draw Formation (Holliday, 1985a). Ages were determined on the NaOH-insoluble fraction of the organic matter. The TL samples were taken from the same buried A horizons in the lunette sampled for radiocarbon, from the top of the Blackwater Draw Formation buried by the lunette, and from the upper Bt horizons of soils b1 and b2 at the type section of the Blackwater Draw Formation. The samples were removed in dark shade from within a tunnel excavated 20 cm into the exposure and, still in the shade, immediately placed in black, plastic film canisters and sealed. Analyses were carried out on the polymineralic, 4 to 11 micron (fine silt) particle size fraction. Additive alpha and beta irradiations were effected with ^{241}Am and ^{90}Sr calibrated plack sources. Initial bleach matching was performed with a 240-watt sun lamp, using a glass filter. Contents of U, Th, and K were measured by thick-source alpha counting and atomic absorption. Water content for calculation was estimated as 75% of saturation, and cosmic dose was taken as 0.14 rads/yr.

SEDIMENTOLOGY AND MINERALOGY

The Blackwater Draw Formation varies in texture from sandy in the south and southwest to silty and clayey in the north and northeast. This is apparent from regional soil maps (Godfrey and others, 1973) (Fig. 1) and regional soil studies (Seitlheko, 1975) (Fig. 3; Table 3). Although these data apply only to the surficial deposits, the texture of the Blackwater Draw Formation is quite similar throughout any one vertical section (discussed below). The texture of the original, unweathered deposits composing the formation is not known because an undetermined amount of illuvial clay is present in almost all portions of all layers examined.

On the basis of the fine-grained texture, blanket-like distribution, and fining patterns, the Blackwater Draw Formation appears to represent an accumulation of eolian sediment derived from the Pecos River valley to the south, southwest, and west of the Southern High Plains (Fig. 1). Within the Pecos Valley, potential source sediments include sand, silt, and clay from the modern and ancient Pecos River, the Ogallala Formation, and various Mesozoic and upper Paleozoic clastic rocks. Eolian sand and extensive dune fields blanket the Pecos Valley today, east (downwind) of the Pecos River (Eifler and Reeves, 1976; Eifler, 1976).

The variation in particle size distribution of the Blackwater Draw Formation as a function of distance from the Pecos Valley is marked (Fig. 3). The correlations are very strong for all of the regressions of sand content versus distance (Figs. 3a–3d; Tables 2a and 2b), but the best statistical description, based on the most variation in sand content expressed by the regressions (R^2), and the lowest estimate of variance about the regression line (S), is an arithmetic linear regression along the southwest-northeast transect (Figs. 3c and 3d; Table 2b). The southwest-northeast transect also provides the best statistical description of decrease in the very fine sand (VFS)/silt ratio as a function of distance (Figs. 3e and 3f; Tables 2a and 2b), although it is difficult to determine whether the change in the

TABLE 2a. REGRESSION-EQUATION DATA FOR SAND PERCENT, MEAN SAND SIZE, AND VERY FINE SAND (VFS)/SILT RATIO FROM SAMPLES ALONG SOUTH-NORTH TRANSECT

X	Y	Equation of line	R^2	S	n
Distance (km) from Pecos River (Fig. 3a)	Sand %	Y = 98.46 - 0.19(X)	0.88	8.03	23
LOG (base 10) of distance from Pecos River	Sand %	Y = 284.80 - 99.84(X)	0.80	10.21	23
Distance (km) from Pecos River (Fig. 3b)	Mean sand size (mm)	Y = 0.29 - 0.0004(X)	0.93	0.013	23
LOG (base 10) of distance from Pecos River	Mean sand size (mm)	Y = 0.73 - 0.23(X)	0.93	0.014	23
Distance (km) from Pecos River	VFS/silt	Y = 4.59 - 0.006(X)	0.31	1.03	22
LOG (base 10) of distance from Pecos River	VFS/silt	Y = 11.09 - 3.41(X)	0.34	1.01	22

