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DEPOSITIONAL ARCHITECTURE OF THE QUATERNARY BLACKWATER DRAW AND TERTIARY OGALLALA FORMATIONS, TEXAS PANHANDLE AND EASTERN NEW MEXICO

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ABSTRACT

Deposition of basal fluvial sediments of the Ogallala Formation was controlled by topography on the middle Tertiary erosional surface. Paleovalley-fill sequences consist of gravelly and sandy-braided stream deposits overlain by eolian sediments deposited as sand sheets and loess. The change from fluvial to eolian sedimentation may have resulted from diversion of Ogallala streams to form the Pecos and Canadian Rivers. Paleostream divides on the middle Tertiary erosional surface are overlain primarily by eolian sediments. Source areas for eolian sediments may initially have been Ogallala braided streams, and later the floodplains of the newly formed Pecos and Canadian Rivers.

Ground-water calcretes are extensively developed in the fluvial portion of Ogallala sediments. Pedogenic calcretes, consisting of nodular, laminated, brecciated and recemented, or pisolitic calcium carbonate occur primarily in the eolian portions of the Ogallala Formation.

The geomorphic processes of eolian deposition, deflation, and pedogenesis have operated on the Southern High Plains from Ogallala time to the present, as evidenced by the distribution of coarse eolian deposits, which make up both the upper part of the Ogallala Formation and all of the Blackwater Draw Formation.

The distinctive reddish sediments of the Blackwater Draw Formation contain as many as six well-developed buried soils that resemble each other, as well as the surface soils, in lithology and morphology. Although the Blackwater Draw Formation was originally assigned an Illinoian age, pedologic similarities of soils beneath ash deposits dated as 1.4 m. y. (Guaje ash) and 0.6 m. y. (Lava Creek "B") in Crosby and Swisher Counties, respectively, to paleosols at a thick section in Lubbock County, suggest that pedogenic processes have operated throughout the Quaternary. It is hypothesized that, at least from near the end of the Pleistocene, eolian sediments aggraded contemporaneously with lacustrine facies in a mosaic of laterally restricted lenses of eolian and playa sediments. Pulses of deposition were separated by relatively long periods of either landscape stability, during which soil development occurred, or deflation,

which stripped surface horizons from newly formed soils. Modern processes appear to be analagous to those that operated much earlier, suggesting that on the Southern High Plains, the present is indeed the key to the past.

INTRODUCTION

In the Texas Panhandle and eastern New Mexico the Tertiary Ogallala and the Quaternary Blackwater Draw Formations underlie the High Plains. Small outcrops of the Ogallala Formation are also present within the adjacent Pecos and Canadian River basins, and the Rolling Plains (fig. 1). The Ogallala Formation contains the High Plains aquifer, the primary source of irrigation water for food and fiber crops in this region. The overlying Blackwater Draw Formation is the conduit through which all recharge to the High Plains aquifer must pass.

The Palo Duro structural basin of the Texas Panhandle and eastern New Mexico contains bedded Permian salts of sufficient thickness and depth to be considered as a potential site for the long-term isolation of high-level nuclear waste (Johnson, 1976). Two locations were recognized within the region; one in central Swisher County and one in north-central Deaf Smith County (fig. 1) (U.S. Department of Energy, 1984a, b). Both locations are within the Southern High Plains and are underlain by the Ogallala and Blackwater Draw Formations.

The Ogallala and Blackwater Draw Formations are being characterized as part of a program designed to determine the potential, if any, for contamination of the High Plains aquifer from releases of nuclear waste either at the surface or from the repository at depth. This report is a preliminary discussion of certain aspects of the geology of these two formations. Depositional environments and processes of deposition are described for both formations. The age and stratigraphic relationship of the Blackwater Draw Formation to other Quaternary Formations on the Southern High Plains are also described.

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Geologic Setting

Structural Development

In the Late Paleozoic, but perhaps as early as Late Cambrian, rocks of the Wichita igneous province and the Red River mobile terrane were faulted and uplifted to form the Wichita Mountains - Amarillo Uplift trend and the Matador Arch (Birsa, 1977). These features are the major positive tectonic elements bounding the Palo Duro Basin.

Movement along the Amarillo Uplift, Matador Arch, and Cimmaron Uplift controlled sedimentation and facies distribution during the Pennsylvanian and apparently continued into the Permian (Dutton and others, 1979). Recent work by Budnik (1983) suggests that tectonic movements continued throughout the Texas Panhandle as late as Tertiary and possibly as late as Quaternary time.

