EOLIAN SEDIMENTATION AND SOIL DEVELOPMENT ON A SEMIARID TO SUBHUMID GRASSLAND, TERTIARY OGALLALA AND QUATERNARY BLACKWATER DRAW FORMATIONS, TEXAS AND NEW MEXICO HIGH PLAINS

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ABSTRACT: **Eolian sediments have accumulated as non-glacigenic loess and thin sand sheets on the Central and Southern High Plains grasslands of Texas and New Mexico since the late Miocene. Locally as much as 110 m of eolian sediments with numerous paleosols are preserved in the Quaternary Blackwater Draw Formation and the upper part of the Miocene–Pliocene Ogallala Formation. These sediments and paleosols, which cover more than 130,000 km^2, are similar to recent surface sediments and soils and record a long period of episodic eolian transport and sedimentation, and pedogenesis on a stable low-relief grass-covered landscape.**

Eolian sections, which comprise the fine sand to coarse silt lithofacies of the Ogallala Formation, and the very fine to fine sand and sandy mud lithofacies of the Blackwater Draw Formation, generally lack primary sedimentary structures. Grain size of Ogallala sediments decreases from west to east, and grain size of Blackwater Draw sediments decreases from southwest to northeast. Soil horizonation is well developed in most sections, and buried calcic and argillic horizons are common. Calcic horizons are characterized by sharply increased $CaCO_3$ content in the form of filaments, nodules, and petrocalcic horizons (calcretes). Argillic horizons are characterized by increased illuvial clay, pedogenic structure, and darker reddish hues. Rhizocretions are common locally. Open root tubules, which are typically less than 1 mm in diameter and characteristic of small plants like grasses, are present in all Ogallala and Blackwater Draw eolian sediments.

Paleosols preserved in eolian sediments of the High Plains reflect periods of sedimentation followed by episodes of landscape stability and pedogenesis, and negligible sedimentation. Episodes of sedimentation and soil development likely resulted from cyclic decreases and increases in available moisture and vegetative cover. Eolian sediments were eroded and transported eastward during dry periods when vegetation was sparse in source areas, such as the western High Plains and the Pecos Valley. During humid periods more abundant vegetation probably protected source areas from deflation, and resulted in landscape stability across the High Plains.

INTRODUCTION

Eolian sedimentation on grasslands under semiarid to subhumid conditions is not well documented in the geologic literature, although the interiors of North and South America, Europe, Africa, Australia, and Asia include vast areas of grasslands. Furthermore, pedogenically altered fluvial overbank mud rocks or siltstones, which lack primary sedimentary structures, may be difficult to distinguish from pedogenically altered eolian silty and sandy muds. For example, The Ogallala and Blackwater Draw Formations in western Texas and eastern New Mexico (U.S.A.) were initially thought to consist of fluvial sediments deposited as a series of coalescing alluvial fans (Johnson 1901; Bretz and Horberg 1949; Frye 1970; Seni 1980). More recently, Gustavson (1996), Gustavson and Winkler (1988), and Winkler (1985), have recognized that although basal Ogallala fluvial sediments fill paleovalleys, widespread Ogallala and Blackwater Draw eolian sections blanket both fluvial sections and the buried uplands between paleovalleys. We suspect that eolian sedimentation on grasslands is much more prevalent than previously recognized.

The Central and Southern High Plains of eastern New Mexico and northwest Texas cover approximately 130,000 km^2 and are underlain by as much as 110 m of eolian sediments that comprise the upper part of the Tertiary Ogallala and the Quaternary Blackwater Draw Formations (Fig. 1). In this paper we compare surface sediments and soils to buried sediments and soils in these formations and argue that modern depositional processes and soil development on the grasslands of the High Plains can be used to interpret sedimentation and pedogenesis during the late Tertiary and Quaternary.

We describe a model in which episodic eolian sedimentation, as non-glacigenic loess and sand sheets and pedogenesis, occurred in response to temporal and geographic variations in climate. Under current climatic conditions, where precipitation decreases from 56 cm/a to 31 cm/a to the west across the High Plains, vegetation decreases and the potential for deflation increases from east to west. We also infer that sediment deflation and transport occurred more frequently in the western part of the High Plains and the Pecos River valley, because of reduced vegetative cover and windier conditions during the drier parts of past climatic cycles. During wetter parts of climatic cycles, increased vegetative cover stabilized the landscape, reduced deflation, and intensified soil development. Conversely, sediment accumulation was more important in the eastern parts of the High Plains because of increased vegetative cover. Pedogenesis increased in relative importance during the humid parts of climatic cycles because the sediment supply from the west was cut off or substantially reduced.

SETTING AND SOIL-FORMING FACTORS ON THE SOUTHERN HIGH PLAINS

Soils on the Southern High Plains, including the widespread Amarillo and Pullman series, are controlled by the same factors that affect soil development everywhere: climate, soil organisms, relief, parent material, and time (Jenny 1941). Thus, if a paleosol with characteristics similar to those of modern soils is recognized, then some of the soil-forming factors that affected the paleosol can be estimated. It is important to understand, however, that factors such as paleoclimate can be only grossly generalized from these data. This is in part because a single soil series develops under a range of climatic conditions that vary geographically and temporally. For example, for Pullman series soils, precipitation ranges from 31 cm/a to 56 cm/a across the area where these soils occur. Furthermore, climatic elements affecting mature soils, such as the Pullman series, also varied temporally because surface soils on the High Plains likely accumulated over the last 30–50 ka (Holliday 1989, 1991).

Climate

The High Plains lie in the rain shadow of the Rocky Mountains, and the climate of the Central and Southern High Plains ranges from subhumid in the east to semiarid in the west. Precipitation ranges from 31 cm/a to 56 cm/a, and mean annual surface temperature ranges from approximately 14°C to 18°C (Fig. 2) (Bomar 1983). Winds are westerly during the winter, and southerly and southeasterly during the summer; strong winds ($>$ 11 m/s) are most frequent from the west (Johnson 1965). The greatest potential for deflation is from November to March because precipitation is minimal, vegetation is dormant or dead, and strong westerly winds are common during this period (Orgill and Sehmel 1976). Annual evaporation rates for most localities on the Southern and Central High Plains exceed 140 cm/a

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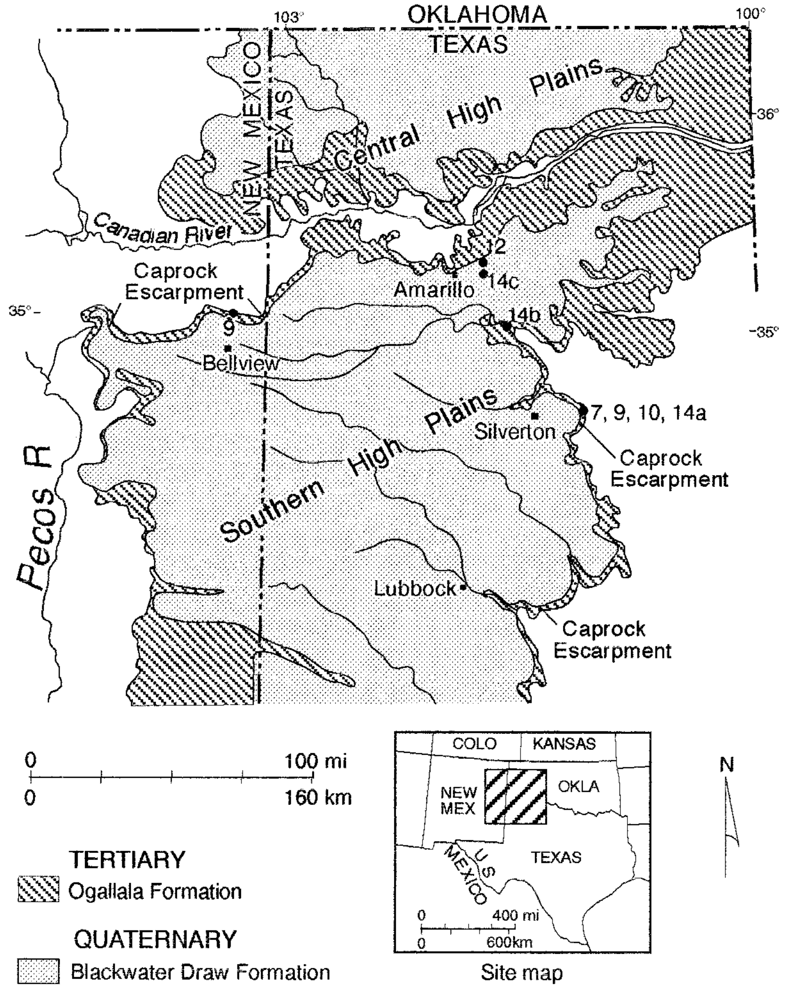


FIG. 1.—Geologic map of Tertiary Ogallala and Quaternary Blackwater Draw Formations, Texas Panhandle and eastern New Mexico. Numbers locate figures.

