FLUVIAL AND EOLIAN DEPOSITIONAL SYSTEMS, PALEOSOLS, AND PALEOCLIMATE: LATE CENOZOIC OGALLALA AND BLACKWATER DRAW FORMATIONS, SOUTHERN HIGH PLAINS, TEXAS AND NEW MEXICO

Final Report

by

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ABSTRACT

The late Tertiary Ogallala Formation contains the Ogallala (High Plains) aquifer, which is the major source for water for agricultural and domestic use on the Southern High Plains of Texas and New Mexico and the overlying perched aquifers. This study, which is based on outcrop and subsurface data including both log and core information, was undertaken to provide regional geologic information necessary to evaluate and provide information for the Department of Energy's (DOE's) efforts to remediate contamination of the vadose zone and of the perched aquifer above the Ogallala aquifer at the DOE's Pantex Plant in eastern Carson County.

Deposition of the basal fluvial sediments of the Ogallala Formation in northwestern Texas and eastern New Mexico was controlled by topography on the underlying erosional surface. Paleovalley-fill facies consist of heterogeneous gravelly and sandy ephemeral-stream deposits and sandy to clayey overbank deposits interbedded with and overlain by eolian sediments deposited as sand sheets and loess. Uplands on the pre-Ogallala erosional surface are overlain by similar eolian sediments. Buried calcic soils consisting mostly of $CaCO_3$ nodules and filaments occur throughout the eolian facies.

The Caprock calcrete, which represents a long period of landscape stability, separates the Ogallala Formation from eolian sediments of the overlying Blackwater Draw Formation. The Caprock calcrete in the eastern part of the Southern High Plains, which is buried by a thick section of Quaternary Blackwater Draw sediments containing numerous buried calcic soils, is not usually brecciated or pisolitic and is generally about 1.5 to 2 m (5 to 6.5 ft) thick. Here the stage IV or V Caprock calcrete apparently formed under a stable landscape and is probably late Pliocene in age. A thicker (4 to 10 m [13 to 33 ft]), complexly brecciated, pisolitic, stage VI Caprock calcrete is widespread beneath large areas of the western High Plains where the Blackwater Draw is only a few decimeters thick. In these areas of thin Blackwater Draw, the accumulations of $CaCO_3$ normally found in about 10 buried calcic soils and the surface calcic

soil of full sections of the Blackwater Draw have apparently been welded onto the uppermost Ogallala calcrete. Thus, part of the Caprock calcrete is locally coeval with the Blackwater Draw Formation and is Quaternary in age. Elsewhere, inliers of Cretaceous limestone and Triassic mudstone crop out on the High Plains and are capped by as much as 9.6 m (32 ft) of complexly brecciated, pisolitic calcrete (stage VI). The thick calcretes that formed on these topographic highs are apparently equivalent to the $CaCO_3$ that accumulated as buried calcic soils in complete sections of the Ogallala and Blackwater Draw. These isolated areas of the Caprock calcrete are probably late Miocene to late Quaternary in age.

Blackwater Draw eolian sediments are similar to Ogallala eolian sediments and also contain numerous buried calcic soils. Eolian facies in both formations, which preserve numerous superposed calcic soils and calcretes and contain common fine root traces, reflect slow episodic aggradation on a stable grass-covered landscape under mostly semiarid to subhumid climatic conditions. The change from fluvial to mostly eolian sedimentation probably resulted from diversion of streams (Panhandle, Clovis, and Slayton paleorivers) that deposited fluvial sediments of the Ogallala Formation to form the Pecos and Canadian Rivers. Source areas for most of these eolian sediments initially may have been floodplains of Ogallala streams and later floodplains of the newly formed Pecos and Canadian Rivers. Buried soils in Tertiary and Quaternary sediments of the southern Great Plains reflect cycles of eolian sedimentation followed by periods of landscape stability and minimal sedimentation in which pedogenesis occurred. Cycles of sedimentation and soil development likely resulted from cyclic decreases and increases in available moisture and vegetative cover in sediment source areas to the west. Eolian sediments were eroded from source areas such as the Pecos Valley during dry periods when vegetation was sparse. During more humid periods, more abundant vegetation probably protected source areas from deflation.

These investigations illustrate the heterogeneity and potential for vertical and lateral compartmentalization of the Ogallala and local overlying perched aquifers. For example, at least five fine-grained low-conductivity zones, including the aquitard at the base of a contaminated perched aquifer, are present in lower Ogallala sediments beneath the Pantex Plant in western Carson County.

INTRODUCTION

The late Tertiary Ogallala Formation and the Quaternary Blackwater Draw Formation in the Texas Panhandle and eastern New Mexico were examined in order to provide a stratigraphic framework for hydrologic assessments of the regional Ogallala (High Plains) aquifer and overlying locally developed perched aquifers. The Ogallala aquifer, which is the primary source of water for agriculture in the region, also supplies a substantial part of the area's water for domestic use. The studies described in this report were undertaken as part of an integrated regional geologic and hydrologic characterization of the U.S. Department of Energy's (DOE) Pantex Plant and vicinity (fig. 1). These studies were completed to provide the State of Texas and its citizens with information necessary to effectively evaluate DOE's program to remediate contamination of a perched aquifer and of the vadose zone above the Ogallala aquifer at the Pantex Plant. Contaminants recognized at the plant include low concentrations of industrial solvents, high explosives, tritium, chromium, and gasoline (U.S. Department of Energy, 1989). These studies were also undertaken to provide geologic and hydrologic information to support DOE's remediation program at the Pantex Plant.

In this examination of the Ogallala and Blackwater Draw Formations, particular emphasis was placed on recognition of stratigraphic heterogeneity and compartmentalization and pathways for preferential ground-water flow. Examination of the Ogallala and Blackwater Draw Formations, moreover, provides insight into the geologic history, geomorphic evolution, depositional environments and processes, and paleoclimate of the Southern High Plains and surrounding areas during the late Tertiary and Quaternary.

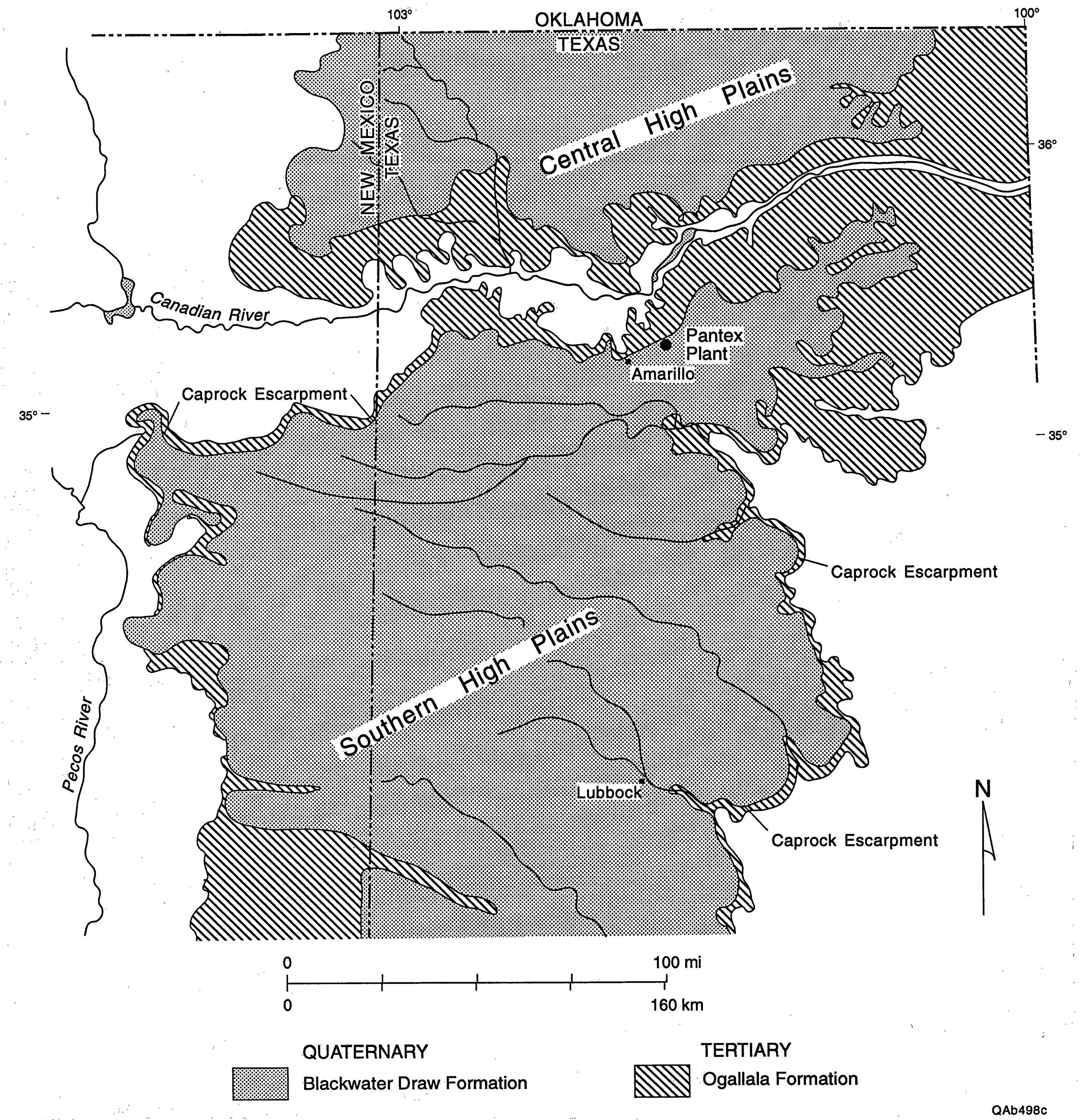


Figure 1. Geologic map of the Tertiary Ogallala and Quaternary Blackwater Draw Formations, Texas Panhandle and eastern New Mexico.

Geologic Setting

The present geographic distribution of the Ogallala and Blackwater Draw Formations roughly coincides with the extent of the Central and Southern High Plains in Texas and New Mexico (fig. 1). The Central and Southern High Plains, which are separated by the Canadian River valley (Canadian Breaks), are bounded on the east and west by the Caprock Escarpments. To the south, the Southern High Plains is physiographically contiguous with the Edwards Plateau. Most of the outcrops of the Ogallala Formation occur in the Canadian Breaks and the Caprock Escarpments. The Blackwater Draw Formation is rarely exposed on the High Plains or its surrounding escarpments, and good exposures are limited to man-made excavations.

Structural History

In the Texas Panhandle and eastern New Mexico, the Palo Duro Basin and its westward extension, the Tucumcari Basin, are bounded on the west by the Pedernal and Sierra Grande uplifts, on the northeast by the Wichita Mountains–Amarillo Uplift trend, and on the south by the Matador Arch–Roosevelt Uplift trend (fig. 2). The Cimarron Arch separates the Dalhart and Anadarko Basins to the north. These major positive tectonic elements resulted from faulting and uplift that began during the Paleozoic, possibly as early as the Late Cambrian (Birsa, 1977). Tectonic movement along the Amarillo Uplift and Matador Arch during the Pennsylvanian and Permian controlled sedimentation and facies distribution in the Palo Duro Basin (Dutton and others, 1979). By early Permian time the Palo Duro and neighboring basins were filled, resulting in an extensive shallow marine shelf that extended from Kansas to West Texas (Presley, 1979a, 1979b, 1980a, 1980b). During the Triassic period, differential epeirogenic uplift resulted in local erosion of Permian strata and produced the basin that contains terrestrial sediments of the Dockum Group (McGowen and others, 1979; Johns, 1989). By Cretaceous time the region had subsided below sea level. Epeirogenic movements continued into the Tertiary and uplifted Cretaceous strata to their present elevation of approximately 850 m (2,800 ft) above sea level

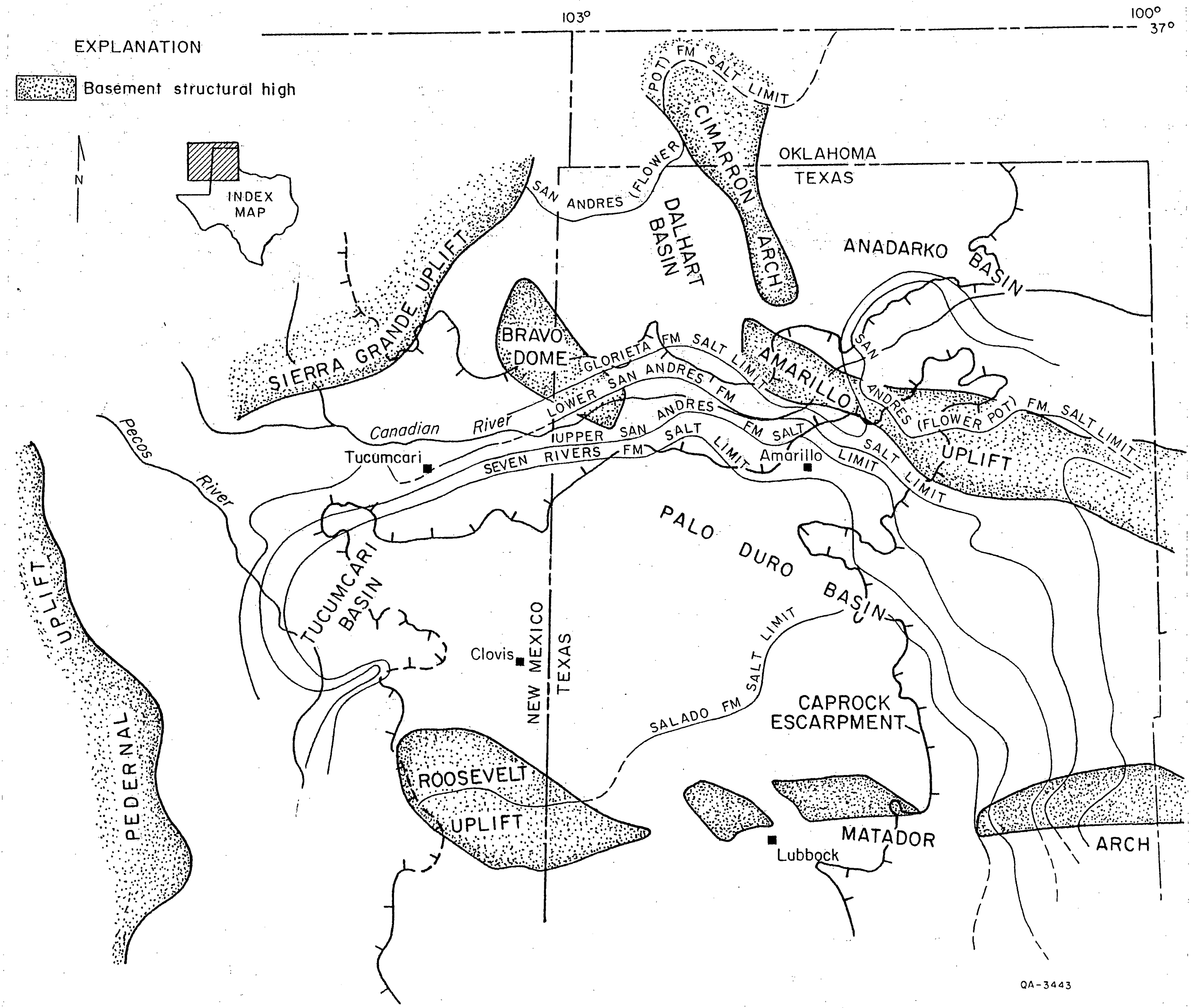


Figure 2. Major structural elements, Texas Panhandle and surrounding areas. After Nicholson (1960). Limits of Permian bedded salts are closely associated with structural margins of the Palo Duro Basin; lines mark updip limit of Permian bedded salt. Each of these units (Salado-Glorieta Formations) has lost substantial thicknesses of salt. Collectively, the salt-limit lines approximate a zone of salt dissolution that rims west, north, and east margins of the Palo Duro Basin. Structurally high salt units are the most likely to be affected by salt dissolution (Gustavson and Finley, 1985).

along the eastern Caprock Escarpment and to more than 1,515 m (5,000 ft) along the western Caprock Escarpment above the northwestern margin of the Palo Duro Basin (Eifler, 1968; Gable and Hatton, 1983; Budnik, 1989).

Nontectonic deformation, in the form of extensive regional subsidence induced by widespread dissolution of Permian bedded salt, has occurred throughout large areas of the Texas Panhandle and eastern New Mexico since the Triassic (Baker, 1915; Gustavson and others, 1980, 1982; Granata, 1981; Johnson, 1981; Gustavson and Budnik, 1985; Gustavson and Finley, 1985; Gustavson, 1986; Reeves and Temple, 1986; McGookey and others, 1988). Dissolution and subsidence that began during the late Tertiary and continued into the Quaternary were probably responsible for the structural troughs along the margins of the Palo Duro Basin beneath the valleys of the Canadian and Pecos Rivers and eastern margin of the Southern High Plains (Reeves, 1972; Gustavson and Finley, 1985; Gustavson, 1986). High solute loads in the Pecos River, Canadian River, and streams draining the eastern part of the Texas Panhandle as well as the recent formation of sinkholes in some of these areas indicate that dissolution and subsidence continues as active processes along the margins of the Palo Duro Basin.

Physical and Genetic Stratigraphy

In the early Paleozoic, episodes of shallow marine-shelf sedimentation alternated with periods of erosion in the vicinity of the Texas Panhandle and eastern New Mexico. Marine shelf carbonates were deposited across the area during the Mississippian. During the late Mississippian and continuing through the Pennsylvanian, terrigenous clastic sediments, informally called granite wash, were derived from and deposited near the principal uplifts that bound the Dalhart, Anadarko, Palo Duro, and Tucumcari Basins (Handford and Dutton, 1980). Shelf carbonates dominated late Pennsylvanian and early Permian sedimentation, and fine-grained clastic sediments filled deeper parts of the basin. Middle and upper Permian strata in the Palo Duro Basin are composed of thick sequences of salt, anhydrite, gypsum, dolomite, limestone, and red beds, which were deposited in a range of subtidal to supratidal environments on an extensive very low relief marine shelf (fig. 3) (Presley, 1979a, 1979b, 1980a, 1980b; Fracasso and Hovorka, 1987).

During the early Triassic period, nonmarine clastic sediments of the Dockum Group were deposited in a large fluvial-lacustrine basin south of the Amarillo Uplift (McGowen and others, 1979; Johns, 1989). Dockum Group strata are overlain in a few areas by the Jurassic Exeter Sandstone and by the Lower Cretaceous Kiamichi Formation (Fredericksburg Group), Dakota Group sandstones and conglomerates, and Kiowa Shale in other areas. Following a period of extensive erosion, which produced the middle Tertiary erosional surface, the Miocene–Pliocene Ogallala Formation was deposited in eastern New Mexico and northwestern Texas (Seni, 1980; Winkler, 1984, 1985, 1987; Gustavson and Holliday, 1985; Gustavson and Winkler, 1988; Wilson, 1988).

Ogallala Formation:--The Ogallala Formation in Texas contains both Clarendonian and Hemphillian vertebrate faunas and thus ranges in age from middle Miocene to early Pliocene (Schultz, 1977, 1990; Winkler, 1985). In the High Plains of western Texas and eastern New Mexico, the Ogallala unconformably overlies Permian through Cretaceous strata and is overlain by the Quaternary Blackwater Draw Formation. The Ogallala Formation underlies much of the Great Plains region (Darton, 1899), including approximately 75,000 km^2 in the Southern High Plains (fig. 1).

In Texas and eastern New Mexico, the Ogallala was initially thought to be composed primarily of fluvial sediments, which were deposited as a series of coalescing alluvial fans or as an alluvial plain and markedly subordinate amounts of eolian sediments (Johnson, 1901; Sellards and others, 1932; Bretz and Horberg, 1949a; Frye and Leonard, 1964; Frye, 1970; Seni, 1980; Reeves, 1984). The Ogallala southwest of Lubbock, Texas, and in southeastern New Mexico, however, was recognized as consisting mostly of eolian sediments (Reeves, 1972; Hawley and others, 1976; Hawley, 1984). The Kosi fan in the Himalaya Mountains of India and Nepal was invoked by Seni (1980) as a modern analog for the Ogallala in Texas and New Mexico, and on this basis the Ogallala was interpreted to have been deposited in a relatively wetter climate than

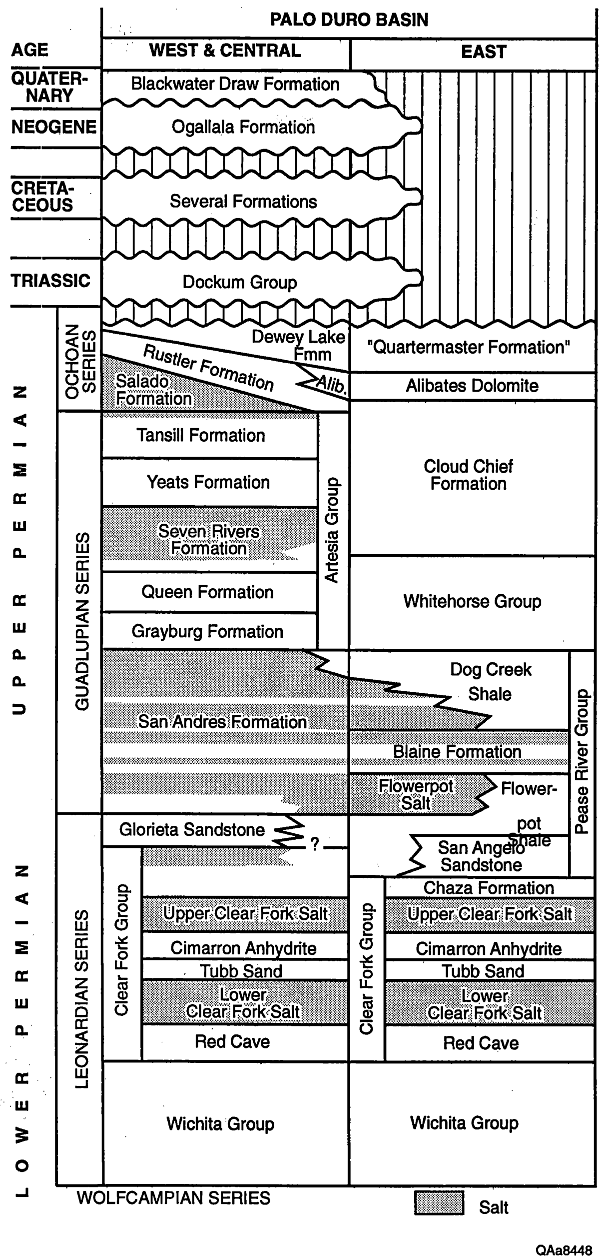


Figure 3. Stratigraphic nomenclature for Permian through Quaternary strata in the Texas Panhandle and eastern New Mexico. From data compiled by Johnson, 1976.

at present. In many of these earlier studies, the Blackwater Draw Formation was not recognized as a separate formation; commonly it was referred to as cover sands overlying the Caprock calcrete (caliche). Later geographically limited or reconnaissance-level investigations of the Ogallala Formation indicate a substantially different scenario for Ogallala deposition in terms of facies components, geometry, and paleoclimate (Gustavson and Holliday, 1985, 1991; Winkler, 1985, 1987; Gustavson and Winkler, 1988; Wilson, 1988). On the basis of outcrop and core studies, the Ogallala in Texas and eastern New Mexico consists of alluvial sediments that partly fill paleovalleys and widespread thick eolian sediments capping paleouplands and most fluvial sections. These strata were apparently deposited under mostly semiarid to subhumid climatic conditions and do not constitute coalescing or overlapping wet alluvial fans.

Nomenclature

The history of the development of Ogallala stratigraphic nomenclature and of the early investigations of this unit has been reviewed extensively by Schultz (1977, 1990) and Winkler (1985). Winkler (1985), as a result of a detailed examination of Ogallala sediments along the southeastern Caprock Escarpment, recognized the Couch and Bridwell Formations and proposed elevating the Ogallala Formation to group status. Because most of the sections described in this report contain no datable materials and can not be mapped and correlated with either the Couch or Bridwell Formations of Winkler (1985), the Ogallala will be treated as a formation.

Caprock Calcrete:--The Caprock (caliche) calcrete that marks the top of the Ogallala Formation in Texas and New Mexico is in most areas a distinctive, approximately 2-m-thick (6-ft) bed of erosion-resistant white calcium carbonate-rich rock that supports the upper rim of the Caprock Escarpment. For the first 50 years of this century, geologists argued about the genesis of this unit. Darton (1899) thought that calcretes were the product of carbonate deposition by evaporation of shallow ground waters drawn near to the surface by capillary action. Darton (1899) observed that caliches form only in arid and semiarid areas and, as a consequence, that climatic conditions during the Late Cenozoic were like those of the present.

Elias (1931) asserted that the Caprock calcrete in Wallace County, Kansas, contained an alga (*Chlorellopsis bradleyi* Elias) that required a permanent body of water for its growth. Based on the presence of the alga, he postulated a lacustrine environment for the deposition of the Caprock calcrete. Many objected to this hypothesis, including Smith (1940), who argued that a widespread lake on the High Plains was improbable because it required tilting the High Plains to a near-horizontal surface during deposition of the lake beds and then returning the High Plains to an easterly tilt of 2 to 2.5 m/km (10.5 to 13.3 ft/mi).

Bretz and Horberg (1949a, 1949b) recognized and described the formation of calcrete (caliche) as a pedogenic process. Based on petrographic analyses of pisolitic parts of the Caprock calcrete, Swineford and others (1958) established that it developed by predominantly soil-forming processes. The work of Smith (1940), Bretz and Horberg (1949a, 1949b), Brown (1957), and Swineford and others (1958) essentially ended the controversy over the origin of the Caprock calcrete.

More recently, Gustavson (1991b) argued that the Ogallala Caprock calcrete is time transgressive and that it is comprised of pedogenic carbonate that accumulated locally from the late Miocene to Quaternary. Furthermore, the Caprock calcrete probably represents a long period of landscape stability rather than a period of increased aridity. Although many authors (especially Reeves, 1976a) have discussed the various attributes of the Caprock calcrete, other buried calcic soils, ground-water calcretes, and silicified calcretes within the Ogallala are not well known.

Blackwater Draw Formation:--The Blackwater Draw Formation is the principal surficial deposit of most of the High Plains of Texas and eastern New Mexico and supports extensive agricultural development. The unit is comprised of eolian sediment that varies in texture from sandy in the southwest to clayey in the northeast (fig. 4). Frye and Leonard (1957) used the informal term "cover sands" for these sediments and considered them to be of "Illinoisian" age. They recognized, however, that the "cover sands ... may include more than one age of deposit" (Frye and Leonard, 1957, p. 28). Frye and Leonard (1957) concluded that the "cover sands" were

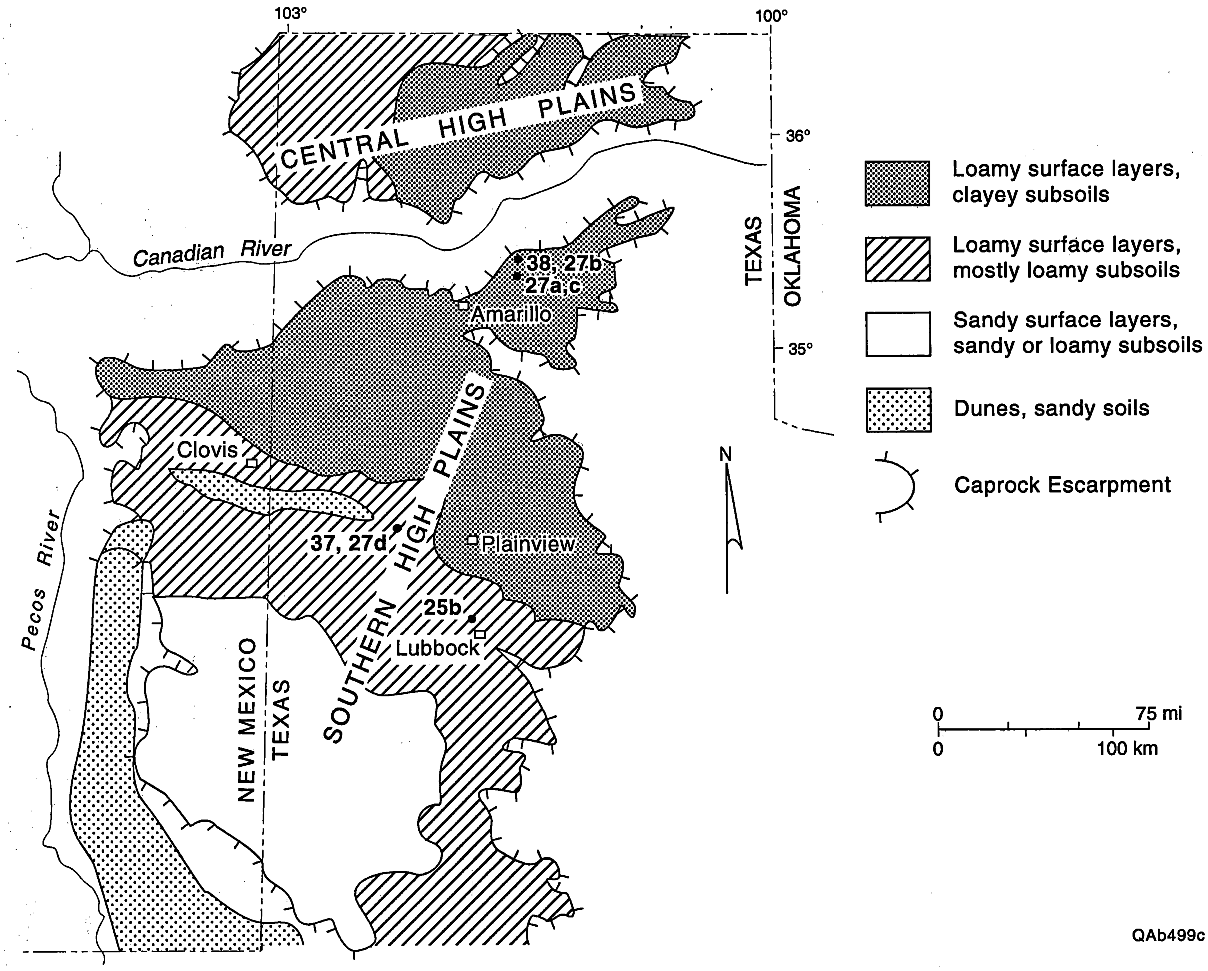


Figure 4. Regional soil texture map illustrating that soils on the High Plains fine to the east and northeast (after Godfrey and others, 1973; Seitlheko, 1975). Numbers locate figures.

of eolian origin, probably derived from some of the large river valleys, such as the Pecos, to the west and southwest.

Reeves (1976b) proposed that the informal term "cover sands" be replaced by the formal designation "Blackwater Draw Formation." He considered the unit to have been deposited during the Illinoisian and recognized that the formation was considerably thicker (locally up to 25 m [83 ft]) than the maximum of about 10 m (33 ft) observed by Frye and Leonard (1957).