TABLE 2b. REGRESSION-EQUATION DATA FOR SAND PERCENT, MEAN SAND SIZE, AND VERY FINE SAND (VFS)/SILT RATIO FROM SAMPLES ALONG SOUTHWEST-NORTHEAST TRANSECT

X	Y	Equation of line	R^2	S	n
Distance (km) from Pecos River (Fig. 3c)	Sand %	Y = 101.53 - 0.23(X)	0.94	5.71	23
LOG (base 10) of distance from Pecos River	Sand %	Y = 292.32 - 104.64(X)	0.85	8.86	23
Distance (km) from Pecos River (Fig. 3d)	Mean sand size (mm)	Y = 0.28 - 0.0004(X)	0.94	0.010	23
LOG (base 10) of distance from Pecos River	Mean sand size (mm)	Y = 0.62 - 0.19(X)	0.89	0.013	23
Distance (km) from Pecos River (Fig. 3e)	VFS/silt	Y = 4.04 - 0.006(X)	0.58	0.36	15
LOG (base 10) of distance from Pecos River (Fig. 3f)	VFS/silt	Y = 11.77 - 3.84(X)	0.67	0.32	15

TABLE 3a. PARTICLE SIZE DATA OF SELECTED SAMPLES AT 15-25 CM DEPTH ALONG THE SOUTH-NORTH TRANSECT (FROM SEITLHEKO, 1975, TABLES 4 AND 8)

Sample	Sand %	Silt %	Clay %	Mean sand size (mm)	VFS*/silt	Distance from Pecos River (km)
5c	73	5	22	0.27	6.1	85
8c	72	7	21	0.22	2.5	146
11c	61	8	31	0.20	3.2	191
14c	51	15	34	0.17	2.4	239
17c	49	15	36	0.17	2.7	289
20c	33	17	50	0.13	3.7	332
23c	17	32	51	0.12	2.4	386
26c	25	26	49	0.12	1.7	426

*VFS, very fine sand.

TABLE 3b. PARTICLE SIZE DATA OF SELECTED SAMPLES AT 15-25 CM DEPTH ALONG THE SOUTHWEST-NORTHEAST TRANSECT (FROM SEITLHEKO, 1975, TABLES 5 AND 9)

Sample	Sand %	Silt %	Clay %	Mean sand size (mm)	VFS*/silt	Distance from Pecos River (km)
3c	78	6	16	0.22	..	88
6c	69	4	27	0.22	..	127
9c	68	6	26	0.21	3.7	172
12c	62	13	25	0.18	2.8	219
15c	46	20	34	0.16	2.2	266
18c	31	29	40	0.14	2.0	314
21c	16	31	53	0.14	2.2	360

*VFS, very fine sand.