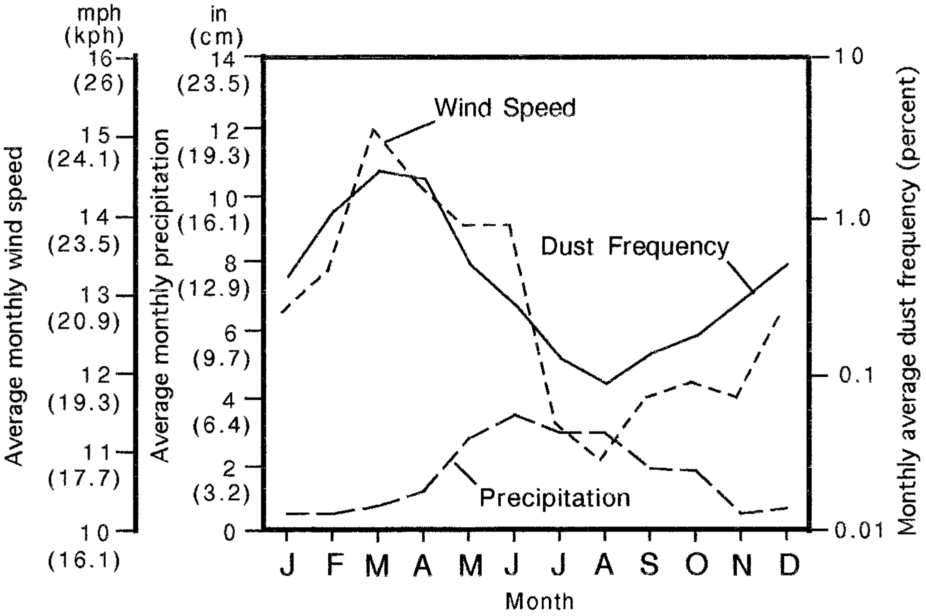


FIG. 2.—Average monthly precipitation, wind speed, and dust frequency at Amarillo, Texas (U.S. Department of Commerce 1978a, 1978b), and monthly dust frequency (south-central United States) (modified from Orgill and Sehmel 1976).

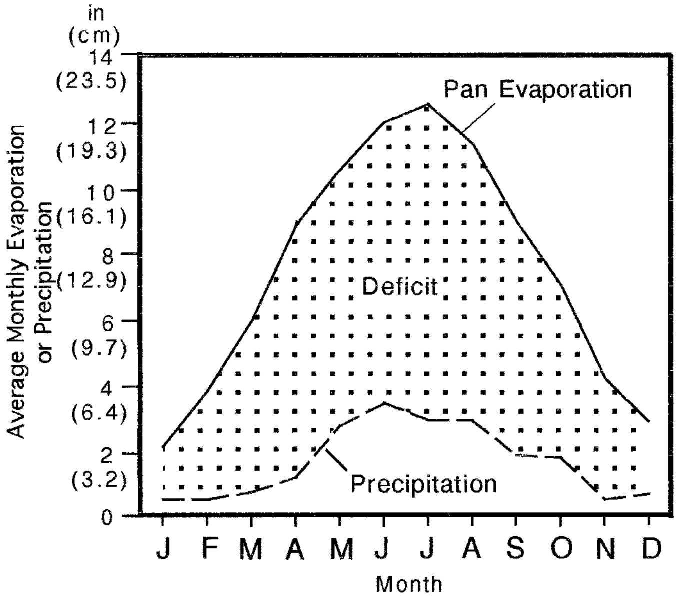


FIG. 3.—Precipitation and pan evaporation data for aridic (upland) soils near Amarillo, Texas, showing a strong moisture deficit throughout the year (U.S. Department of Commerce 1978b).

(Bomar 1983), resulting in a deficit of soil moisture (Fig. 3). Semiarid to subhumid climatic conditions have likely existed here since the middle Tertiary because of the development of the rain-shadow effect following uplift of the Rocky Mountains to the west of the High Plains. Fossil faunas (Schultz 1990) and floras (Thomasson 1990) and calcic paleosols (Winkler 1985; Gustavson 1996) all suggest a semiarid to subhumid climate since about 11 Ma.

Physiography (Relief)

The Southern and Central High Plains exhibit low relief and slope about 2 m/km to the southeast. Drainage is not integrated but, with the exception of a few ephemeral streams, is internal into approximately 20,000 small playa basins. Interplaya areas, which are occupied mostly by the Amarillo and Pullman soil series, are flat and featureless. Paleosols of the Ogallala and Blackwater Draw Formations parallel the High Plains surface, indicating that low relief and a regional slope to the southeast have prevailed since the late Miocene.

Vegetation

The present natural vegetative cover of the Southern High Plains is primarily short-grass prairie (Kuchler 1970). Woody plants make up less than 5% of the natural vegetation of the Amarillo soils and are not common to the Pullman soils (U.S. Department of Agriculture, Soil Conservation Service 1972, 1973). Past vegetative cover probably varied with climatic conditions but were primarily grasslands (Thomasson 1990). Similarly, Tertiary and Quaternary vertebrate faunas indicate the presence of grasslands and a semiarid to arid climate (Schultz 1990; Winkler 1987). At present the transition from short-grass prairie vegetation of the High Plains to desert shrub vegetation of the Pecos Plains roughly coincides with the physiographic boundary between the High Plains and the Pecos River Valley to the west (Kuchler 1970) (Fig. 1). In the past, Southern High Plains short-grass prairie may have been partly replaced by steppe vegetation or desert shrubs during warm, dry segments of climatic episodes. Studies of native grasslands on the Great Plains clearly show that vegetative cover is significantly reduced following several years of drought (Tomanek and Hulett 1970). Conversely, prairie grasses may have replaced desert shrub vegetation in the Pecos River valley during cool, moist periods.

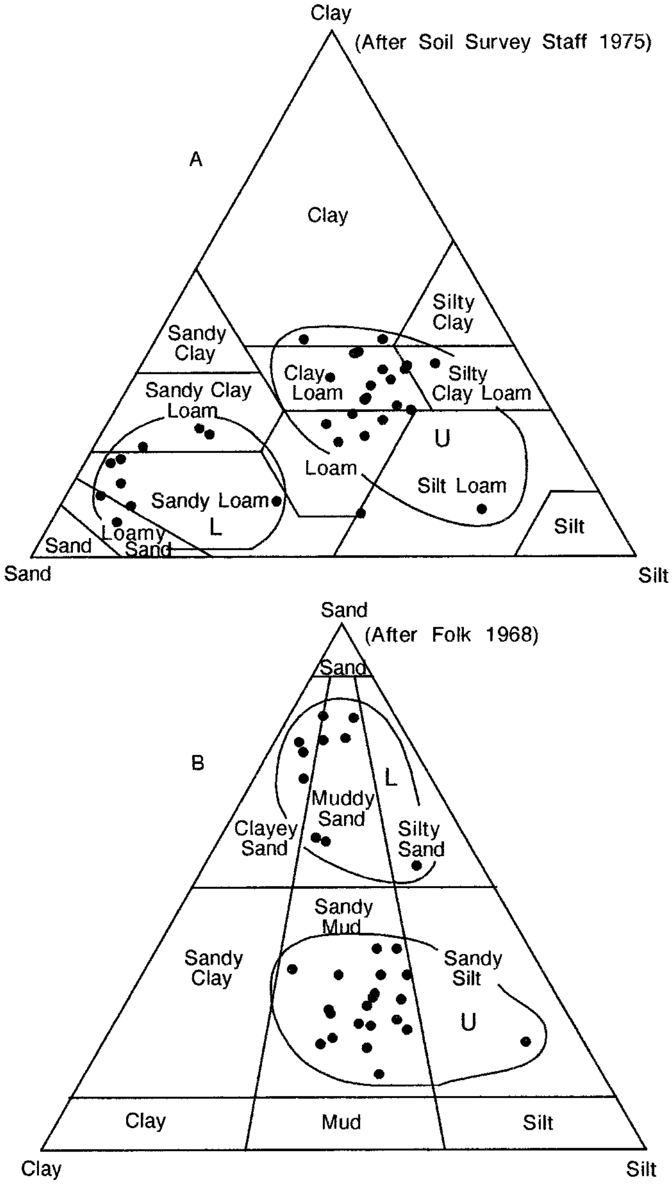


FIG. 4.—Sand, silt, and clay distribution in upper (U) Blackwater Draw and lower (L) Blackwater Draw Formation sediments. Note that sand and clay apices are reversed between triangular plot A and B. Soil classes are after Soil Conservation Service Staff (1975). Sediment classes are after Folk (1968).

Parent Material

The Blackwater Draw Formation, which underlies the High Plains, consists of clayey sand to sandy mud that has been modified by pedogenesis (soil texture ranges mostly from sandy loam to clay loam) (Holliday 1989, 1990a; Gustavson 1996) (Fig. 4). These sediments consist mainly of quartz, feldspar, and clays with minor amounts of calcite, mica, and other minerals. Grain size of the surface sediments decreases to the northeast away from the Pecos and Canadian River valleys, the probable sources of these eolian sediments (Lotspeich and Coover 1962; Seitlheko 1975) (Fig. 5).

Johnson (1965) observed that the strongest winds on the High Plains occurred during drought years, and that atmospheric dust is more common

FIG. 5.—Low-level oblique aerial photograph of lobate sand sheets produced by deflation of the Blackwater Draw Formation during severe dust storms of 1–3 April 1983. See Figure 6 for location.

during dry periods because higher-than-average soil temperatures during droughts result in unusually turbulent air and stronger, gusty winds near the surface. Clay is a significant component of dust in the region (Warn and Cox 1951; LaPrade 1957; Gillette and Walker 1977; Holliday 1988), and aerosolic clays probably are an important source of the illuvial clay in the Bt horizons of soils of the region (Goss et al. 1973). Calcium carbonate dust and Ca^{2+} in rainwater are the primary sources of calcium carbonate in soils in the southwestern US (Gile et al. 1981; Machette 1985). Junge and Werby (1958) showed that for the Southern and Central High Plains the average Ca^{2+} concentration in rainfall ranges from 2 mg/l to 3 mg/l. Atmospheric dust collected near Lubbock contained 2–4 weight percent $CaCO_3$ (Holliday 1988, table 4).

Time

The ages of regional surface soils such as those of the Amarillo or Pullman Series can be estimated from the degree of soil development (especially the content of secondary clay and $CaCO_3$) or by dating of the uppermost layer of the Blackwater Draw Formation. Numerical ages determined by radiocarbon and thermoluminescence techniques and pedologic characteristics such as 5YR to 2.5YR hues, thick continuous clay films in argillic horizons > 1 m thick, and Stage III calcic horizons indicate that both surface sediments and the soils developed in them are probably <100 ka old and likely in the range of 30 to 50 ka old (Holliday 1989, 1990a, 1990b).