Several additional investigations have shed new light on the age and origin of the Blackwater Draw Formation. Seitlheko (1975) described the textural variation of the surface soil of the Blackwater Draw Formation and concluded that it fined downwind, from southwest to northeast, supporting the hypothesis that the sediments originated in the Pecos River valley. A similar textural gradation is present across the Central High Plains in the northern Texas Panhandle, suggesting that the source of these sediments is the Canadian River valley (fig. 4). Allen and Goss (1974), Hawley and others (1976), and Holliday (1989, 1990a, 1990b) recognized that locally the Blackwater Draw Formation contains as many as six well-developed buried soils. This illustrates that the unit was deposited episodically. Limited absolute age control indicates that deposition took place throughout much of the Pleistocene (Holliday, 1984; Gustavson and Holliday, 1985; Machenberg and others, 1985; Holliday, 1989). Holliday (1989) has shown that locally, one of the buried soils in the formation occurs below the 0.6 Ma Lava Creek ash. Elsewhere, one and possibly two buried soils are exposed below the 1.4 Ma Guaje ash of Izett and others (1972). A preliminary paleomagnetic study of the lowermost of five buried soils in the Blackwater Draw Formation near Bushland, Texas, approximately 16 km (10 mi) west of Amarillo, Texas, demonstrates that the remnant magnetization, apparently acquired during pedogenesis, is dominantly reversed (Patterson and Larson, 1990). This suggests that the soil formed during the last reversed polarity epoch, which ended about 0.79 Ma.

Geomorphology

A flat, low-relief surface partly covered with small playa lake basins characterizes the High Plains landscape. The theories describing the origin and development of playa basins were reviewed by Gustavson and others (1995), and the internal stratigraphy is described by Hovorka (in press). Drainage of the High Plains is mostly internal into these basins. Widely separated draws (ephemeral-stream valleys) having very narrow drainage basins slope to the east and southeast. Draw stratigraphy and development are described by Holliday (in press). Adjacent draws do not share common drainage divides but rather are separated by broad interfluves containing numerous playa lake basins. The relief of the Caprock Escarpment, which forms the erosional margin of the High Plains, is supported by resistant calcretes and silicified zones of the Ogallala Formation and resistant sandstones of the Dockum Group and Permian Quartermaster Formation. The escarpment parallels and overlies the margin of the zone of extensive dissolution of Permian bedded salt (Gustavson and others, 1981; Gustavson and Finley, 1985).

Regional physiography has been strongly influenced by subsidence resulting from dissolution of Permian salt. For example, the valleys of the Canadian and Pecos Rivers overlie areas where as much as 200 m (660 ft) of Permian salt has been dissolved (fig. 2). These valleys were probably formed by diversion of Tertiary drainage into subsidence troughs induced by dissolution of Permian evaporites (Gustavson and Finley, 1985; Gustavson, 1986).

Climate

Climate throughout the Quaternary and Tertiary certainly influenced Ogallala and Blackwater Draw Formation sedimentation, and certain aspects of climate during that time such as regional wind and precipitation patterns probably resembled recent climatic patterns, especially during interglacials. It is thus useful to be able to compare Ogallala and Blackwater Draw depositional and pedogenic processes to modern processes in the context of modern climate on the Southern High Plains. Furthermore, it is appropriate to compare paleoclimatic interpretations to modern High Plains climate.

Climate in the Southern High Plains of Texas and eastern New Mexico is continental (steppe) semiarid to subhumid (30 to 56 cm [12 to 22 inches] annual precipitation) and is characterized by wide variations in mean annual precipitation, humidity, and temperature (Orton, 1974; U.S. Department of Commerce, 1978a, 1978b; Larkin and Bomar, 1983). Approximately 80 percent of the annual precipitation falls between the beginning of March and the end of August (fig. 5). Average annual gross lake surface evaporation is approximately 185 cm (73 inches) (Larkin and Bomar, 1983). Rapid temperature changes and large ranges in daily and annual temperature are characteristic of the region (Orton, 1974).

The climatic conditions that characterize the Southern High Plains are largely controlled by the air masses that move through the region. Maritime tropical air masses from the Gulf of Mexico are typically warm and moist, while continental Arctic or polar air masses are typically cold and dry (Larkin and Bomar, 1983). Maritime polar air from the pacific northwest is also typically cold, but milder than polar air masses. Continental tropical air masses from the southwest are hot and dry. Precipitation throughout the fall, winter, and spring months mostly results from the interaction of cold polar or Arctic air masses with warm moist air flowing inland from the Gulf of Mexico or the Pacific. In these instances precipitation results along frontal zones as warm moist air rises over denser cold dry air. During the summer months, precipitation is primarily from thunderstorms. The movement of these air masses, generally from west to east, is guided by winds aloft, including the polar jet stream during the winter and the subtropical jet, a northeasterly flow of warm moist air from the Pacific, during the spring, summer, and fall. In turn, these major climatic elements are driven by the annual warming and cooling of oceans and continental and mountainous land masses.

Periodic severe droughts characterize the High Plains and occurred nine times between 1931 and 1985 (Riggio and others, 1987). During these periods, soil water loss through evaporation and transpiration far exceeds precipitation. Under normal summer weather conditions, winds

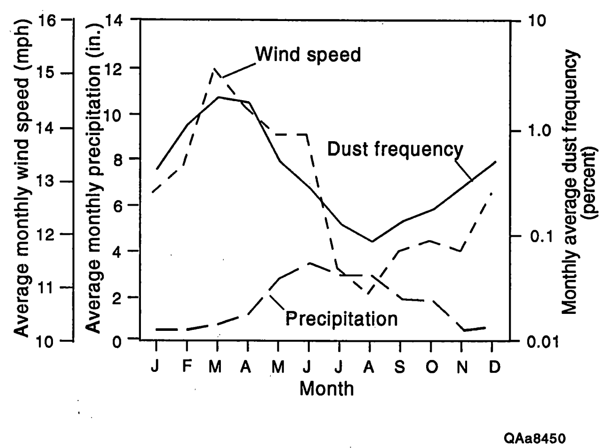


Figure 5. Average monthly precipitation and wind speed at Amarillo, Texas (U.S. Department of Commerce, 1978a, 1978b), and monthly dust frequency (south-central United States) (modified from Orgill and Sehmel, 1976).

from the south and southeast carry sufficient warm moist air into the Southern High Plains to maintain a dew point temperature of about 70°, keep air temperatures at or below 100°, and supply sufficient moisture for cloud formation and precipitation. Droughts typically are associated with the presence of a large subtropical high-pressure cell in the southwestern United States during the summer months. This dome of descending hot dry air inhibits thunderstorm development, the primary source of precipitation on the High Plains. The lack of cloud development allows a maximum influx of solar radiation, which in turn results in very high surface temperatures. Typically, with the formation of this high-pressure cell, southwest winds carry hot dry air into the High Plains, helping to maintain high air temperatures and to minimize precipitation.

The Southern and Central High Plains are among the windiest areas in the United States, with winter (December–March) wind speeds commonly exceeding 25 mph (fig. 6) (Johnson, 1965). Furthermore, the strongest winds on the High Plains occur during periods of drought. Higher than average soil temperatures result in unusually strong turbulent mixing of the air.

Wind regimes and precipitation patterns are closely related on the High Plains (Johnson, 1965). For example, little precipitation falls during winter months because the sources for westerly winds are dry continental areas (figs. 5 and 7). On the other hand, during the summer months, which are the wettest on the High Plains, south and southeast winds favor movement of moist maritime air from the Gulf of Mexico into the High Plains.

Dust and sandstorms are relatively common occurrences on the High Plains and may be particularly severe during droughts (McCauley and others, 1981). Lubbock, Texas, typically experiences 22 days with blowing dust each year (Bomar, 1983). Blowing dust occurs most frequently during February to May, the "dry season" on the High Plains (fig. 5).

Climatic cycles at a variety of time scales and using a variety of evidence have also been proposed for the High Plains. For example, Riggio and others (1987) recognized numerous short-term climatic cycles (periodic droughts) between 1931 and 1985 from precipitation records (decadal scale or less). Other climatic cycles, which reflect longer term fluctuations in available

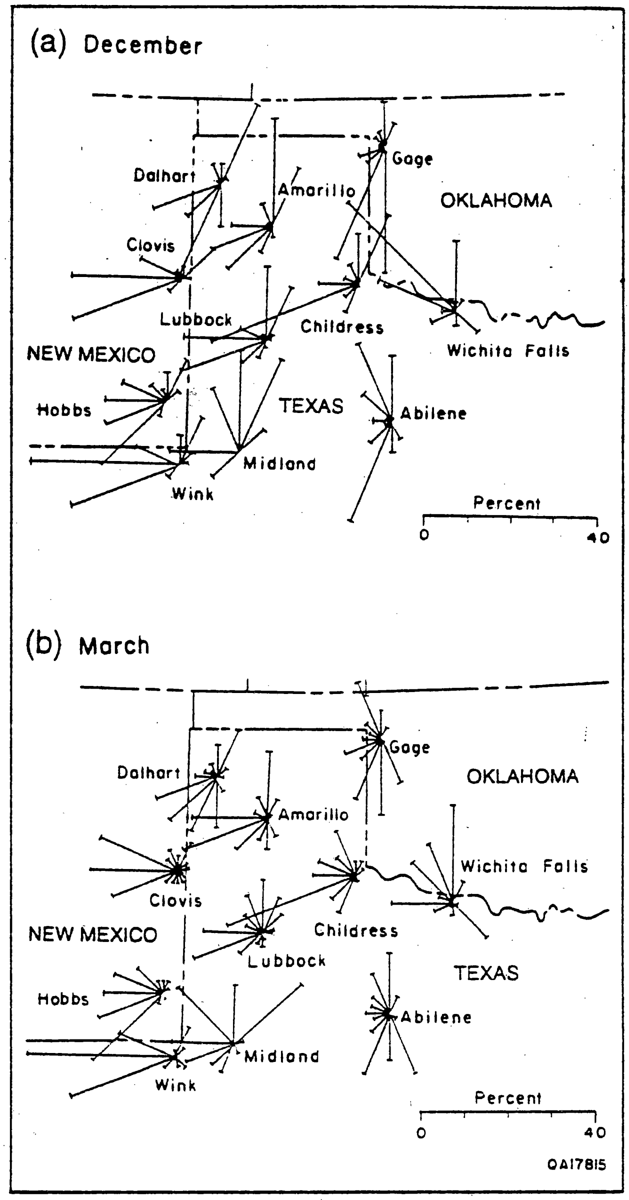


Figure 6. Hourly observations of winds 40 kmph (25 mph) and stronger in percent from different directions in December and March (Johnson, 1965). Scale converts length of line to percent.

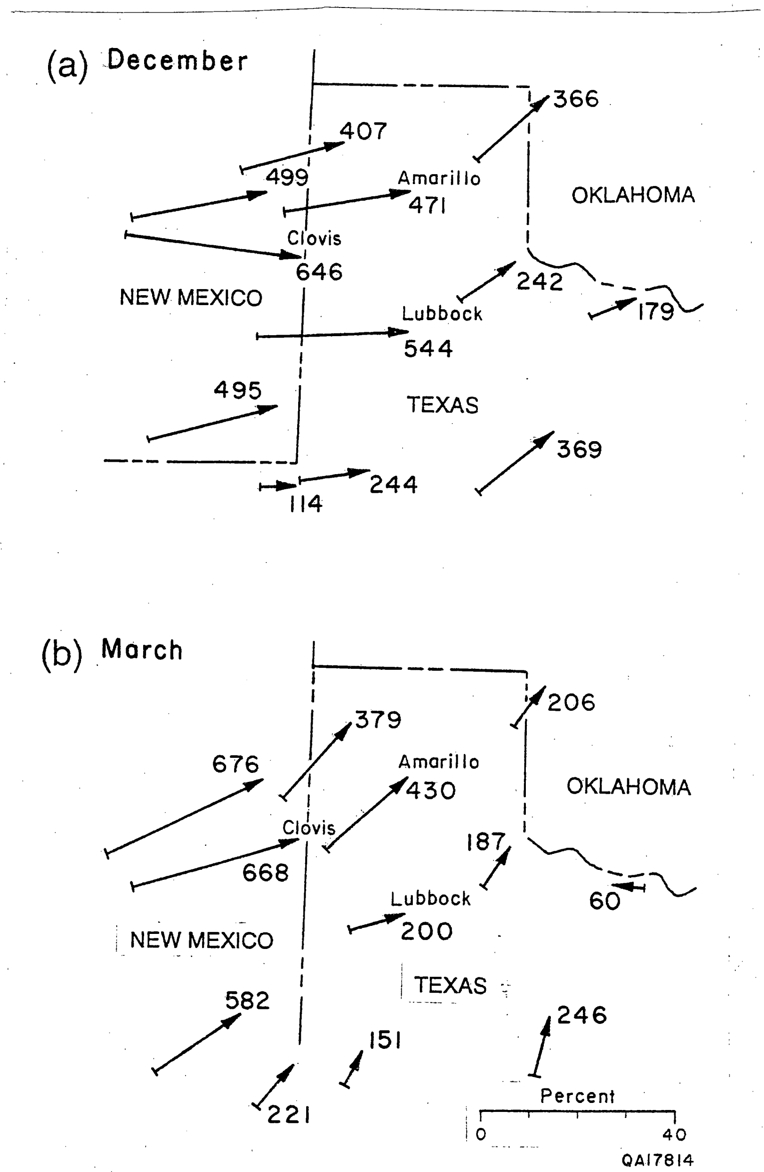


Figure 7. Resultant winds for December and March (Johnson, 1965). Arrows indicate wind direction; numbers indicate air movement in miles in 100 h; arrow tip indicates station location. Length of arrow is proportional to resultant wind movement.

moisture, have also been recognized from sediments and buried soils preserved in draws (millennial scale) and within the Blackwater Draw Formation (several tens of millennia scale) (Holliday, 1989, in press)

Soils

The modern soils that are developing in the Texas Panhandle and eastern New Mexico are a product of the climatic conditions of the area (Jenny, 1941; Machette, 1985). These soils are typically Mollisols and to a lesser extent Alfisols, Aridisols, and Entisols (Godfrey and others, 1973). Soil development on the High Plains is typical of grasslands in semiarid to subhumid climatic conditions. All major upland soil series that have developed on the Southern High Plains are calcic soils, which contain significant secondary accumulations of $CaCO_3$. These include the Amarillo, Pullman, Estacado, Mansker, Olton, Posey, and Tulia series, to name only a few (U.S. Department of Agriculture, 1972a, 1973). Locally, the Randall series has developed in playa basins (U.S. Department of Agriculture, 1972c).

Recognition of buried soils with characteristics similar to those of surface soils of the High Plains is strong evidence for interpretation of paleoclimatic conditions. However, paleoclimatic conditions can only be generalized from these data. In the unlikely event that a buried soil could be correlated with a specific surface soil series, paleoclimatic conditions could still only be roughly estimated. This is because surface soils develop under a range of climatic conditions that vary geographically and temporally. For example, average annual precipitation ranges from 30.5 to 55.9 cm (12 to 22 inches), and average annual temperature ranges from 13.6 C° to 15.6 C° (56.5 F° to 60 F°) across the area where the Pullman Soil Series developed on the Southern High Plains. Furthermore, Holliday (1989) has shown that surface soils accumulated over the last 30 to 50 Ka, during which climatic conditions also varied temporally.

Vegetation

The present natural vegetative cover of the Southern High Plains is short grass prairie (Kuchler, 1970), and the presence of buried calcic soils and fossil floras and vertebrate faunas in Ogallala or younger sediments suggests that savannas, savanna parklands, or prairie grasslands prevailed throughout much of the late Tertiary and Quaternary (Elias, 1942; Webb, 1977; Winkler, 1985; Gustavson and Winkler, 1988; Holliday, 1989, 1990b; Schultz, 1990; Thomasson, 1990; Holliday and Gustavson, 1991). Vegetative cover, however, probably varied with climatic conditions. Currently, 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 (Kuchler, 1970) (fig. 1). In the past, in the western parts of the Southern High Plains, short grass prairie may have been partly replaced by steppe or desert shrub vegetation during warm dry segments of climatic cycles. Studies of native grasslands on the Great Plains clearly show that the vegetative cover is significantly reduced following several years of drought, resulting in severe deflation and movement of large amounts of sediment by the wind (Weaver and Albertson, 1943; Tomanek and Hulett, 1970). Stronger and gustier winds and the likelihood of diminished vegetation indicate that wind erosion and transport became increasingly important during prolonged warm dry periods. Conversely, during relatively cooler and wetter climatic conditions, the boundary between desert shrub and grasslands may have shifted to the west and into the Pecos Plains, stabilizing the landscape of the Pecos River valley.

Methods

The interpretations of Ogallala and Blackwater Draw lithofacies and depositional environments described below are based on core and geophysical logs taken from stratigraphic and hydrologic test holes and on examination of exposures mostly in the Caprock Escarpment (fig. 8). These two approaches provide two different views of the Ogallala and Blackwater Draw

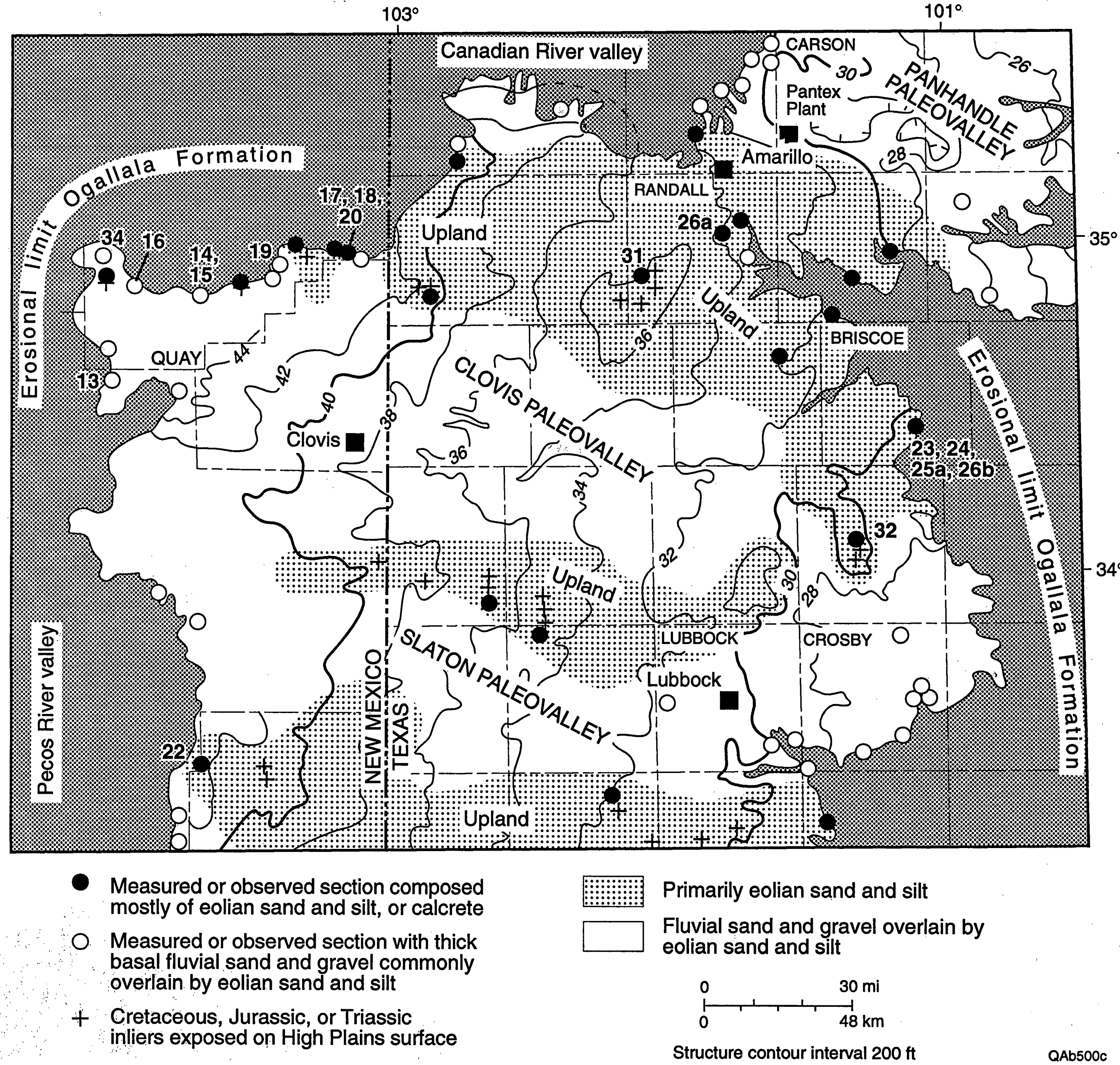


Figure 8. Regional structure-contour map on the pre-Ogallala erosional surface illustrates paleotopographic highs (stippled) and paleovalleys. Paleovalleys are partly filled with fluvial sediments that are in turn overlain by eolian deposits (open circles). Paleouplands are overlain by eolian deposits (filled circles). Circles locate measured or observed sections. Numbers locate figures.

Formations. Examination of outcrops, most of which are artificial exposures in widely separated road cuts, allows for detailed descriptions of lithofacies, bounding surfaces, and spatial relationships. But, because most outcrops are separated by significant distances where strata are obscured by colluvium and vegetation and because of the heterogeneity of fluvial facies, correlation between outcrops is typically at the formation level. These data provide only descriptions of a series of points in space and only a gross three-dimensional view of the Ogallala and Blackwater Draw Formations. Core descriptions, on the other hand, do not allow for complete description of lithofacies. However, using core descriptions and geophysical logs of wells that are commonly less than 1 km (0.6 mi) apart allows correlations at the lithofacies level. In this case, the three-dimensional distribution of Ogallala and Blackwater Draw lithofacies can be depicted with some confidence.

Two boreholes were drilled on the Pantex Plant northeast of Amarillo, Texas, for the purpose of gathering stratigraphic and hydrologic data from the Blackwater Draw and Ogallala Formations. These holes were drilled to a depth of approximately 21 m (69.3 ft) using hollow-stem augers, and for this interval core recovery was approximately 90 percent. Below 21 m (69.3 ft), a mud rotary coring procedure was used, and core recovery decreased to approximately 25 percent in BEG/PTX NO. 3 and to approximately 82 percent in BEG-PTX 2. Forty-five stratigraphic and hydrologic test holes have been drilled in the area surrounding Pantex Plant. These holes were drilled using hollow-stem augers, and core recovery was nearly 100 percent. Cores from these holes are as deep as 34.8 m (114.2 ft) and penetrate the Blackwater Draw Formation and upper part of the Ogallala Formation. Five additional cores of the Blackwater Draw and Ogallala Formations were taken at the Reese Air Force Base west of Lubbock, Texas. Core recovery from these boreholes was also 100 percent. Two cores were also available from the Department of Energy/Gruy Federal No. 1 Rex White and No. 1 Grabbe wells. Cores of Blackwater Draw and Ogallala sediments from these wells are 82 and 55 m (270 and 180 ft) deep, respectively, with better than 75 percent recovery. Cores were examined for primary sedimentary structures, pedogenic structures, biogenic structures, texture, $CaCO_3$ content, and color.

A variety of high-quality wireline logs are available for the BEG/PTX No. 2 and BEG/PTX No. 3 wells including gamma-ray, caliper, litho-density, compensated neutron, induction, borehole compensated sonic, and vertical seismic profile logs. Wireline logs are also available for ground-water production wells in the City of Amarillo well field north of the Pantex Plant; however, these are mostly resistivity and spontaneous potential logs. Gamma-ray, neutron and resistivity logs are available for wells on the Pantex Plant. Water-well driller's logs are available for numerous water wells throughout the Southern High Plains. Although these logs describe the texture and color of sediments removed from the borehole in very general terms, they were not used in this report because of the difficulty in correlating from well to well and the because of the difficulty of interpreting deposition environments without recognizing primary sedimentary and pedogenic structures. Driller's logs, however, commonly provide accurate depth to the base of the Ogallala data.

More than 60 outcrops of the Ogallala and Blackwater Draw Formations have been examined and described (fig. 8). These exposures are predominately road cuts through the Caprock Escarpment that bounds the Southern High Plains and bluffs along draws (ephemeral-stream valleys). For both the Ogallala and Blackwater Draw Formations, bed thickness, color, texture, lithology, primary sedimentary structures, and pedogenic structures were described. Core and outcrop samples were analyzed for grain size using sieve and hydrometer or rapid sediment analyzer methods.

MIDDLE TERTIARY EROSIONAL SURFACE

Permian, Triassic, Jurassic, and Cretaceous strata underlie the middle Tertiary erosional surface beneath the Central and Southern High Plains. Figure 8, which is a structure-contour map of the base of the Ogallala (High Plains) aquifer, closely approximates this surface because in most areas the base of the High Plains aquifer is the base of the Ogallala Formation. The presence of a system of major paleovalleys as part of the middle Tertiary erosional surface is indicated by aligned groups of broadly V shaped contour lines, which point upslope. Paleostream segments appear to have flowed to the southeast over most of the paleosurface.

Three broad paleovalley systems are recognizable on the middle Tertiary erosional surface, the Slaton, Clovis, and Panhandle paleovalleys (figs. 8 and 9). The Slaton and Clovis paleovalleys have as much as 60 m (200 ft) of relief. The Panhandle paleovalley, on the other hand, has more than 150 m (500 ft) of relief and is a closed structural basin attributed to salt dissolution. Paleoupland areas separate the paleovalleys, and inliers of pre-Ogallala strata on the High Plains surface occur above paleouplands.

Salt Dissolution and the Origin of the Panhandle Paleovalley

The area surrounding the Pantex Plant and the Panhandle paleovalley in Carson County northeast of Amarillo, Texas, overlies the northeast margin of the Paleozoic Palo Duro Basin. Upwarping of the western, northern, and eastern margins of the Palo Duro Basin during post-Permian time placed thick sequences of bedded Permian evaporites in the structural position where they were susceptible to dissolution by ground water (Gustavson and Finley, 1985; Gustavson, 1986; Gustavson and Simpkins, 1989; Dutton, 1987). Dissolution of Permian halite (salt) and gypsum strongly affected the northeastern margin of the basin where approximately 210 m (700 ft) of salt was dissolved (McGookey and others, 1988). As a result of dissolution, subsidence of the Tertiary Ogallala Formation and the Quaternary Blackwater Draw Formation occurred both during and subsequent to deposition.

A structure-contour map on the Permian Tubb Formation, which underlies most of the salt, shows a broad surface dipping to the south beneath the Pantex Plant in western Carson County at about 3.4 m/km (18 ft/mi) (fig. 10). Permian bedded halite above the Tubb Formation thins rapidly beneath this area as a result of dissolution, and as much as 210 m (700 ft) of salt has been lost in areas of maximum dissolution (fig. 11). Dissolution of salt has allowed subsidence of

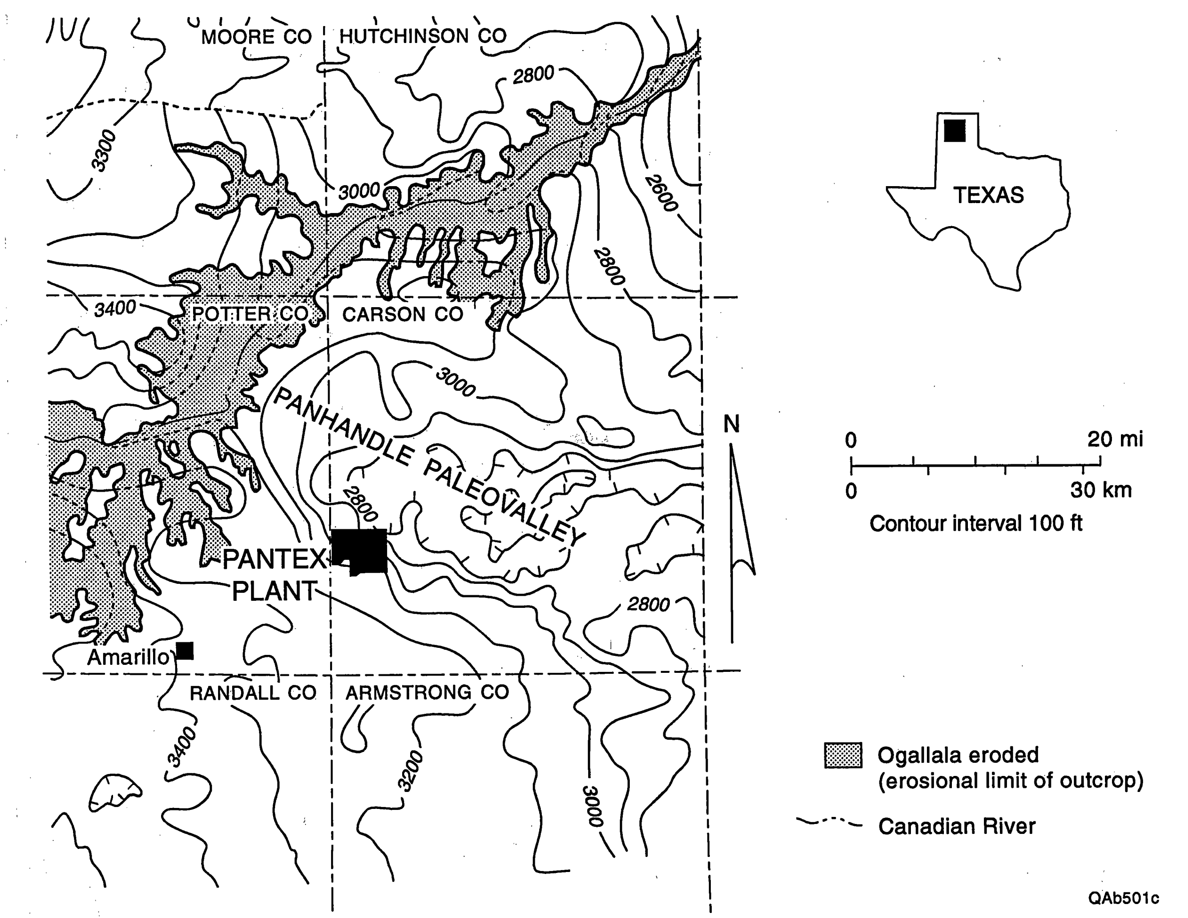


Figure 9. Structure-contour map of the middle Tertiary erosional surface. The closed depression to the northeast of the Pantex Plant likely resulted from dissolution of underlying Permian salt during the Tertiary and Quaternary and from erosion of pre-Ogallala strata (after Gustavson, 1986).