Sedimentation

During the early Paleozoic, periods of erosion alternated with episodes of shallow marine-shelf deposition in the Texas Panhandle. During Mississippian time, marine-shelf carbonates were deposited across the area. Major tectonic activity began in the Late Mississippian and continued through the Pennsylvanian to form the bounding elements of the Anadarko, Dalhart, and Palo Duro Basins. Deposition of terrigenous clastic sediments, informally called granite wash, was prevalent during the Pennsylvanian and Early Permian. Granite wash was derived from, and was deposited near, the principal uplifts (Handford and Dutton, 1980). Sedimentation during the Late Pennsylvanian was dominated by shelf carbonates. Deeper parts of the basin were filled by fine-grained clastic sediments. Salt, anhydrite, dolomite, limestone, and red beds compose middle and upper Permian strata in the Anadarko, Dalhart, and Palo Duro Basins (Presley, 1979a, b, 1980a, b). These rock types were probably deposited in subtidal to supratidal environments on a very extensive, low-relief marine shelf.

The Triassic Dockum Group consists of fluvial, deltaic, and lacustrine sandstones and mudstones that accumulated in a large fluvial-lacustrine basin (McGowen and others, 1979). Dockum Group strata are overlain unconformably by the Upper Jurassic Exeter Sandstone in the northwestern part of the Texas Panhandle and adjacent parts of New

Mexico. Throughout the southern part of the study area Dockum Group sediments are overlain unconformably by Lower Cretaceous Kiamichi Formation (Fredericksburg Group), Dakota Group sandstones and conglomerates, and Kiowa Shale. After a period of extensive erosion, which produced the middle Tertiary erosional surface, the Miocene-Pliocene fluvial and eolian Ogallala Formation was deposited in northwestern Texas, western Okalahoma, and eastern New Mexico. The Ogallala Formation is overlain locally by Late Pliocene lacustrine sediments of the Blanco and Rita Blanca Formations, and by the Quaternary eolian Blackwater Draw Formation and the lacustrine Tule, Double Lakes, and Tahoka Formations.

Physiography

The Texas Panhandle lies within the Great Plains physiographic province (Fenneman, 1931, 1938). The surface of the High Plains, which is underlain primarily by the Blackwater Draw Formation, is broken by the valley of the Canadian River, also known as the Canadian Breaks (fig. 1). South of the Canadian Breaks is the Southern High Plains or Llano Estacado, and the Central High Plains lie north of the Canadian Breaks. The Southern High Plains are truncated to the east and west at the Caprock Escarpment, a series of erosional scarps where relief locally exceeds 500 m (1500 ft). The Caprock Escarpment is supported by the massive Caprock caliche that marks the top of the Ogallala Formation, and by well-indurated sandstones that are in the upper part of the Triassic Dockum and Permian Whitehorse Groups.

Regional Climate

The climate of the Texas Panhandle and eastern New Mexico has been variously described as ranging from subhumid or Modified Marine (Rolling Plains) to semiarid continental or Continental Steppe (High Plains)(Orton, 1964; U. S. Department of Commerce, 1978a, b; Larkin and Bomar, 1983).

Precipitation decreases from east to west across the study area from 58 cm (23 in) to 36 cm (14 in) (Haragan, 1976). Annual evaporation increases from east to west across the study area from 137 cm (54 in) to 163 cm (64 in)(Kier and others, 1977).

The mean annual temperature is 15.4° C (59.7° F) at Lubbock, Texas and 14.1° C (57.4° F) at Amarillo, Texas (U.S. Department of Commerce, 1978a, b).

Westerly flow generally dominates the movement of air across the western United States, including the southern Great Plains. Air masses that originate over the Pacific are generally dry by the time they reach the Great Plains because of the topographic effects of western mountain ranges and high plateaus (Bryson and Hare, 1974). An exception to the pattern of westerly zonal flow occurs over the southern Plains where strong components of southerly flow are likely. The influx of warm, moist air from the Gulf of Mexico is in large part responsible for the summer precipitation of the southern Great Plains. Exceptions to the generalized pattern of air movement in the southern Great Plains result from local topographic effects and the passage of frontal systems and the remnants of tropical storms.

The calcic soils that are developing in the Texas Panhandle and eastern New Mexico are in part a product of the climatic conditions of the area (Jenny, 1941; Machette, 1985). Similarly the calcic soils and calcretes of the Tertiary Ogallala and Quaternary Blackwater Draw Formations that are described below were probably the products of climatic conditions similar to the modern regional climate.

MIDDLE TERTIARY EROSIONAL SURFACE

Permian, Triassic, and Cretaceous strata underlie the middle Tertiary erosional surface beneath the High Plains. Figure 2, a structure-contour map of the base of the 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. However, small parts of the Triassic Dockum Group are locally included in the High Plains aquifer.