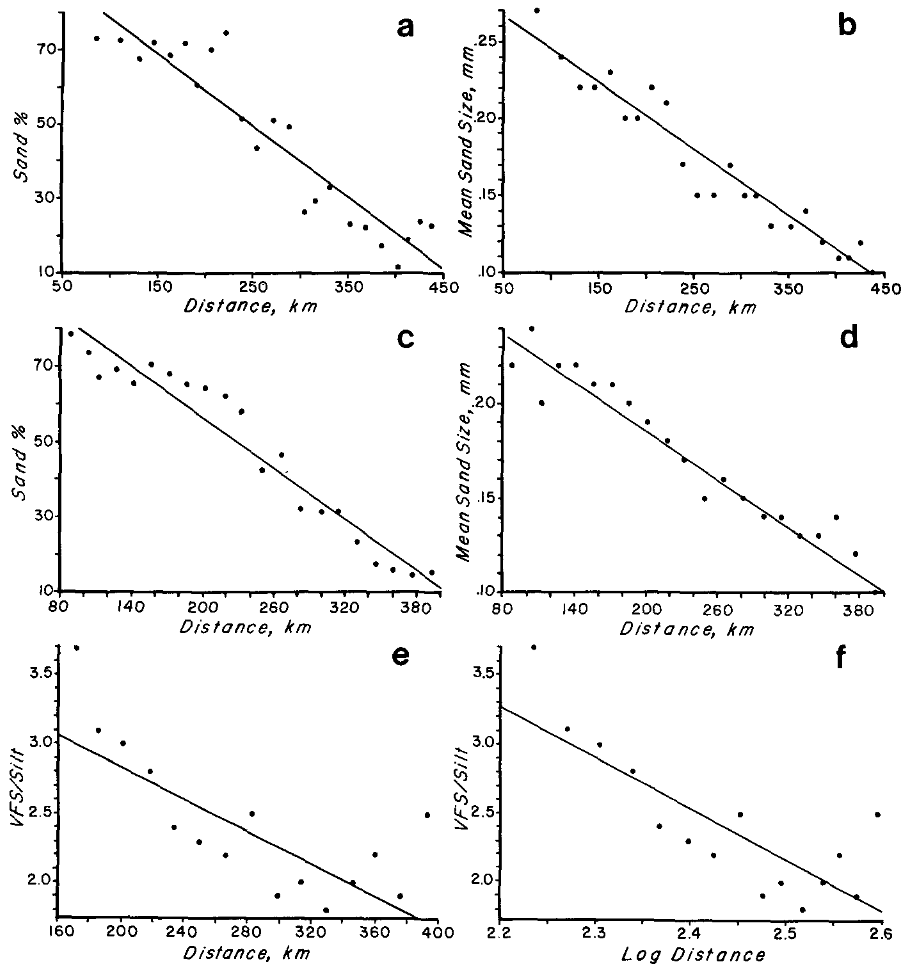

Figure 3. Data plots and regression lines illustrating the relationship of sand content and mean sand size as a function of distance from the Pecos River, for both the south-north transect (a, b) and southwest-northeast transect (c, d), and the relationship of the very fine sand (VFS)/silt ratio as a function of distance and log of distance for the southwest-northeast transect (e, f). See Tables 2a and 2b for regression equations, and Figure 1 for locations of transects.

ratio is best expressed as an arithmetic linear function of distance or as a log linear function. Studies of loess show the best statistical description of downwind fining of the coarser fraction to be a logarithmic or exponential function of distance from source (Ruhe, 1969; Frazee and others, 1970; Worcester, 1973).

Reeves (1976, p. 217) observed that the Blackwater Draw Formation varies in thickness from a "feather edge" in the southwest to "at least 27 m" in the northeast. Downwind thickening is in sharp contrast to the downwind thinning that typifies loess sheets (Ruhe, 1983). Soil stratigraphy helps to clarify the thickness relationships. Although the total thickness of sections in the Blackwater Draw Formation increases to the northeast, the thickness of individual layers composing the formation is generally 1 to 2 m (discussed below). Thicker sections have more layers preserved; that is, there are more layers in the Blackwater Draw Formation in the northeastern portion of the Southern High Plains than in the southwestern part of the region. In the southwest, the Blackwater Draw Formation in most instances consists of a single layer of sandy sediment about 1 m thick or less. Locally, there is no sandy sediment, and the Ogallala calcrete is exposed.

The mineralogy of the Blackwater Draw Formation is known largely from studies of soils formed in the surface layer (Rogers, 1969; Allen and others, 1972; Soil Conservation Service, 1976; Walters, 1988), although limited information is available on the buried soils. Mineralogical data, from sites that include the loamy sand, sandy clay loam, and clay textural zones, are from X-ray diffractometry and thin-section studies. The coarse (sand and silt) and fine (clay) mineralogy of the surface soil is remarkably uniform. The coarse minerals are typically 80%–90% quartz, with the rest of the fraction composed of feldspar and mica. The clay minerals are predominantly illite and smectite with minor amounts of kaolinite. X-ray data from three buried soils (Rogers, 1969; Allen and others, 1972) and thin-section data from Bushland (Allen and Goss, 1974), the Tule Basin site, Mount Blanco, and the type section indicate that the mineralogy of the deeper layers of the Blackwater Draw Formation is very similar to the mineralogy of the surface layer. There is no evidence of authigenic clay forming in the Blackwater Draw Formation.