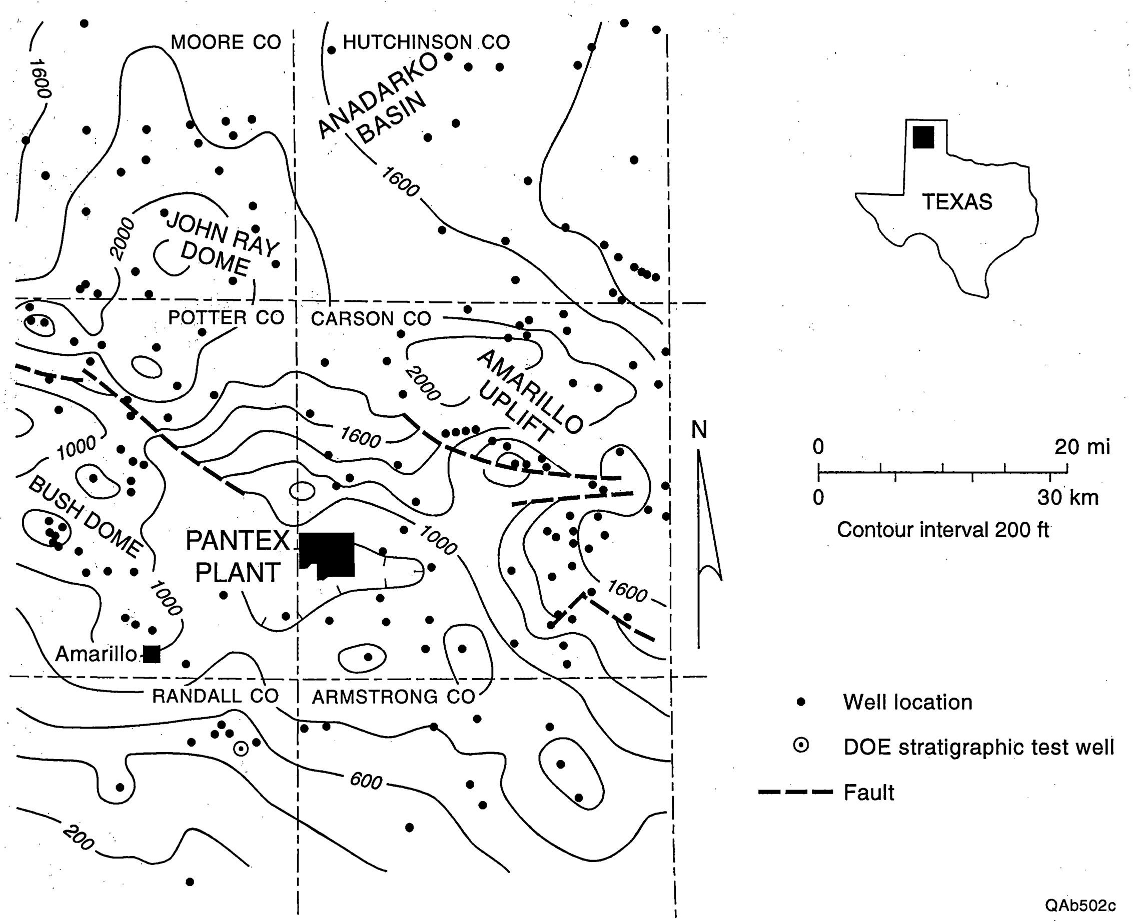


Figure 10. Structure-contour map on the Permian Tubb Formation. The Pantex Plant in western Carson County overlies a broad shallow basin, and regional dip beneath this area is to the south (after Gustavson, 1986).

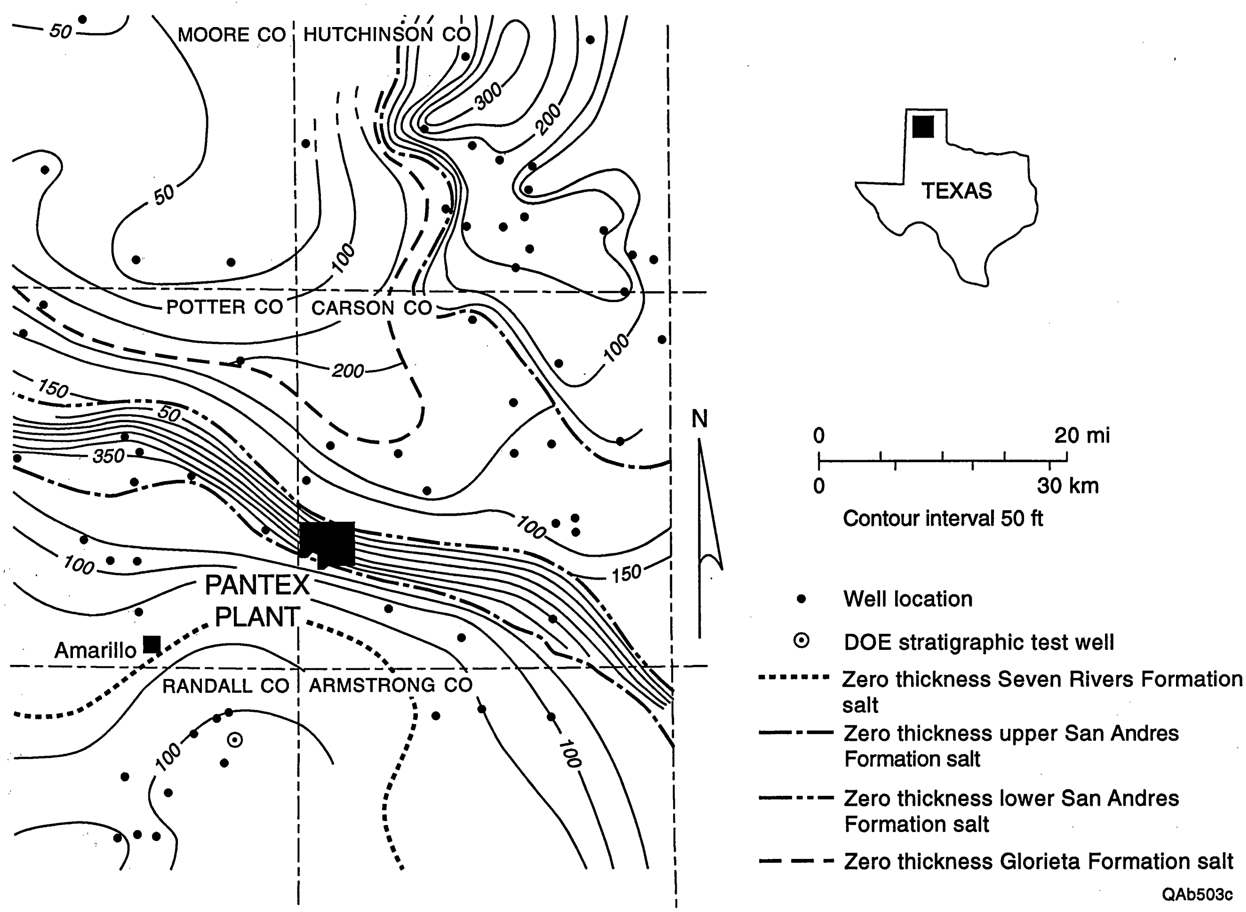


Figure 11. Salt thickness map of the Permian Seven Rivers, San Andres, and Glorieta Formations. Abrupt loss of salt beneath western Carson County is due to dissolution of salts in the San Andres Formation (after Gustavson, 1986).

overlying units including the Permian Alibates Formation (fig. 12), which overlies all salt-bearing units, resulting in a structural basin with in excess of 180 m (600 ft) of relief. A structural/erosional basin on the Late Tertiary erosional surface overlies the Alibates structural basin and indicates that most of the dissolution and subsidence occurred during Ogallala time (fig. 9). This subsidence basin is the Panhandle paleovalley and contains the thickest (~250 m [~800 ft]) known sequence of Ogallala sediments in the Texas Panhandle (Seni, 1980).

Gustavson (1986) and Gustavson and Simpkins (1989) have shown that this subsidence basin extends from south-central Carson County northwestward into eastern Potter County. On the basis of subsurface mapping of the unconformity that underlies the Ogallala Formation, no faults were recognized beneath the Pantex Plant. However, 16 km (10 mi) to the northwest in Potter County this basin is in part bounded on its northeast flank by basement faults that penetrate Triassic Dockum Group strata and Neogene Ogallala strata (Budnik, 1989; Wilson, 1988). Wilson (1988) indicates that the final episode of faulting occurred following deposition of undifferentiated upper Ogallala sediments that overlie the Coetas beds. (The Coetas beds are a series of thin lacustrine sediments [Wilson, 1988] that lie within the Ogallala Formation and contain a Clarendonian Land Mammal Age fauna that ranges in age from 9–11 Ma.) In Carson County approximately 32 km (20 mi) to the northeast of the Pantex Plant, Budnik (1989) suggests that faults, which bound the White Deer graben, may offset lower Ogallala strata. Vertebrate remains recovered from basal Ogallala sediments near the southeast end of this basin in the valley of the Salt Fork of the Red River are Clarendonian in age (9 to 11 Ma) (Schultz, 1977).

The effects of dissolution-induced subsidence are expressed in outcrops of Permian and younger strata along the northwest end of the Panhandle paleovalley, which is exposed in the Canadian River valley and along the southeast end of the paleovalley, which is exposed in the Salt Fork of the Red River valley. Permian rocks in the Canadian River valley are deformed by a series of broad open folds with wavelengths that are hundreds of meters long and amplitudes that are tens of meters high (Gustavson and others, 1980; Collins, 1984; Wilson, 1988). Similar

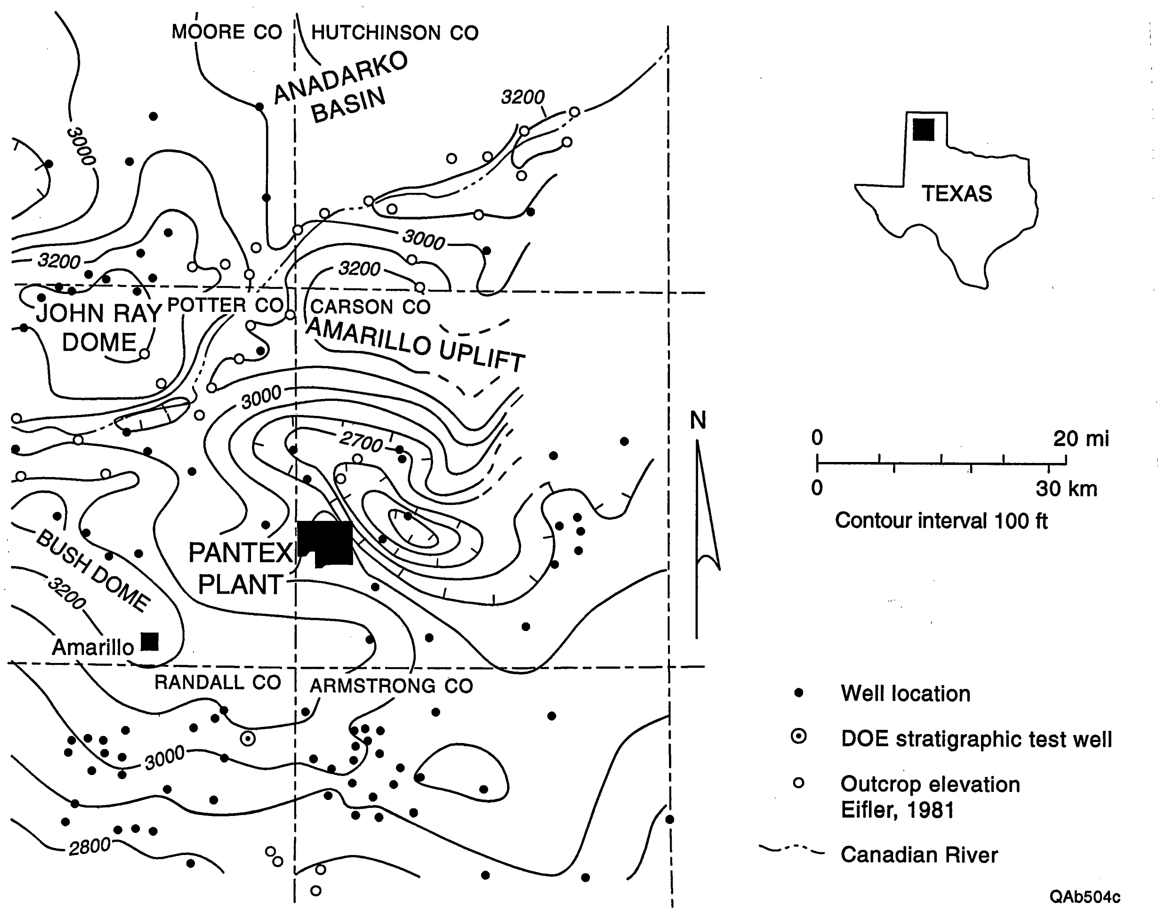


Figure 12. Structure-contour map on the Permian Alibates Formation. The closed basin to the northeast of Pantex Plant resulted from dissolution of underlying salt and collapse of overlying Permian strata (after Gustavson, 1986).

features are exposed in the valley of the Salt Fork suggesting that these types of structures are also present on the mid-Tertiary erosion surface beneath the Panhandle paleovalley. Chimneys filled with collapse breccia of highly deformed sediments are commonly exposed in the lower parts of the Canadian River valley, in parts of the Rolling Plains (Gustavson and others, 1980), and in lower Ogallala sediments in Donley County approximately 100 km (60 mi) east of Amarillo, Texas (Schultz, 1977). These features formed by a process of natural stoping or roof collapse into caverns created by salt dissolution and may also be present in the subsurface beneath parts of Potter, Carson, and Armstrong Counties.

Recent studies at the Pantex Plant and vicinity, in areas overlying the Panhandle paleovalley, have identified small-scale subsidence features, which have been attributed to dissolution. Lake McClelland; an unnamed playa basin south of Pampa, Texas; Sevenmile Basin to the south of Pantex Plant; and playa 1 and playa 3 on Pantex Plant all show similar patterns of downwarping of underlying strata that is best explained by dissolution-induced subsidence (Gustavson and others, 1980; Paine, 1994). Subsidence beneath these playa basins probably began during the late Tertiary because Paine (1994) has shown that Ogallala strata thicken beneath some of these basins. Subsidence likely continued into the Quaternary because these basins are inset into the Blackwater Draw Formation, and basin-filling sediments are interbedded with Blackwater Draw strata. Collectively, these data suggest that dissolution has preceded, coincided with, and followed deposition of the Ogallala and Blackwater Draw Formations.

REGIONAL STRATIGRAPHY OF THE OGALLALA FORMATION

The Miocene–Pliocene Ogallala Formation unconformably overlies Permian, Triassic, Jurassic, and Cretaceous strata in northwest Texas and eastern New Mexico. In the study area, Ogallala sediments are as much as 180 m (600 ft) thick where they fill paleovalleys. Typically Ogallala sediments are 10 m (33 ft) to 30 m (100 ft) thick above the paleouplands that separate paleovalleys. However, locally pre-Ogallala sediments that underlie paleouplands are exposed as inliers on the High Plains surface (fig. 8). The Caprock (caliche) calcrete separates the Ogallala from the overlying Quaternary Blackwater Draw Formation.

Two sets of data were used to interpret Ogallala lithofacies and depositional environments; outcrop descriptions and geophysical and lithologic well logs. For most of the study area, descriptions of outcrops that were exposed in the Caprock Escarpment or along draws incised into the Southern High Plains provided data from which lithofacies and regional depositional environments could be inferred. Seven lithofacies were recognized in the Ogallala Formation: (I) gravel; (II) sand and gravel; (III) sand (fluvial); (IV) fine sand and mud; (V) laminated fine sand to silt and laminated to massive clay; (VI) sand (eolian); and (VII) fine sand to coarse silt. These lithofacies are interpreted to represent fluvial deposition in high-energy ephemeral streams and related floodplains including shallow ephemeral lakes (I–V) and eolian deposition as dunes or sand sheets and loess (VI and VII). Fluvial and lacustrine lithofacies are preserved in paleovalleys eroded into pre-Ogallala strata; eolian lithofacies generally overlie or are interbedded with fluvial facies in paleovalleys and overlie paleoupland areas that separate paleovalleys.

Gravel Lithofacies

Gravel lithofacies of the Ogallala Formation (table 1, lithofacies I) consist primarily of clast-supported pebble- to boulder-sized clasts. Gravel is typically poorly to well cemented by $CaCO_3$ (figs. 13, 14, and 15). The gravel is comprised primarily of subrounded to well-rounded metamorphic, quartzite, and volcanic clasts, which are commonly imbricated. Intermediate axis lengths of 7 cm (3 inches) are common. Near the base of channel-filling gravel sequences, angular to subangular megaclasts (long axis as much as 3 m [3.3 ft]) of pre-Ogallala strata may be included. Matrix consists of poorly sorted $CaCO_3$ cemented mud (5YR 8/1). Gravel lithofacies exposed in the western part of the study area in New Mexico in the western limits of the Clovis and Slaton paleovalleys typically contain cobbles and boulders of highly weathered amygdaloidal basalt. The source of the basalt clasts is likely the Ocate or Raton volcanic fields in

Table 1. Ogallala Formation lithofacies and interpreted depositional environments.

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-sized 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 silt-clay drapes; locally $CaCO_3$ cemented or upward fining.	Ephemeral stream
IV. Fine sand and mud	Locally channel filling, in part upward-fining, crossbedded 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.	Floodplain 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 open 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 savanna or prairie

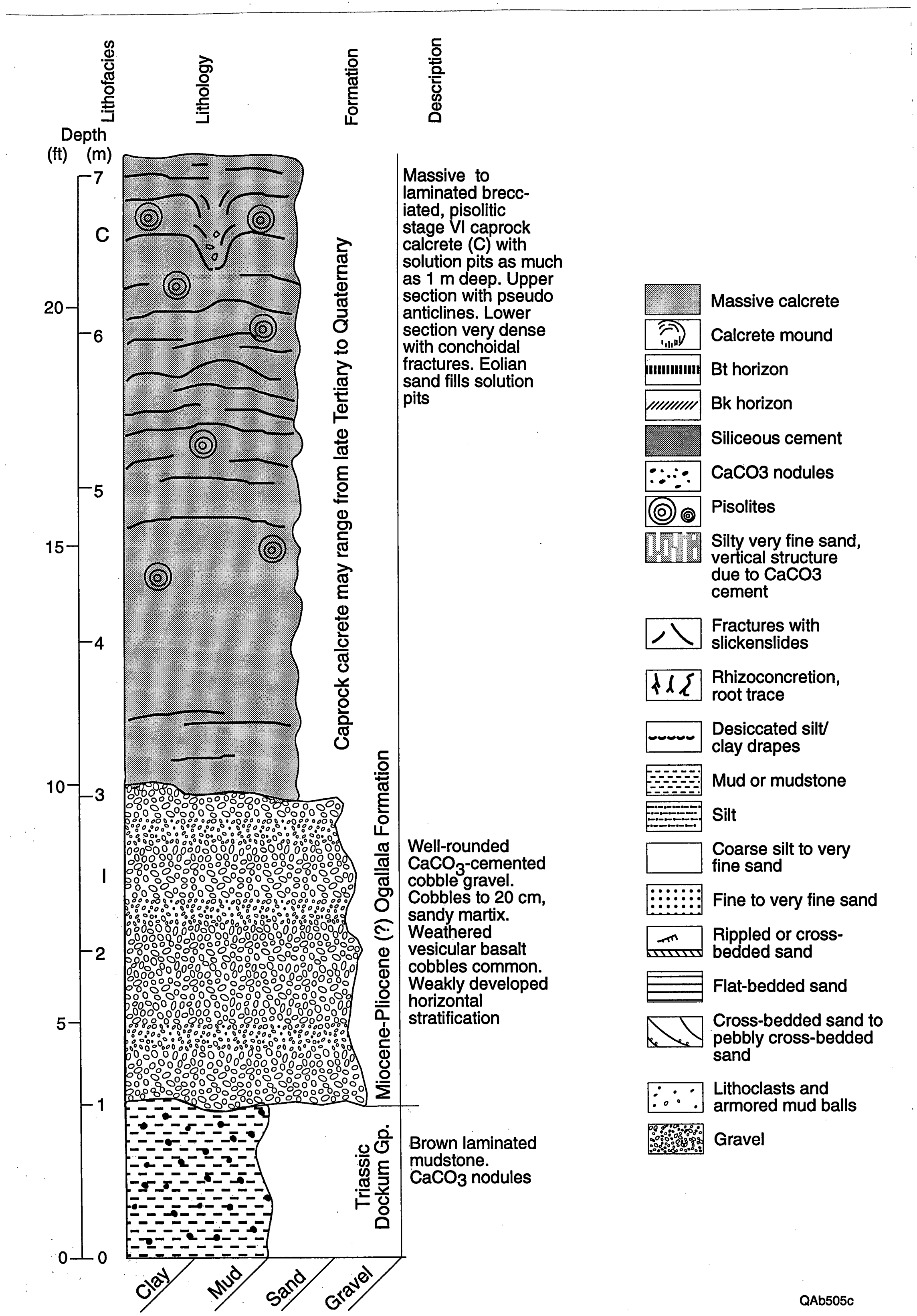


Figure 13. Stratigraphic section of the Ogallala Formation exposed along the Gerhardt Valley Road, New Mexico, 1.6 km (1 mi) west of NM 252 and approximately 1.2 km (3/4 mi) south of the Quay County–DeBaca County boundary (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

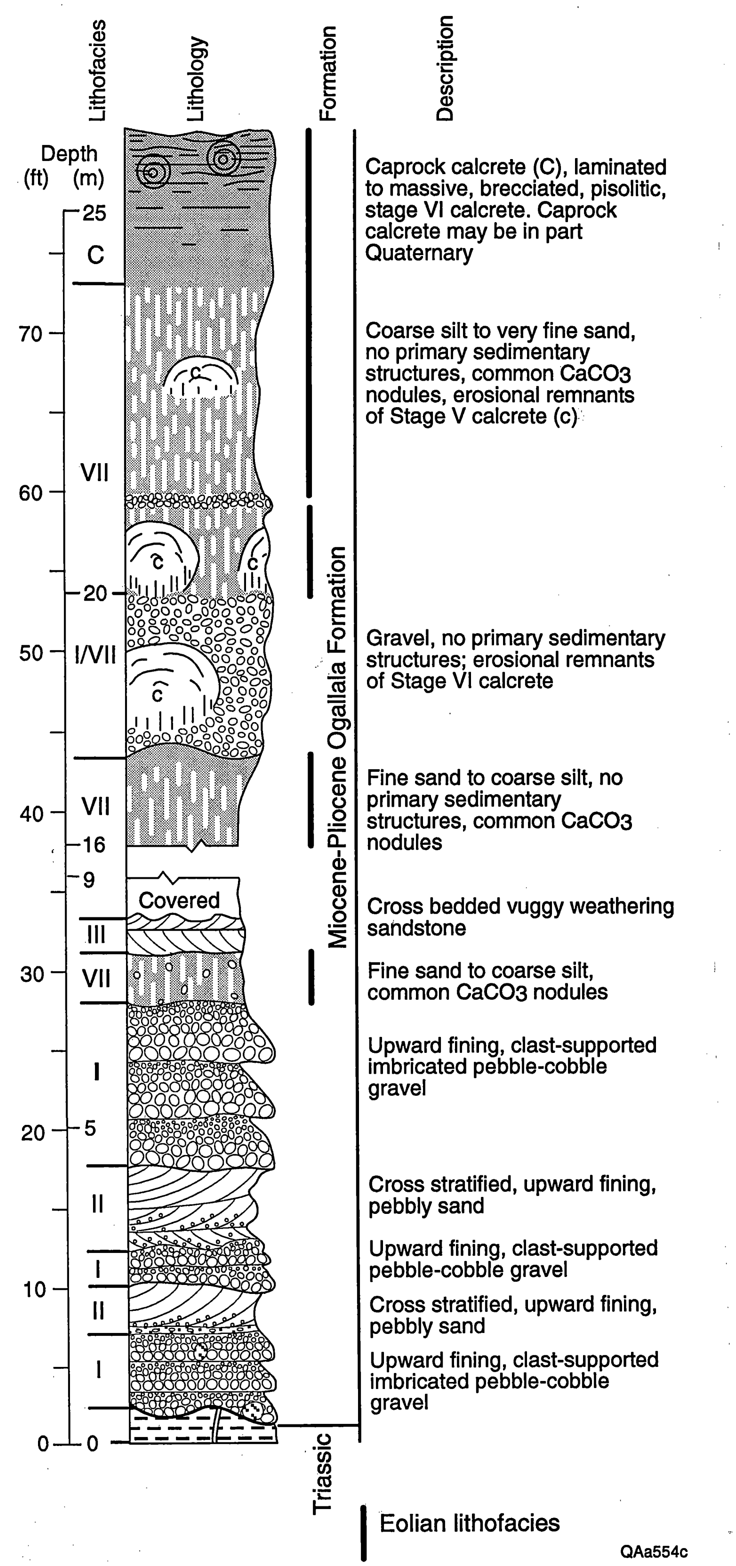


Figure 14. Stratigraphic section of the Ogallala Formation exposed in the Caprock Escarpment, NM 209 at Ragland approximately 38.4 km (24 mi) south of Tucumcari, New Mexico (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

(a)

(b)

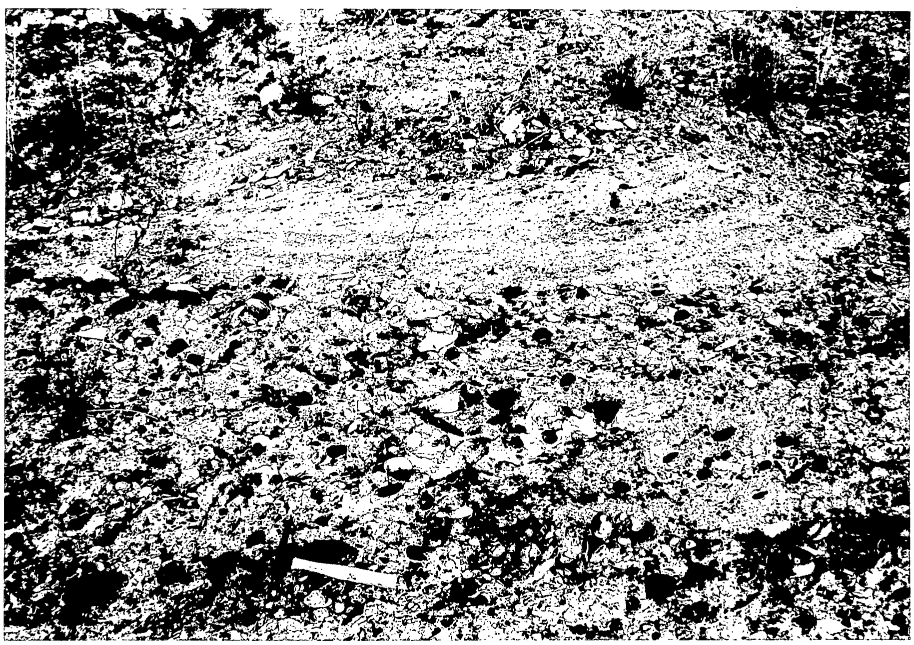


Figure 15. Gravel lithofacies of the Ogallala Formation exposed in the Caprock Escarpment along NM 209 at Ragland, New Mexico, approximately 38.4 (24 mi) south of Tucumcari, New Mexico (see fig. 8 for location). (a) Several sequences of pebble-cobble, clast-supported, $CaCO_3$-cemented, upward-fining, imbricated gravel consist of basalt, quartzites, schists, and gneisses that unconformably overlie Triassic Dockum Group mudstone. Megaclast beneath the hammer is a boulder of Triassic mudstone. (b) Sand and gravel lithofacies typified by crossbedded pebbly sand overlying gravel lithofacies. Hammer is approximately 30 cm (1 ft) long.

eastern New Mexico (Stormer, 1972; Mehnert and O'Neill, 1980). These coarse sediments are typically massive to horizontally stratified and interbedded with thin (10- to 50-cm-thick) units of flat-bedded to crossbedded pebbly sand. Locally, upward-fining sequences are preserved in the gravel lithofacies.

Gravel lithofacies typically occupy the floors of broad erosional valleys. Valley-filling gravels are exposed in the Caprock Escarpment north of the Cunevea Basin and along New Mexico Highway 209 (formerly New Mexico Highway 18) near Ragland, Mew Mexico, and in the McBride Ranch area of the Lake Meredith National Recreation Area in Texas. Valleys in New Mexico appear entirely erosional with the pre-Ogallala Clovis paleovalley incised into Dockum Group strata. The base of the Panhandle paleovalley, which is exposed in the Lake Meredith Recreational Area in the Canadian River valley, is in part structurally controlled and occupies a small but sharply defined syncline. The upper Permian Alibates Formation marks the valley sides and dips beneath basal Ogallala sediments.

The clast-supported, imbricated, horizontally bedded gravel lithofacies that make up the basal parts of paleovalley fill sequences of the Ogallala Formation are similar to models for gravel-dominated braided stream deposits described by Williams and Rust (1969), Smith (1970, 1971), Rust (1972), Gustavson (1974), Boothroyd and Ashley (1975), Miall (1978), Brierley (1991), and Reinfelds and Nanson (1993). Clast-supported, horizontally bedded massive to upward-fining gravels accumulated as longitudinal bars that were roughly parallel to stream flow during flood stage. Upward-fining gravel sequences result from diminished transport capacity as flow velocity and depths declined because of diminishing discharge or because of accretion. Thin flat-bedded to crossbedded sand sequences filled channels or scour troughs at bar margins (Rust, 1972).

Sand and Gravel Lithofacies

Sand and gravel lithofacies (table 1, lithofacies II) consist mostly of upward-fining trough cross-stratified medium sand to pebble gravel interbedded with flat-bedded pebbly sand and thin, pebble-cobble, clast-supported, $CaCO_3$-cemented, imbricated gravel (figs. 16, 17, and 18). Gravel is horizontally bedded, and clasts are well rounded to subrounded. Gravel-sized clasts include quartzite, vein quartz, metamorphic and volcanic clasts, silicified fossils of *Gryphea* sp., and lithoclasts of Ogallala muds. Some larger lithoclasts are armored mud balls. Upward-fining sequences range in thickness up to 0.8 m (2.3 ft). Crossbeds sets are typically 5 to 50 cm (2 to 20 inches) thick. Sands are pinkish-gray (5YR 8/1). These sediments are partly $CaCO_3$ cemented.

Sediment sequences are locally capped by 0.5- to 2-cm-thick (0.2- to 0.8-cm) silt-clay drapes indicating bar surfaces and locally channel surfaces. Typically clay-silt drapes preserve desiccation cracks. Small fragments of dried clay-silt drapes were also transported short distances and incorporated in overlying strata as lithoclasts.

The sand and gravel lithofacies are similar to the model for sandy braided streams with minor amounts of gravel (Donjek type) described by Williams and Rust (1969) and Rust (1972). Upward-fining trough crossbed sets represent the passage of sinuous crested dunes in channels. Clast-supported horizontally bedded gravel interbeds were likely deposited as longitudinal bars. Clay-silt drapes indicate that standing water was present locally after stream flow ceased. Clay-silt drapes with desiccation cracks and armored mud balls both suggest that bar surfaces were periodically exposed and that these streams were ephemeral. Ephemeral streams in turn suggest a dry (subhumid to arid) climate.