Paleotopographic elements are clearly recognizable in many areas, and the presence of a system of major paleovalleys is indicated by aligned groups of V-shaped contour lines that point upslope (fig. 2). These relationships are clear on the part of the erosional surface that underlies the Southern High Plains; however, much of the area that underlies the Central High Plains has been affected by subsidence resulting from salt dissolution and the paleotopography is no longer recognizable (Gustavson and Finley,

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985). In the Southern High Plains paleostream segments appear to have flowed to the southeast over parts of the paleosurface. In northern Hale and southern Castro Counties, a major paleovalley contained streams that flowed west to east. This paleovalley extends northwestward into southeastern Quay County, New Mexico. In southeastern Deaf Smith and southwestern Randall Counties, Texas, a paleostream divide lies 150 m (500 ft) above the paleostream valley in northern Hale County (fig. 2). Other divides occur in southeastern Hale and central Floyd Counties.

OGALLALA FORMATION

The Ogallala Formation covers much of the Great Plains region, extending over 1,200 km (800 mi) from South Dakota to Texas, and east to west as much as 500 km (300 mi). In the study area the Ogallala Formation covers most of the Texas Panhandle and parts of eastern New Mexico (fig. 1).

The Ogallala was deposited unconformably on Permian, Triassic, and Cretaceous strata. Thickness of the Ogallala reflects the paleotopography on the underlying middle Tertiary erosional surface and varies from less than 30 m (100 ft) to greater than 150 m (500 ft) beneath most of the Southern High Plains (fig. 3). Locally, over subsidence basins induced by salt dissolution (Gustavson and others, 1980; Gustavson and Finley, 1985), thicknesses may exceed 235 m (800 ft). As a generalization, however, areas of thick accumulations occur in paleovalleys and thin accumulations overlie paleotopographic divides.

Previously Published Work

The Ogallala Formation was first described by Darton (1899) in Nebraska. Baker (1915) recognized that the Late Cenozoic deposits of the Texas Panhandle resulted from uplift and erosion of the Rocky Mountains to the west and that these deposits were primarily fluvial and to a lesser extent eolian. He named the "cap-rock" caliche that marks the top of the Cenozoic section (Ogallala Formation) and recognized that the Caprock caliche "is clearly a secondary deposit, formed after the deposition of the sediments which it binds together, by the precipitation of ... calcium carbonate dissolved

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in ground water." He thought that caliches were the product of carbonate deposition by evaporation of shallow ground waters drawn near to the surface by capillary action. Although his interpretation of the process by which caliche forms is now recognized to be incorrect, he did observe 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 caliche 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 caliche. 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 to 12 ft/mi).

Bretz and Horberg (1949a, b) recognized and described the formation of caliche as a pedogenic process. Based on petrographic analyses of pisolitic parts of the Caprock caliche, Swineford and others (1958) established that it developed by predominately soil-forming processes. The work of Smith (1940), Bretz and Horberg (1949a, b), Brown (1957) and Swineford and others (1958) essentially ended the controversy over the origin of the Caprock caliche. Although many authors have discussed the various attributes of the Caprock caliche, pedogenic and ground water calcretes and silcretes within the Ogallala, and especially at the base of the formation, have either been ignored or mentioned only in passing.

Most authors, including Johnson (1901), Sellards and others (1932), Smith (1940), Bretz and Horberg (1949a, b), Frye and Leonard (1964), Frye (1970), Seni (1980), Hawley (1984), Reeves (1984), and Winkler (1985) have thought that the Ogallala Formation in Texas and New Mexico is composed primarily of fluvial sediments, and that the fluvial part originated as a series of deposits from ephemeral streams, or as a great alluvial plain or bahada. All these authors recognized that an erosional surface with deep, wide valleys was invaded and buried during the Late Tertiary, and that the present High Plains surface is a reflection of the depositional slope of the Ogallala. Although many of these authors recognized that eolian sediments are present in the Ogallala, in general they have not recognized the importance of eolian sedimentation. Seni (1980), for example, thought that the Ogallala Formation was constructed entirely by fluvial processes. On the other hand, Evans and Meade (1945) suggested that locally the upper part of the Ogallala was eolian, Reeves (1972) thought that much of the Ogallala south of Lubbock, Texas was eolian, and Winkler (1985) interpreted that fine sands and silt facies in the Ogallala southeast of Lubbock were eolian sediments deposited from suspension and as sand sheets.

Depositional Systems

Recent studies in the Texas Panhandle have emphasized that the depositional environment of the Ogallala Formation was similar to that of both modern and ancient wet alluvial fans. Seni (1980) compared the Ogallala to the Kosi River fan in Nepal and India (Gole and Chitale, 1966). The distal portion of the Kosi fan is fine grained, consisting mostly of sand and fine sand. Seni (1980) thought the texture of the Kosi fan and its large size (15,400 km^2 to 20,500 km^2 [6,000 mi^2 to 8,000 mi^2]) made it a suitable modern analog for the Ogallala Formation. Reeves (1984) suggested several ancient analogs including the sandstone delta facies of the Van Horn Formation, Texas (McGowen and Groat, 1971), the East Rand fan of the Witwatersrand basin, Africa (Pretorius, 1974), and the Salt Wash Member of the Morrison Formation (Mullens and Freeman, 1957), as well as an additional modern analog, the Riverine Plain, Australia (Schumm, 1968). Seni's (1980) study was based entirely on analyses of well logs. Field studies were not incorporated into his analyses of depositional environments. Reeves' (1984) study seems to be mostly a review and assessment of existing literature.