SEDIMENT TRANSPORT

Most of the natural vegetation of the High Plains has been destroyed by cultivation or greatly modified by grazing, and the original thick sod largely disaggregated. Thus, the potential for deflation of surface sediments is far greater now than in the past when vegetative cover was intact. Nevertheless, observed transport processes form the basis of a depositional model for the Ogallala and Blackwater Draw Formations. The results of eolian transport of fine sand-, silt-, and clay-size particles are observable throughout the western parts of the Southern High Plains and the Pecos valley as sand sheets, small dunes, and blowouts in sandy sediments. Transport of eolian sediments is demonstrated by the passage of dust storms and dust devils, and as accumulations of dust washed out of the air by precipitation.

In several instances we have observed large, very thin, lobate sand sheets that formed during dust/sand storms on the High Plains (Fig. 6). These thin sand sheets result from sand moving by saltation under high-velocity winds. Thicknesses of sand sheets ranges from a few centimeters to several decimeters, but in many areas does not fully cover short vegetation on the surfaces where they were deposited. McCauley et al. (1981) described the aftereffects of the movement of a severe winter dust storm across the Southern High Plains on 23 February 1977. As a result of the storm, surface sediments on which Amarillo and related soil associations are developed were locally eroded to depths of greater than 1 m in the western part of the study area. Numerous thin lobate sand sheets were deposited along the border of Texas and New Mexico. That significant quantities of sediment were also transported as suspended load or as atmospheric dust is indicated by the dust plume that was still visible above the eastern Atlantic Ocean on GEOS-1 imagery on February 26. Eolian transport occurs most frequently as dust storms associated with the passage of winter frontal systems. Sediment transport and deposition is both as suspended load, which is deposited as loess, and by traction load, which is deposited as sand sheets. These processes were also likely responsible for transport and deposition of eolian sediments in the past.

STRATIGRAPHY OF THE OGALLALA AND BLACKWATER DRAW FORMATIONS

Ogallala Formation

The Ogallala Formation, which unconformably overlies Permian through Cretaceous strata, is as much as 250 m thick where it fills paleovalleys and 10–30 m thick in areas between paleovalleys. The Ogallala contains vertebrate faunas indicating an age range of approximately 4.5 Ma to 11 Ma (Schultz 1990). These strata were initially thought to be composed mainly of fluvial sediments deposited as coalesced alluvial fans, and smaller amounts of eolian sediments (Johnson 1901; Seni 1980). Later investigations indicate that the Ogallala in Texas and New Mexico consists of fluvial sediments that partly fill paleovalleys and eolian sediments that cap fluvial sections and paleo-uplands between paleovalleys (Winkler 1985, 1987; Gustavson and Winkler 1988). Paleosols are commonly preserved in the eolian sediments. Recently Gustavson (1996) described Ogallala lithofacies (Table 1), including the eolian fine sand to coarse silt lithofacies. Reeves and Reeves (1996) provide a thorough review of the complex history of Ogallala stratigraphy.

Fine Sand to Coarse Silt Lithofacies.—The fine sand to coarse silt lithofacies (Table 1) consists of sediments that have been extensively modified by pedogenesis. Typically, this unit exhibits a blocky to coarsely prismatic structure, rare to common rhizocretions, locally common root tubules, and few to common $CaCO_3$ nodules (Fig. 7). No primary sedimentary structures have been recognized in these sediments. Buried argillic horizons are common, and buried calcic horizons are preserved in every exposure. Fine sand to coarse silt is the most extensive lithofacies of the Ogallala Formation on the Southern High Plains. This lithofacies may reach 30 m in thickness where it was deposited above paleo-uplands on the pre-Ogallala erosional surface (Fig. 7). In areas that overlie Ogallala paleochannels and fluvial facies, the fine sand to coarse silt lithofacies may be as much as 75 m thick. Representative textural samples of this lithofacies range from a muddy or silty sand to a sand (Fig. 8). In terms of soil textures, these sediments are sands, loamy sands, and sandy loams, with the textures of buried argillic horizons being sandy clays and sandy clay loams. The median diameter (Md) ranges from 2.3 to 3 ϕ (0.2 to 0.125 mm) for the Bellview section, and from 2.7 to 3.7 ϕ (0.15 to 0.07 mm) for the Silverton section. Comparison of samples from this lithofacies from the Bellview section in eastern New Mexico to sediments from the Silverton section exposed 200 km to the east, shows that this facies fines from west to east (Fig. 9).

The episodic nature of deposition and pedogenesis is well expressed in the very fine sand to coarse silt lithofacies exposed in the Caprock Escarpment east of Silverton, Texas (Figs. 7, 10), where nine episodes of sedi-

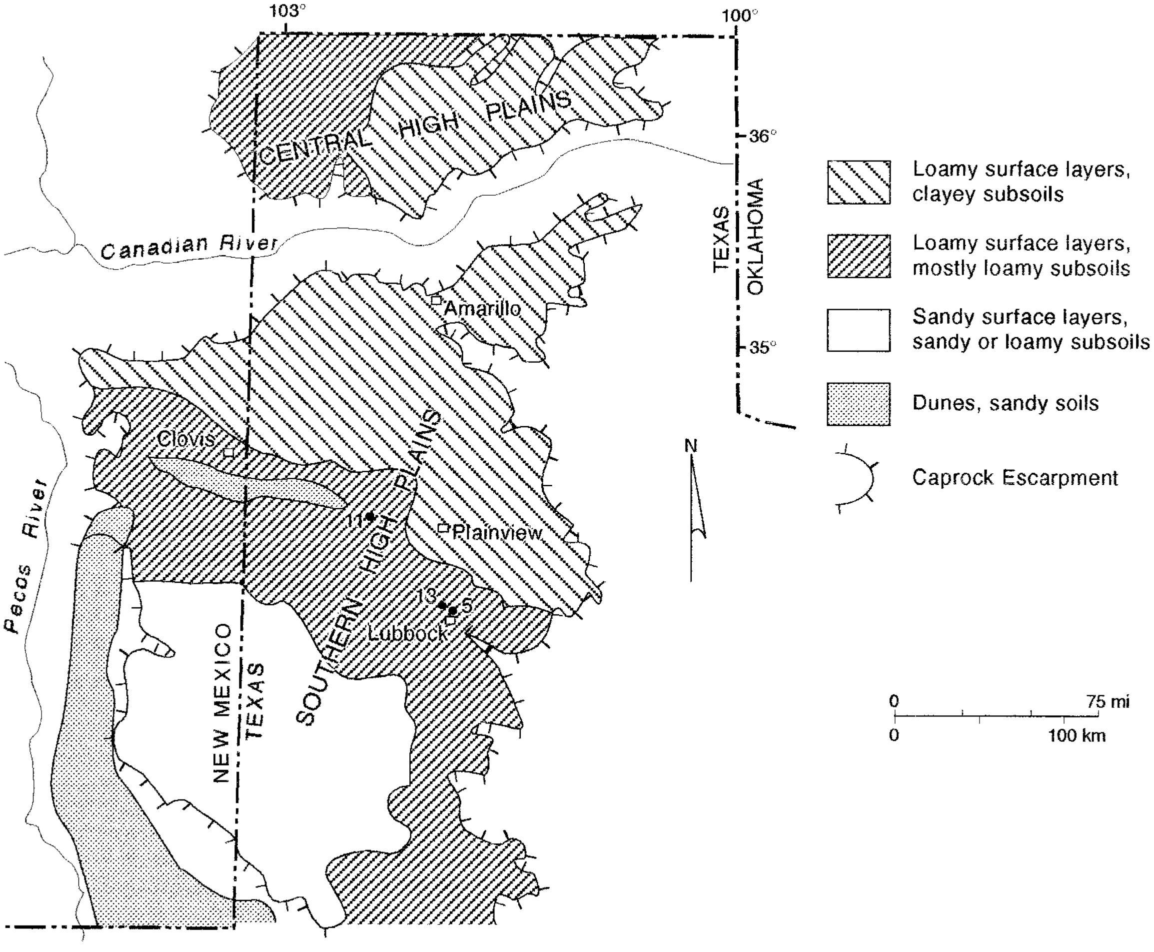


FIG. 6.—Regional soil-texture map illustrating that soils on the High Plains fine to the east and northeast (after Godfrey et al. 1973; Seitlheko 1975). Numbers locate figures.

mentation and pedogenesis are preserved. Buried Btk–Bk horizons at Silverton, which are thick (0.9 to 1.6 m), reddish brown (2.5 to 5YR hues), and have continuous clay films and prismatic structure, are similar to paleosols and surface soils of the Blackwater Draw Formation (Holliday 1989). The four lower, indurated calcretes are characterized by an abrupt upper boundary and a gradational lower boundary. Grains of silt and very fine sand float in the soil carbonate. The calcretes are hard and dense, with a crude vertical prismatic structure that becomes massive to partly nodular near the top of each unit. Buried calcic horizons in the Silverton section contain few to common $CaCO_3$ nodules (Stages I to III). Soil structure ranges from weakly blocky to strongly prismatic. Locally $CaCO_3$ nodules were precipitated preferentially along the fractures that separate soil prisms. The top 5 m of this exposure is occupied by the stage V Caprock calcrete.