Sand Lithofacies

The sand lithofacies (table I, lithofacies III) typically consist of flat-bedded to planar-, trough-, or ripple-cross-stratified silty fine to medium sand. Sand sequences commonly contain silt-clay drapes with desiccation cracks (figs. 16, 17, and 19). Rare decimeter-thick upward-fining mud-cracked sandy mud to mud lenses fill shallow channels. Individual beds range in thickness from a few centimeters to a few decimeters (an inch to a foot). These sediments also typically contain upward-fining sequences and are largely uncemented. Those sequences that are

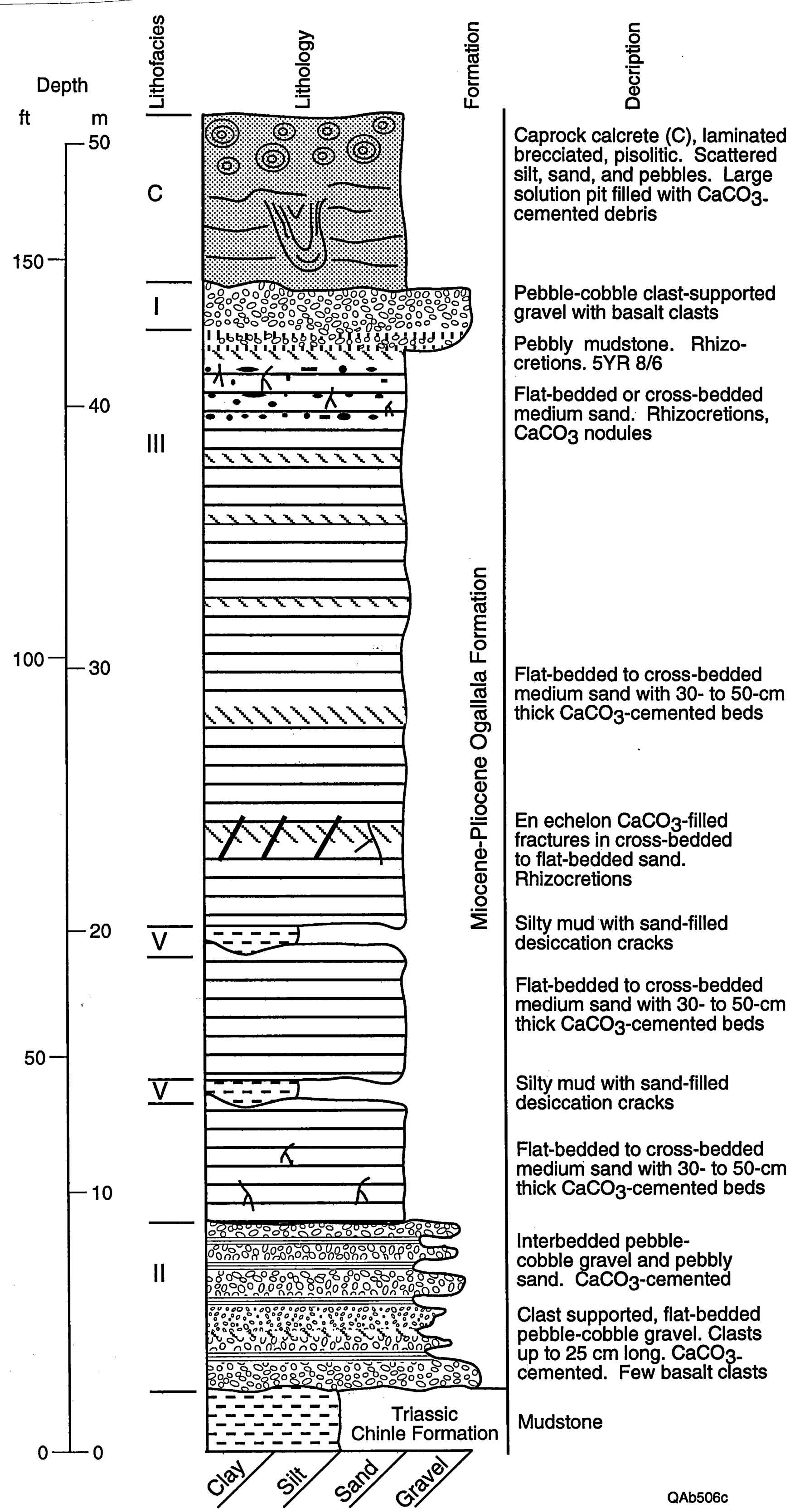


Figure 16. Ogallala section exposed in the Caprock Escarpment at Lyons Ranch, New Mexico, approximately 19.2 km (12 mi) west of NM 209 (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

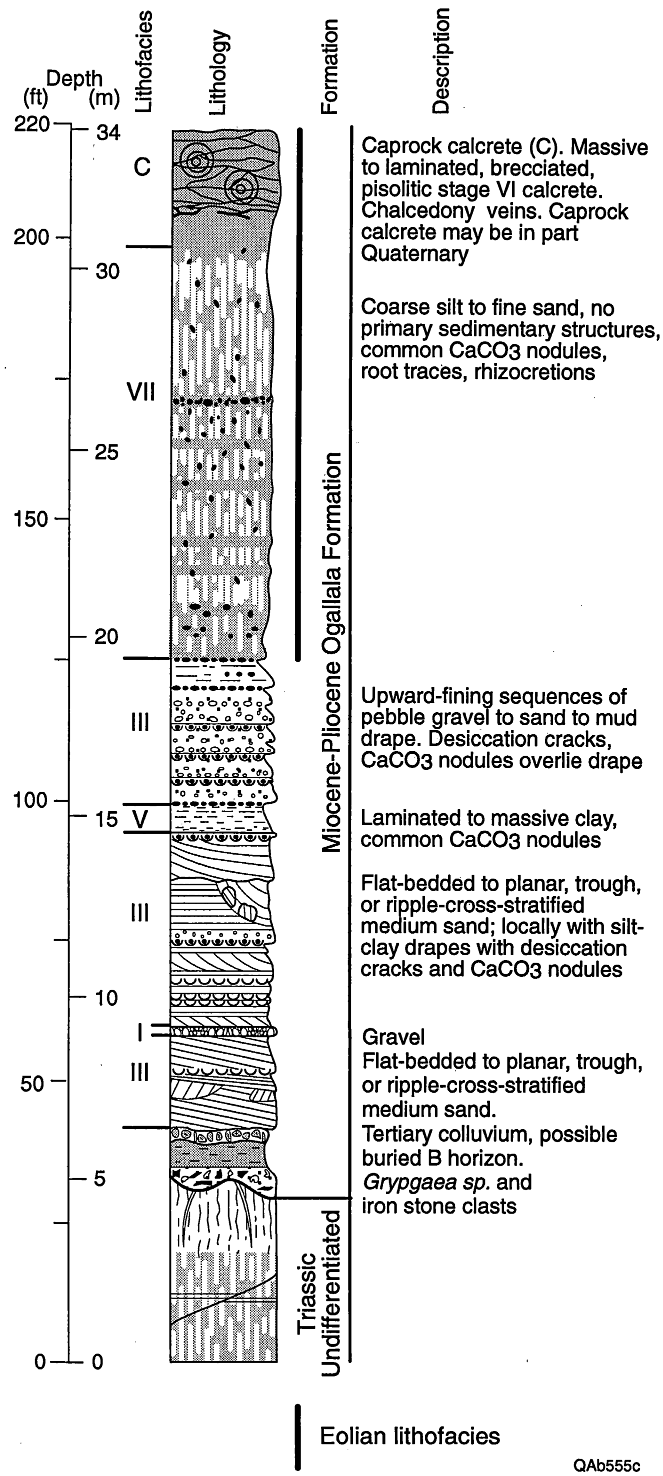


Figure 17. Ogallala section exposed in Caprock Escarpment along NM Highway 93, approximately 14.4 km (9 mi) north of Bellview, New Mexico (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

Figure 18. Mudballs, armored mudballs, and lithoclasts lie at the top of a unit of sand and gravel lithofacies and apparently mark a former channel surface in an exposure in the Caprock Escarpment along New Mexico Highway 93, approximately 14.4 km (9 mi) north of Bellview, New Mexico (see fig. 8 for location). Scale is 30 cm (1 ft).

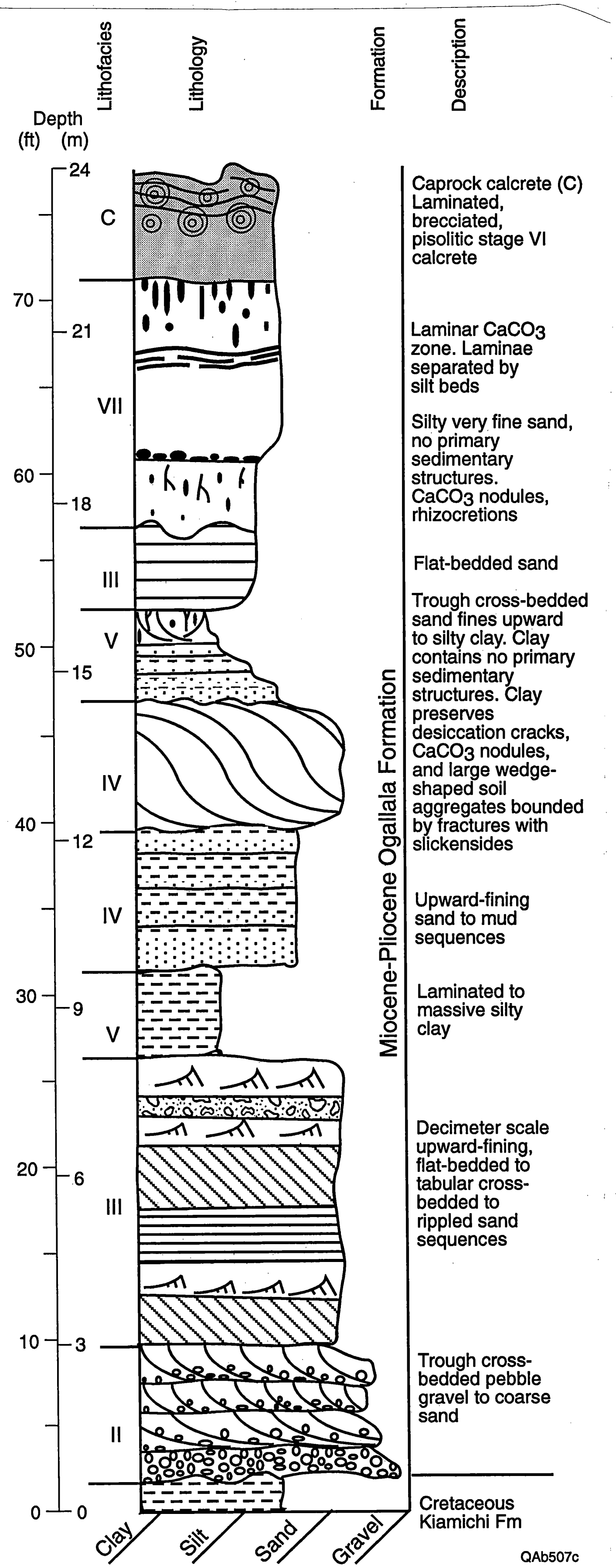


Figure 19. Ogallala section exposed in the Caprock Escarpment along New Mexico Highway 278, approximately 9.6 km (6 mi) north of New Mexico 209 and 36.8 km (23 mi) west of the Texas–New Mexico border (see fig. 8 for location). Roman numerals identify Ogallala lithofacies.

$CaCO_3$ cemented are usually no more than a few decimeters thick and are not laterally extensive. Calcium carbonate filaments are preserved on clay drapes. A few rhizocretions, which are thin downward-branching tubules of carbonate-cemented sand, are preserved in the Lyons Ranch section in New Mexico. Similarly, this section contains a few horizons of pedogenic $CaCO_3$ nodules.

Preserved primary sedimentary structures indicate that sediments of the sand lithofacies were deposited by shallow streams. Preserved silt-clay drapes and mud channel fills with desiccation cracks, which indicate exposure to the atmosphere, suggest that these sands were deposited by ephemeral streams. The presence of rhizocretions and of pedogenic $CaCO_3$ nodules also suggests that local stream channels were periodically abandoned allowing vegetation to become established or for incipient soils to develop.

Fine Sand and Mud Lithofacies

The fine sand and mud lithofacies (table I, lithofacies IV) consist of a range of largely upward fining, crossbedded to laminated sand to mud sequences. Upward-fining sequences are typically less than 4 m (13 ft) thick and have erosional bases. One sequence exposed in the section along New Mexico Highway 278 consists of a 4-m-thick (13-ft) upward-fining unit that begins with decimeter-thick cross-stratified sand beds that thin upward to centimeter-thick to laminated silty fine sand capped by a 1-m-thick (3.3-ft) mud bed (fig. 19). The mud bed contains desiccation cracks that are filled with sand to a depth of 60 cm (2 ft), numerous large wedge-shaped soil aggregates bounded by fractures with slickensides, and pedogenic $CaCO_3$ nodules. No primary sedimentary structures are preserved in these muddy sediments.

Preserved primary sedimentary structures indicate that the fine sand and mud lithofacies were deposited by fluvial processes. The upward-fining sequences are capped by thick mud beds that probably represent accumulation of overbank deposits on a floodplain or in an abandoned channel from many sedimentation events. Vertic soil characteristics such as deep desiccation cracks, large wedge-shaped soil aggregates bounded by fractures with slickensides, and pedogenic carbonate nodules all indicate prolonged surface exposure and repeated episodes of wetting and expansion followed by desiccation and contraction.

Ground Water Calcrete:--In many exposures of Ogallala sediments where silt-clay drapes cap fluvial sands, including lithofacies II, III, and IV, $CaCO_3$ has accumulated as nodules (fig. 20). Carbonate nodules, which may be as much as a decimeter in diameter, are micritic and contain essentially no clastic sediments. In essentially every case, $CaCO_3$ nodules occur immediately above clay-silt drapes or mud channel fills. Nodules are rounded to botryoidal in shape, and surrounding sediments have apparently been pushed aside by nodule growth.

Carbonate nodules, which show no evidence of transport and which have deformed surrounding sediments, apparently grew in place. Preferential development of nodules above clayey sediments suggests that nodules formed in an evaporative setting from downward percolating ground water that accumulated temporarily above thin aquitards of poorly permeable clayey or muddy strata. The lack of soil development in fluvial sequences and the lack of rhizocretions suggest that uptake of ground water through roots and transpiration by plants did not play important roles in nodule development.

If the proposed origin of carbonate nodules in Ogallala fluvial sediments is correct, then their presence can be used to infer paleohydrologic and paleoclimatic conditions. Nodule growth by evaporation of shallow ground water in fluvial sediments suggests that associated streams were ephemeral, with recharge occurring during flow events followed by evaporation of shallow ground water during periods of no flow. Under these conditions, several cycles of ground-water recharge and evaporation could occur each year. Ephemeral streams in turn suggest a dry paleoclimate (subhumid to arid).

Laminated Fine Sand and Silt and Laminated to Massive Clay Lithofacies

The laminated fine sand and silt and laminated to massive clay lithofacies (table 1, lithofacies V) typically consist of upward-fining sequences of thinly laminated silt and fine sand that are overlain by thick sequences of laminated to massive silty clay (figs. 19 and 21). Primary

Figure 20. Micritic $CaCO_3$ nodules above a thin silt-clay drape (a) and overlying and interbedded with a channel-filling mud (b). Nodules develop from evaporation of shallow ground water, which contains Ca^{++}, trapped above poorly permeable layers. Scale is 30 cm (1 ft). These sediments are exposed in the Caprock Escarpment along New Mexico Highway 93, approximately 14.4 km (9 mi) north of Bellview, New Mexico (see fig. 8 for location).

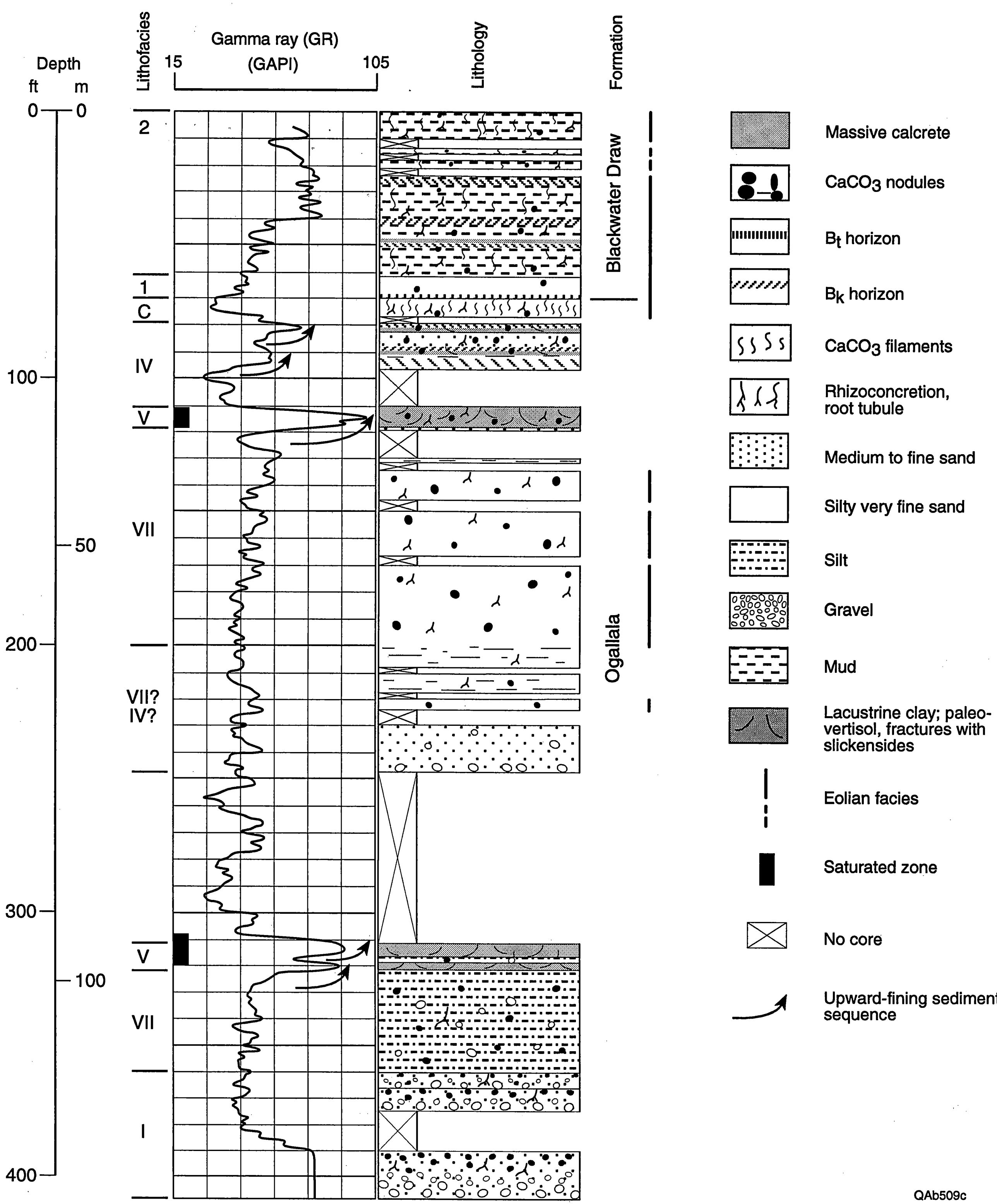


Figure 21. Stratigraphic section of Ogallala and Blackwater Draw Formations interpreted from core from BEG/PTX No. 2 drilled in DOE's Pantex Plant (see fig. 40 for location). Lithologies are plotted opposite a gamma-ray log trace. Zones saturated with ground water are shown as black bars. Roman numerals and Arabic numbers identify Ogallala and Blackwater Draw lithofacies (tables 1 and 2).

sedimentary structures are not preserved in the massive clays, but desiccation cracks partly filled with silt and sand and large wedge-shaped soil structural aggregates bounded by fractures with slickensides are characteristic of vertic soil development. $CaCO_3$ nodules, which are also commonly developed pedogenic structures in this facies, are micritic and contain dispersed clastic grains. Root tubules, which are the open spaces formerly occupied by roots, are preserved in some sections of this facies. Massive clay intervals range from 1 to 3 m (3.3 to 10 ft) thick in core and as much as 20 m (66 ft) thick as interpreted from geophysical logs.

The distribution of the laminated fine sand and silt and laminated to massive clay lithofacies is also depicted on a series of stratigraphic cross sections from western Carson County (Plates I–IV). The distribution of these sediments is bounded to the south and west by the limits of the Panhandle paleovalley. The limits to the east are unknown, and no well data is available to the north and northwest.

Lithofacies V is interpreted to have been deposited as primarily overbank or floodplain sediments, although locally some of these sediments may have been deposited in floodplain lakes or in abandoned channels. In an earlier preliminary report, the uppermost fine-grained unit was correlated with the Coetas lacustrine beds described from exposures in the Canadian River valley by Wilson (1988). Recognition that at least six sequences of these relatively thinly bedded sediments extend over many tens of square kilometers and that they are interbedded with coarse fluvial sediments supports an interpretation of floodplain deposition. Laminated fine sand and silts were deposited in a low-energy environment, and massive silty clays or muds were deposited largely from standing water. Calcic and vertic soil structures in the silty clays indicate that these sediments were periodically exposed. Furthermore, the presence of vertic features such as desiccation cracks and slickensides indicates periodic expansion and contraction of clay soils as a result of flooding and desiccation (Gustavson, 1991a). The presence of calcic soil features such as $CaCO_3$ nodules suggests that dry (arid to subhumid) climatic condition prevailed (Machette, 1985). Stratigraphic sections (discussed in detail in sections that follow) indicate that overbank facies are widespread along the axis and that they thicken and become more numerous into the axis of the Panhandle paleovalley.

Sand (Eolian) Lithofacies

Sand lithofacies (lithofacies VI, table 1) typically consist of mostly planar cosets of tabular to slightly concave upward cross-stratified, moderately well sorted, fine to medium sand (fig. 22). Well-rounded frosted sand grains are common. Crossbed sets are as much as 2.5 m (8 ft) thick. A few clay bands, which are accumulations of illuvial clay, are locally preserved, indicating the initial stages of development of an argillic horizon (Gile, 1985). Rhizocretions and $CaCO_3$ nodules are locally preserved. Sand (eolian) lithofacies are not commonly preserved in the Ogallala Formation and were found only in sections exposed at the Caprock Escarpment at the entrance to the New Mexico Caprock Amphitheater south of San Jon, New Mexico, along New Mexico Route 249 west of Lovington, New Mexico, and where Texas Highway 998 crosses Punta de Agua Creek southwest of Hartley, Texas. Only single crossbed sets of the sand lithofacies are preserved at exposures along Texas Highway 998 and at the Caprock Amphitheater in New Mexico, but a 12-m-thick (40-ft) section containing numerous crossbed sets as much as 2 m (6.6 ft) thick is exposed along NM Highway 249.

The sand lithofacies were likely deposited as small eolian dunes and are similar to, but much less extensive than, the recent to late Quaternary sand dunes described by Gile (1985) in the Sand Hills of the Southern High Plains. Preservation of the sand lithofacies at only 3 of more than 60 Ogallala exposures and preservation of this lithofacies as single crossbed sets indicate that these landforms were not widespread. Furthermore, the presence of incipient argillic horizons, $CaCO_3$ nodules, and rhizocretions suggests that these eolian sands were stabilized by vegetation shortly after deposition.

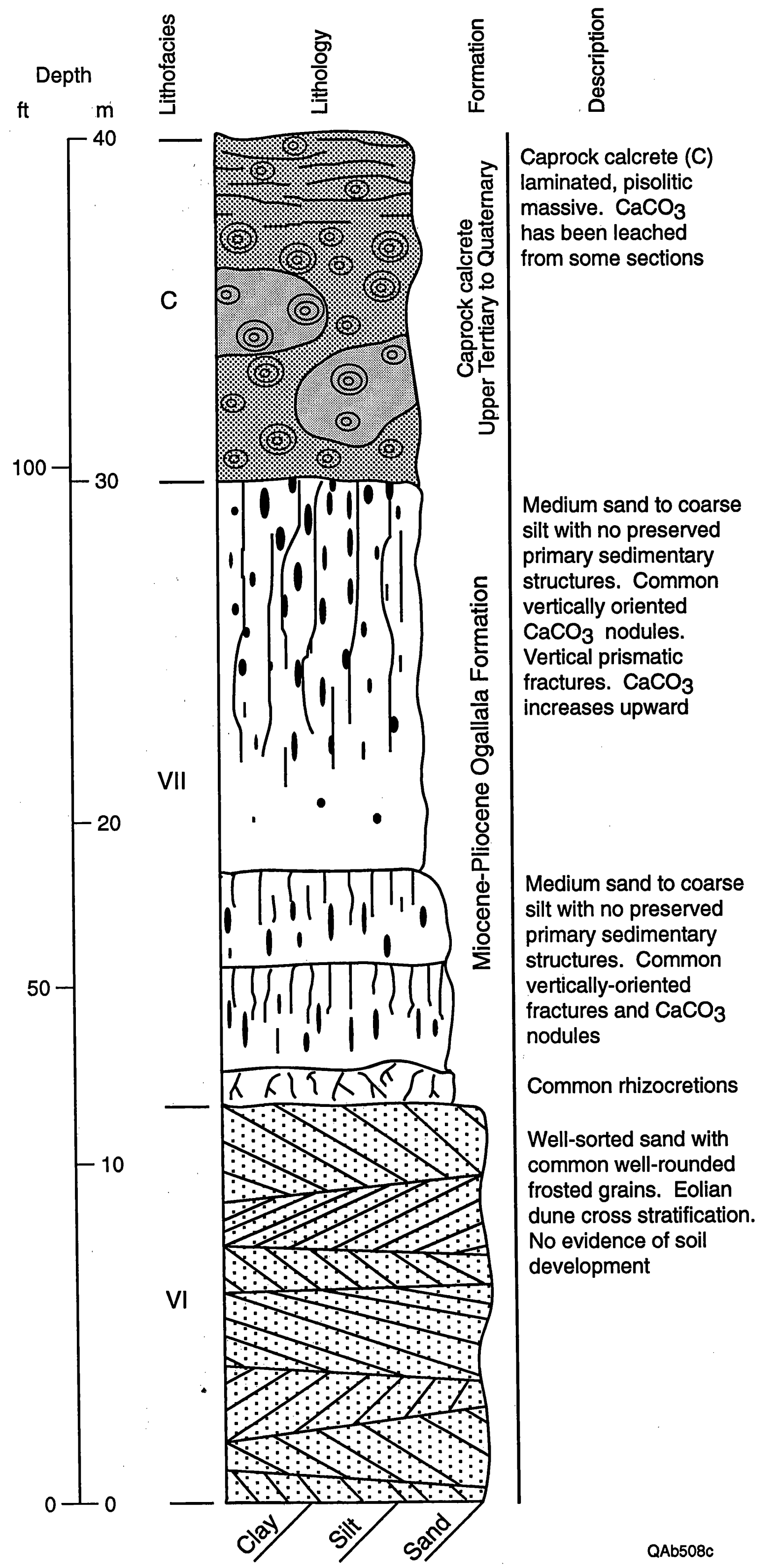


Figure 22. Ogallala section exposed along New Mexico Highway 249, approximately 48 km (30 mi) west of Lovington, New Mexico (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

Fine Sand to Coarse Silt Lithofacies

The fine sand to coarse silt lithofacies (table I, lithofacies VII) consist of coarse silt to very fine sand with rare to common rhizocretions, locally numerous open root tubules, and common $CaCO_3$ nodules (figs. 22, 23, 24, 25, 26, and 27). No primary sedimentary structures have been recognized in these sediments. Isolated pebble- or granule-sized clasts are occasionally found in the lower one or two meters of this lithofacies. 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 exceed 30 m (98 ft) in thickness where it was deposited above paleouplands on the pre-Ogallala erosional surface. In areas that overlie Ogallala paleochannels and fluvial facies, the fine sand to coarse silt lithofacies may be as much as 17 m (56 ft) thick.

Representative textural samples of the coarse silt to very fine sand lithofacies range from a muddy or silty sand to a sand (fig. 28). 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) of these sediments ranges from 2.3 to 3 Ø (0.2 to 0.125 mm) for the Bellview section and from 2.6 to 3.7 Ø (0.16 to 0.07 mm) for the Silverton section. Sand comprises 60 to 90 percent. Comparison of samples of lithofacies VII sediments from the Bellview section in eastern New Mexico to samples of lithofacies VII sediments from the Silverton section exposed along the eastern Caprock Escarpment, approximately 200 km (125 mi) to the east, shows that this facies fines from west to east (fig. 29). For example, the Bellview section is 50 to 80 percent fine sand (3 Ø [0.125 mm]) or coarser, while the Silverton section is 25 to 60 percent fine sand or coarser. These sediments are interpreted as a mix of loess and thin sand sheet deposits, and their origin is further described under the section on "Transportation and Depositional Environment of the Eolian Lithofacies Ogallala and Blackwater Draw Formations" (p. 83).

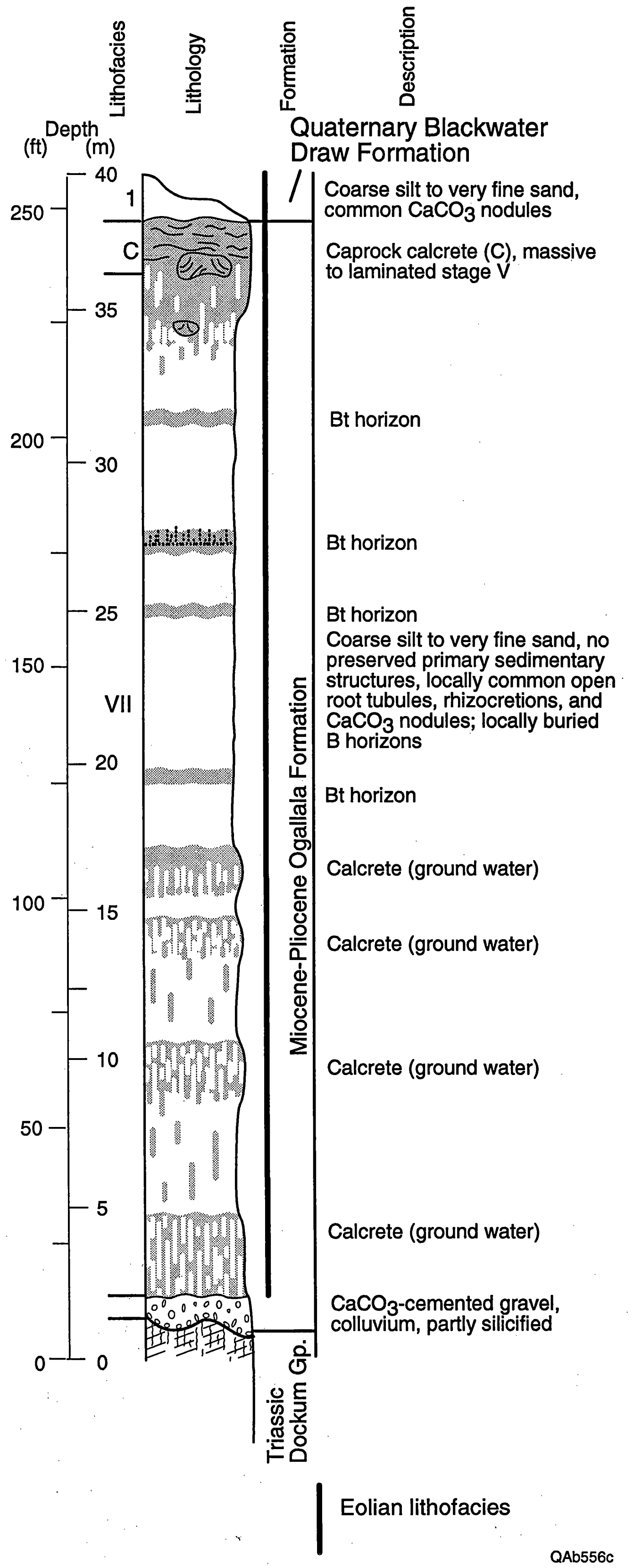


Figure 23. Composite stratigraphic section of the Ogallala Formation exposed along Texas Highway 256, approximately 19.2 km (12 mi) east of Silverton, Texas (see fig. 8 for location). Roman and Arabic numerals identify Ogallala and Blackwater Draw Formation lithofacies (tables 1 and 2).