Winkler (1985), following extensive field studies in the vicinity of Crosby County, Texas, described the depositional architecture and biostratigraphy of the Ogallala Formation. He differed from the interpretations of Seni (1980) and Reeves (1984) and suggested that the fluvial facies that he described were similar to those produced by recent flooding on Bijou Creek, Colorado, an ephemeral high-energy stream (McKee and others, 1967). Furthermore, Winkler (1985) suggested that the fine-grained eolian part of the Ogallala resembled eolian sand sheets (Fryberger and others, 1979; Kocurek and Neilson, in press). He emphasized that the processes of channel cutting and infilling with coarse alluvium were important in the vicinity of the Slaton Channel.

Field studies of the Ogallala Formation completed during FY-1985 include descriptions of sections deposited as basal Ogallala channel fills and sections deposited over paleotopographic divides or upland areas on the middle Tertiary erosional surface. Three fluvial sections and two upland sections are described below to compare and contrast depositional environments during the late Tertiary.

Fluvial sections near Ragland and Bellview, New Mexico occur along the axis and northeast flank, respectively, of a broad pre-Ogallala paleovalley that trends southeast across the middle Tertiary erosional surface. The two upland sections, at Buffalo Lake and east of Silverton, Texas, occur higher on the northeast flank of the paleovalley and on or near the paleodrainage divide. The Palo Duro Canyon State Park section occurs in a second paleovalley northeast of the divide.

Ragland, New Mexico Section

The Ragland, New Mexico section is exposed along New Mexico Highway 18, approximately 37 km (23 mi) south of Tucumcari, New Mexico in a north-facing segment of the Caprock Escarpment (fig. 2). This section exposes approximately 25 m (85 ft) of the Ogallala Formation (fig. 4). The Ogallala was deposited unconformably on Triassic Dockum Group strata. Deformation of Dockum strata has resulted in clastic dikes that are filled with carbonate-cemented fragments of Dockum Group sediments.

Depositional Facies

The lower 1.5 m (5 ft) of the Ogallala Formation exposed in the Ragland section is a clast-supported siliceous gravel composed primarily of well-rounded volcanic quartzite and metamorphic clasts. Intermediate axis lengths of 7 cm (3 in) are common. Rare angular clasts of Dockum sediment up to 20 cm (8 in) long are present, but because of their angularity and relative softness have not been transported any significant distance.

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These basal gravels are horizontally bedded, are imbricated, and include at least three fining-upward sequences. Calcium carbonate is a pervasive cement occupying most available pore space.

Overlying the basal conglomerate is 7 m (23 ft) of interbedded clast-supported carbonate-cemented siliceous conglomerates and pebbly sandstones. Conglomerates are horizontally bedded and clasts are well rounded and imbricated with fining-upward sequences ranging up to 0.8 m (2.3 ft) thick. Sandstones are composed of pinkish-gray, pebbly, coarse sand preserved as low-angle tangential cross sets. This section is capped by 0.75 m (2 ft) of pinkish-gray, cross-bedded, vuggy weathering, carbonate-cemented sandstone. The apparent paleoflow direction as determined from cross set orientations was to the southeast.

Overlying approximately 2.4 m (7.9 ft) of section obscured by slope wash is 4 m (13 ft) of interbedded pebbly sand and gravel. No primary sedimentary structures are recognizable. Original sediment appears to have been medium sand with dispersed pebbles interbedded with medium gravel (intermediate axis up to 5 cm [2 in]). At least two and possibly three zones of pedogenic calcrete (caliche) formed within these sediments. The degree of calcrete development, or carbonate cementation, increases upward. Initially, vertical zones of dispersed carbonate cement result in a crude vertical columnar structure in coarse sands, with carbonate becoming nodular and then massive near the top of this section. Individual carbonate nodules range up to approximately 2 cm (0.75 in) in diameter. The original clastic ground mass is generally excluded from these nodules. Nodules increase in number and size upward. Massive carbonate near the top of this section is in part brecciated, recemented, and pisolitic, and contains chalcedony in veins. It is these features that distinguish pedogenic calcretes (Bachman and Machette, 1977).

Massive carbonate occurs in crude mound-like structures with relatively sharp upper boundaries. Clastics that are part of the original sediments are generally excluded from the massive carbonate, although minor sand and gravel clasts floating in the carbonate mass are present. The spaces between the mounds are filled with structureless, poorly cemented sand or gravel. The massive carbonate horizons represent at least one, and probably two, Stage IV or V pedogenic calcretes (Bachman and Machette, 1977). The spaces between the mounds probably resulted from carbonate solution to form pit-like features in the calcrete. Later fluvial sedimentation filled the pits, and the process of pedogenesis and carbonate solution was repeated to form the second calcrete.