Blackwater Draw Formation

The Blackwater Draw Formation is as much as 25 m thick. Recently, Gustavson (1996) described Blackwater Draw lithofacies (Table 2), including the eolian very fine to fine sand and sandy mud lithofacies. Holliday (1987) discussed the eolian processes and sediments that characterize the upper part of the Blackwater Draw Formation. Seitlheko (1975) described the textural variation of the surface soils of the Blackwater Draw Formation and concluded that it fines downwind, from southwest to northeast, supporting the hypothesis that these sediments originated in the Pecos River valley. Allen and Goss (1974) and Holliday (1988, 1989, 1990a, 1990b) recognized that locally the Blackwater Draw Formation contains as many as six well-developed paleosols. In areas where Blackwater Draw sediments are more than 25 m thick, Hovorka (1995) recognized as many as 14 paleosols in core. Limited numerical age control and paleomagnetic data indicate that deposition and pedogenesis took place throughout much of the Quaternary (Holliday 1988, 1989; Patterson and Larson 1990).

Very Fine to Fine Sand Lithofacies.—The very fine to fine sand lithofacies (Table 2, Fig. 11) of the Blackwater Draw Formation is typically light brown (5 YR 6/4 to 5/6), and consists mostly of fine to very fine sand with less than 50% silt or clay, and is a clayey or muddy sand (described as a sediment) or a sandy loam or sandy clay loam (described as a soil) (Fig. 4). Amarillo series soils are commonly developed on sediments with this texture. Primary sedimentary structures are not preserved in this lithofacies, and these sediments have been strongly modified by pedogenesis. Soil horizonation is well developed in most sections, and buried calcic and argillic horizons are common. Calcic horizons are characterized by increased $CaCO_3$ content in the form of filaments, nodules, and coalesced nodules. Buried argillic horizons are recognized by increased clay content and darker color. Rhizocretions and root traces are common locally. Soil peds are typically blocky to prismatic with argillans, mangans, and/or $CaCO_3$ filaments or nodules developed on bounding fractures. Root tubules, which are typically $>$ 1 mm in diameter, are present in all Blackwater Draw sediments. This lithofacies makes up most of the core from the BEG Olton No. 1 borehole (Fig. 11). The source of these sediments was probably the Pecos River valley (Gustavson 1996).

TABLE 1.—*Ogallala Formation lithofacies and interpreted depositional environments (from Gustavson 1996).*

Lithofacies	Sedimentary, Diagenetic and Pedogenic Characteristics	Depositional Environments
I. Gravel	Mostly flat-bedded, clast-supported, partly imbricated, locally $CaCO_3$-cemented, matrix-supported, or upward-fining pebble- to boulder-size gravel. Typical basal Ogallala deposits.	High-energy ephemeral stream
II. Sand and gravel	Mostly trough cross-stratified upward-fining coarse sand- to pebble-sized gravel; locally $CaCO_3$ cemented.	High-energy ephemeral stream
III. Sand (fluvial)	Flat-bedded to planar-, trough-, or ripple-cross-stratified medium sand; locally with clay-silt drapes; locally $CaCO_3$ cemented or upward fining.	Ephemeral stream
IV. Fine sand and mud	Locally channel filling, in part upward-fining, cross-bedded to laminated, fine sand and mud; common desiccation cracks; common $CaCO_3$ nodules.	Abandoned channel or floodplain
V. Laminated fine sand and silt and laminated to massive clay	No preserved primary sedimentary structures, desiccation cracks partly filled with silt to very fine sand, $CaCO_3$ nodules, large wedge-shaped soil aggregates bounded by fractures with slickensides.	Flood plain or ephemeral pond
VI. Sand (eolian)	Eolian trough cross-stratified, well-sorted, fine to medium sand, well-rounded frosted grains, locally with preserved clay bands, rhizocretions, or $CaCO_3$ nodules, locally $CaCO_3$ cemented.	Eolian dunes associated with an ephemeral stream
VII. Fine sand to coarse silt	Coarse silt to very fine sand, no preserved primary sedimentary structures, locally common root tubules, rhizocretions, and $CaCO_3$ nodules; locally buried B (soil) horizons preserve high clay content or sand or silt-filled desiccation cracks.	Loess accumulation on grassland or prairie

Sandy Mud Lithofacies.—The sandy mud lithofacies (Table 2), which consists of 10–40% sand and roughly equal amounts of silt and clay, may also be described as a loam, clay loam, or silty clay loam (Fig. 4). No primary sedimentary structures are preserved in this lithofacies. These sediments are typically reddish brown (5YR 5/4). They are strongly modified by pedogenesis and contain numerous paleosol horizons. Locally, buried argillic horizons preserve high clay content with sand- or silt-filled desiccation cracks. $CaCO_3$ nodules and filaments are common, as are root tubules and rhizocretions. This lithofacies is similar to the loamy surface soils/clayey subsoils (e.g., Pullman series soils) that characterize the Blackwater Draw Formation across the northern and northeastern part of the Southern High Plains. The sandy mud lithofacies is the fine-grained downwind equivalent of the very fine to fine sand lithofacies of the Blackwater Draw Formation. It is also finer grained than the fine sand to coarse silt lithofacies of the Ogallala Formation.

The cyclic nature of Blackwater Draw sedimentation and pedogenesis is well expressed in core from western Carson County, Texas and at the type section north of Lubbock, Texas, where these paleosols have been described in detail by Holliday (1989) (Fig. 12).

MODERN SOILS OF THE SOUTHERN HIGH PLAINS

Surface soils of the region (e.g., Amarillo and Pullman series) are characterized by relatively thick (> 1 m) and red to reddish brown (5YR and 2.5YR hues) B horizons with significant amounts of illuvial clay and carbonate (usually Stage III calcic horizons up to 1 m thick). These soils are dry with little or no leaching of mineral grains. Secondary $CaCO_3$ accumulation begins as shallow as 38 cm to 44 cm and consists of filaments, nodules, and coalesced nodules. Calcic horizons contain 30–70% $CaCO_3$ by volume in the Pullman clay loam, and 20–60% $CaCO_3$ by volume in the Amarillo sandy loam.

There are significant morphological and chemical variations among these

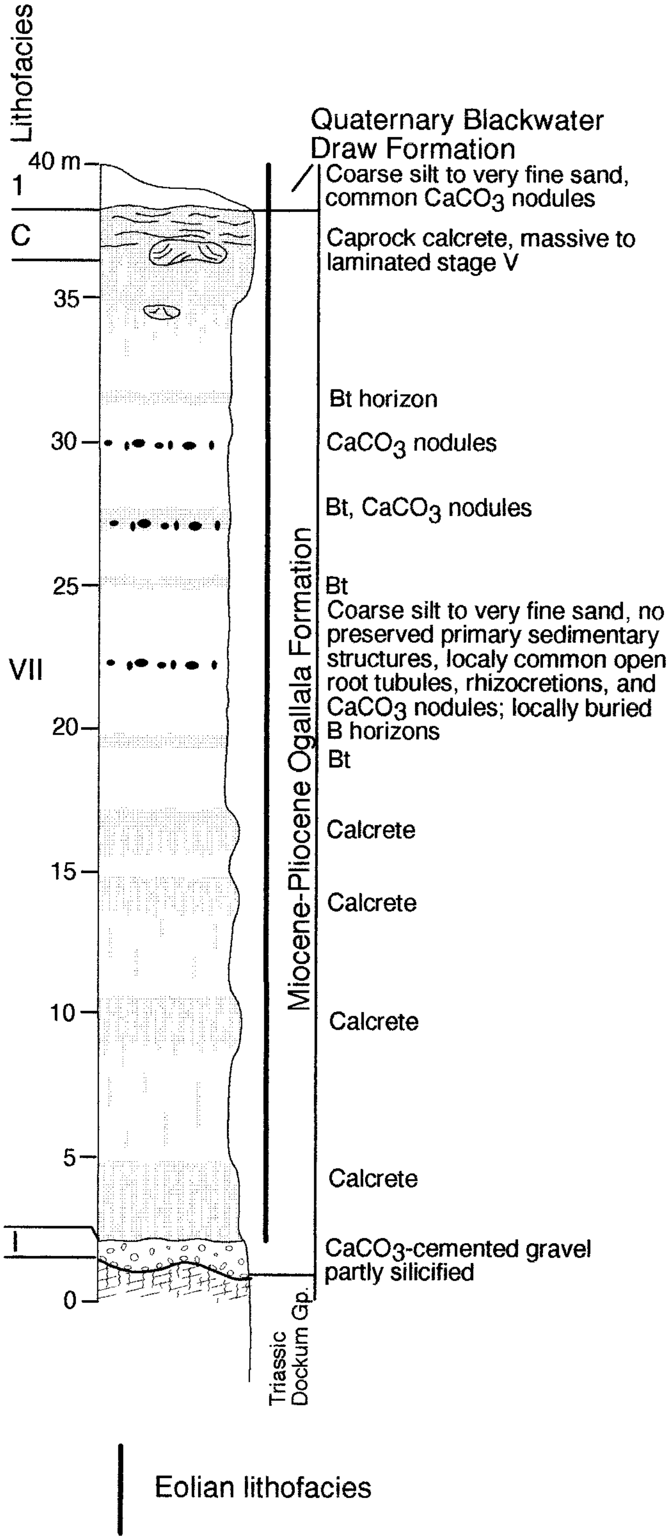


FIG. 7.—Composite stratigraphic section of the Ogallala Formation exposed along the eastern Caprock Escarpment approximately 6 km east of Silverton, Texas on Texas Highway 256 (see Figure 1 for location). Roman and Arabic numerals identify Ogallala and Blackwater Draw Formation lithofacies (Tables 1 and 2).