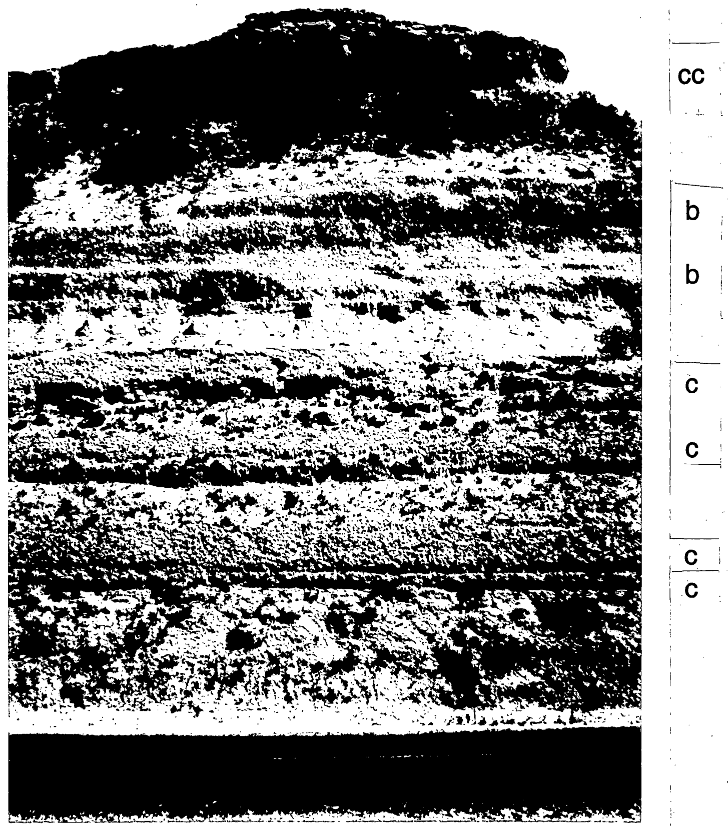


Figure 24. Exposure of Ogallala sediments in the Caprock Escarpment depicted in figure 23 along Texas Highway 256, approximately 19.2 (12 mi) east of Silverton, Texas (see fig. 8 for location). Dark bands (b) are buried B soil horizons. Intermediate gray erosionally resistant units are calcretes (c). The exposure is capped by the Caprock calcrete (cc). Scale is approximately 1 m (~3.3 ft).

(a)

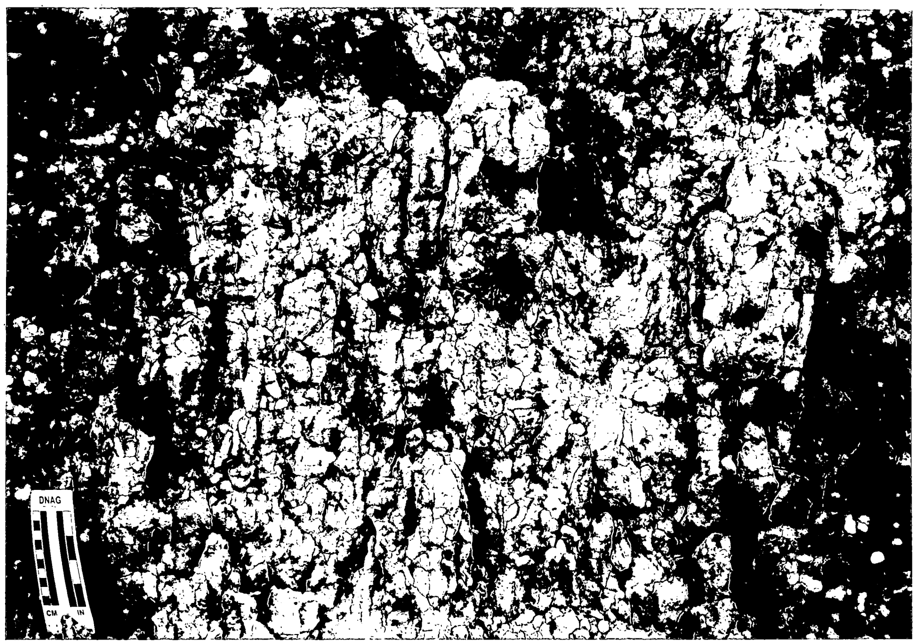


Figure 25a. Pedogenic $CaCO_3$ nodules comprise a buried stage II calcic horizon in the fine sand to coarse silt lithofacies of the Ogallala Formation exposed along Texas Highway 256, approximately 19.2 km (12 mi) east of Silverton, Texas (see fig. 8 for location). Scale is 10 cm (4 in).

(b)

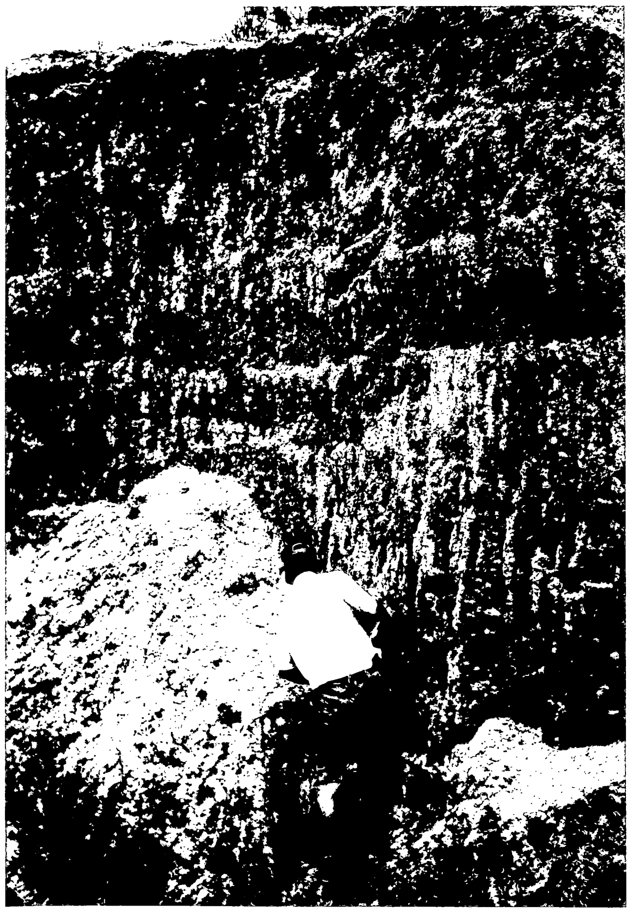


Figure 25b. Multiple buried soils with stage III calcic horizons at Blackwater Draw type sections, approximately 3.2 km (2 mi) northwest of New Deal, Texas (see fig. 4 for location). Note numerous large soil carbonate nodules typical of buried calcic soils in the Blackwater Draw Formation. Surface soil in this exposure is the Amarillo sandy loam.

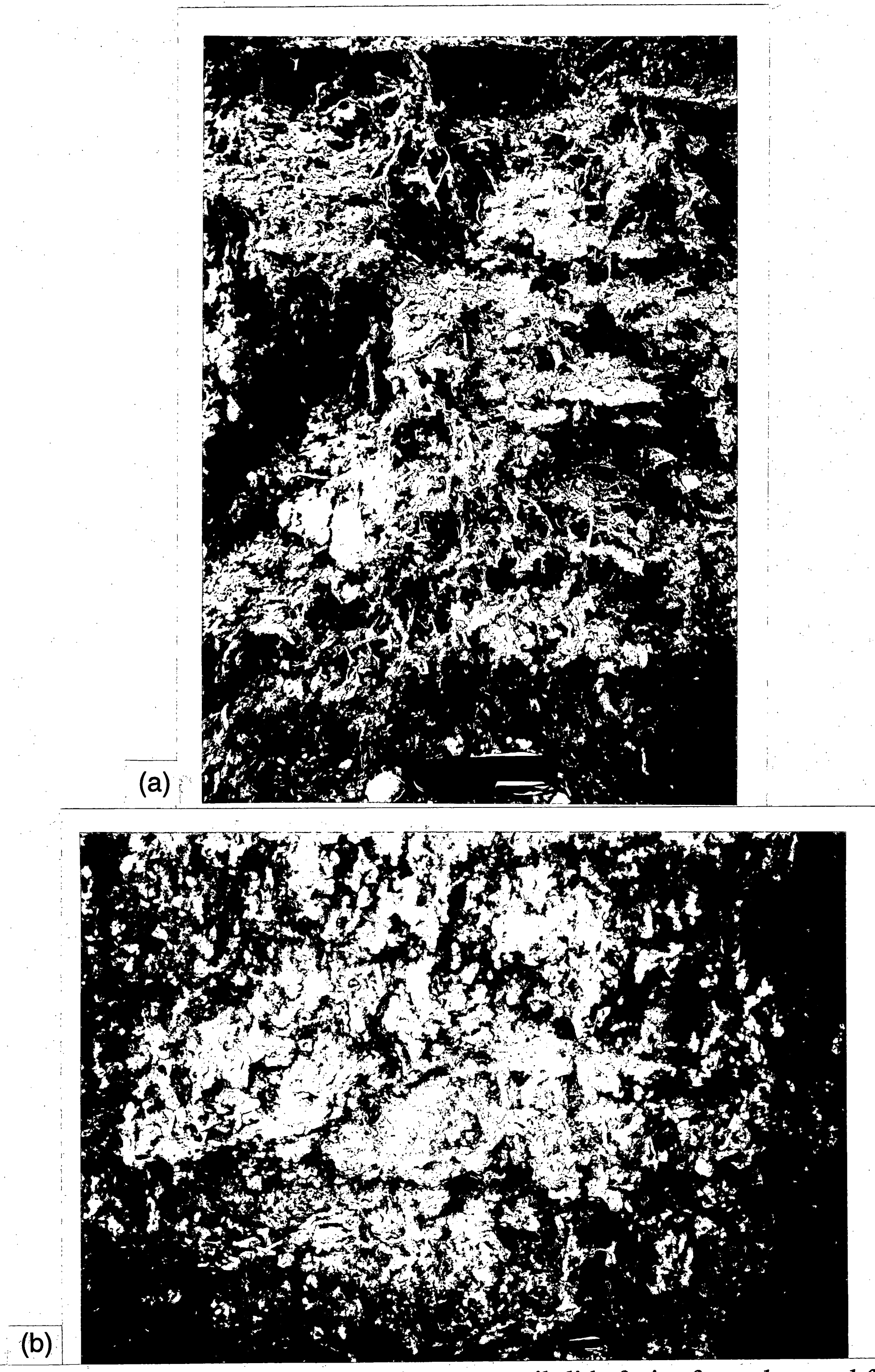
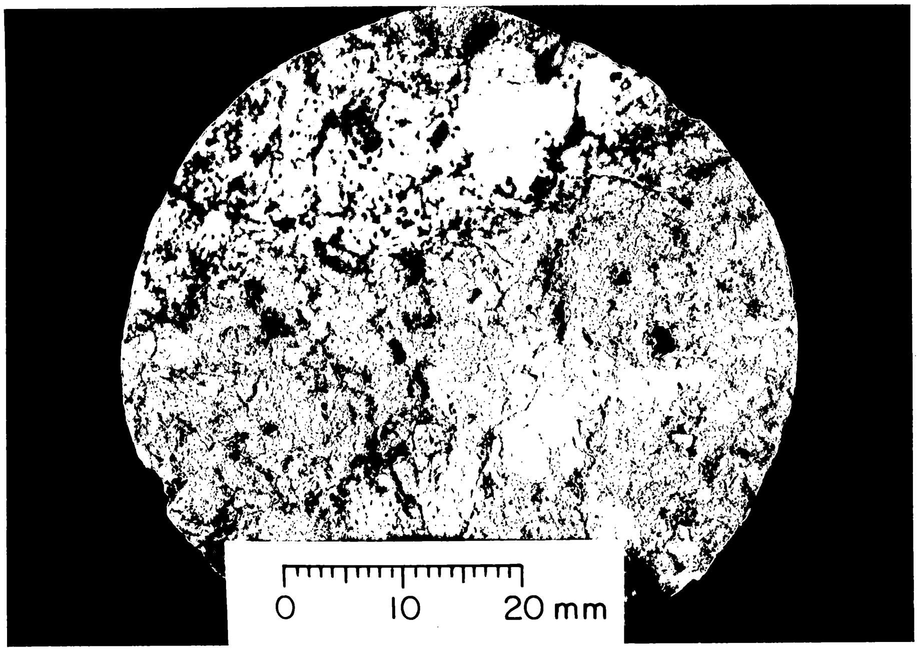
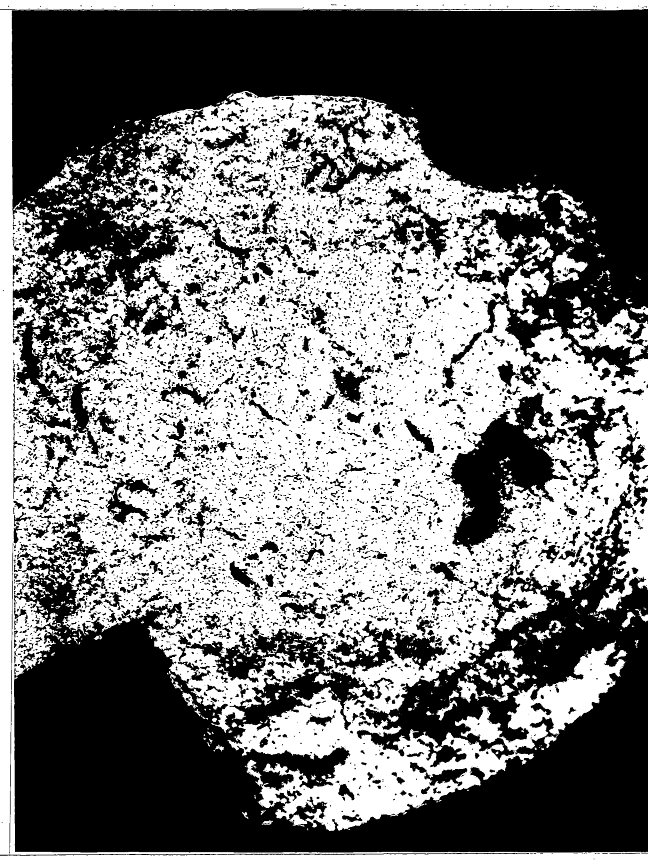


Figure 26. Rhizocretions in the fine sand to coarse silt lithofacies formed around former plant root paths. (a) Thin rhizocretions in the coarse silt lithofacies of the Ogallala Formation consist of fragile, slightly $CaCO_3$-cemented sand and silt grains marking the path of a former root. Exposure is in the Caprock Escarpment at Palo Duro Canyon State Park (see fig. 8 for location). (b) Thick rhizocretions in the coarse silt lithofacies of the Ogallala Formation consist of mostly $CaCO_3$ and minor amounts of silt and sand that accumulated along the trace of a former root. Exposure is on Texas Highway 256, approximately 19.2 km (12 mi) east of Silverton, Texas (see fig. 8 for location). Knife is 6 cm (3.5 inches) long.

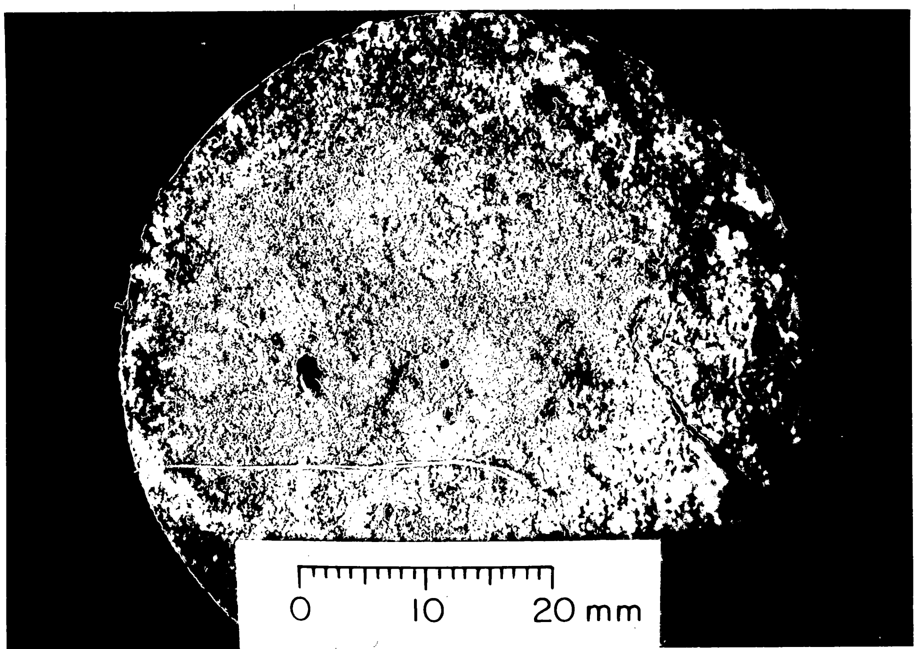


(a)



(b)

Figure 27. Photographs illustrate open root tubules, root traces, and modern roots in core of the Ogallala and Blackwater Draw Formations. All cores are 5 cm (2 in) in diameter. (a) Black spots are open root tubules and white spots are pedogenic $CaCO_3$ nodules in uncemented Blackwater Draw sandy mud at a depth of approximately 11 m (~35 ft) in BEG Seven Mile Basin No. 7 (see fig. 4 for location). (b) Black spots are open root tubules in a well-cemented calcrete at a depth of approximately 24 m (~78 ft) in BEG TDCJ No. 27 (see fig. 4 for location). (c) Black spots are open root tubules, and white spots or white streaks are $CaCO_3$ filaments in core from a depth of 14 m (46 ft) in the BEG Seven Mile Basin No. 7 well (see fig. 4 for location). Note that some of



(c)

(d)

the $CaCO_3$ areas have a very small central black spot. These also mark open root tubules. A small modern rootlet, which lies above the scale, occupied the much larger open tubule shown 1.5 cm (0.6 inch) above left end of the scale. This illustrates that roots are opportunistic and can reoccupy and connect older root tubules to significant depths. (d) Fracture surface lined with illuvial clay. White streaks are $CaCO_3$ that accumulated along the traces of former roots. Black spots are manganese oxide or hydroxide stains. Core is from the BEG Olton No. 1 well at a depth of 7.4 m (24 ft) (see fig. 4 for location).

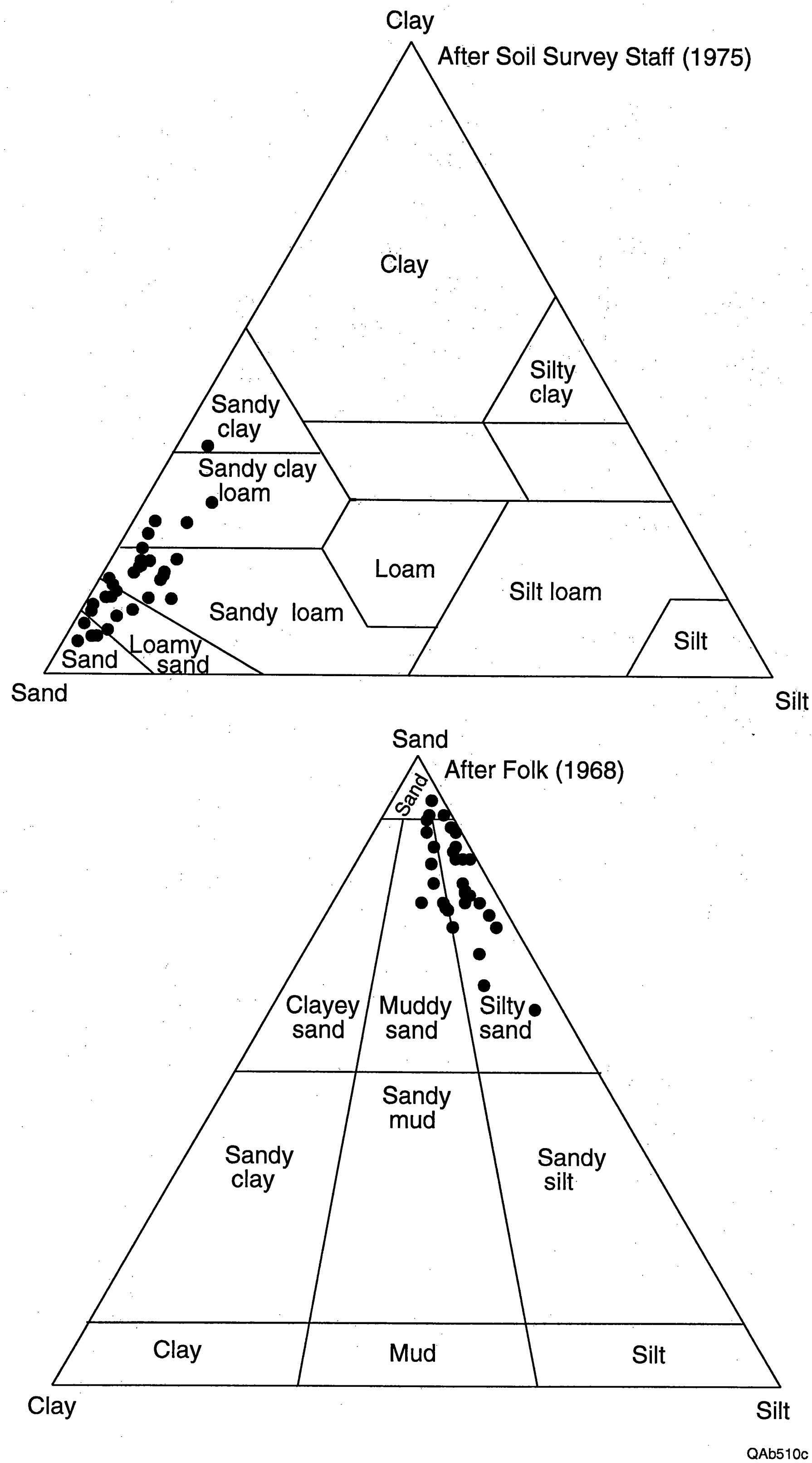


Figure 28. Sand, silt, and clay distribution for the Ogallala Formation for sediment (lower triangle) and soil (upper triangle) textural classes.

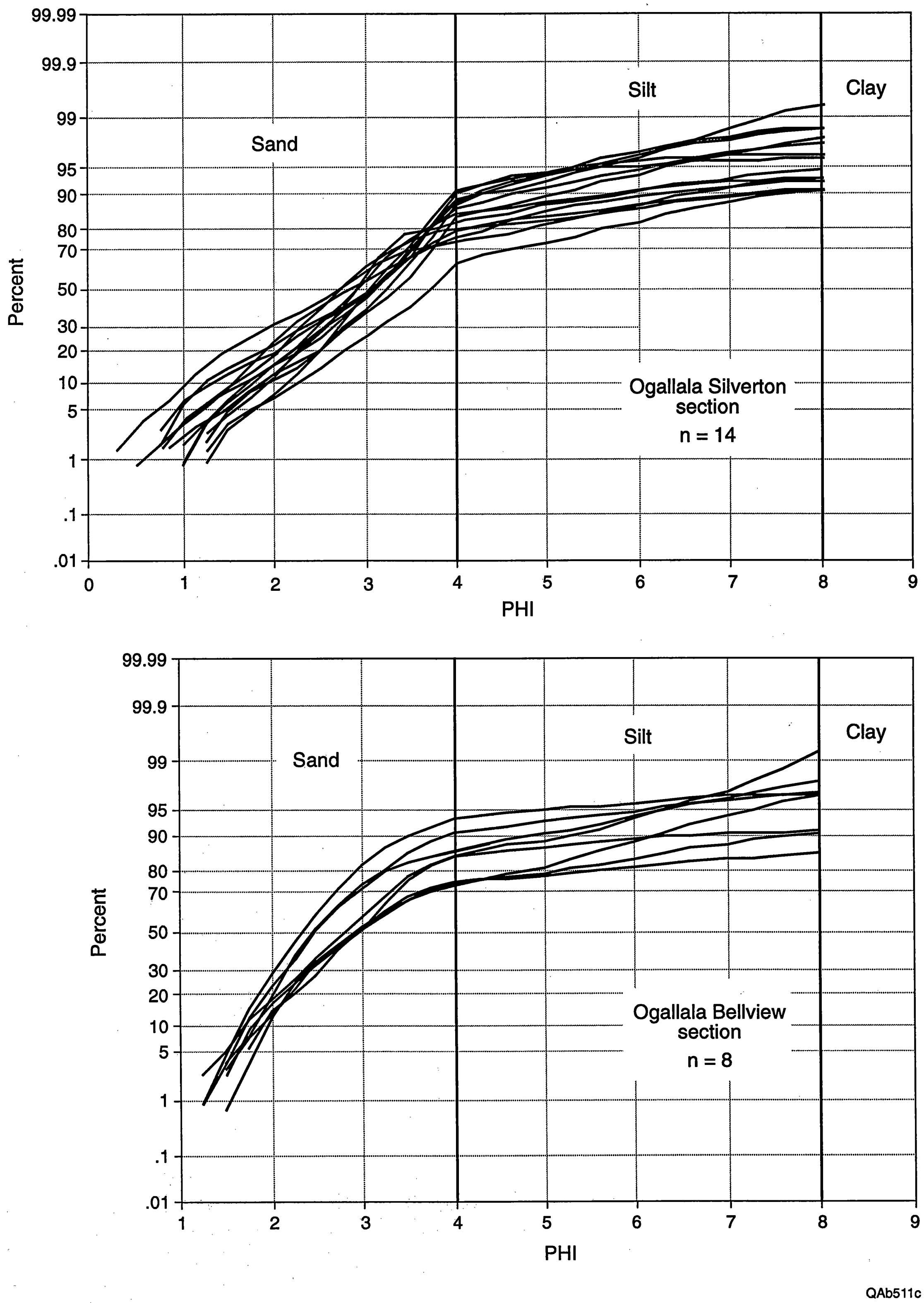


Figure 29. Sediment texture distribution for samples of Ogallala fine sand to coarse silt lithofacies. The Bellview section (northern Cap Rock Escarpment) lies approximately 160 km (100 mi) west of the Silverton section (eastern Cap Rock Escarpment). See figures 17 and 23 for described sections.

Age of Ogallala Sediments

No new datable fossil material was found in the sections examined in this study. However, rounded basalt cobbles were found in coarse basal gravels exposed along the western Caprock Escarpment in the Gerhardt Road, Lyons Ranch, and Ragland sections (figs. 13, 14, and 16). Basalt flows northwest of these sections in the Ragland and Ocate volcanic fields in northeastern New Mexico have been dated as 8.3 Ma or younger (Stormer, 1972; Mehnert and O'Neill, 1980). These flows are the nearest extrusive basic volcanics up the regional paleoslope from the Ogallala sections and within the likely drainage area of Ogallala streams. Therefore, basal gravels in the Clovis and Slaton paleovalleys in exposures in New Mexico are younger than 8.3 Ma (fig. 30) and may be coeval with sections carrying Hemphillian Land Mammal Age faunas.

Fossil vertebrate faunas have been described from exposures along the eastern margin of the Southern High Plains of both fluvial and eolian strata that filled the Clovis and Slaton paleovalleys (Winkler, 1985) and the Panhandle paleovalley (Schultz, 1990). Fluvial sand and gravel as well as the lacustrine Coetas beds from the Panhandle paleovalley contain Clarendonian Land Mammal Age faunas, indicating that these sediments began to accumulate approximately 9 to 11 Ma. However, no younger Ogallala fossil material has been obtained from these sediments, suggesting that at least the lower fluvial sections are no younger than approximately 9 Ma. The Clovis and Slaton paleovalleys both contain Clarendonian and Hemphillian Land Mammal Age faunas where these strata are exposed in the Eastern Caprock Escarpment, indicating that parts of these valleys were actively infilling from approximately 11 to 4.5 Ma. The Ogallala Formation is overlain unconformably by the Blanco and Cita Formations, which contain Blancan Land Mammal Age faunas and range in age from approximately 2 to 3 Ma. These are very localized lacustrine deposits and are not further described in this report. (See Schultz, 1977, or Pierce, 1974, for descriptions of the Blanco

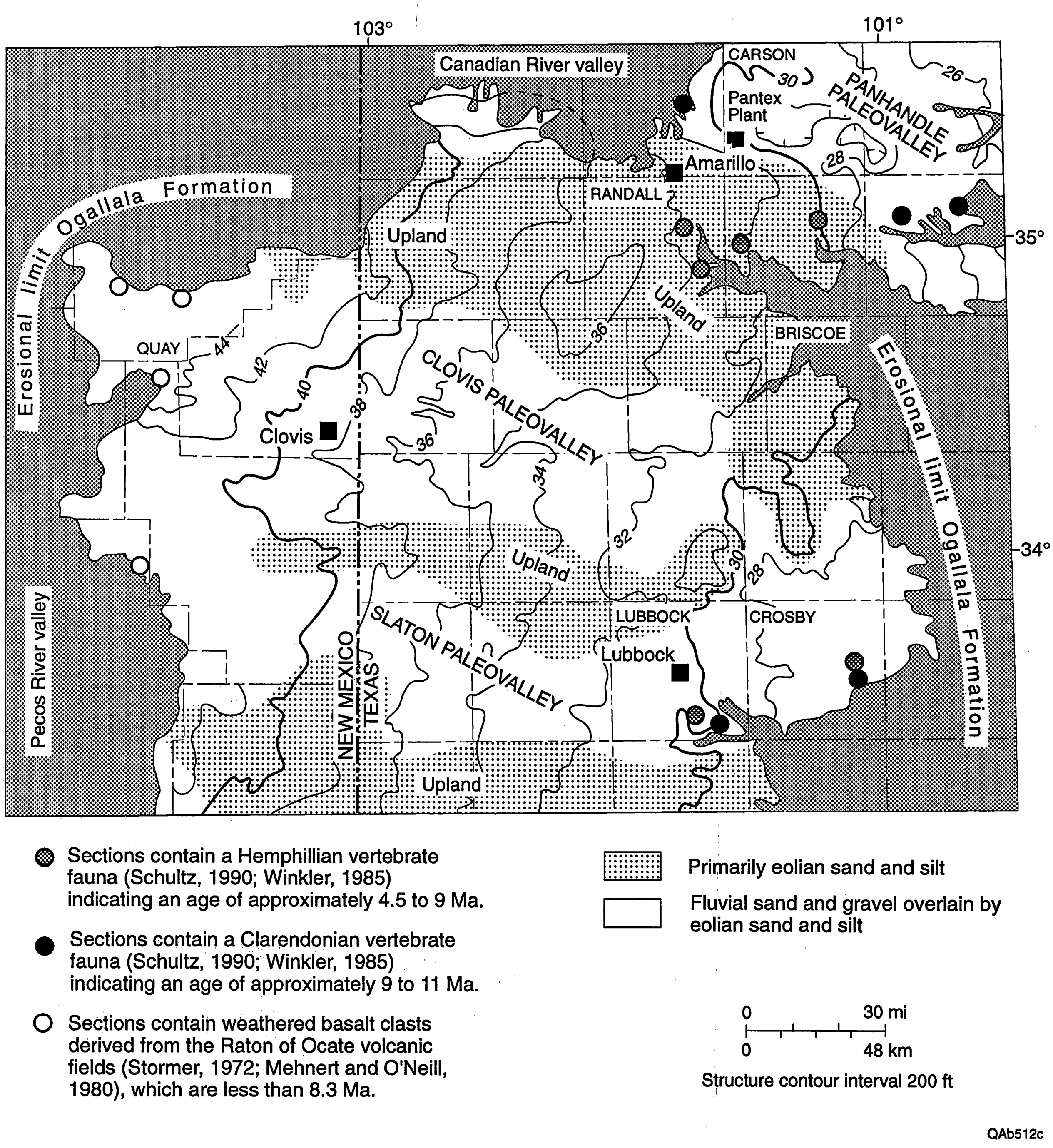


Figure 30. Approximate maximum ages of Ogallala sections are shown for sections that preserve Clarendonian or Hemphillian faunas or basaltic volcanic clasts. Regional structure-contour map on the pre-Ogallala erosional surface illustrates paleotopographic highs (stippled) and paleovalleys. Paleovalleys are partly filled with fluvial sediments that are in turn overlain by eolian deposits. Paleouplands are overlain by eolian deposits.