The style of sedimentation changes radically approximately 16.5 m (55 ft) above the channel floor. The clastic material that comprises the upper 5 m (16 ft) is primarily pinkish-gray, fine to very fine sand. Many sand grains are rounded and frosted, and no primary sedimentary structures are preserved. Carbonate content increases upward. Carbonate cement deposited preferentially along vertical infiltration pathways has produced a crude vertical or columnar structure. Carbonate nodules increase in size and number upward, leading to a massive 2.2-m- (7.3-ft-) thick pedogenic calcrete, the Caprock caliche, at the top of the section. This massive pinkish-gray calcrete is complexly brecciated and recemented at the surface. The upper part is deeply weathered, and the preserved portion is probably equivalent to a Stage V pedogenic calcrete of Bachman and Machette (1977).

Facies Interpretation

The fluvial sands and gravels exposed in the Ragland section were deposited in a major channel system that contained streams that flowed southeasterly across the middle Tertiary landscape (fig. 3). The fluvial section fines upward from being gravel-dominant near the base of the channel to being sand-dominant near the top. Fining-upward sequences of horizontally bedded gravels overlain by cross-bedded sands suggest deposition as superimposed bars by high-energy, high-sediment load, braided, and possibly ephemeral, streams. The change from gravel-dominant to sand-dominant facies suggests that at least two modern analogs may apply. These are the Scott River type, coarse gravel, braided-stream model for the gravel sequences (Boothroyd and Ashley, 1975) and the Donjek River type, sand and gravel, braided-stream model for the entire section (Williams and Rust, 1969; Rust, 1972).

The upper 6 m (20 ft) of the Ragland section consists of fine to very fine sand with rare floating granules or small pebbles. Certain sand grains are frosted. The lack of preserved sedimentary structures and the pervasive development of calcic soils and pedogenic calcrete makes it difficult to interpret the process by which this part of the section was deposited. However, the presence of frosted grains and the grain size of these sediments suggests deposition by eolian processes.

These fine to very fine sands are probably too coarse to have been deposited entirely from suspension as loess. However, the presence of a significant proportion of silt- and clay- sized material makes it likely that eolian dust contributed to these sediments. The coarser fraction, especially fine and very fine sand, either moved primarily as material in saltation or was temporarily suspended within a meter or two of the surface. Modern and Wisconsinan analogs would be loess or dust deposits (Miller and others, 1984; Pewe, 1981) and the deposition of sand sheets as described by Fryberger and others (1979) and Kocurek and Neilson (in press). Winkler (1985) described similar silty, fine sand facies in his studies of the Ogallala southeast of Lubbock, Texas and also attributed their deposition to processes important in the deposition of loess and sand sheet.

Cementation

Carbonate cementation in the lower fluvial part of the section increases downward, and is irregularly expressed as erosionally resistant lenses in sandy facies. Carbonate cement fills void spaces between gravel clasts near the contact with the underlying Dockum and partly coats clasts higher in the section. There is no evidence of clast displacement by carbonate cement and none of the structures characteristic of pedogenic calcretes were recognized. For these reasons it seems probable that the calcretes in the lower part of the fluvial section were deposited from ground water.

Age

The Ragland section contains neither fossil material nor tephra, and as a consequence the age of these deposits has not been determined with confidence. Numerous large, rounded, amygdaloidal basalt cobbles occur in the basal gravels. Basic volcanic flows northeast of the Ragland section in the Ocate and Raton volcanic fields have been dated as 8.3 m. y. or younger (O'Neil and Mehnert, 1980; Stormer, 1972). date These flows are the nearest extrusive basic volcanics northwest of the described section. One or the other of these fields is thought to be the source of the basic volcanic clasts in the Ragland section, and thus the basal portion of the Ogallala in this section is no older than 8.3 m. y.

Bellview Section

The Bellview section is located at the Caprock Escarpment approximately 13 km (8 mi) north of Bellview, New Mexico on New Mexico Highway 93 (fig. 2). Twenty-nine meters (96 ft) of Ogallala Formation strata are exposed in the Caprock Escarpment (fig.5). The Ogallala Formation at the Bellview section rests unconformably on weathered and faulted Triassic Dockum Group strata. Clastic dikes in the Dockum are filled with basal Ogallala sediments.

Depositional Facies

Overlying the unconformity is a one-meter-thick sequence consisting of angular to subangular gravel overlain by a light-brown (5YR 5/6), sandy clay loam. Color and lower soil texture suggest that this is a buried B soil horizon. No primary sedimentary structures are preserved in this unit. Most of the gravel clasts contained in this unit are angular to subangular fragments of ferricrete or silicified valves of the Cretaceous pelecypod Gryphaea.