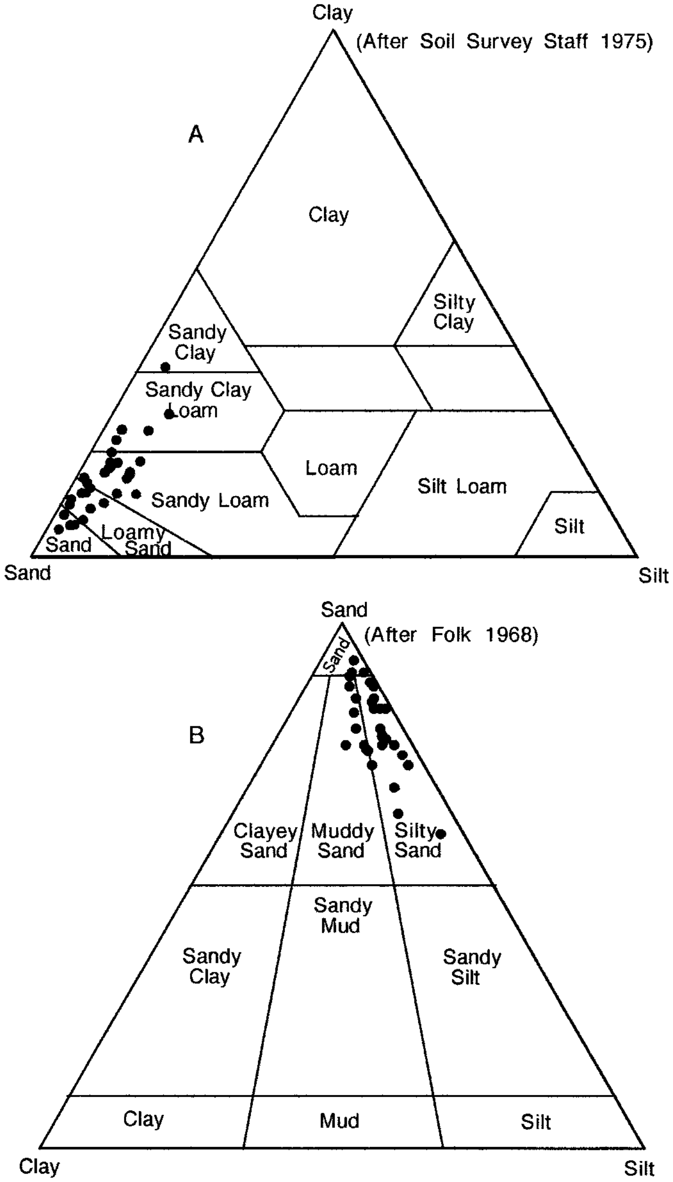


FIG. 8.—Distribution of sand, silt, and clay for the Ogallala Formation for **A)** sediment and **B)** soil textural classes (from Gustavson 1996).

soils, mostly due to regional variations in the soil-forming factors (Holliday 1990b). Amarillo Series soils are typical of sandy loam soils developed in the central and southwestern Southern High Plains, and the Pullman Series soils are typical of clay loam soils developed in the central and northeastern parts of the region. Amarillo series soils have a thin A horizon, a thick (> 1 m), reddish brown (5YR hues), sandy clay loam argillic horizon with a pronounced clay bulge and prismatic structure, and a Stage III calcic horizon locally over 1 m thick. Pullman Series soils have a thicker, darker A horizon (clay loam) high in organic carbon, and have a clay to clay loam argillic horizon with prismatic structure, over a Stage III calcic horizon.

The principal differences between the soils of the southwestern region and those of the central and northeastern region are the sandier textures and shallower depths to calcic horizons in the southwest. The soils in the southwest also vary considerably in thickness. Blackwater Draw Formation sediment is coarser in the southwest because it is closer to the source area (Seitlheko 1975; Holliday 1989). The soils in the southwestern region are commonly thinner than those farther north and east because the parent material, the Blackwater Draw Formation, is typically thin in this region and more frequently subject to deflation.

PALEOSOLS OF THE OGALLALA AND BLACKWATER DRAW FORMATIONS

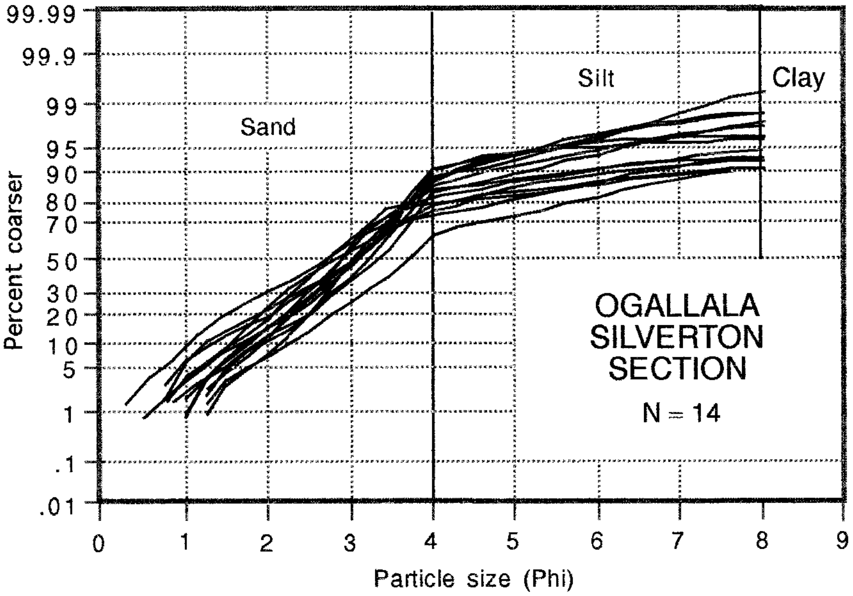
Eolian lithofacies of the Ogallala and Blackwater Draw Formations are characterized by numerous buried argillic, calcic, and petrocalcic paleosols (Allan and Goss 1974; Winkler 1987; Gustavson and Winkler 1988; Holliday 1988, 1989, 1990b). A horizons are not preserved in the Ogallala Formation and are only rarely preserved in the Blackwater Draw Formation. Apparently, the distinguishing organic content of A horizons was eroded prior to burial or oxidized or consumed upon burial. Paleosols in the eolian facies of the Ogallala Formation commonly contain calcic (Bk) horizons, occasionally contain argillic (Bt and Btk) horizons, and are strikingly similar to the paleosols and surface soils of the Blackwater Draw Formation: the Btk–Bk profiles in the Ogallala are thick (~ 1.0–1.6 m) and reddish brown (2.5 to 5YR hues) and have argillic horizons with continuous clay films, high content of illuvial clay, and prismatic structure. Locally, calcic horizons, which are typically Stage I or II, are as much as 3 m thick, suggesting that these soils are cumulic and that deposition occurred as pedogenesis progressed. Morphologically, these paleosols are generally similar to those of the High Plains surface. The paleosols of the Blackwater Draw Formation have thick (> 1 m), red to reddish brown (2.5YR to 5YR hues) argillic horizons with high content of illuvial clay and prismatic structure, and Stage II to III calcic horizons. Calcic horizons of the Blackwater Draw are commonly developed in the upper argillic horizon of the next lower paleosol. The paleosols also commonly display stronger pedogenic expression than the surface soils, exhibiting 2.5YR hues and thicker and more continuous clay films (Holliday 1989). The number of paleosols in the Blackwater Draw Formation varies geographically, and sediments unaltered by pedogenesis are rare. Typically both surface soils and paleosols are welded, and paleosols are more numerous in the northeastern part of the Southern High Plains, where the formation is thickest.

Buried argillic horizons in the Ogallala and Blackwater Draw Formations commonly exhibit a very coarse vertical prismatic to weakly subangular blocky structure and are recognized by an increase in clay content and by an increase in red/brown color. Pedogenic carbonate, argillans, or mangans on fracture surfaces or lining root traces are common. Calcic horizons in both formations are typically defined by accumulations of $CaCO_3$ as filaments, nodules, and coalesced nodules that range from a few millimeters to more than ten centimeters in diameter and typically contain dispersed silt- and sand-size clastic grains consisting mostly of quartz. In some sections, development of $CaCO_3$ nodules is pervasive over several meters vertically, and no distinct soil horizons can be distinguished.

Calcic paleosols that are preserved in the Blackwater Draw and Ogallala Formations are typically stage I to stage III (Figs. 12, 13A) and are less commonly stage IV or V (thin to thick lamellae, to thick lamellae with pisolites). The Caprock Calcrete, which occurs at the top of the Ogallala Formation, however, typically ranges from stage IV to a thick (~ 8 m) stage VI. Rhizocretions, which are commonly preserved in eolian lithofacies of both the Ogallala and Blackwater Draw Formations, range from roughly cylindrical, thin (< 5 mm in diameter), and delicate to thick (~ 15 mm in diameter) and hard, downward-branching $CaCO_3$-cemented concretions (Fig. 13B). Rhizocretions may be very common, forming complex interwoven networks. Where hollow, the remaining open space in these rhizocretions is typically 1 mm or less. In certain rhizocretions, concentric bands of cement are preserved. Open fine root tubules are also very commonly preserved in all lithofacies except gravel (Fig. 13C). Most tubules, which range in diameter from < 1 mm to as much as 5 mm, are open, but a few have been partly filled with $CaCO_3$.