Formation, and see Johnston and Savage, 1955, or Schultz, 1977, for discussions of the Cita Formation.)

CAPROCK CALCRETE

The Ogallala "Caprock" has been described as a thick calcrete (caliche) that separates the Mio-Pliocene Ogallala Formation from the overlying Quaternary Blackwater Draw Formation in the High Plains of northwestern Texas and eastern New Mexico (Reeves, 1976b). The Ogallala "Caprock" also has been cited as evidence of an increasingly arid climate at the end of Ogallala deposition (Schultz, 1977). Recent studies, however, indicate that (1) at least locally the Caprock calcrete may range in age from late Miocene(?) to late Quaternary, (2) calcrete development ranges from stage IV to a very thick stage VI, and (3) thick calcretes at the top of the Ogallala, which developed during long periods of landscape stability and minimal eolian sedimentation, probably represent intervals of increased humidity rather than increased aridity (Gustavson, 1991b).

Age of the Caprock Calcrete

Buried calcic soils (stages I-III [see Bachman and Machette, 1977, or Machette, 1985, for discussions of stages of calcrete development]) are common in eolian lithofacies (fine sand to coarse silt) of the Ogallala Formation and eolian lithofacies (very fine to fine sand and sandy mud) of the Blackwater Draw Formation. Where the Ogallala is overlain by thick Blackwater Draw sections, the uppermost Ogallala commonly contains a stage V or locally one or two stage IV calcretes (fig. 31) and only rarely a thin (<0.5 m [<1.6 ft]) stage VI calcrete (fig. 21). Thick (1.5 to 10 m [5 to 53 ft]), complexly brecciated, pisolitic, stage VI Caprock calcrete is widespread beneath large areas of the western High Plains where the Blackwater Draw is only a few decimeters thick or missing (figs. 1, 13, 16, and 22). In these areas of thin Blackwater Draw sediments, it appears that some or perhaps most of the accumulations of $CaCO_3$ normally found

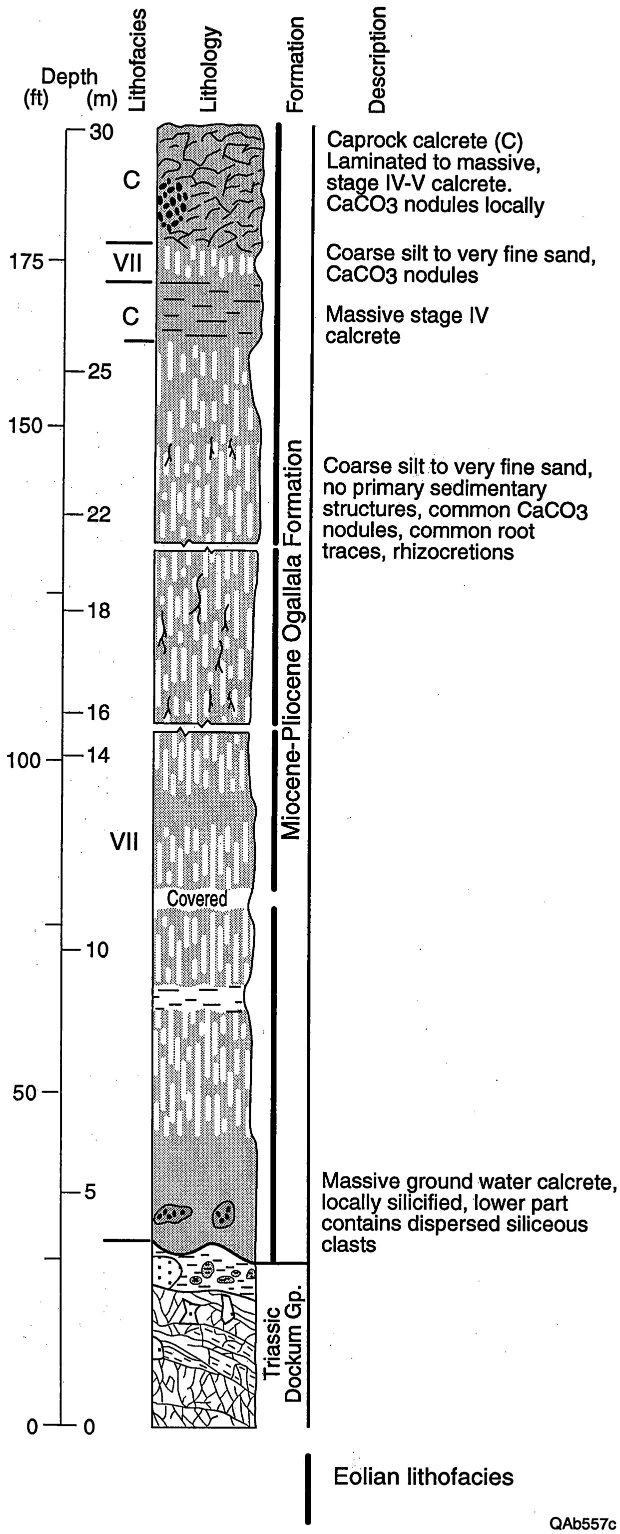


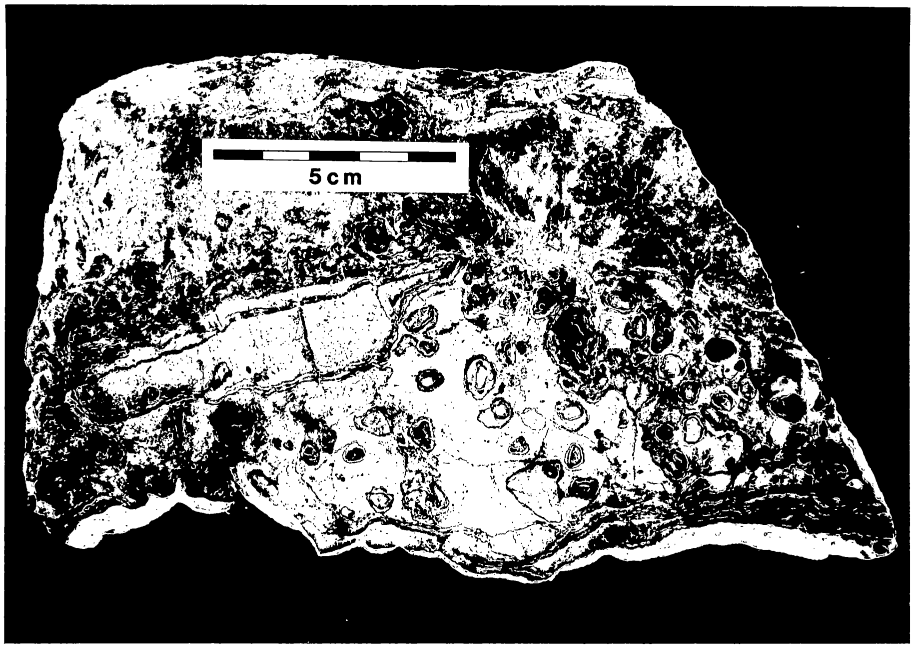
Figure 31. Stratigraphic section exposed at the Buffalo Lake National Wildlife Refuge, approximately 18 km (10.1 mi) southwest of Canyon, Texas, on Texas Highway 168 (see fig. 8 for location). Roman numerals identify Ogallala lithofacies (table 1).

in the numerous buried calcic soils and the surface calcic soil of full sections of the Blackwater Draw have been welded onto the uppermost Ogallala calcrete. Thus, part of the Caprock calcrete is locally coeval with the Blackwater Draw Formation and is Quaternary in age.

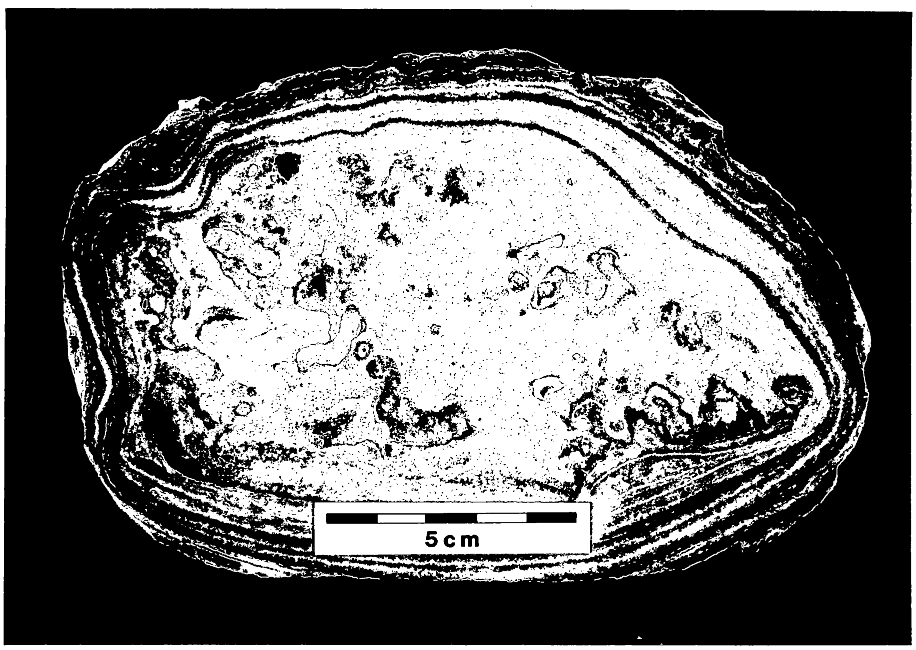
Several inliers of Cretaceous limestone crop out on the High Plains and are capped by as much as 9.6 m (32 ft) of complexly brecciated, pisolitic calcrete (stage VI) (fig. 32, 33, and 34). These exposures occur where the paleotopographic highs that separate Ogallala paleovalleys are at or slightly below the present Southern High Plains surface. Typically these exposures consist of thick (6 to 9.6 m [20 to 32 ft]) sequences of laminated and pisolitic calcrete developed directly on Cretaceous or Jurassic bedrock. These thick sections of stage VI calcrete that developed on inliers appear to have resulted from the amalgamation of $CaCO_3$ normally found in the numerous buried calcic soils of both the Ogallala and Blackwater Draw Formations (fig. 35). Thus, part of the Caprock calcrete is coeval with Blackwater Draw Formation and with at least the upper part of the Ogallala Formation and may range in age from late Miocene to late Quaternary. Rather than progressing through the early developmental stages for a calcic soil, which include formation of $CaCO_3$ filaments, nodules, and coalescing nodules to form a plugged horizon, these soils that formed on bedrock inliers began development as laminae because the underlying limestone or sandstone bedrock acted as a plugged horizon.

Areas where thick sequences of stage VI calcrete developed on bedrock inliers accumulated only minor amounts of silt grains dispersed in the calcrete. At least two factors probably contributed to the nondeposition or nonpreservation of clastic sediment over the higher parts of paleouplands. First, since the beginning of Ogallala deposition these areas were low hills on the landscape. Elevation and higher slopes would have made these surfaces more susceptible to erosion than surrounding low-relief areas. Second, coarser eolian sediment moving during dust storms was less likely to be transported up onto these low hills than it was to be carried into surrounding low-relief areas.

The thick sequence of brecciated, pisolitic, and recemented (stage VI) calcrete represents numerous episodes of exposure or near exposure during which the surface of the calcrete was



(a)



(b)

Figure 32. Polished sections of pisolitic and brecciated Caprock calcrete developed on the Edwards Limestone exposed as an inlier on the High Plains. This and other similar inliers occur where the paleoupland between the Slaton and Clovis paleovalleys are incompletely covered by Ogallala and Blackwater Draw Formation sediments (see fig. 8 for location). (a) Numerous small pisolites represent several episodes of brecciation and recementation. (b) A single large pisolite developed on a core of smaller pisolites.

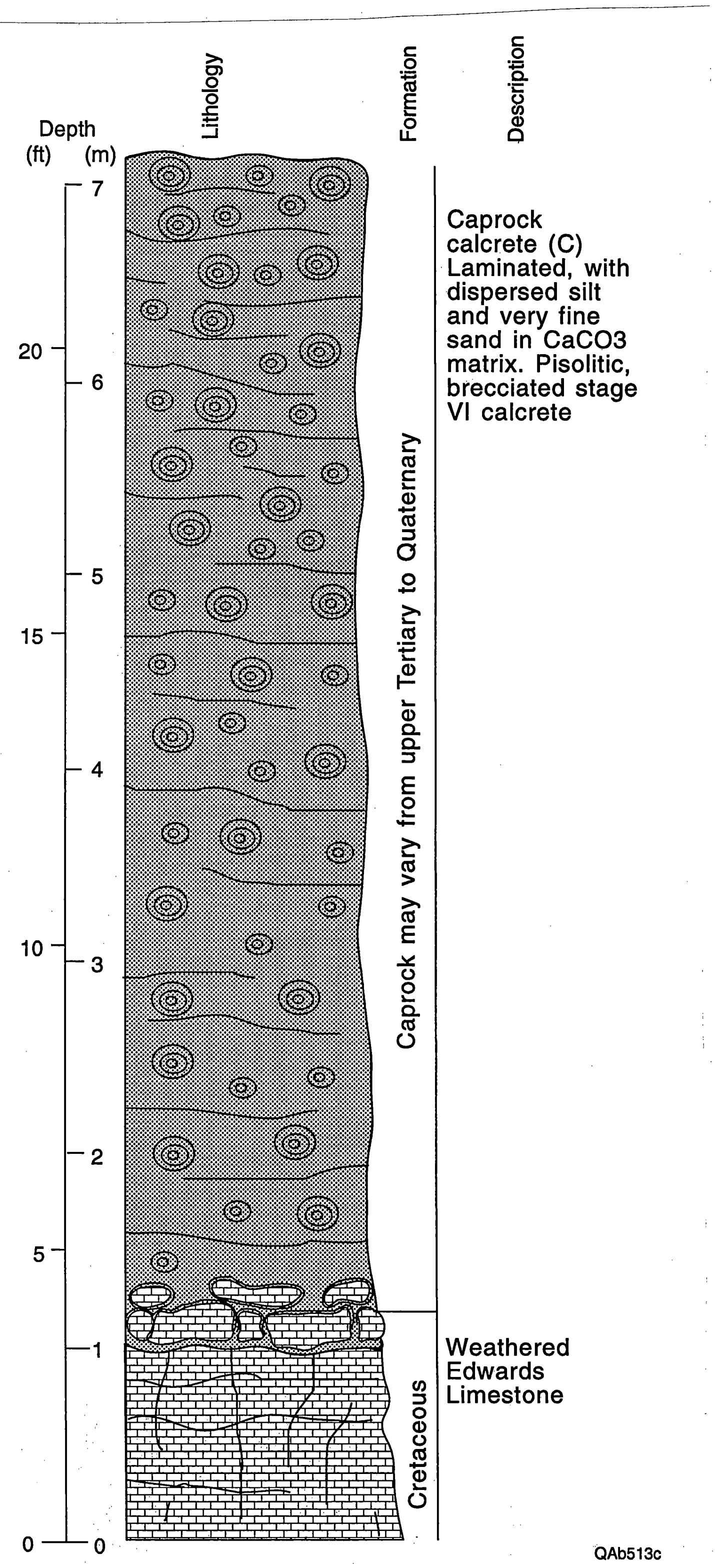


Figure 33. Stratigraphic section exposed in the eastern Caprock Escarpment along Texas Highway 1054, approximately 5 km (0.3 mi) north of U.S. 180 in northwest Borden County, Texas.

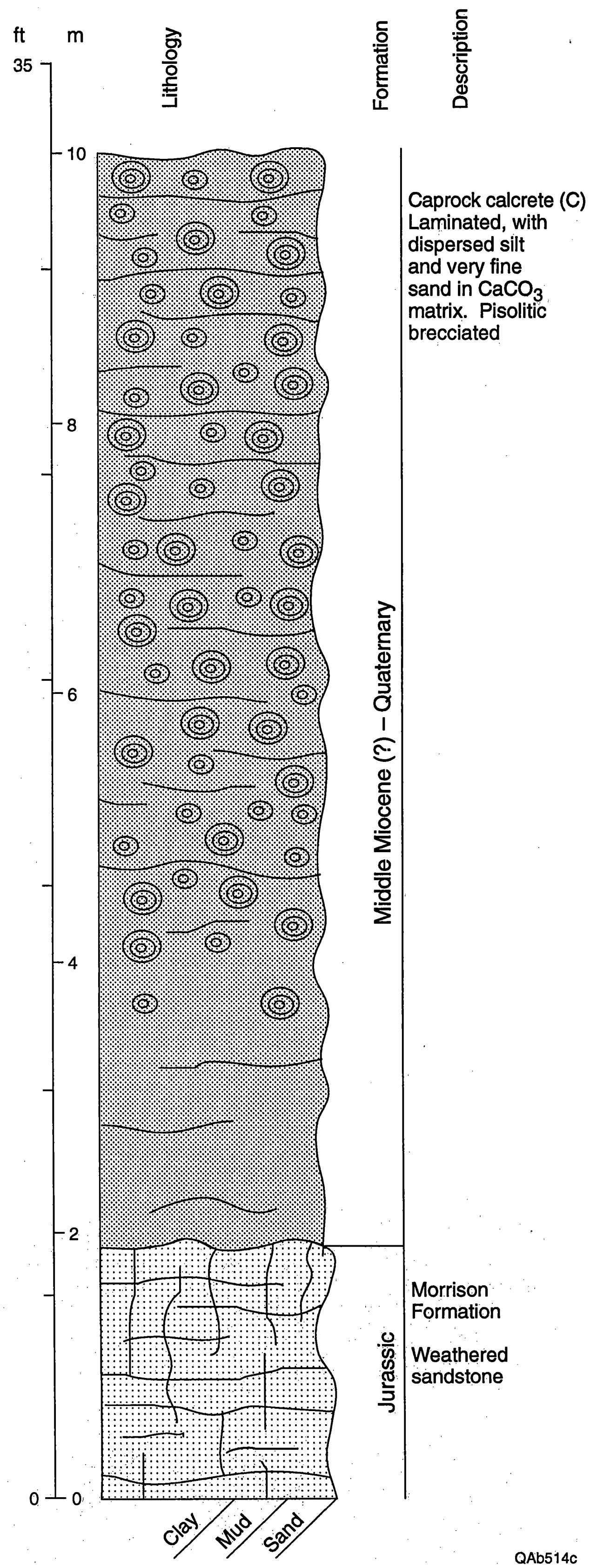


Figure 34. Stratigraphic section exposed in the western Caprock Escarpment along New Mexico Highway 156 in western Quay County (see fig. 8 for location).

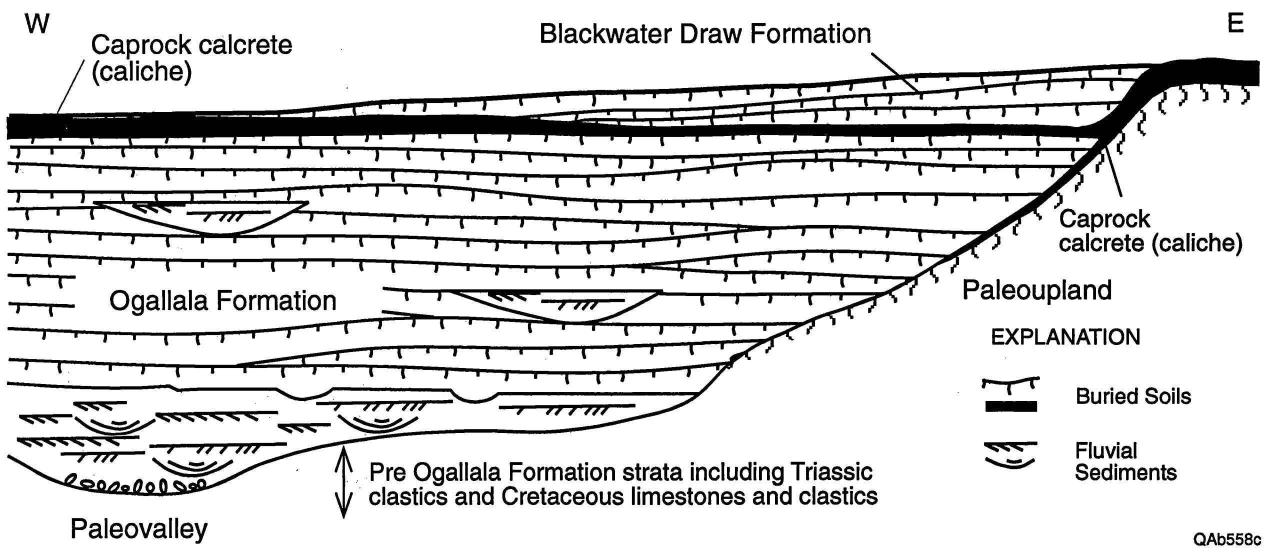


Figure 35. Schematic model illustrating the distribution of sediments and calcic soils in the Tertiary Ogallala and Quaternary Blackwater Draw Formations, Southern High Plains, Texas and New Mexico. Ogallala fluvial sediments typically occupy paleovalleys. Ogallala eolian sediments, which contain numerous buried soils, overlie uplands, and they overlie and are locally interbedded with fluvial sediments. The Caprock calcrete formed locally on pre-Ogallala sediments, on Ogallala sediments, and from east to west contain progressively greater amounts of soil carbonate coeval with soil carbonate in buried soils in eolian sediments of the overlying Blackwater Draw Formation. Model illustrates how (1) calcic soils are welded together over inliers and the higher parts of paleouplands forming a calcrete that could range in age from late Miocene to Quaternary and (2) calcic soils are welded together in areas of thin or no Blackwater Draw Formation accumulation forming a calcrete that could be in large part Quaternary. Eolian sediments and buried soils of the Ogallala and Blackwater Draw Formations were formed under a mostly semiarid climate and on a grassland savanna.

weathered, partly dissolved, and brecciated. Reburial of the weathered and brecciated calcrete followed periods of exposure, and as a result of evapotranspiration, precipitation of $CaCO_3$ was continued, forming laminae around breccia fragments. As $CaCO_3$ is precipitated, silt and sand grains are incorporated.

Climate During Deposition of the Caprock Calcrete

Episodes of brecciation of calcrete probably resulted from exposure due to thinning or erosion of overlying soil/sediment. Throughout the western parts of the Southern High Plains where the Blackwater Draw is thin (less than a few decimeters) or missing, the underlying K horizon (the Caprock calcrete) typically shows evidence of multiple episodes of exposure, brecciation, reburial, and recementation with an intensely fractured surface. Throughout eastern parts of the Southern High Plains where the Caprock calcrete is overlain by a relatively thick accumulation of Blackwater Draw sediments, it is massive to coarsely laminated and well indurated in outcrop, with little evidence of repeated exposure and weathering.

The numerous episodes of brecciation and recementation recorded in the stage VI (western) parts of the Caprock calcrete apparently resulted from repeated cycles of exposure and reburial. It is likely that exposure results from destabilization and erosion of surface soils due to the loss or reduction of vegetative cover during periods of increased aridity. Studies of native grasslands on the Great Plains clearly show that the vegetative cover is significantly reduced after several years of drought, resulting in severe deflation and movement of large amounts of sediment by the wind (Weaver and Albertson, 1943; Tomanek and Hulett, 1970). Less $CaCO_3$ is likely to accumulate from evaporation of rainfall under these conditions because the infiltration capacity of exposed calcrete and areas where the calcrete is thinly covered is very low and most rainfall would run off. Thus, the availability of Ca^{++} may be reduced during dry climatic conditions both because of diminished rainfall and because the ability to capture precipitation is reduced. Conversely, during periods of increased available moisture, increased vegetative cover would result in a stable landscape surface, accumulation of sediment, and precipitation of $CaCO_3$ as a result of evapotranspiration. Not only is more Ca^{++} potentially available because of increased rainfall, but also the thicker soils covering the calcrete have a greater infiltration capacity and can hold more water. Therefore, a potentially larger volume of Ca^{++} is available for longer period of time as a source of soil carbonate.

The stage IV–V calcretes that cap upper Ogallala sediments and underlie a normal sequence of Blackwater Draw strata in the eastern part of the Southern High Plains show fewer or no pisolites and little evidence of repeated episodes of brecciation and recementation and therefore represent a protracted period of landscape stability at the end of Ogallala time. Moreover, the Caprock calcrete represents a long period of minimal influx of eolian sediment, no evidence of significant surface erosion, and no evidence of significant interruptions of soil development. In the model suggested here, this condition of widespread landscape stability resulted from increased vegetative cover that stabilized source areas of eolian sediment in the western High Plains, in the Pecos Plains of eastern New Mexico, or in the Canadian Breaks. Increased vegetative cover probably developed from increased available moisture, perhaps in part due to a cooler climate towards the end of the Pliocene (Lamb, 1977). Therefore, the primary cause of landscape stability and of the development of thick calcretes at the top of the Ogallala may have been a slightly wetter climate rather than increased aridity.

There is additional regional stratigraphic evidence that supports the idea of a wetter climate towards the end of the Tertiary. Blancan Age (late Pliocene) lacustrine deposits in the Texas Panhandle, including the Blanco Formation exposed in the eastern Caprock Escarpment, the Cita Formation exposed in Palo Duro State Park, an unnamed diatomite exposed in Mulberry Canyon, and the Rita Blanca Formation exposed in Hartley County, all overlie unconformably or are inset into the Ogallala Formation but are older than the Blackwater Draw Formation (Evans, 1948; Anderson and Kirkland, 1969; Izett and others, 1972). The Blanco Formation locally is capped by a stage IV calcrete. The stratigraphic position as well as the fact that eroded blocks of Caprock calcrete have been recognized in the Blanco Formation (Izett and others, 1972) suggest that the Blanco Formation and other Blancan Age units are either slightly older or perhaps in part coeval with the Caprock calcrete in the vicinity of the eastern Caprock Escarpment.

The Blancan lacustrine units were all deposited in broad shallow subsidence basins that likely formed as a result of dissolution of underlying Permian salt (Gustavson and others, 1980; Gustavson and Finley, 1985; Gustavson and Simpkins, 1989; Gustavson, 1986). Flooding of each of these roughly coeval lacustrine basins indicates that the local ground-water table was high enough to form a permanent body of water. Because these sediments were all laid down at about the same time and because the lacustrine basins are found over a fairly wide area, I believe that a significant rise in the regional water table occurred at or near the end of Ogallala deposition. This postulated water-table rise was most likely driven by an increase in water available for recharge, perhaps in part due to cooler temperatures and decreased evaporation or increased rainfall, or both.

REGIONAL STRATIGRAPHY OF THE BLACKWATER DRAW FORMATION

The Quaternary Blackwater Draw Formation overlies the Ogallala Formation on the Southern High Plains and is largely composed of clay, silt, and fine to very fine sand-sized eolian sediments, which have been strongly modified by soil-forming processes. Allen and Goss, (1974) and Holliday (1989) described as many as six buried soils from the Blackwater Draw Formation near Bushland, Texas. In parts of this study area, which preserve thicker Blackwater Draw sections than the Bushland area, as many as 11 buried soils were recognized from core of the Blackwater Draw Formation recovered from borehole BEG/PTX No. 2 in eastern Carson County (fig. 21).

Four lithofacies have been recognized from core and exposures of Blackwater Draw sediments including: (1) very fine to fine sand; (2) sandy mud; (3) laminated very fine sand, silt, and clay; and (4) clay (table 2). Within the study area, lithofacies I and II make up the bulk of the Blackwater Draw Formation. This study does not consider playa lake sediments, saline lake

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.

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 savanna or prairie
2. Sandy mud	Coarse silt to very fine sand, no preserved primary sedimentary structures, locally common open 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 savanna 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

sediments or associated lee dunes, or alluvium in draws. (For discussions of these units, see Hovorka, in press; Gustavson and others, 1995; Wood and others, 1992; and Holliday, in press.)

Very Fine to Fine Sand Lithofacies

The very fine to fine sand lithofacies (lithofacies 1, table 2) consist mostly of fine to very fine sand and less than 50 percent silt or clay and are a clayey or muddy sand if described as a sediment or a sandy loam or sandy clay loam if described as a soil (fig. 36). 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 sharply increased $CaCO_3$ content in the form of filaments, nodules, and petrocalcic horizons (calcretes). 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 columnar with argilans, mangans, and/or $CaCO_3$ filaments or nodules developed on bounding fractures. In these strata, as many as 11 cycles of slow sediment accumulation on a stable landscape followed by a long period of pedogenesis occurred.