Unconformably above the paleosol are 14 m (46 ft) of flat-bedded and cross-bedded Uncf pebbly sands. Two channel cutbanks are preserved in this sequence. Blocks of collapsed bank material, lithoclasts, and armored mudballs occur in the channel fills. A third channel is filled by 0.75 m (2.5 ft) of laminated carbonate-cemented mudstone at a depth of approximately 15 m (49 ft). Numerous sequences consist of horizontally bedded pebble gravel or pebbly sand at the base that fine upward to horizontally bedded or cross-bedded sand. Usually, these sequences are capped by thin silt/clay drapes. Curled-up edges along cracks through the drapes indicate that desiccation occurred after deposition. Clay drapes are commonly overlain by amorphous, nodular, calcium-carbonate beds that range up to 10 cm (4 in) thick. No clastic sedimentary material occurs in these nodules.

Carbonate cement occurs preferentially in or above finer grained sediments, but is not pervasive. In the upper 1.5 m (5 ft) of the fluvial section pedogenic carbonate nodules occur dispersed in fluvial sands.

The upper 14.75 m (49 ft) of the Bellview section is markedly different from the underlying strata and consists predominately of fine to very fine pinkish-gray (5YR 8/1) sand capped by the 4-m- (13-ft-) thick Caprock caliche. The fine and very fine sand section is characterized by a crude vertical columnar structure apparently due to differential carbonate cementation. Carbonate nodules occur throughout this part of the section. At about 13 m (43 ft) below the surface, two slightly darker (5YR 5/6), light-brown zones preserve a higher clay content and apparently are buried B horizons. Six and possibly seven buried pedogenic calcretes are indicated by diffuse zones of increased carbonate cement or carbonate nodules. No primary sedimentary structures were preserved in this material.

The massive Caprock caliche that caps the Bellview section is pinkish-gray (5 YR 8/1) and is nearly 4 m (13 ft) thick. The base of the Caprock caliche is marked by an upward increase in the size and number of carbonate nodules. Toward the surface the calcrete becomes progressively more massive. Numerous chalcedony veins occur at about 2 m (6 ft) below the surface. The upper part is laminated, brecciated, and pisolitic and represents a Stage VI calcrete (Bachman and Machette, 1977).

Facies Interpretation

The fine-grained, clay-rich paleosol overlying a thin zone of angular fragments at the base of the section represents a weathering and soil-forming horizon. The angularity of the coarse fragments suggests accumulation without significant transport. This unit preserves a thin colluvial deposit on the middle Tertiary erosional surface.

The fluvial sands and gravels exposed at the Bellview section make up channel fills and several fining-upward sequences within a single major fining-upward unit. Horizontally bedded and cross-bedded pebbly sands fine upward and are capped by

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desiccated silt-clay drapes. Channel-fill sequences begin at erosion surfaces and include armored mudballs and rotated slump blocks near the channel floors. These sediments were deposited by medium-energy, high-sediment load, ephemeral streams. Each fining-upward sequence capped by clay-silt drape represents a flood event followed by subaerial exposure. The Bijou Creek or South Saskatchewan River types of sandy, braided, ephemeral streams appear to be modern analogs for these deposits (McKee and others, 1967; Cant and Walker, 1978).

At a depth of approximately 14 m (46 ft) a fundamental change in depositional processes is preserved in the sedimentary record. The upper part of the Bellview section consists primarily of fine to very fine sand with no preserved primary sedimentary structures. The development of paleosols in this part of the section is indicated by several preserved pedogenic calcretes and two B horizons. Carbonate nodules (caliche) are very abundant and occur throughout the upper part of the section. Grain-size distribution and the lack of grain-size change throughout the upper part of the section suggests deposition by eolian processes similar to the upper part of the Ragland section and to the eolian sections of the Ogallala described by Winkler (1985). The stacked paleosols show no evidence of erosion between paleosols, suggesting that the surface of accumulation was a stable landscape. The absence of sedimentary structures also suggests bioturbation. The development of pedogenic calcretes and B horizons suggests long-term stability during which pedogenic processes would have a chance to operate. These observations suggest that deposition was mixed and probably included eolian sand sheets and loess deposited on a stable grass-covered landscape (see Frye and Leonard [1957] for discussions of Ogallala flora). As suggested by Fryberger and others (1979) and Kocurek and Neilson (in press), vegetation, particularly grasses, probably play a significant role in stabilizing eolian sand sheets. Clearly, vegetation would also serve to baffle and stabilize windblown dust.

Ogallala sediments preserved at the Bellview section differ from the Ogallala sediments described at the Ragland section in several possibly significant ways. The Bellview section is primarily sand while the Ragland section is mixed sand and coarse gravel, especially at the base of that section. Gravel clasts at the Bellview section

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consist mostly of fragments of ferricrete, Gryphaea, and quartzite pebbles. Ferricrete clasts do not occur at the Ragland section, and Gryphaea are rare. Basic volcanic cobbles are common at the Ragland section and do not occur at the Bellview site. These data indicate that the fluvial systems operating at these two sites during the late Tertiary had significantly different flow regimes and that the sources of sediment available to the two stream systems may also have been significantly different.