EPISODIC SEDIMENTATION AND PEDOGENESIS

Numerous episodes of eolian sedimentation and pedogenesis are preserved in the Ogallala and Blackwater Draw Formations, which likely re-



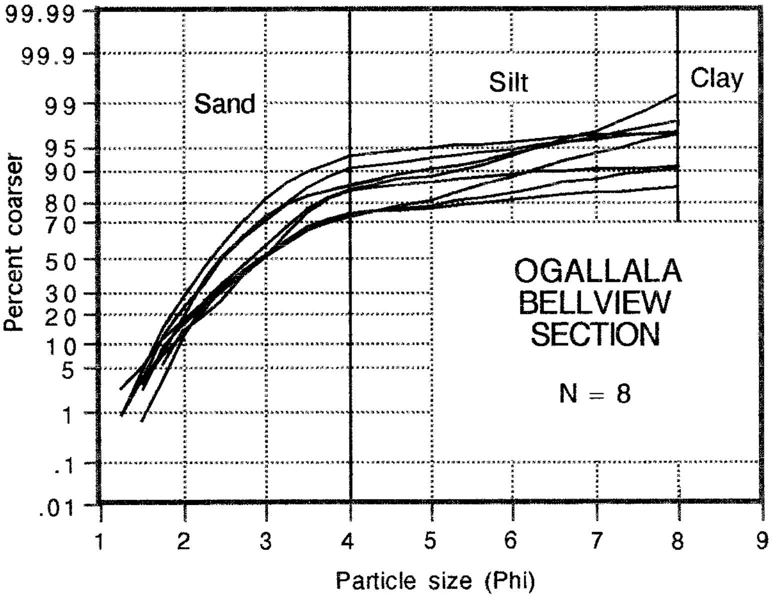


FIG. 9.—Distribution of sediment texture for samples of Ogallala fine sand to coarse silt lithofacies fine from west to east over a distance of 200 km. The Bellview section is located on New Mexico highway 93, 14.4 km north of Bellview, New Mexico. The Silverton section is located 200 km to the east on Texas highway 256 about 25 km east of Silverton, Texas (see Figure 1 for location).

flect long-term climatic variations on the order of 10 to 100 ky or longer. Episodes of sedimentation and pedogenesis varied considerably, as shown by differences in thickness of loess–paleosol pairs that range from less than a meter to several meters, and by differences in the degree of calcic soil development, which range from Stage I to Stage VI. In addition long sections of sediments (1–15 m) containing common pedogenic $CaCO_3$ nodules, but with little or no evidence of horizonation, apparently record long periods during which soil development kept up with sediment accumulation. Episodes of sedimentation and pedogenesis in the Blackwater Draw Formation can be inferred to range from many tens of thousands of years to perhaps 100,000 yr or so, on the basis of the age of this formation (1.9 Ma to present) and the number of preserved paleosols (Hovorka 1995 recognized 14), on the degree of calcic soil development, and on comparison of paleosols with the surface soils of the High Plains (Holliday, 1989). Although no dates are available to determine the duration of episodes of sedimentation and pedogenesis in the Ogallala Formation, the stages of development of buried argillic and calcic horizons suggest that pedogenesis occurred over periods of tens of thousands of years to more than a hundred thousand years for some paleosols.

Interbedded non-glacigenic loess and paleosols from central China have been dated and compared to oxygen-isotope variations in deep-sea sediments in order to establish a relationship between dust falls, pedogenesis, and climate (Kukla et al. 1988; Verosub et al. 1993). However, until data on magnetic susceptibility are available for full sections of Ogallala and Blackwater Draw loess and paleosol sequences, comparison of High Plains and Chinese loess is difficult, and a direct analogy cannot be drawn between late Tertiary and Quaternary sedimentation and pedogenesis on the High Plains and oxygen-isotope fluctuations in deep marine sediments and global

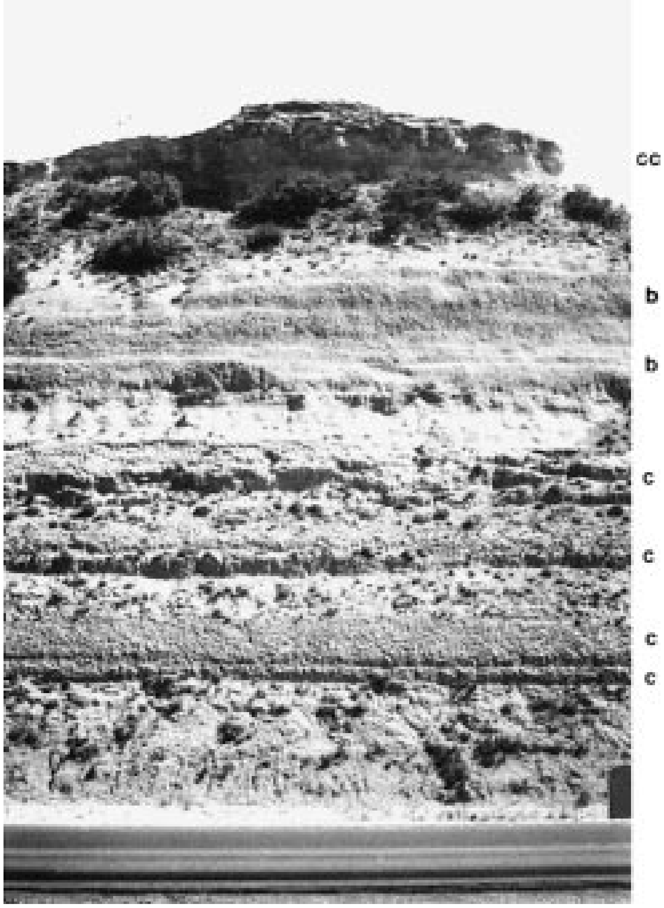


FIG. 10.—Ogallala sediments in the Caprock Escarpment approximately 25 km east of Silverton, Texas on Texas Highway 256, depicting some of the buried soil horizons shown in the composite section in figure 7 (see Fig. 1 for location). Dark bands (b) are buried B soil horizons. Intermediate gray erosionally resistant units are calcretes (c). The exposure is capped by the Caprock calcrete (cc). Scale is approximately 1 m.

TABLE 2.—*Blackwater Draw Formation lithofacies and interpreted depositional environments. This table does not include sediments that partly fill draws or playa basins on the Southern or Central High Plains (from Gustavson 1996).*

Lithofacies	Sedimentary, Diagenetic and Pedogenic Characteristics	Depositional Environments
1. Very fine to fine sand	Fine to very fine sand with no preserved primary sedimentary structures; rare to common $CaCO_3$ nodules or filaments; large $CaCO_3$ nodules may be pedodes; rare to common root tubules.	Sand sheet on grassland or prairie
2. Sandy mud	Coarse silt to very fine sand', no preserved primary sedimentary structures, locally common root tubules, rhizocretions, and $CaCO_3$ nodules; locally buried B (soil) horizons preserve high clay content or sand or silt-filled desiccation cracks.	Loess accumulation on grassland or prairie
3. Laminated very fine sand, silt, and clay	Thinly laminated very fine sand, silt, and clay; upward-fining centimeter-scale sequences; desiccation cracks.	Ephemeral pond
4. Clay	No preserved primary sedimentary structures, desiccation cracks partly filled with silt to very fine sand, $CaCO_3$ nodules, large wedge-shaped soil aggregates bounded by fractures with slickensides.	Ephemeral pond

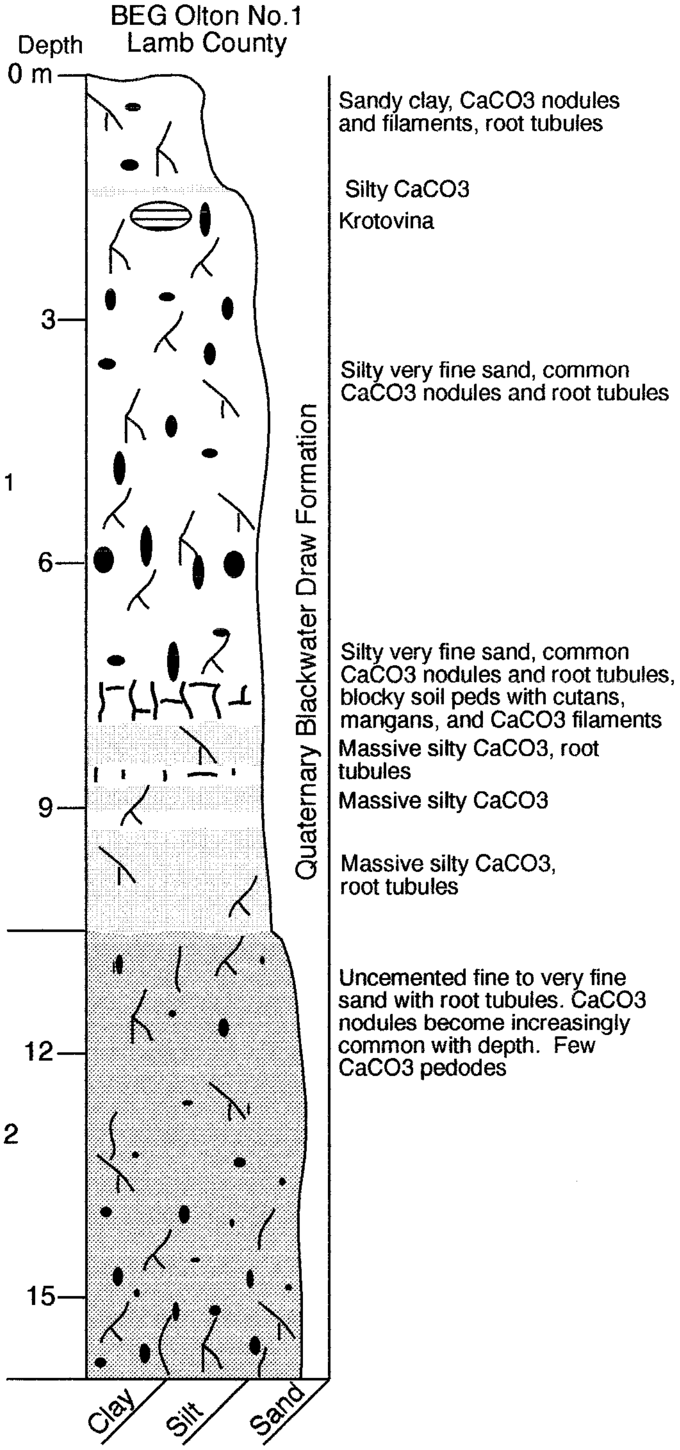


FIG. 11.—Description of core of the Quaternary Blackwater Draw Formation from BEG Olton No. 1 well, Lamb County, Texas (see Figure 5 for location). Numbers identify Blackwater Draw lithofacies (Table 1).

climate. Nevertheless, because of the inferred age spans of loess–paleosol pairs (3×10^4 to 10^5 years) and the number of loess–paleosol pairs (14) during the Quaternary, loess–paleosol pairs preserved on the High Plains may be analogous to Quaternary loess–paleosol pairs in China and elsewhere, and are probably related to climate cycles.