In other intervals of the Blackwater Draw strata where horizonation is lacking, common pedogenic $CaCO_3$ nodules may occur over vertical distances of several meters. In these sections, slow sedimentation occurred simultaneously with pedogenesis. Open root tubules, which are typically less than 1 mm (0.04 inches) in diameter and characteristic of small plants like grasses, are present in all Blackwater Draw sediments. These lithofacies make up most of the core from the BEG Olton No. 1 borehole in Lamb County where Blackwater Draw sediments are typically light brown (5 YR 6/4 to 5/6) (fig. 37). These lithofacies also make up the lower part of the Blackwater Draw Formation locally in eastern Carson and Armstrong Counties, where they are typically pale reddish brown (10 R 5/4) to moderate reddish brown (10 R 4/6). The coarser texture and redder color of this lithofacies in the Carson and Armstrong Counties area (northeast quadrant of the Texas Panhandle) may suggest a nearby source area to the north such as the

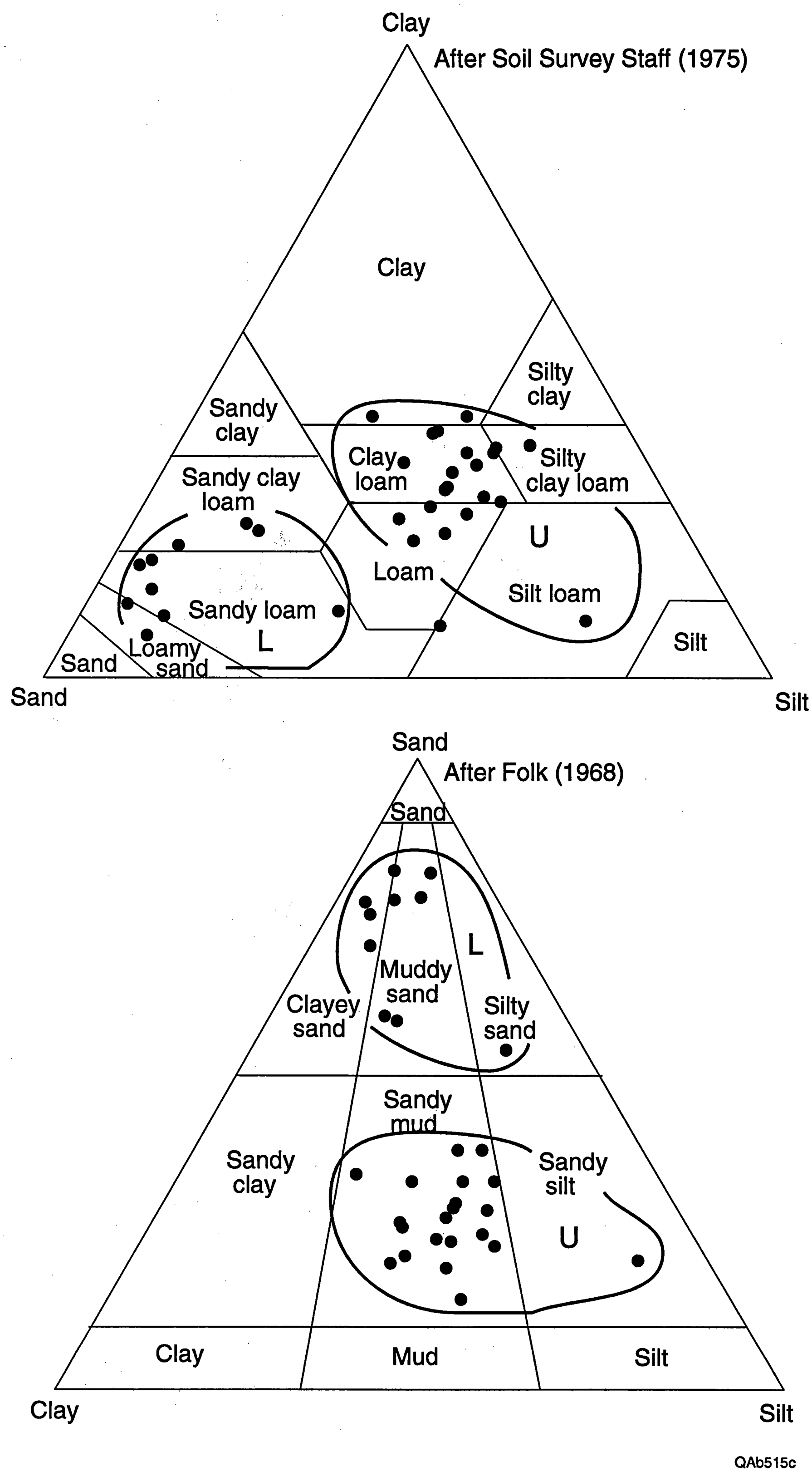


Figure 36. Sand, silt, and clay distribution in upper (U) and lower (L) Blackwater Draw Formation sediments. Soil classes are after Soil Conservation Service Staff (1975). Sediment classes are after Folk (1968).

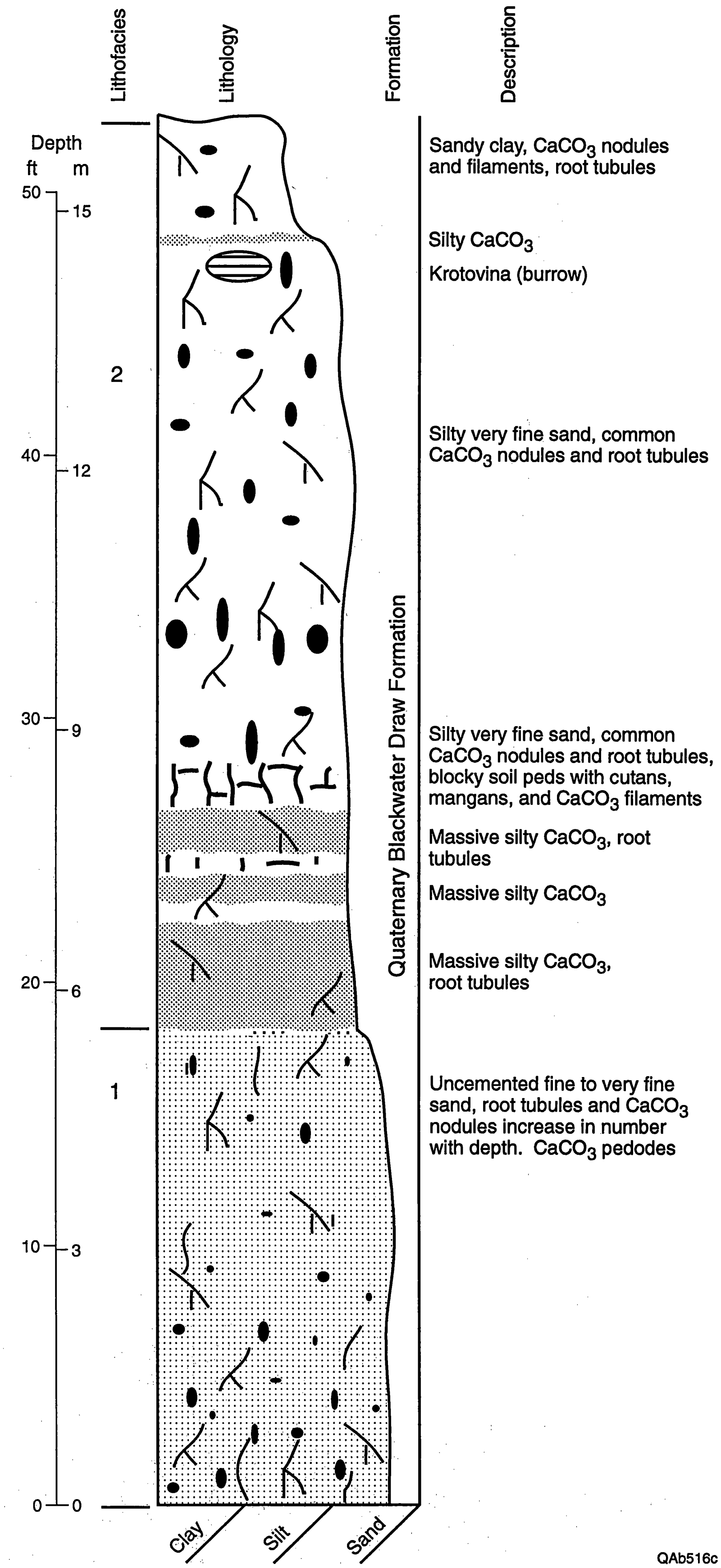


Figure 37. Description of core of the Quaternary Blackwater Draw Formation from BEG Olton No. 1 well, Lamb County, Texas (see fig. 4 for location). Numbers identify Blackwater Draw lithofacies (table 2).

Canadian River valley where Permian red beds, which are also reddish brown (10 R 5/6 to 10 R 4/6), were being eroded during the early Quaternary. The source area for these sediments in BEG/Olton No. 1 in Lamb County (southwest quadrant of the Southern High Plains) was probably the Pecos River valley.

The origin of these sediments, which were probably deposited as a mix of loess and thin sand sheets, is described under the section on "Transportation and Depositional Environment of the Eolian Lithofacies Ogallala And Blackwater Draw Formations" (p. 83).

Sandy Mud Lithofacies

The sandy mud lithofacies (lithofacies 2, table 2), which consists of 10 to 40 percent sand and roughly equal amounts of silt and clay, may also be described as a loam, clay loam, or silty clay loam (fig. 36). No primary sedimentary structures are preserved in this lithofacies. These sediments are typically reddish brown (5 YR 5/4). They are strongly modified by pedogenesis and contain numerous buried soil 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 open root tubules and rhizocretions. These lithofacies are similar to the loamy surface soils/clayey subsoils that characterize the Blackwater Draw Formation across the northern and northeastern part of the Southern High Plains. However, the sandy mud lithofacies are finer grained than either the very fine to fine sand lithofacies of the Blackwater Draw Formation or the fine sand to coarse silt lithofacies of the Ogallala Formation.

These sediments were deposited as a mix of loess and thin sand sheets. These processes are described under the section on "Transportation And Depositional Environment of the Eolian Lithofacies Ogallala And Blackwater Draw Formations" (p. 83).

Laminated Very Fine Sand, Silt, and Clay

The laminated very fine sand, silt, and clay lithofacies (lithofacies 3, table 2) consist of centimeter-scale upward-fining sequences of thinly laminated very fine sand, silt, and clay. Desiccation cracks are preserved, but the thin laminations are not disturbed. These lithofacies are only rarely preserved in core and are limited to half-meter-long sequences in BEG/TDCJ No. 5 (fig. 38). These sediments are preserved in core taken near to the margin of a playa lake. The laminated sands and silts could have been deposited in small paleodrainages that discharged into the playa. Alternatively, they could have been deposited at the playa margin during a high lake stage. Hovorka (in press) described similar sediments in a extensive study of the stratigraphy of playa-filling sediments.

Clay

The clay lithofacies (lithofacies 4, table 2) consist primarily of clay with small amounts of coarser clastic sediments (fig. 38). No primary sedimentary structures are preserved, but pedogenic structures are well developed. For example, desiccation cracks are partly filled with silt and very fine sand, $CaCO_3$ filaments and nodules are rare to common, and large wedge-shaped soil aggregates are bounded by fractures with slickensides. These soil structures are characteristic of soils with vertic properties.

These lithofacies likely represent an internally drained playa basin that formerly existed on the High Plains, perhaps even an incipient playa basin (see fig. 13, Gustavson and others, 1995). Vertic soil properties indicate that this was an ephemeral pond that was periodically flooded and desiccated.

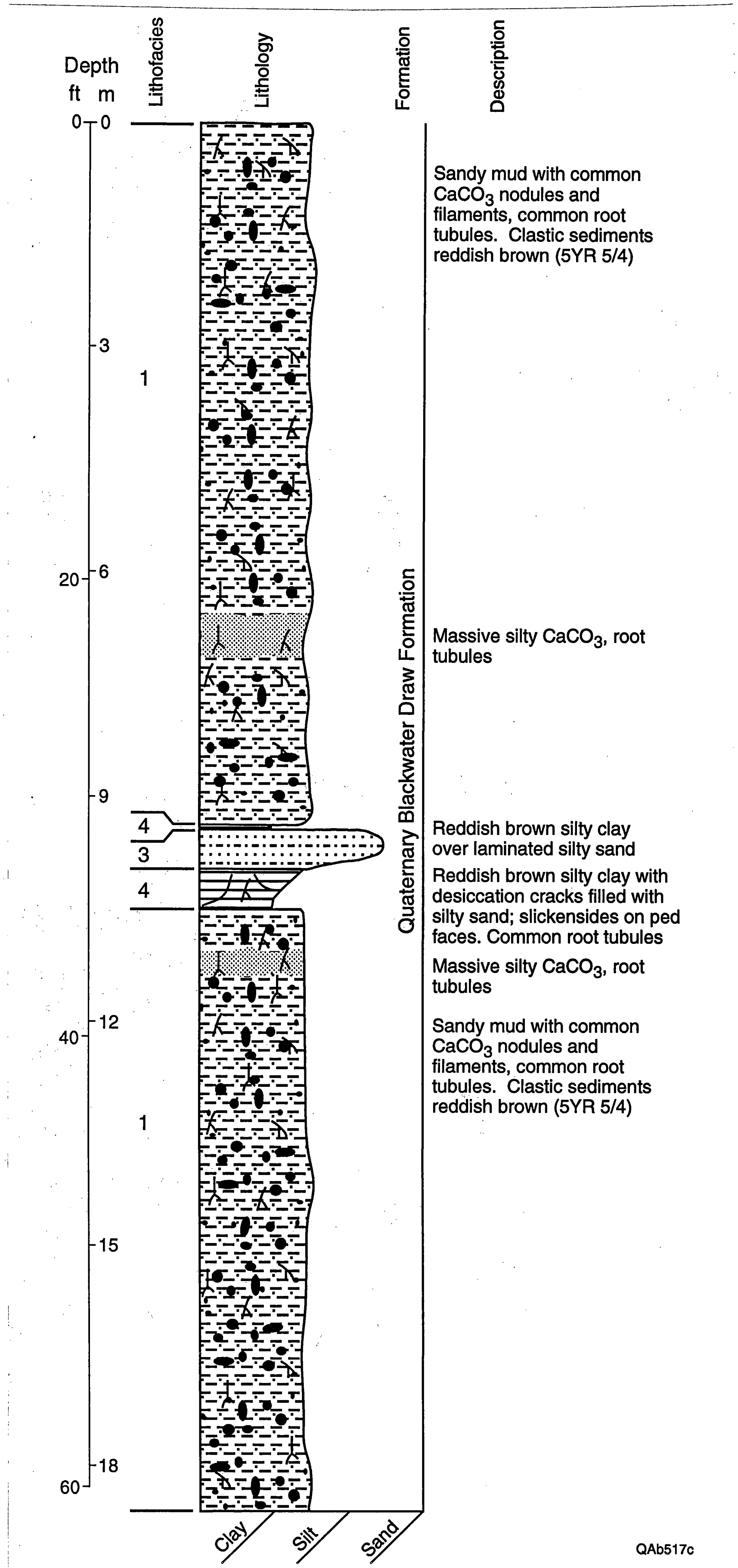


Figure 38. Description of core of the Quaternary Blackwater Draw Formation from BEG/TDCJ No. 5 well, Carson County, Texas (see fig. 4 for location). Numbers identify Blackwater Draw lithofacies (table 2).

Age of the Blackwater Draw Formation

The Blackwater Draw Formation was first described by Frye and Leonard (1957, 1964), who used the informal term "cover sands" and considered these sediments to be of "Illinoian" age. They also recognized the strongly developed surface soil of the Blackwater Draw Formation as "Sangamon Soil." Reeves (1976b) proposed that the term "cover sands" be replaced by Blackwater Draw Formation and continued to consider these sediments as "Illinoian" in age. More recent data indicate that the Blackwater Draw Formation encompasses all of the Quaternary. Machenberg and others (1985) and Holliday (1989) both pointed out that the Blackwater Draw locally contains the 1.4 My Guaje ash. Holliday (1989) also recognized that there was about 1 m (3.3 ft) of Blackwater Draw sediment below the Guaje ash with a stage IV calcic soil suggesting that Blackwater Draw sediments began to be deposited about 1.6 Ma. Patterson and Larson (1990) recognized several reversely magnetized buried soils in a series of exposures of the Blackwater Draw Formation and estimated a maximum age of 1.4 to 1.8 Ma.

BURIED SOIL DEVELOPMENT

Eolian lithofacies of the Ogallala and Blackwater Draw Formations are characterized by numerous buried argillic and calcic horizons; however, no A horizons are preserved. Apparently, the distinguishing organic content of A horizons is oxidized or consumed upon burial. Locally buried Vertisols are preserved in floodplain and lake sediments.

Buried argillic horizons that are preserved in the Ogallala and Blackwater Draw Formations commonly exhibit a very coarse vertical prismatic structure and are recognized by an increase in clay content and by an increase in red/brown color. Where sufficient exposures are available along the eastern Caprock Escarpment, buried argillic horizons in the Ogallala Formation may be traced uninterrupted for several kilometers. Calcic horizons in both formations are typically defined by accumulations of $CaCO_3$ as filaments or as nodules that range from a few millimeters to more than ten centimeters in diameter and typically contain dispersed silt- and sand-sized clastic grains. Vertical or horizontal intergrowth of nodules has produced distinctive patterns of nodules locally. For example, pedogenic $CaCO_3$ accumulated preferentially in fractures that separate soil prisms resulting in vertically aligned groups of nodules on vertical exposures and as a prismatic network of nodules in horizontal exposures. In some sections, $CaCO_3$ nodule development is pervasive over several meters vertically, and no distinct soil horizons can be distinguished. Calcic horizons also typically exhibit a crude columnar structure.

Buried calcic soils of the Ogallala and Blackwater Draw Formations are similar to modern soils on the Southern High Plains such as the Amarillo and Pullman Series Soils. The Pullman clay loam is a Torrertic Paleustoll, and the Amarillo sandy loam is an Aridic Paleustalf; these soils have an aridic or near aridic moisture regime (U.S. Department of Agriculture, 1972a, 1973; Soil Survey Staff, 1975). The Amarillo and Pullman soils are typical of Southern High Plains upland areas and formed in the upper 1.5 m (5 ft) of the Blackwater Draw Formation (Holliday, 1990b). Soils with an aridic moisture regime are dry more than half of the time and never moist for as long as 90 consecutive days (Soil Survey Staff, 1975). Water has not percolated to depths in excess of 1 to 2 m (3.3 to 6.3 ft) historically in the Pullman clay loam in areas of natural or revegetated grassland (Aronovici, 1971). Analyses of High Plains surface (Pullman soil) and near-surface sediments of the Quaternary Blackwater Draw Formation by Aronovici (1971) and more recently by Stone (1990) and Scanlon and others (1994) show that these materials have high chloride and low moisture contents. Aronovici (1971), Stone (1990), and Scanlon and others (1994) interpreted chloride data from these sediments to indicate that evapotranspiration at shallow depths concentrated chloride that is present in low concentrations (0.1 to 0.2 mg/L) in rainfall (Junge and Werby, 1958). Similarly, calcium, which is also present in small amounts (2 to 3 mg/L) in rainfall (Junge and Werby, 1958), is concentrated in soil as $CaCO_3$ by evapotranspiration. Secondary $CaCO_3$ accumulation begins as shallow as 38 to 44 cm (15 to 17 inches) (Bt horizon) in these soils. Calcic horizons contain 30 to 70 percent $CaCO_3$ by volume in the Pullman clay loam and 20 to 60 percent $CaCO_3$ by volume in the Amarillo sandy loam (U.S. Department of Agriculture, 1972a, 1973).

The buried calcic soils that are preserved in the Blackwater Draw and Ogallala Formations are typically stage I to stage III (sparse to common carbonate filaments to many coalesced $CaCO_3$ nodules in a firmly cemented matrix) in Machette's (1985) classification of stages of soil carbonate morphology. Buried calcic soils are less commonly stage IV or V (thin to thick lamellae to thick lamellae with pisolites). The Caprock Calcrete, however, typically ranges from stage IV to a thick (~8 m [~26.2 ft]) stage VI (thick lamellae and pisolites to multiple generations of laminae, breccia, and pisolites).

Machette (1985) critically reviewed the application of processes of soil $CaCO_3$ accumulation to soil development in the southwestern United States and concluded that airborne $CaCO_3$ dust and Ca^{++} dissolved in rainwater were the primary sources of carbonate in soil. Junge and Werby (1958) showed that for the Southern High Plains the average Ca^{++} concentration in rainfall ranges from 2 to 3 mg/L. Gile and others (1981) measured $CaCO_3$ dust accumulation rates of 0.2 to 0.4 $g/m^2/yr$ near Las Cruces, New Mexico. Wright and Tucker (1991) suggested that the most important mechanisms for soil carbonate deposition were evaporation, evapotranspiration, microbial activity, and degassing of CO_2. With respect to these processes, soil carbonate precipitation in most areas of the High Plains is probably most active during the warm summer months when precipitation rates, evaporation rates, and biological activity are high and least significant during cool winter months when precipitation, evaporation and biological activity are low.

Rhizocretions, which are commonly preserved in eolian lithofacies (Ogallala fine sand to coarse silt lithofacies) range from roughly cylindrical, thin (<5 mm [<0.2 inch] in diameter), and delicate to thick (15 mm [6 inches] in diameter) and hard, downward-branching $CaCO_3$-cemented concretions (fig. 26). Rhizocretions may be very common, forming a complex of interwoven networks. Where hollow, the remaining open space in these rhizocretions is typically 1 mm (0.04 inch) 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. 27). Most tubules, which range in diameter from <1 mm (<0.04 inch) to as much as 5 mm (0.2 inch), are open, but a few have been partly filled with $CaCO_3$.

Pedogenic carbonate, argillans, or mangans on fracture surfaces or lining root traces are evidence that recharging waters flowing through the vadose zone formerly utilized these features as flow paths. Scanlon and others (1994) have shown that fractures and root tubules are preferred flow paths for recharge through modern soils on the Southern High Plains. Common root traces and soil fractures in Ogallala and Blackwater Draw sediments suggest that these features may be important preferred flow paths for ground water.

Buried Vertisols developed on floodplain and lake sediments preserved in Ogallala and Blackwater Draw sediments are similar to modern Vertisols on the Southern High Plains such as the Randall clay (U.S. Department of Agriculture, 1972c). Vertisols owe their characteristic soil structures to numerous episodes of expansion and contraction of the smectite-rich clay in which they developed. Swelling of clayey sediments results from periodic flooding, and these sediments contract as floodwaters recede and clays are desiccated. A thin veneer of clay and silt is added to the soil surface as a result of each flood event. Repeated episodes of expansion and contraction result in the development of large wedge-shaped soil aggregates that are bounded by slickensides, desiccation cracks that are commonly filled with surface sediments, and microtopography of small knolls and intervening depressions that are 8 to 20 cm (3 to 8 inches) deep. (Wilding and Tessier, 1988, and Gustavson, 1991a, described the formation of Vertisols and their characteristic structures.) $CaCO_3$ content in the Randall clay typically varies from a few fine nodules in the AC1 horizon at a depth of 50 to 100 cm (20 to 49 inches) to less than 10 percent soft carbonate masses in the AC3 horizon at a depth of 150 to 170 cm (60 to 67 inches).

TRANSPORTATION AND DEPOSITIONAL ENVIRONMENT OF THE EOLIAN LITHOFACIES OF THE OGALLALA AND BLACKWATER DRAW FORMATIONS

Interpretation of the depositional environments of the fine sand to coarse silt (lithofacies VII) of the Ogallala Formation and the very fine to fine sand (lithofacies 1) and sandy mud (lithofacies 2) of the Blackwater Draw Formation as eolian is based on both observed evidence, such as texture and pedogenic structures, and the absence of certain evidence, such as cross-stratification. These three lithofacies have comparable characteristics in that they lack primary sedimentary structures and contain similar pedogenic features including numerous calcic soil horizons. They differ only in grain size distribution and may be near end members of a more or less continuum of grain sizes that ranges from mostly sand and coarse silt to mostly fine silt and clay. I believe that the transport and deposition of sediments that make up each of these lithofacies were nearly identical, and, therefore, to avoid repetition in the following discussion of transportation and depositional environment, these lithofacies are grouped.

Thick sequences of Ogallala eolian fine sand to coarse silt overlie paleoupland surfaces and fluvial sequences that fill paleovalleys and in turn are overlain by Blackwater Draw eolian sediments. Ogallala eolian sediments are also locally interbedded with fluvial sediments in paleovalley fill. The transition from mostly fluvial sedimentation to mostly eolian sedimentation on the Southern High Plains resulted from diversion of the streams that drained east and southeast across Texas and New Mexico as late as the Pliocene. Regional subsidence resulting from dissolution of as much as 200 m (660 ft) of Permian bedded salt along the northern and western margins of the Southern High Plains during the late Tertiary led to the development of the Canadian and Pecos River valleys (Kelley, 1972; Gustavson and Finley, 1985; Gustavson, 1986). Age dating of vertebrate fossils and volcanic clasts in Ogallala fluvial sediments suggests that diversion of southeast-flowing streams that occupied the Slaton and Clovis paleovalleys occurred no earlier late Hemphillian time (4.5 to 6 Ma) and that diversion of the stream that occupied the Panhandle paleovalley occurred no later than Clarendonian time (9 to 11.5 Ma) (fig. 30).

Surface sediments and soils of the Blackwater Draw Formation fine from southwest to northeast (fig. 4), and Ogallala eolian sediments fine from west to east across the Southern High Plains (fig. 29), suggesting that the Pecos and Canadian River valleys and the western part of the Southern High Plains were sources of eolian sediments during the late Tertiary and Quaternary because these areas are currently sources for eolian sediments (McCauley and others, 1981). Prior to diversion of Ogallala streams to the Pecos and Canadian River drainages, the floodplains and eroded valley walls of the Slaton, Clovis, and Panhandle paleovalleys could also have served as sources of eolian sediments.

Preservation of rhizocretions and a complex network of fine root tubules, which are typically less than 1 mm (0.04 inch) in diameter, in conjunction with fossil floral and faunal evidence (Elias, 1942; Webb, 1977; Winkler, 1985, 1987, 1990b; Schultz, 1990; Thomasson, 1990), indicates that fine sand to coarse silt lithofacies of the Ogallala Formation accumulated on a grassland. In addition, the presence of root tubules, rhizocretions, krotovina, and fossil floral evidence, in conjunction with buried argillic and calcic horizons and common pedogenic $CaCO_3$ nodules, suggests that primary sedimentary structures, if they ever existed, were destroyed by soil development and bioturbation. The presence of similar buried soils having mature argillic horizons and common Stage I–III calcic horizons in the Blackwater Draw Formation also suggests slow sedimentation and pedogenesis on a stable grass-covered landscape. No buried A horizons were recognized in exposures or core of either the Ogallala or Blackwater Draw Formations. This suggests that the original A horizons were either eroded before the next influx of sediment, or more likely A horizons were slowly buried, and their organic content was oxidized or leached as additional sediment was added to the surface. In the few areas where buried argillic and calcic horizons are exposed continuously for distances of 0.5 km (0.3 mi) or more, there is no evidence for erosional truncation of soil horizons.

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 blanket deposits; they are highly calcareous; 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 Ø (0.063 mm) (very fine sand), are significantly coarser than loess, which has a median diameter of 5 to 6 Ø (0.031 to 0.016 mm) (medium to coarse silt) (Péwé, 1981; Miller and others, 1984). Even the finer grained proportion of the Blackwater Draw Formation contains 15 to 40 percent sand. Furthermore, the lack of typical eolian sedimentary features such as horizontally laminated or crossbedded well-sorted sand in the fine sand to coarse silt, very fine to fine sand, and sandy mud lithofacies precludes recognition of sediment sequences deposited as dunes or as thick sand sheets such as those described by Fryberger and others (1979) and Kocurek and Nielson (1986). Fine-grained eolian lithofacies of the Ogallala and Blackwater Draw Formations also contain no evidence of erosion surfaces. There are no lag concentrations of coarse material to mark former deflation surfaces or channel bottoms.

Most likely, eolian sediment transport and deposition during Ogallala and Blackwater Draw time were similar to historic sediment transport and deposition on the High Plains, which are primarily as thin sand sheets and as loess. Deposition of the fine-grained eolian lithofacies probably occurred under a variety of wind and climatic conditions. During each transport event, the clay-sized and finer silt-sized fraction probably moved more frequently, farther, at higher elevations, and under lower wind velocities than the coarser silt- and sand-sized fraction. This is consistent with available textural data, which shows that the coarse silt and sand lithofacies of the Ogallala Formation fine from west to east, and that surface sediments of the Blackwater Draw Formation, which include the very fine to fine sand and sandy mud lithofacies, fine from southwest to northeast. The finer textured eolian sediments were likely transported in much the same fashion as eolian dust is transported on the High Plains historically, including dust storms and dust devils (fig. 39). Coarse silt- and sand-sized sediment likely moved by saltation and was deposited primarily as thin lobate sand sheets. I have observed very thin lobate sand sheets that were both derived from and deposited in cultivated field during dust storms on the High Plains. These thin sand sheets did not fully cover short vegetation in the fields were they were deposited. Similar thin lobate sand sheets were reported by McCauley and others (1981). Silt- and clay-sized particles also make up significant percentages of the Ogallala and Blackwater Draw Formations. Most of these sediments, which range from 4 to >8Ø (0.063 to >0.004 mm) in size, can be transported from a few meters to a few tens to a few hundreds of kilometers by dust devils or dust storms in a single event (Péwé, 1981). Deposition of both thin sand sheets and atmospheric dust would have been aided by the baffling effects of grassland vegetation on the High Plains. Vegetation probably prevented development of stratification for most depositional events, or initial stratification was quickly destroyed by bioturbation and pedogenesis. Eolian sediments accumulated slowly in thin increments, and there was ample time for pedogenic and biologic processes to destroy any primary sedimentary structures. Winkler (1985) and Gustavson and Winkler (1988) also suggested that Ogallala eolian sediments may have been deposited as a mix of loess and sand sheets.

Accumulation of eolian sediments during Ogallala and Blackwater Draw time was probably slow and incremental, which allowed for the destruction of any primary sedimentary structures and for the development of fairly mature soils. 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 was more important closer to source areas, and deposition as loess was common in downwind areas. Pedogenesis and bioturbation quickly homogenized these sediments shortly after deposition.

Typical exposures of the coarse silt and sand lithofacies contain numerous buried calcic and argillic horizons. Some of these buried soil sequences have argillic and calcic horizons that rival those of the surface soil of the High Plains, which Holliday (1990) estimates is as much as 50,000 yr old. Most buried calcic soil horizons on the Southern High Plains are similar to the

Figure 39. The characteristic roll front of an approaching dust storm on the Southern High Plains near Lubbock, Texas. Turbulent winds carry fine dust particles high into the atmosphere, as coarser material is moved within a meter or two of the ground surface.

Stage I–III calcic soils described by Machette (1985). According to Bachman and Machette (1977) and Machette (1985), Stage I calcic soils that accumulated during the late Quaternary in eastern New Mexico may take as long as 10,000 to 15,000 yr to accumulate their characteristic $CaCO_3$ content, and Stage III calcic soils may take as long as 50,000 yr. The presence of numerous well-developed calcic and argillic horizons in these sediments indicates that accumulation of these eolian sediments was slow episodic process. The lack of evidence of erosion events as well as the presence of numerous well-developed buried soils indicates that deposition occurred on a stable landscape.

STRATIGRAPHY OF THE OGALLALA AND BLACKWATER DRAW FORMATIONS, WESTERN CARSON COUNTY

In western Carson County, geophysical and lithologic logs from City of Amarillo ground-water production wells and from ground-water production, ground-water monitoring, and stratigraphic test wells on the DOE's Pantex Plant provide additional data for interpreting lithofacies and depositional environments in sediments filling the Panhandle paleovalley (fig. 9). Certain of the wells also had lithologic logs on which textural categories such as gravel, sand and gravel, mud, or clay were identified.