SOIL STRATIGRAPHY

Much of the focus of this study is on the pedologic and soil-stratigraphic characteristics of the Blackwater Draw Formation. With few exceptions, soils provide the only stratigraphic markers of individual beds, and the obvious field characteristics of the formation, such as color and structure, are pedogenic features. At each of the study sites, the soils are very similar, although the number of buried soils can range from zero to six within small areas. The degree of development of the soils may provide information on the age of the Blackwater Draw Formation.

The surficial layer of the Blackwater Draw Formation appears to be continuous across the High Plains surface, based on observations at many exposures (in addition to those described below) and based on county soil surveys. The morphology of the soil in the surface layer is generally similar in any given area and grossly similar across the Southern High Plains, although varying somewhat with the textural variation (Table 4). All of these soils tend to be 1.5 to 2.0 m thick, if not eroded, and have a very well developed argillic horizon with 5YR hues, common clay films on ped faces, and prismatic structure. These Paleustalfs and Paleustolls (Table 4) typically have a Stage III Bk horizon with an abrupt upper boundary. The Bk is in most cases welded to the Bt horizon of the first buried soil, and therefore, C horizons are seldom present. The Pullman soils (Table 4) are typi-

TABLE 4. GENERALIZED TYPES OF SURFACE SOILS OF THE BLACKWATER DRAW FORMATION (FROM GODFREY AND OTHERS, 1973)

Textural region	Soil series	Classification
Clayey northeastern section ("loess")	Pullman	Paleustoll
	Olton	Paleustoll
	Mansker	Paleustoll
Loamy central section	Amarillo	Paleustalf
	Acuff	Paleustoll
	Mansker	Paleustoll
Sandy southwestern section	Patricia	Paleustalf
	Brownfield	Paleustalf
	Triomas	Haplargid
	Jalmar	Haplargid

cally darker than the other surface soils, owing to higher organic-matter content and finer texture, but in many cases bury a soil similar in morphology to the Paleustalfs (for example, Geiger and others, 1968). More variability in the morphology of the surface soil would be expected if the surface of the Blackwater Draw Formation were not composed of a single, continuous layer.

Blackwater Draw Formation Type Section

The type section of the Blackwater Draw Formation is about 19 km north of Lubbock, along a roadcut on the west side of Blackwater Draw (Fig. 1). The exposure is about 10 m thick, with the Ogallala "caprock caliche" at the bottom, marking the top of the Ogallala Formation (Fig. 2).

The two most striking features of the type section are the presence of at least four strongly developed buried soils in addition to the modern surface soil (Fig. 2) and the similar pedogenic characteristics and degree of pedogenic expression shared by the soils. All of the soils are welded together, and no A or C horizons or primary sedimentary structures are apparent other than the A horizon of the surface soil.

The surface soil (Paleustalf) at the type section has a thick (~1 m), reddish-brown (5YR hues), argillic horizon, with predominantly coarse prismatic structure, and sandy clay loam texture. Clay films are apparent on ped faces and very common in thin section (Fig. 4a; Table 1). Below the argillic horizon is a Stage III calcic horizon more than 1 m thick. The boundary between the argillic and calcic horizons is very abrupt and subhorizontal and typical of the regional surface soils.

Morphologically, the buried soils in the section are somewhat more strongly developed than the surface soil, although all are sandy clay loams. At least some parts of each profile exhibit 2.5YR hues, and, relative to the surface soil, more continuous clay films on ped faces and a higher percentage of argillans in thin section (Figs. 4b and 4c; Table 1). The boundaries between the buried soils become increasingly indistinct with depth. The morphologies of the calcic horizons in the buried soils are somewhat similar to one another but distinctly different from that in the surface soil. The buried calcic horizons are expressed either as patchy films and coats on ped faces, generally the vertical faces, or as vertically oriented, root-like concretions as much as 1.0 m long and 1 to 5 cm in diameter. These nodules appear to follow the joints between prismatic peds, and this general morphology is sometimes informally referred to as "ladder matrix" carbonate (McGrath, 1984, p. 131).