Episodic development of eolian sediments and soils on the High Plains

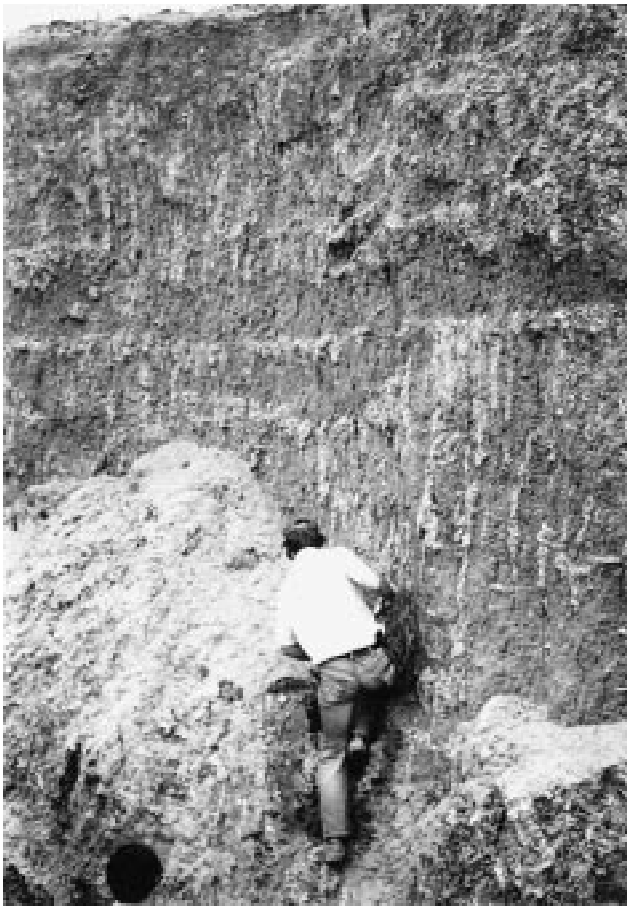


FIG. 12.—Multiple paleosols with stage III calcic horizons at Blackwater Draw type sections, approximately 3.2 km northwest of New Deal, Texas (see Figure 5 for location). Note numerous large soil carbonate nodules typical of buried calcic soils in the Blackwater Draw Formation.

resulted from the processes of sedimentation and pedogenesis acting in concert. Both processes were active throughout the cycle but occurred at different rates, largely in response to climatic conditions, which varied both temporally and geographically. At any point in time sediment erosion and transport was probably more frequent in the western part of the High Plains because of a drier climate and diminished vegetative cover. Conversely, sediment trapping and stabilization was more efficient in the eastern High Plains because there a more humid climate resulted in increased vegetative cover. Erosion and transportation were dominant during warmer drier times because grass cover was likely diminished or partly replaced by desert shrubs in the western part of the High Plains and Pecos River valley, making sediment more available. Warmer temperatures also resulted in higher wind velocities with the capacity to move more sediment farther. Pedogenesis dominated during cooler, wetter times because increased grass cover, especially in eolian sediment source areas in the western parts of the High Plains and the Pecos River valley, resulted in a stable landscape.

An alternative process is that deposition of the Blackwater Draw and Ogallala Formations was indirectly controlled by climate, in that episodic accumulation of large quantities of fine-grained alluvium in the Pecos Valley may have influenced sedimentation on the High Plains. McDonald and Busacca (1988, 1992) and Busacca (1989) report a long (possibly 1.5–2.0 My) record of multiple paleosols in loess in eastern Washington that appears to be linked to periodic flooding of the Channeled Scabland rather than linked to immediate environmental changes. The alluvial history of the Pecos Valley is very poorly known, however, and until that record is established the influence of Pecos River alluviation on High Plains sedimentation will remain unknown. Recent observations are that the most important source areas for eolian sediment lie along the eastern margin of the Pecos Valley (McCauley et al. 1981).

The Ogallala and Blackwater Draw Formations vary considerably in texture across the Southern High Plains, from sandy in the west or southwest to silty and clayey in the east and northeast. The textural fining appears to be the result of downwind sorting, but such marked though gradual textural changes over such a large area are not common. Neither the Ogallala nor the Blackwater Draw is a typical sand sheet (e.g., Kocurek and Nielson 1986), cover sand (e.g., Catt 1986), or loess sheet (e.g., 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 analog to the Ogallala and Blackwater Draw Formations appears to be the eolian sediment of the Loess Plateau of northern China, with its ''sandy loess'', ''loam loess'', and ''clayey loess'' (Liu et al. 1982; Kes 1984). This is significant because, like the Ogallala and Blackwater Draw Formations, the extensive eolian deposits of northern China appear to be of desert origin rather than of glacial origin (Pye 1987).

DISCUSSION

Recognition of the eolian origin of the upper part of the Ogallala Formation of the Blackwater Draw Formation is based on texture, pedogenic structures, and observed modern processes such as dust and sand storms as well as the absence of evidence, such as stratification. Furthermore, by comparison with modern soils, factors that control soil development (climate, organisms, relief, parent material, and time) can be estimated for paleosols of the Ogallala and Blackwater Draw Formations. Interpretation of the characteristic features of the sediments and paleosols that make up the eolian facies of the Ogallala and Blackwater Draw Formations indicate that slow eolian sedimentation has occurred on grasslands on the Southern and Central High Plains since middle Miocene time under mostly semiarid to subhumid climatic conditions.

Numerous well-developed buried calcic horizons in the Ogallala and Blackwater Draw Formations indicate conditions of aridic soil moisture where evapotranspiration exceeded precipitation such that $CaCO_3$ was precipitated under subhumid to semiarid climatic conditions. Preservation of common rhizocretions and complex networks of fine root tubules, in conjunction with fossil floral and faunal evidence (Elias 1942; Webb 1977; Winkler 1985, 1987; Schultz 1990; Thomasson 1990), indicates that fine sand to coarse silt lithofacies of the Ogallala Formation accumulated on a grassland, which is also indicative of a semiarid to subhumid climate (Machette 1985). The presence of similar paleosols having mature argillic horizons, common Stage I–III calcic horizons, and common small root tubules in the Blackwater Draw Formation also implies slow sedimentation and pedogenesis on a stable grass-covered landscape. Furthermore, textural gradations of Ogallala and Blackwater Draw sediments illustrate that paleowinds were dominantly from the west and southwest.

Both Blackwater Draw and Ogallala sediments are primarily quartz and feldspar. Surface sediments and soils of the Blackwater Draw Formation fine from southwest to northeast, and Ogallala sediments fine from west to east across the Southern High Plains, suggesting that the Pecos and western Canadian River valleys and the western part of the Southern High Plains were sources of eolian sediments during the late Tertiary and Quaternary, much as they are today (McCauley et al. 1981). Source sediments include poorly indurated Permian fine sandstones, Triassic sandstones and mudstones, and Quaternary terrace and alluvial sediments, which are extensively exposed in the Pecos and Canadian valleys. Furthermore, at least a small part of Blackwater Draw sediments are derived from the Ogallala Formation where it is exposed in the Pecos and Canadian valleys and along the western Caprock Escarpment. Thus, parent materials for modern soils