Cementation

Carbonate cementation is widespread but variable within the fluvial and colluvial sediments that make up the lower part of the Bellview section. Most of the section is poorly cemented, but certain finer grained sand and mud units are moderately well cemented. The degree of carbonate cementation in this section is significantly less than that at the Ragland section.

Beds of calcium carbonate up to 10 cm (4 in) thick have accumulated above thin, mudcracked silt-clay drapes. The carbonate beds are nodular, white and have not incorporated any of the adjacent clastic material. The mechanism by which this material accumulated is not understood, nor are we aware of any modern or ancient analogs that might provide an explanation for the accumulation of calcium carbonate in ephemeral stream environments. Pedogenic carbonate nodules form at shallow depths in soils by precipitation from soil waters, and in the process of formation exclude most soil particles. Perhaps a similar process accounts for the carbonate beds in this section, but the precipitation of calcium carbonate is from groundwater, not shallow soil water.

$CaCO_3$ beds [illegible]

Age

No datable material was observed at the Bellview section. No basic volcanic clasts were recognized at the Bellview section, so the relative age of the section can not be determined.

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Palo Duro Section

The Palo Duro Canyon State Park Section is exposed along the park entrance road where the road crosses and begins to descend the Caprock Escarpment (fig. 2). At the base of the Palo Duro Canyon State Park section the Ogallala Formation unconformably overlies Triassic Dockum Group mudstone (fig. 6). Beneath the middle Tertiary erosional surface that separates these two units Dockum Group light olive-gray (5Y 6/1) mudstone is weathered to yellowish gray (5Y 7/2) to a depth of 1.5 m (5 ft).

Depositional Facies

Basal Ogallala sediments in the Palo Duro Park section consist of rounded pebble- to cobble-sized, partly carbonate-cemented gravel comprised of quartzite and intrusive and metamorphic clasts. These gravels occur in shallow, narrow channels to a depth of 1 to 2 m (3 to 6 ft). Neither volcanic clasts nor primary sedimentary structures were recognized in this unit. Calcium carbonate (caliche) nodules are preserved in the cemented zones.

Overlying the basal gravel is 5.75 m (19 ft) of fine to very fine sand containing dispersed siliceous pebbles. No preserved sedimentary structures are present within this section. Calcium carbonate (caliche) nodules up to 3 cm (1.25 in) in diameter are common. The lower 1 to 1.5 m (3 to 5 ft) is carbonate cemented. Caliche nodules are preserved in the carbonate cement. Locally this unit contains siliceous nodules or is entirely silicified. Silicified parts are nodular to massive, reddish brown (10R 4/6), and fracture conchoidally. Ghosts of caliche nodules are recognizable within the silicified zone, but the nodules also have been silicified. The silicified zone is fractured, and locally fracture faces are partly covered with opal films.

The upper 2 m (6 ft) of this unit is strongly carbonate cemented to form a massive conchoidally fracturing calcrete. Uncemented enclosures of fine sand and carbonate nodules are present. Ghosts of carbonate nodules remain along with rare dispersed siliceous pebbles.

Approximately 2 m (6 ft) of the section above the calcrete is covered by colluvium, but above that, 5.5 m (18 ft) of horizontally bedded, cross-bedded and ripple-laminated sands are present. This 5.5 m (18 ft) section fines upward from medium sand at the base to fine sand near the top; the thickness of cross beds also diminishes upward from 20 to 30 cm (8 to 12 in) at the base to 2 to 10 cm (0.8 to 4 in) near the top of the exposure. Silty clay drapes showing evidence of desiccation overlie fining-upward ripple-laminated sequences. This sequence does not contain calcium carbonate (caliche) nodules.

This part of the section is poorly cemented, although local case hardening occurs where the surfaces of some strata are carbonate cemented. Lenses of carbonate-cemented sand (ground-water calcretes) are also present.

Overlying the fluvial section described above are 3.5 m (12 ft) of section covered with colluvium. The top of the section exposes a weathered and extensively fractured portion of the Caprock caliche.

Facies Interpretations

The lack of preserved primary sedimentary structures in the lower 6.75 m (22.3 ft) of the Palo Duro Canyon State Park section (fig. 6) makes it difficult to interpret the environments of deposition. The channel-filling rounded gravel clasts at the base of the section were probably deposited by small, possibly braided, streams. The 5.75 m (19 ft) of fine to very fine sand overlying the gravel is similar in grain size to eolian material described in the Ragland and Bellview sections with the exception of a few dispersed gravel-sized clasts. The lack of primary sedimentary structures and the presence of caliche nodules indicates that the section has been altered by pedogenic processes and perhaps bioturbated. The presence of pedogenic caliche nodules in this part of the section suggests that a stable landscape and a slow rate of accumulation of sediment prevailed when the nodules were being formed.