Log data were used to construct a series of roughly north-south and east-west cross sections through a segment of the southwestern flank of the Panhandle paleovalley (pls. I–IV; fig. 40). However, construction and interpretation of cross sections were hindered by poor log quality for some wells, logs that begin at a depth below the Blackwater Draw Formation, logs that cannot be used to discriminate calcretes (sandy/silty limestone), and the lack of lithologic logs in some wells. In many cases it is not possible to identify the same variety of lithofacies that can be recognized in outcrop or core. Lithologic log data are sufficient to identify gross textural classes, i.e., gravel can be distinguished from sand and sand can be distinguished from clay. Coarse sediments such as gravel and sand and gravel can be inferred to have been deposited by high-energy streams, but fine textural classes such as silt and clay are difficult to interpret with

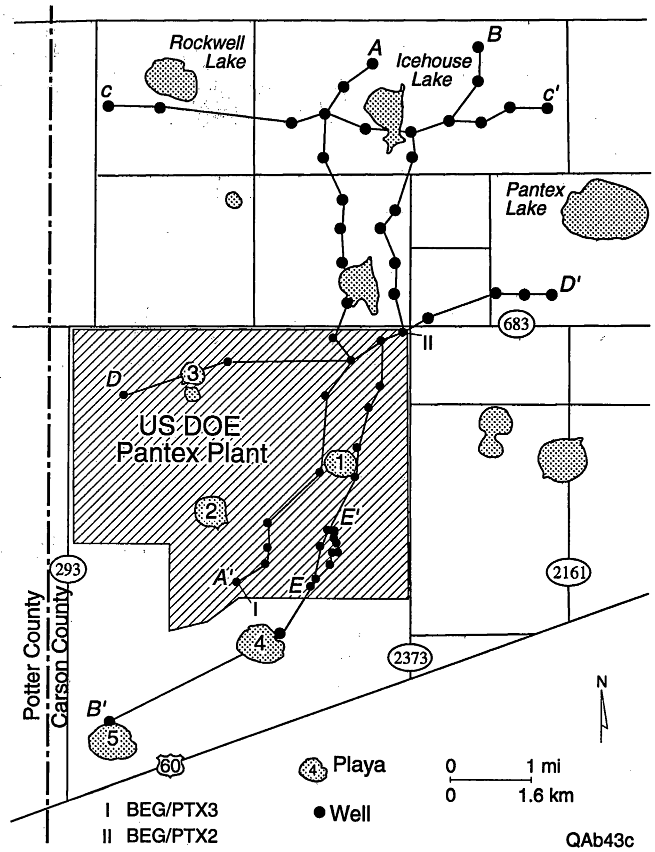


Figure 40. Location map for stratigraphic cross sections A–A′, B–B′, C–C′, D–D′, and E–E′ (pls. I–IV).

certainty without additional data. For example, are clays and muds overbank deposits or lacustrine deposits; is sand eolian sand or fluvial sand? Furthermore, most of the wells in question were drilled with compressed air. In these wells, the lag time required to carry pebble- to cobble-sized gravel from the depth that it is first encountered by the drill bit to the surface may be substantial and may account for driller's logs that show gravel at depths where geophysical logs show mud or clay interbeds.

Core was available from two wells drilled on the Pantex Plant (BEG-PTX No. 2 and BEG-PTX No. 3) (figs. 21 and 41). (See Gustavson (1994) for detailed descriptions of these core.) Cores from these wells were used to validate lithologic interpretations of geophysical logs. In the remainder of the wells used to construct these cross sections, geophysical logs were used to interpret stratigraphy and driller's logs were used primarily as supporting data. Furthermore, in attempting to interpret lithofacies from geophysical and lithologic logs some lithofacies identified in outcrop and core were combined, for example, gravel and sand and gravel.

Two fluvial gravel sequences (Ogallala lithofacies I and II) are preserved in core from BEG/PTX No. 2 in intervals from 106.7 to 122 m (350 to 400 ft) and from 70.1 to 75.6 m (230 to 248 ft) (fig. 21). Upward-fining sequences capped by overbank silty clays (Ogallala lithofacies V) are preserved at depths of 95.1 to 98.1 m (312 to 322 ft) and at 34.1 to 36.6 m (112 to 120 ft). The remaining Ogallala and Blackwater Draw sediments are eolian sediments. With the exceptions of upward-fining sequences capped by silty clay at depths of approximately 82.3 to 85.3 m (270 to 280 ft) and of a gravel unit at 72.8 to 73.5 m (239 to 241 ft), all of the sediments preserved in core from BEG/PTX No. 3 are eolian. The Caprock calcrete is preserved in both cores and marks the boundary between the Ogallala and Blackwater Draw Formations.

Perching Horizon(s) and Perched Aquifer

Both BEG/PTX No. 2 and BEG/PTX No. 3 penetrate the perched aquifer and perching horizons based on interpretations of geophysical logs recorded in these wells and core examinations. In BEG/PTX No. 2 the perched aquifer is associated with a series of upward-

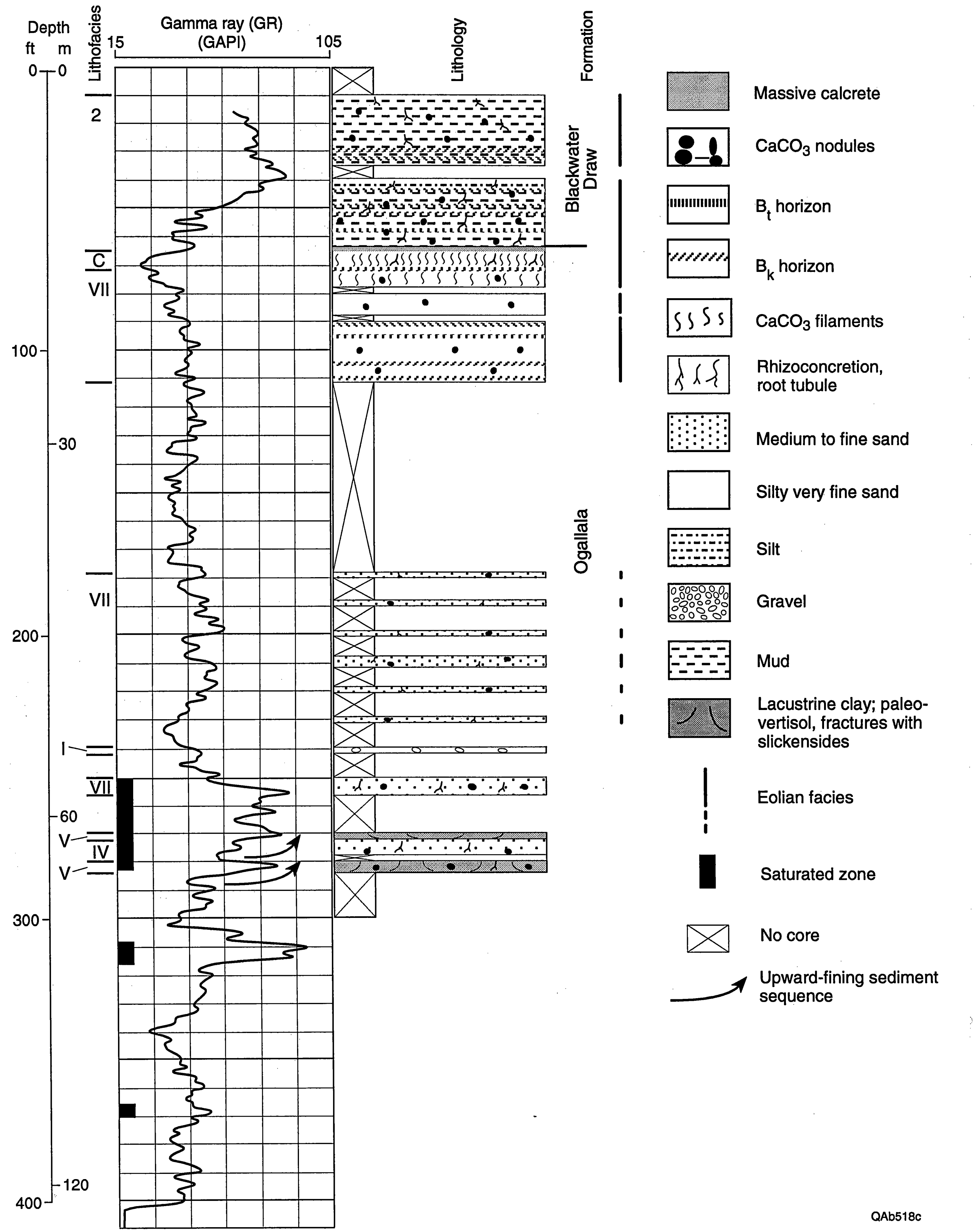


Figure 41. Stratigraphic section of Ogallala and Blackwater Draw Formations interpreted from core from BEG/PTX No. 3 well. Lithologies are plotted opposite a gamma-ray log trace. Zones saturated with ground water are shown as black bars (see fig. 40 for location). Roman numerals and Arabic numbers identify Ogallala and Blackwater Draw lithofacies (tables 1 and 2).

fining clastic sequences where sandy silt grades up to clay beds that are 1 to 1.3 m (3 to 4 ft) thick at a depth of 95.1 to 98.1 m (312 to 323 ft) (elevation above sea level is 983.9 to 980.5 m [3,228 to 3,217 ft]). In BEG/PTX No. 3 the perched aquifer is also associated with a series of upward-fining sequences where sandy silt grades up to clay beds that are 0.6 to 1 m (2 to 3 ft) thick at a depth of 82.3 m (270 ft). Similar units are recorded in the geophysical logs for BEG/PTX No. 3 at depths of 78.3 to 82.3 m (257 to 270 ft) (elevation above sea level 999.1 to 995.2 m [3,278 to 3,265 ft]), but core was not retrieved from this interval.

The stratigraphic sections through the Ogallala Formation beneath the City of Amarillo water well field and the Pantex Plant provide a regional view of the sediments that filled the Panhandle paleovalley (pls. I–IV; fig. 40). These sections lie along the southwest flank of the paleovalley and related subsidence basin. At least six cycles of sedimentation consisting of fluvial gravel and coarse sand sequences overlain by or possibly fining up to laminated fine sand and silt and laminated to massive clay (lithofacies V) are present. The muddy units thicken slightly and increase in number into the basin, suggesting regional subsidence as the basin was filling.

Most of the six fine-grained units can be correlated over an area of more than 102 km^2 (40 mi^2). As preserved in core from BEG/PTX No. 2 and No. 3, clay units of lithofacies V are typically only 0.6 to 2 m (2 to 7 ft) thick, and many of the other fine-grained units are no more than 5 m (15 ft) thick. These clays also typically contain vertic soil structures including curved fractures with slickensides, pedogenic $CaCO_3$ nodules and filaments, and root tubules. Soil development indicates many episodes of wetting and drying as well as periodic inputs of sediment. These sediments are only rarely laminated, and typically no primary sedimentary structures are preserved. Fine-grained units are commonly interbedded with coarse fluvial gravels or medium to coarse fluvial sand.

The lateral extent, interbedding with coarse fluvial sediments, and degree of soil developments suggest that these fine-grained units are overbank or floodplain deposits. The fine-grained units are interbedded with gravel and sand sequences that fill the basal 180 m (600 ft) of the Panhandle paleovalley (cross section B–B′) and are probably correlative to the Potter Member of the Ogallala Formation (formerly Potter Gravel) where it is exposed in the Canadian River valley (Wilson, 1988). These same strata are probably equivalent to the Clarendon beds exposed in Donley County along the eastern Caprock Escarpment.

STRATIGRAPHIC AND STRUCTURAL HETEROGENEITIES OF THE OGALLALA AND BLACKWATER DRAW FORMATIONS

A hierarchy of stratigraphic and structural heterogeneities characterizes both the Ogallala and Blackwater Draw Formations and probably influences hydrologic variables such as recharge rates, permeability, and transport of contaminants. Stratigraphic heterogeneities include grain size differences and the presence of argillic horizons and well-cemented zones. Structural heterogeneities are mostly pedogenic and include fractures that bound soil aggregates and open root tubules.

Stratigraphic Heterogeneities

The regional stratigraphic heterogeneity of the Ogallala and Blackwater Draw Formations is illustrated by the recognition of seven distinctive lithofacies in the Ogallala Formation and four in the Blackwater Draw Formation that are based largely on grain size differences (tables 1 and 2). Typically grain size also varies within a lithofacies (fig. 15). In addition, the presence of numerous argillic horizons, calcretes, and cemented zones further complicates the stratigraphy (fig. 24).

Plates I through IV illustrate the local stratigraphy of the Ogallala and Blackwater Draw Formations in western Carson County. These sections show the lateral extent of fine-grained clay-rich units (lithofacies V) and the variability of sand and gravel distribution. Although descriptions of cuttings for some of these wells show the distribution of gravel and sand, geophysical logs do not distinguish sand from gravel, nor do they distinguish coarse fluvial sand from fine eolian sand. For these reasons, only the fine-grained floodplain overbank or lacustrine deposits have been correlated from well to well. Nevertheless, these cross sections illustrate the vertical and lateral heterogeneity of sediment texture of the Ogallala Formation.

Several fine-grained units (lithofacies V) are present beneath the Pantex Plant, including the unit that comprises the lower aquitard portion of a perched aquifer (figs. 21 and 41). This unit is present beneath all of the eastern half of the Pantex Plant and extends south beyond the plant nearly to U.S. Highway 60 and north to beyond the City of Amarillo well field. Figures 21 and 41, which are composites of core data and gamma-ray log traces from stratigraphic test wells, provide detailed descriptions of the Ogallala and Blackwater Draw Formations on the Pantex Plant. The main perched aquifer in both wells consists of sequences of water-saturated laminated sand and silt that fine upward to clay. Two upward-fining sequences are present in BEG/PTX No. 2, and four upward-fining sequences are present in BEG/PTX No. 3. Vertical hydraulic conductivity for clays versus fine sands from these sequences differs by as much as three orders of magnitude (Mullican and others, 1994, 1995).

Figure 42 is a cross section designed to illustrate the heterogeneity in sediment texture within the upper coarse-grained part of the perched aquifer at the Pantex Plant, in an area where the perched aquifer is relatively thick. The perched aquifer lies above the Ogallala aquifer at a depth of approximately 75 to 90 m (250 to 300 ft) and consists of locally water saturated strata above a fine-grained aquitard (lithofacies V). Lithologic descriptions from eight closely spaced wells are plotted to show the distribution of lithologies within the main perched aquifer, the potentiometric surface of the main perched aquifer, and the contact between the coarse-grained and fine-grained fractions of the main perched aquifer. Saturated thickness in the coarse-grained section is as much as 10.7 m (35 ft)thick, and the coarse-grained section ranges in texture from gravel to sand. Saturated sections of the fine-grained part of the main perched aquifer are interbedded clay, silt, and sand. Furthermore, even in these closely spaced wells, correlation of predominantly sand and predominantly gravel lithofacies cannot be accomplished with certainty.

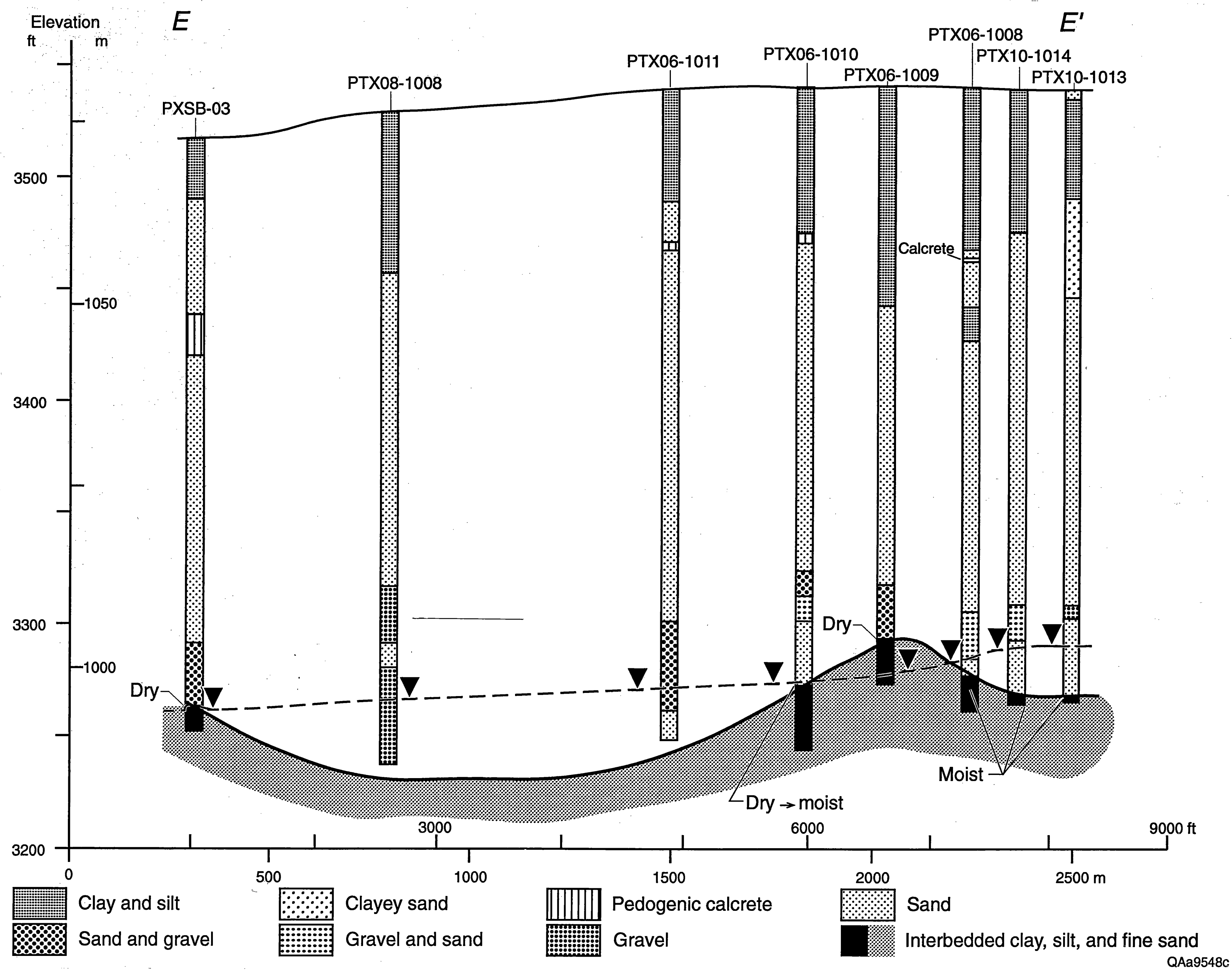


Figure 42. Cross section E–E′, showing the lithologic variability of the sediments containing the perched aquifer. See figure 40 for location.

The stratigraphic heterogeneities described here are illustrated in two dimensions but should be considered in three dimensions. For example, it is important to recognize that lenses of coarse permeable saturated sediment can be encapsulated by fine-grained sediments having low permeability. Sediments of both the Ogallala and perched aquifers can be compartmentalized in this fashion. Because of compartmentalization, some sections of a contaminated aquifer may remain clean because they are protected by low-permeability barriers. Conversely, some sections of compartmentalized contaminated aquifers may not be affected by remediation efforts because of low-permeability barriers.

Structural Heterogeneities

Pedogenic structures, which are commonly preserved in buried soils in Ogallala and Blackwater Draw sediments, include fractures that bound ped (soil aggregates) faces. Fractures are commonly lined with clay cutans, $CaCO_3$ filaments, and Mn oxide/hydroxide films. Large curved fractures with slickensides bound wedge-shaped clay soil aggregates in buried Vertisols and may nearly penetrate clay sequences.

Biologic structures such as root tubules are found throughout the Ogallala and Blackwater Draw Formations. Open tubules, which are typically ~1 mm (~0.04 inch) in diameter, range to as much as 6 mm (0.25 inch) in diameter and are preserved as discontinuous open conduits at depths as great as 114 m (374 ft) in the Ogallala Formation. Root tubules are commonly lined with Mn oxide/hydroxide films or with $CaCO_3$. Tubules penetrate all sediment types, including pedogenic $CaCO_3$ nodules and buried calcrete horizons. The deepest tubule occupied by a modern root was encountered at 14 m (46 ft). The root hair, which was approximately 0.2 mm (0.01 inch) in diameter, occupied a root tubule that was approximately 3 mm (0.1 inch) in diameter. This root hair in a large root tubule illustrates that roots are opportunistic and will invade existing root holes to potentially enhance the connectivity of tubules. Burrows are less commonly preserved than tubules but are typically 1 to 2 cm (0.4 to 0.8 inch) in diameter, commonly circular in cross section, and loosely filled with sediment.

Most of these pedogenic structural heterogeneities show evidence of past soil-water flow such as clay cutans, $CaCO_3$ filaments, and Mn oxide/hydroxide films, indicating that they are or were preferred flow paths. These features are most common in the Blackwater Draw Formation and in the eolian fine sand to coarse silt lithofacies (VII) of the upper part of the Ogallala Formation, and they probably help to explain the observed rapid rates of recharge to the Ogallala aquifer.

Stratigraphic and structural heterogeneities are common throughout the Ogallala and Blackwater Draw Formation and have the potential to affect not only rates of recharge to aquifers but also the distribution of contaminants as well as the removal of contaminants. Therefore, options for remediation of the contaminated perched aquifer and overlying vadose zone at the Pantex Plant must consider the heterogeneity and possible compartmentalization of the Ogallala and Blackwater Draw Formations.

PALEOCLIMATE

Paleoclimatic conditions for the High Plains region throughout the late Tertiary and Quaternary can be inferred from several types of stratigraphic, paleontologic, and pedologic information. Data from each of these disciplines indicate a long history of landscape stability under mostly semiarid to subhumid conditions (Gustavson and Holliday, 1991). Past paleoclimate interpretations have been based primarily on fossil floral and mammalian data. However, buried calcic soils in Ogallala and Blackwater Draw Formation strata and deposits of ephemeral streams of the Ogallala Formation also suggest a semiarid to subhumid climate.

Paleontologic Evidence

The Texas Panhandle contains the type localities of the faunas on which three of the Provincial Ages of the Tertiary are based, i.e., the Clarendonian, Hemphillian, and Blancan (Wood and others, 1941). The Clarendonian faunas primarily occur in fluvial sediments of the

Ogallala Formation that were deposited in the paleovalleys and are dominated by medium to large grazing, some mixed feeding, and a few browsing and predatory mammals (Schultz, 1990). Schultz (1990) characterized the area as parkland savanna with a mild, subhumid, somewhat subtropical climate. Because of the loss of most browsing and many grazing species and because of the development of calcic soils by late Hemphillian time, Schultz (1990) also suggested that the High Plains climate became increasing arid and that the savanna was replaced by grassland prairie or steppe. Winkler (1987) also recognized buried calcic soils in sediments, and on the basis of these soils and an extensive (Clarendonian Land Mammal Age) fossil vertebrate fauna, he suggested that a subhumid or semiarid climate prevailed and that grasslands had developed in the Southern High Plains by about 10–11 Ma. On the basis of fossil floral evidence, Thomasson (1990) also argued that grasslands prevailed in the Central High Plains by about 5–8 Ma and perhaps as early as 10–11 Ma in the Southern High Plains.

Pedogenic Evidence

Pedogenic evidence supports the fossil floral and faunal evidence for the development of grasslands and for a subhumid to semiarid climate on the High Plains as early as 10–11 Ma. $CaCO_3$ nodules and the Silver Falls Geosol (a pedogenic calcrete) in the Crosbyton Member of the lower Ogallala Formation indicate that calcic soils began to form in the Southern High Plains by 10–11 Ma (Winkler, 1985) and continued through the Quaternary (Holliday 1989, 1991). In the northern High Plains, in Oligocene sediments exposed in the Badlands National Park of South Dakota, Retallack (1983a, 1983b) recognized the development of grasslands based in part on evidence from paleosols. He argued that the presence of $CaCO_3$ nodules, calcareous horizons, and contiguous mats of fine root traces are evidence for dry soils and grasslands. Machette (1985) pointed out that modern calcic soils are forming primarily under grassland vegetation in warm dry climates with aridic (torric), ustic, or xeric soil moisture regimes (see Soil Survey Staff, 1975, for a full definition of these terms). These soil moisture conditions are typical of dry or arid to subhumid climates. Soils presently forming on upland surfaces of the Southern High

Plains, where the climate is continental dry subhumid to semiarid, typically carry aridic or ustic soil moisture regimes. As described in the foregoing sections, evidence of the development of calcic soils throughout much of Ogallala and Blackwater Draw time is present in the form of buried pedogenic calcretes and calcic soils.

Very fine root traces (typically <1 mm [<0.04 inch] in diameter) range from few to common in most eolian fine sand and (lithofacies VII) coarse silt sections and in several sandy fluvial sections of the Ogallala Formation and in the very fine to fine sand and sandy mud eolian lithofacies (1 and 2) of the Blackwater Draw Formation. Only rarely are coarse root tubules as much as 5 mm (0.2 inch) in diameter preserved. Collectively, the presence of buried calcic soils and very fine root traces throughout the Ogallala and Blackwater Draw suggests that the Ogallala and Blackwater Draw landscapes were occupied by grasslands under climatic conditions that were primarily continental semiarid to dry subhumid.

Stratigraphic Evidence

Paleoclimatic conditions can be interpreted or suggested from a variety of stratigraphic data, but all require supporting evidence. For example, thin silt-clay drapes with desiccation cracks that cap bar or pool sequences in some Ogallala fluvial sediments indicate that flow ceased and that these sediments were exposed to the air. Armored mud balls like those found in Ogallala fluvial deposits (fig. 18) are also typical of flashy or ephemeral streams where hard dry overbank muds are eroded, transported a short distance, and redeposited. Micritic carbonate nodules, as described under the fine sand and mud lithofacies (IV), apparently grew in place above thin poorly permeable clayey or muddy strata. Nodules grew by evaporation of shallow ground water in fluvial sediments, suggesting that the streams were ephemeral. All of these kinds of features are most likely to form in or beneath shallow flashy or ephemeral streams, which in turn are most likely found in dry climates.

SUMMARY AND CONCLUSIONS

During the early Tertiary, substantial parts of Permian through Cretaceous strata were stripped away in the Southern High Plains region, resulting in a series of broad paleovalleys and intervening paleouplands. During middle Miocene time or prior to about 11 Ma, a fundamental change occurred in the study area. Sediments carried by high-energy gravel-transporting streams began to fill paleovalleys. Locally as much as 180 m (600 ft) of fluvial sand and gravel accumulated in the Panhandle paleovalley in part as a result of subsidence induced by dissolution of underlying Permain salts. More typically, fluvial sediments fill the lower 10 to 40 m (30 to 120 ft) of paleovalleys. Fluvial deposition was confined to the valleys and did not overtop divide areas to form coalescing alluvial fans. Silt-clay drapes with desiccation cracks on bar and channel surfaces and thin ground-water calcretes, which developed above silt-clay drapes and channel filling muds, indicate that streams were ephemeral and the climate mostly semiarid to subhumid.

Subsidence troughs, which resulted from dissolution of underlying Permian salt along the present axes of the Pecos and Canadian Rivers, diverted late Miocene streams to the northeast along the present Canadian River drainage or to the south to the present Pecos River drainage. The Clovis and Slaton paleovalleys are partly filled with fluvial sediments that contain Clarendonian and Hemphillian Land Mammal Age faunas and basalt clasts from either the Raton or Ocate volcanic fields and thus potentially range in age from approximately 11 to 4.5 Ma. The absence of younger fossil material, however, suggests that diversion of these streams may have occurred prior to about 4.5 Ma.

Ogallala eolian coarse silt and very fine sand were deposited over most of the fluvial sections as well as over upland sections between paleovalleys. Sections of these sediments are as much as 33 m (108 ft) thick and typically contain numerous buried soils, common rhizocretions, root traces, or open root tubules, and no primary sedimentary structures. Buried calcic soils in these sediments indicate that they formed in a grassland environment under mostly semiarid to subhumid climatic conditions. Evidence of abundant small roots or root mats and the lack of evidence of roots from large plants also suggest the presence of grasslands. The lack of primary sedimentary structures or of evidence of erosion suggests that sedimentation occurred on a stable grass-covered landscape. In large part, primary sedimentary structures may never have formed because of the presence of grass, and those structures that did form were quickly destroyed by bioturbation. Like their former counterparts, which were responsible for Ogallala fluvial sedimentation, the early Pecos and Canadian Rivers also were probably high-energy streams that had wide fluctuations in water and sediment discharge. The floodplains and valley walls of these early streams were the primary sources of eolian sediment of the Ogallala Formation. Sediment transport was likely episodic and in the form of thin sand sheets and atmospheric dust, as is most recent sediment transport on the High Plains and Pecos Plains. Soil formation was probably a continuous process, but eolian sedimentation rates varied such that a series of buried soils developed. During relatively dryer and hotter periods, diminished vegetation in the source areas and stronger winds meant that relatively larger amounts of sediment were available for eolian erosion and transport. Under these conditions, eolian sediment accumulated on the High Plains. Conversely, during relatively wetter or cooler periods, increased vegetation in the source areas and less windy conditions meant that less sediment was transported. Landscape stability as a result of suppressed eolian erosion and transport in the Pecos and Canadian River valleys and in the westernmost parts of the High Plains allowed development of calcic soils.

The Caprock calcrete is a thick (stage IV to stage VI) calcic soil that ranges from late Pliocene to Quaternary and marks the top of the Ogallala Formation throughout most of the High Plains of Texas and New Mexico. This calcrete represents at least several hundred thousand years of landscape stability during which the eolian sedimentation was minimal throughout much of the High Plains. Most likely the cessation of eolian sedimentation resulted from stabilization of sediment source areas in the Canadian and Pecos River valleys and the western High Plains by vegetation. Landscape stability in the source areas and in turn the Caprock calcrete likely resulted from increased available moisture at the end of the Tertiary owing to either increased precipitation or cooler temperatures, or both.

Thicker sections of the Caprock calcrete that are brecciated and pisolitic occur regionally in the western part of the High Plains where the Quaternary Blackwater Draw Formation is thin or missing and where the Caprock calcrete is developed directly on Cretaceous and Jurassic inliers on the High Plains. These are areas where eolian sediments were either not preserved or were only incompletely preserved, but where soil carbonate accumulated. In these areas, eolian sediments were periodically eroded, exposing the underlying pedogenic calcrete. The calcrete was brecciated upon exposure or near exposure, only to be recemented by soil carbonate following the next influx of eolian sediment. Locally thick sections of brecciated and pisolitic Caprock contain soil carbonate that is coeval with both Ogallala and Blackwater Draw Formation soil carbonate and thus may range in age from Miocene (?) to Quaternary.

The Quaternary Blackwater Draw Formation consists of as much as 23 m (76 ft) of eolian sand and silt with numerous buried calcic soils, common rhizocretions, root traces, and open root tubules, and no primary sedimentary structures. The Blackwater Draw Formation fines and thickens to the east and northeast away from its probable source areas, the Pecos and Canadian River valleys. Similar to the Ogallala Formation, the widespread presence of calcic soils, fine root traces, rhizocretions, and open root tubules indicates that a grassland environment prevailed as Blackwater Draw sediments accumulated. Also similar to the Ogallala Formation are the stacked sequences of as many as 11 buried soils. Cyclic soil development likely resulted from climatic cycles where sediments accumulated during relatively dry, warm, and windy periods as a result of erosion in source areas in the Pecos River and Canadian River valleys, and calcic soils developed during relatively moist, cool, and less windy periods when sediment source areas were stabilized by vegetation.

Paleoclimatic conditions during the late Tertiary and Quaternary can be generally inferred from the pedogenic and stratigraphic evidence recognized in the Blackwater Draw and Ogallala Formations. Most important is the development of calcic soils. These soils, which are preserved in the fine-grained eolian sediments of both of these formations, typically develop under semiarid to dry subhumid conditions beneath grasslands and are the surface soils of the Southern and Central High Plains of Texas and eastern New Mexico. They form under aridic soil moisture regimes where potential evapotranspiration substantially exceeds precipitation and soluble solutes carried in precipitation such as Cl^- and Ca^{++} accumulate in the soil.

Ogallala and Blackwater Draw sediments consist of lithofacies, which are characterized by sediment sizes that range from gravels to clays and which have hydraulic properties such as conductivity that vary by several orders of magnitude. Furthermore, interbedded Ogallala fluvial gravels, sands, and clays illustrate the depositional heterogeneity of the Ogallala and the potential for vertical and lateral compartmentalization of the Ogallala and overlying perched aquifers. Pathways for preferential ground-water flow, such as soil fractures and root traces, are also common heterogeneities in Ogallala and Backwater Draw sediments. If cleanup of the contaminated perched aquifer beneath the DOE's Pantex Plant is to be successful, then remediation options that are designed to accommodate the heterogeneity of the Ogallala and Blackwater Draw sediments should be used.

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