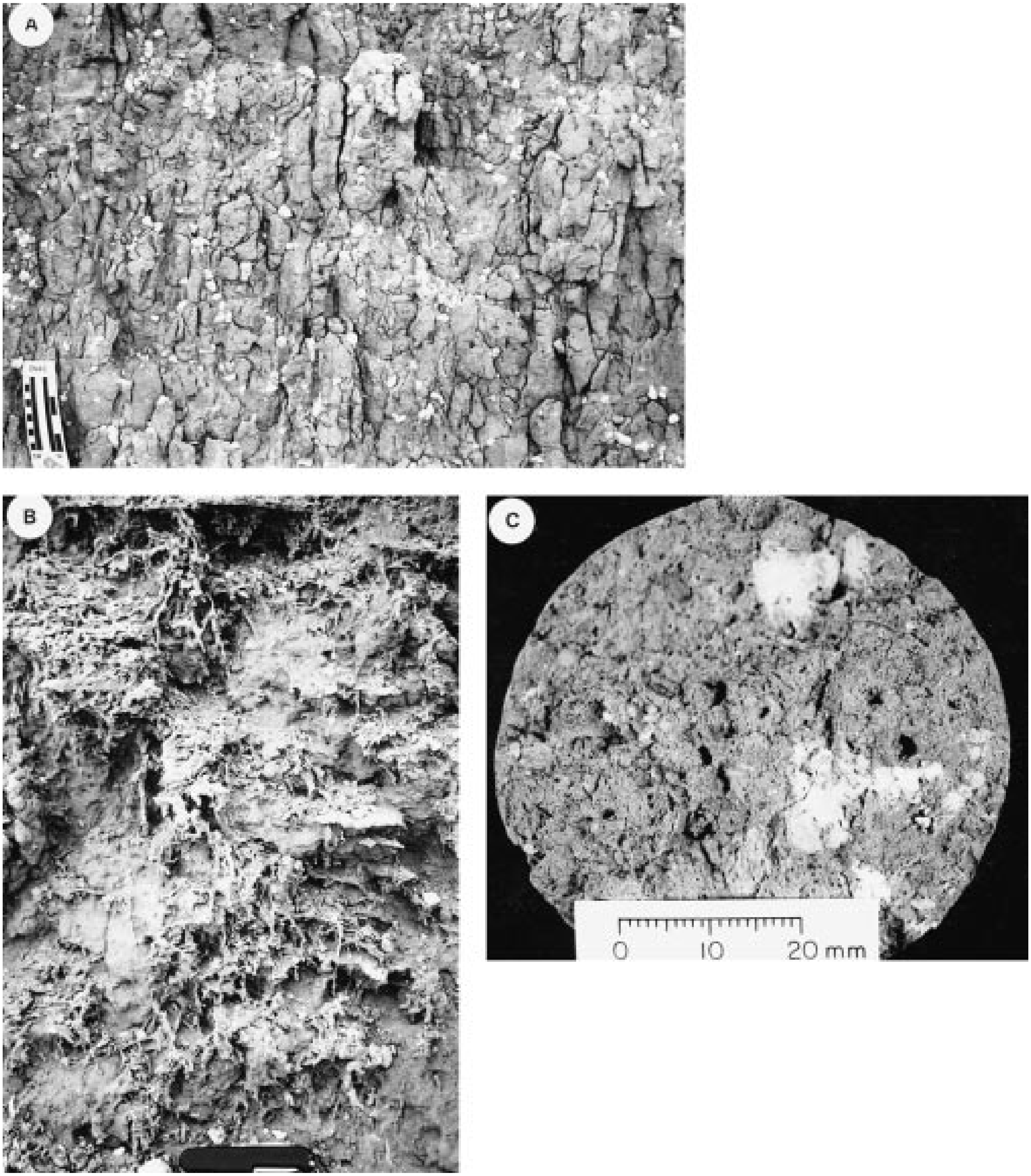


FIG. 13.—**A)** Pedogenic $CaCO_3$ nodules within a buried stage II calcic horizon in the fine sand to coarse silt lithofacies of the Ogallala Formation exposed along eastern Caprock Escarpment (see Figure 1 for location). Scale is 10 cm. **B)** Rhizocretions in the fine sand to coarse silt lithofacies formed around former plant root paths. Thin rhizocretions in the coarse silt lithofacies of the Ogallala Formation consist of fragile, slightly $CaCO_3$-cemented sand and silt grains marking the path of a former root. Exposure is in the Caprock Escarpment at Palo Duro Canyon State Park (see Figure 1 for location). Pocket knife is 6 cm long. **C)** Black spots are root tubules and white spots are pedogenic $CaCO_3$ nodules in uncemented Blackwater Draw sandy mud at a depth of approximately 11 m in core from BEG Seven Mile Basin No. 7 (see Figure 1 for location). Core is 5 cm in diameter.

on the High Plains, as well as paleosols in the Ogallala and Blackwater Draw Formations, have similar gross mineralogy, texture, and source areas.

In every exposure of the Ogallala or Blackwater Draw Formations, paleosols parallel the High Plains surface and the Caprock calcrete, if it is present. Consequently, surface slopes (relief factor) during development of paleosols must have approximated current slopes on the Southern High Plains, and clearly indicate that a flat, nearly featureless landscape has prevailed on the Central and Southern High Plains since the late Miocene.

Paleosol sequences in the Ogallala and Blackwater Draw Formations have argillic and calcic horizons that are similar to those of the surface soil of the High Plains, which Holliday (1989, 1990) estimated are as much as 50 ka old. Most buried calcic soil horizons on the Southern High Plains are similar to the Stage I–III calcic soils described by Machette (1985). According to Bachman and Machette (1977) and Machette (1985), Stage I calcic soils that developed during the late Quaternary in eastern New Mexico may take as long as 10 to 15 ky to accumulate their characteristic $CaCO_3$ content, and Stage III calcic soils may take as long as 50 ky. The presence of numerous well-developed calcic and argillic horizons in these sediments indicates that accumulation of these eolian sediments was a slow, episodic process.

In addition to paleosols with well developed horizonation there are thick sequences (1–15 m) of Ogallala and Blackwater Draw sediments that are strongly pedogenically altered and contain common $CaCO_3$ nodules, columnar fracture pattern, rhizocretions, common root tubules, no preserved primary sedimentary structures, and either no soil horizonation or weakly developed horizonation. These sections represent long episodes of slow sedimentation and pedogenesis on a stable surface. Typically, these sections carry accumulations of soil carbonate similar to Stage I–III calcic horizons but are much thicker, and thus they represent substantially longer periods of deposition and pedogenesis than those estimated for more typical calcic horizons ($<$ 1 m thick).

The presence of root tubules, rhizocretions, and fossil floral evidence, in conjunction with buried argillic and calcic horizons, suggests that primary sedimentary structures, if they ever existed, were destroyed by soil development and bioturbation. The presence of similar paleosols having mature argillic horizons and common Stage I–III calcic horizons in the Blackwater Draw Formation also implies slow sedimentation and pedogenesis on a stable grass-covered landscape. In the few areas where buried argillic and calcic horizons of the Ogallala Formation are exposed continuously for distances of 0.5 km or more, there is no evidence for erosional truncation of soil horizons.

Sediment transport and deposition during Ogallala and Blackwater Draw time were likely similar to historic sediment transport and deposition on the High Plains, which was primarily as thin sand sheets and as loess or atmospheric dust. The fine sand to coarse silt lithofacies of the Ogallala Formation and the very fine to fine sand and sandy mud lithofacies of the Blackwater Draw Formation have many of the attributes of loess: they preserve no primary sedimentary structures; they are highly calcareous blanket deposits; root tubules, root traces, and rhizocretions are common; they typically show a crude vertical structure; and although they are not lithified, they are locally capable of supporting vertical outcrops. However, most of these sediments, which have a median diameter of 4.0 ϕ (0.063 mm) (very fine sand), are coarser than loess, which has a median diameter of 5 to 6 ϕ (0.031 to 0.016 mm) (medium to coarse silt) (Péwé 1981; Miller et al. 1984). Furthermore, the lack of typical eolian sedimentary features such as horizontally laminated or cross-bedded well-sorted sand precludes recognition of sediment sequences deposited as dunes or as thick sand sheets such as those described by Fryberger et al. (1979) and Kocurek and Nielson (1986). Similarly, the lack of primary sedimentary structures or pedogenic aggregates and a lower clay content distinguishes Ogallala and Blackwater Draw loess from fluvial mudrocks such as those described by Rust and Nanson (1989). Although A horizons are not preserved in the Ogallala Formation and are only rarely preserved in the Blackwater Draw Formation, there is no evidence of erosion surfaces such as lag concentrations. Thus, we cannot tell if the distinguishing organic content of A horizons was eroded prior to burial or oxidized or consumed upon burial.

The fine-grained lithofacies was probably deposited under a variety of wind and climatic conditions, with sediment moving over a vegetated surface. During transport events, the clay-size and finer silt-size fraction moved more frequently, for a greater distance, at higher elevations, and under lower wind velocities than the coarser silt- and sand-size fraction. This is consistent with textural data from both the Ogallala and Blackwater Draw, which shows that eolian lithofacies fine from west to east, and from southwest to northeast, respectively. The finer-textured eolian sediments were likely transported in much the same way as eolian dust is transported on the High Plains historically, including dust storms and dust devils. Most of these sediments, which range from 4 ϕ to $>$ 8 ϕ (0.063 to $<$ 0.004 mm) in size, can be transported up to many hundreds of kilometers in a single event (Péwé 1981; Tsoar and Pye 1987).

Coarse silt- and sand-size sediment likely moved by saltation and was deposited mainly as thin lobate sand sheets. Silt- and clay-size particles also make up significant percentages of the Ogallala and Blackwater Draw Formations. Deposition as a mix of loess or atmospheric dust and thin sand sheets accounts for the downwind fining of both Ogallala and Blackwater Draw eolian sediments. Deposition as sand sheets likely was more important closer to source areas, and deposition as loess was more common in downwind areas. Deposition by these processes would have been aided by the baffling effects of grassland vegetation on the High Plains, which probably prevented development of primary stratification for most depositional events, or initial stratification was quickly destroyed by bioturbation. Eolian sediments accumulated slowly in thin increments, and there was ample time for pedogenic and biologic processes to destroy any primary sedimentary structures and to homogenize sediments.

CONCLUSIONS

1. The non-glacigenic loess of the Ogallala and Blackwater Draw Formations is similar to glacigenic loess in that both groups of sediments lack preserved sedimentary structures, are calcareous but not lithified, have a crude vertical structure, and support vertical outcrops.
2. The paleosols of these formations are similar to the modern soils of the High Plains, which are developing beneath a grassland under semiarid to subhumid climatic conditions.
3. Paleosols preserved in the Ogallala and Blackwater Draw Formations, as well as common root tubules, rhizocretions, and fossil flora, all indicate the presence of extensive grasslands that flourished under semiarid to subhumid climatic conditions.
4. Sediments that make up the Ogallala and Blackwater Draw Formations fine to the east, suggesting a source area in the Pecos River valley or in the western part of the High Plains. Deposition of these sediments was as a mix of loess or atmospheric dust and as sand sheets, with deposition as sand sheets more important near to the western source areas and deposition as loess more important in downwind areas.
5. Numerous episodes of sedimentation and pedogenesis are preserved in Ogallala and Blackwater Draw sediments as loess–paleosol pairs. Erosion and transport were more important during warmer, drier times because grass cover was likely diminished or partly replaced by desert shrubs in the western part of the High Plains and Pecos River valley, making sediment more available. Pedogenesis dominated during cooler, wetter times because increased grass cover, especially in eolian sediment source areas in the western parts of the High Plains and the Pecos River valley, resulted in a stable landscape.
6. Loess–paleosol pairs in the Late Tertiary Ogallala and Quaternary Blackwater Draw Formations resulted from climatically influenced cycles of sedimentation and pedogenesis. The loess–paleosol pairs, and therefore the climatic variations that they reflect, mostly developed over time periods on the order of 30 to 100 ky.

ACKNOWLEDGMENTS

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