Dune Site

The Dune site, on the north side of Lubbock (Fig. 1), is a lunette on top of the Blackwater Draw Formation (Holliday, 1983, 1985a). The dune rests on the surface soil of the formation, based on an examination of natural and artificial exposures in and adjacent to the lunette. The dune buried the Blackwater Draw Formation about 30,000 yr ago (discussed below) and, besides providing a minimum age for deposition of the formation, allows an initial assessment of the rate of development of the surface soil in the formation. The buried soil is less developed than unburied equivalents near the dune (Paleustalfs). The Bt horizon exhibits 7.5YR hues, weak to moderate prismatic structure, few clay films on ped faces, and a Stage II calcic horizon. Maximum clay content of the Bt horizon is 18% (Holliday, 1982), compared with 20% to 35% clay in typical unburied Paleustalfs of the region (for example, Allen and others, 1972; Soil Conservation Service, 1976).

Mount Blanco Section

Mount Blanco, the type section for the Blanco Formation (Pliocene), is on the eastern edge of the Southern High Plains, along the west side of Blanco Canyon (which contains a tributary of the Brazos River) (Fig. 1). The section, a roadcut of State Highway 193, is discussed by Holliday (1988a) but can be summarized as follows. The Blackwater Draw Formation is more than 5 m thick and rests on lacustrine sediments of the Blanco Formation. The Blackwater Draw Formation contains three well-expressed buried soils [5YR hues, argillic horizons $\geqslant$1 m thick (Figs. 4d and 4e), Stage III and IV calcic horizons] and the regional surface soil (Paleustalf) with a morphology similar to those of the buried soils. The surface soil and upper two buried soils are welded together. These soils are morphologically very similar to those exposed at the type section. The 1.4 Ma Guaje Ash (Izett and others, 1972), derived from the Jemez volcanic field in New Mexico, occurs within the lower Blackwater Draw Formation and is separated from the Blanco Formation by about 1 m of sediment that includes the lowest buried soil (b3; Fig. 2). The lowest buried soil exhibits a Stage IV calcrete formed at the base of the Blackwater Draw Formation and in the top of the Blanco Formation and on the basis of the degree of calcrete development, may have required several hundred thousand years to form (Holliday, 1988a). These data suggest that deposition of the Blanco sediments may have ended by about 1.6 Ma or earlier. Since that time, the Blackwater Draw Formation has accumulated episodically.

Tule Basin Section

The Tule Basin section is on the south side of Tule Canyon (which contains a tributary of the Red River) (Fig. 1). In the section is an exposure of fine-grained, apparently eolian sediments that contain the 0.6 Ma Lava Creek B (formerly Pearlette O) volcanic ash (Izett and Wilcox, 1982), from the Yellowstone area, and overlying lacustrine sediments of the Tule Formation (Schultz, 1977). The eolian sediments containing the ash are considered to be the Blackwater Draw Formation, conforming to the original definition that the Blackwater Draw Formation consists of those eolian sediments overlying the Tule Formation (Reeves, 1976).

The Blackwater Draw Formation is more than 4 m thick in this exposure (Fig. 2). The texture is predominantly silty, ranging from silty clay to silty clay loam to silt loam. The upper 1.5 m of the section contains the well-developed modern surface soil with A-Bt-Bk horizonation, reddish-brown (7.5YR) hues, moderate structural development, and a Stage III calcic horizon. Below the calcic horizon and welded to it is a buried soil consisting of a well-expressed argillic horizon (Btb1, Fig. 2) (7.5YR hues and common clay films on ped faces and abundant illuvial clay) and a calcic horizon (Bkb1, Fig. 2). The zone of pure ash underlies the buried soil and varies in thickness from a feather edge to about 30 cm. The ash overlies about 90 cm of Blackwater Draw Formation that has a well-developed soil with a Bt horizon exhibiting illuvial clay (Fig. 4f), 7.5YR hues, and moderate structural development. A thin Stage III calcic horizon related to the lowest buried soil formed in the top of the Tule Formation.

Bushland Section

The Bushland locality is in a large borrow pit 1.6 km south of Bushland, 24 km west of Amarillo (Fig. 1). The soils were described and the micromorphology analyzed by Allen and Goss (1974). At least six buried soils are present in addition to the surface soil in an exposure almost 7 m thick (Fig. 2). The soils have clay to clay loam texture; otherwise they are morphologically identical to the soils at the Blackwater Draw Formation type section. The soils average about 1 m thick; all have well-expressed argillic horizons, indicated by abundant illuvial clay in thin section; most exhibit 5YR hues; and all soils have Stage II–III calcic horizons. There are no C horizons or buried A horizons; all of the soils are welded together. Clay films are rare on ped surfaces, apparently owing to the high clay content and related shrink-swell potential in a climate that has a pronounced dry season (Nettleton and others, 1969; Allen and Goss, 1974).

DATING AND GEOCHRONOLOGY

A variety of dating techniques provides an initial assessment of the geochronology of the Blackwater Draw Formation. The volcanic ashes at Mount Blanco and Tule Basin provide a first approximation for the time represented by the deposit. The degree of soil development is also indicative of age, and minimum estimates for the rate of development of the surface soil are available from radiocarbon dating. At the Gentry locality north of Lubbock (Holliday, 1985a), a lake basin truncates the well-developed argillic and calcic horizons of the surface soil in the Blackstone Draw Formation, clearly demonstrating that the lake basin formed long after pedogenesis began in the surface sediments. Sediments in the basin are as old as 10,000 yr (Osterkamp, 1987), thereby indicating that the surface soil in the Blackwater Draw Formation is considerably older than 10,000 yr.

Radiocarbon ages are available from the lunette that buries the Blackwater Draw Formation at the Dune site. The suitability of dating organic matter from sediments and soils in the area is well documented (Haas and others, 1986), and all of the ages from the dune are stratigraphically consistent (Holliday, 1985a). The A horizon of the deepest buried soil in the dune is dated to 33,750 ± 3600 yr B.P., and the A horizon of the next higher buried soil yielded a date of 29,080 ± 1030 yr B.P. (Holliday, 1985a). These indicate that the dune was accreting well before about 30,000 yr B.P. and, therefore, the upper several meters of the Blackwater Draw Formation has been in place several tens of thousands of years and probably at least 40,000 yr.

Four TL ages were secured in attempts to date the Blackwater Draw Formation. TL dating has, at best, accuracy limits of ±10% when applied to suitable Quaternary deposits such as fine-grained eolian sediments (Wintle and Huntley, 1982; Berger, 1988), but the method can provide valuable minimum age estimates for the parent materials of buried soils. To determine the suitability of TL dating for the Blackwater Draw Formation, control samples were collected from radiocarbon-dated sediment of the lunette at the Dune site, discussed above, and from the Blackwater Draw Formation immediately below the lunette (Holliday, 1985a). At least some portion of the material analyzed in the Blackwater Draw Formation (very fine silt) is illuvial (due to pedogenesis), and therefore, the resulting ages are minima for the age of burial by the dune. The A horizon of the deepest buried soil in the lunette yielded an age of 42,720 ± 4,470 yr (Alpha 809), and the top of the Blackwater Draw Formation yielded 28,600 ± 4,000 yr (Alpha 918). Interpreting these results is difficult. The TL age from the dune is the same order of magnitude as the corresponding radiocarbon age, but the TL age from the Blackwater Draw Formation is younger than both of the overlying radiocarbon ages. Nevertheless, the approximate order of magnitude for the time of burial of the Blackwater Draw Formation is indicated by the TL age.

Two samples for TL dating were taken at the Blackwater Draw Formation type section. A sample from the upper Btb1 horizon yielded an age of 118,000 ± 14,000 yr (Alpha 1750), and a sample from the upper Btb2 horizon was dated at >270,000 yr B.P. (Alpha 1751). These determinations provide either order-of-magnitude ages or at least minimal ages for the deposition of the parent materials of the two buried soils.

Magnetostratigraphy has been successfully used for establishing broad age limits for lower Pleistocene soils in Colorado (Patterson and others, 1984). Similar studies were carried out at the type section of the Blackwater Draw Formation (Patterson and others, 1988; Patterson and Larson, 1989). These analyses show that the surface soil and b1 soil are normally magnetized, which suggests that their formation occurred within the past 730,000 yr, consistent with the TL data. The b2 soil is strongly magnetically reversed, however, suggesting that it formed entirely during a reversed polarity interval, most likely 0.90 to 0.73 Ma, which is also broadly consistent with the TL age of >0.27 Ma. The lower buried soils at the type section exhibit both normal and reversed components, and therefore, their magnetic ages cannot be determined other than that they are >0.90 m.y. old.

The various dating methods applied to the Blackwater Draw Formation demonstrate that the deposit has accumulated for perhaps 1.6 m.y. The age and duration of soil development in individual layers is less clear. Deposition of the surficial layer apparently occurred between about 120,000 and 30,000 yr B.P., based on radiocarbon dates from the Dune site and the TL age of 0.118 m.y. from the first buried soil at the type section. Because most of the buried soils are more strongly developed than the surface soil, they may represent depositional hiatuses considerably longer than the few tens of thousands of years of the surface layer, perhaps as much as several hundred thousand years. This is suggested by the TL and paleomagnetic information from the type section and the age estimate of 0.20 m.y. for the soil buried by the ash at Mount Blanco, determined from the degree of K-horizon development (Holliday, 1988a).

REGIONAL COMPARISONS

The Blackwater Draw Formation is identified only on the Southern High Plains, but limited data suggest that correlative units occur in adjacent physiographic regions. Soils identical to those of the Blackwater Draw Formation are mapped in the northern Texas Panhandle by Godfrey and others (1973) and in county soil surveys. These soils also fine texturally to the northeast (Godfrey and others, 1973). On geologic maps of the northern Texas Panhandle, the Oklahoma Panhandle, and northeastern New Mexico, large areas of the High Plains surface are identified as Quaternary eolian sediment (Eifler, 1969; Eifler and Fay, 1970, 1984; Eifler and others, 1983).

East of the Southern High Plains, on the Rolling Plains, Caran and Baumgardner (1988) have identified the Lingos Formation, a Quaternary unit composed of fluvial, lacustrine, and eolian sediments. The upper Lingos Formation, particularly the surficial deposits, is predominantly eolian and contains a well-developed surface soil, morphologically identical to those of the Blackwater Draw Formation, and in many instances contains several buried soils. On the basis of the sedimentology, the location of the Lingos Formation downwind of the Southern High Plains, and the degree of soil development, Holliday (in Gustavson and Holliday, 1988) considered the eolian sediments of the Lingos Formation to be genetically related to those of the Blackwater Draw Formation.

DISCUSSION AND CONCLUSIONS

Recent data have led to a refinement and revision of the sedimentological and depositional history, soil stratigraphy, and age of the Blackwater Draw Formation. The formation varies considerably in texture across the Southern High Plains, from sandy in the southwest to silty and clayey in the northeast. The textural fining appears to be the result of downwind sorting, but such marked, although gradual, textural changes over such a large area are not common. The Blackwater Draw Formation is not a typical sand sheet (for example, Kocurek and Nielson, 1986), cover sand (for example, Catt, 1986), or loess sheet (for example, Pye, 1984, 1987). Zones texturally intermediate between sands and loess ("coverloams" or "sandloess") occur in northern Europe, but in relatively narrow belts 10–30 km wide (Catt, 1986, p. 37). In terms of both textural gradation and areal extent, the closest analogue to the Blackwater Draw Formation appears to be the eolian sediment of the Loess Plateau of northern China, with its "sandy loess," "loam loess," and "clayey loess" (Liu Tung-sheng and others, 1982; Kes, 1984). This is significant because like the Blackwater Draw Formation, the extensive eolian deposits of northern China appear to be of desert origin rather than of glacial origin (Pye, 1987).

The Blackwater Draw Formation is composed of a number of individual beds, each strongly modified by pedogenesis. Deposition of each layer probably occurred under conditions of prolonged aridity. Data from historic and geologic records from throughout the Great Plains indicate that wind erosion and eolian sedimentation occur in the region during droughts and that strong winds commonly accompany dry conditions (Holliday, 1987, 1989).

The original texture and thickness and the total number of beds within the Blackwater Draw Formation are difficult to determine. Sediments with no illuvial clay are rare in all sections studied, and therefore, samples of unweathered parent material are not available for study. The surface layer appears to be continuous across the region, suggesting that each layer began as a continuous unit. Erosion prior to burial of each layer is suggested by the varying number of buried soils in each section, the absence of buried A horizons, and the presence of unconformable contacts. Alternatively, if each layer was not originally continuous, but deposited locally, this could account for the variation in number of layers from section to section. The seven soils identified at Bushland indicate a minimum number of seven depositional events for the Blackwater Draw Formation in at least some areas.

The morphological, mineralogical, and chemical similarities between the buried soils and the surface soils suggest that the buried soils formed under conditions generally similar to those of the surface soils. The surface soils have formed apparently throughout the late Quaternary, under conditions that were probably subhumid in the late Pleistocene and became semiarid in the Holocene (Johnson, 1986; Holliday, 1989). Data from the Dune site and several Holocene localities (Holliday, 1985b, 1985c, 1988b) show that late Quaternary pedogenic processes include both reddening and the translocation of clay and carbonate, processes that continue today (Holliday, 1988b). Much of the clay and carbonate is probably derived from argillaceous, calcareous dust, abundant in the region today and throughout at least the Holocene (Holliday, 1988b, 1989).

Available data suggest the following general model for development of the Blackwater Draw Formation. The geologic history of the deposit is cyclic. Each cycle began with eolian deposition, was followed by nondeposition with landscape stability and soil formation, and possibly ended with erosion. Wind has probably been the predominant geomorphic and sedimentologic agent of the region throughout late Cenozoic time; however, at any given time, wind erosion and sedimentation probably operated concurrently with pedogenic processes, as is happening today. During depositional periods, material derived from the Pecos Valley blew onto the High Plains surface at a rate faster than erosion or pedogenesis, resulting in deposition of a more or less continuous sheet of eolian sediment across the area. Sedimentation then slowed, and if erosion was minimal, a soil formed in the eolian sheet. Enough time elapsed to allow formation of a well-developed soil similar to the surface soils of the area. Slow aggradation during pedogenesis resulted in overthickening of argillic horizons and engulfing of the lower argillic horizon by an overthickened calcic horizon. Erosion by wind deflation must have followed at least some pedogenic cycles, destroying the lateral continuity of the eolian sediment in many areas, especially the upwind regions. In other places, more easily eroded A horizons may have been removed down to the more resistant Bt horizons. The erosion occurred immediately before or perhaps coeval with early stages of the subsequent depositional event. Deflation in one region of the Southern High Plains could have resulted in deposition in a downwind area.

After several cycles of deposition-stability-erosion, the result was a stack of sedimentary units disconformably overlying one another, varying in number from one section to the next, but with each unit exhibiting similar pedologic properties. This process began more than 1.4 m.y. ago and appears to be continuing. At present, the Southern High Plains are well into the phase of the cycle dominated by landscape stability and soil formation, following at least six complete cycles.

The general uniformity of depositional styles and pedogenic processes inferred from the Blackwater Draw Formation further suggests that the environment of the Southern High Plains has oscillated throughout the Quaternary. Stable landscapes obtained under subhumid to semiarid conditions similar to those of the past several tens of thousands of years. Regional wind deflation and eolian deposition occurred during periods of prolonged drought. This environmental cyclicity is similar on a longer time scale to the environmental fluctuations that have characterized the region during the Holocene (Holliday, 1989).

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