The lower part of the 5.5-m- (18-ft-) thick sequence of fluvial sediments in the middle of the Palo Duro Canyon State Park section consists primarily of planar and trough crossbeds and horizontal beds. Ripple cross stratification and silt-clay drapes are missing. The types of sedimentary structures present seem to represent superimposed bars similar to those preserved in a Platte River (Smith, 1970) type of sandy braided stream.

The upper part of the fluvial sequence of the Palo Duro Park section includes numerous fining-upward sequences capped by ripple cross stratification and silty-clay drapes showing evidence of desiccation. These structures suggest deposition during repeated flood events by high-energy, shallow ephemeral streams similar to the Bijou Creek (McKee and others, 1967) type of sandy braided stream.

Cementation

It is probable that several episodes of cementation have affected the Palo Duro section. Two ground-water calcretes are present near the base of the section. The base of the Ogallala section is strongly carbonate cemented to a thickness of about 2 m (6 ft). Ground-water calcretes do not display any of the characteristics of pedogenic calcretes. The basal calcrete is not laminated and does not appear to be fractured and recemented. Ghosts of caliche nodules are present. Clasts of the original sediment in this section may have been slightly dispersed by the cementation process, but are not excluded from the calcrete. Locally this calcrete has been silicified. A second calcrete occurs about 2 m (6 ft) above the basal calcrete and is similar in character to the basal calcrete. In addition, numerous individual beds within the fluvial section are cemented by calcium carbonate to form thin, discontinuous, ground-water calcretes.

Age

No datable materials were observed in this section.

Buffalo Lake Section

The Buffalo Lake section is exposed on the southeast side of Texas Highway 168 in the Buffalo Lake National Wildlife Refuge, approximately 5 km (3 mi) south of Umbarger, Texas. The base of the section starts at an elevation of about 3,620 ft 0.3 km (0.25 mi) east of the Buffalo Lake dam. Triassic Dockum Group strata exposed in the base of the section consist of brecciated sandstones and mudstones that dip approximately 20° southwest (fig. 7). Fractures are filled with carbonate-cemented fragments of Dockum strata. The upper 1 to 1.5 m (3 to 5 ft) consists of brecciated

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mudstones partly displaced by laminated calcium carbonate (calcrete). This may be a remnant of a pedogenic calcrete developed at the middle Tertiary erosional surface on Dockum strata.

Facies Description

A massive, 2.2-m- (7-ft-) thick calcrete occurs at the base of the Ogallala Formation. The calcrete is brecciated in a few small areas and locally silicified. Silicification boundaries cut across breccia clasts. Rare quartzite pebbles are dispersed in the calcrete.

Overlying the calcrete are 21 m (70 ft) of fine to very fine pinkish-gray (5 YR 8/1) sand and silt. No primary sedimentary structures are preserved in this sequence. Numerous white carbonate (calcrete) nodules occur throughout the section. A crude vertical columnar structure is present throughout most of this sequence. This structure apparently reflects differential carbonate cementation along soil ped faces. The slightly resistant areas are more heavily carbonate cemented. Opalized, downward branching tubules, apparently representing silicified root traces, are present locally. Several paleosols are present as pedogenic carbonate horizons near the top of the section. Near the top of the section the number and size of calcrete nodules increases. The pedogenic Ogallala Caprock Caliche occurs at the top of the section and is approximately 2.5 m (8.25 ft) thick. The upper part is massive and intensely fractured. No secondary laminations were observed.

Facies Interpretation

Dockum strata below the middle Tertiary erosional surface appear to have undergone pedogenesis, which resulted in the development of a pedogenic calcrete. If this is correct, then the middle Tertiary erosional surface in this locale was a stable surface for sufficient time to develop a very mature soil profile.

There is no evidence of fluvial deposition at the Buffalo Lake section. The 21 m (70 ft) of Ogallala Formation sediments exposed at the Buffalo Lake section are predominately a fine to very fine silty sand. Some sand grains are frosted and well

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rounded. The presence of frosted, well-rounded sand grains, and the texture of the sediments that make up these strata, suggest that the entire section was deposited by eolian processes similar to the upper parts of the Ragland and Bellview sections. The large percentage of fine to very fine sand is too coarse for loess, but the presence of a significant proportion of silt- and clay-sized material suggests a minor amount of loess deposition. The lack of preserved sedimentary structures, preserved root traces and paleosols and caliche nodules suggests slow accumulation of sediment on a stable landscape. The mix of sand-, silt-, and clay-sized material suggests that mixed eolian processes account for deposition of this section. Example modern analogs would be loess deposition (Miller, 1985) and deposition as sand sheets (Fryberger and others, 1979; Kocurek and Neilson, in press).

Cementation

The entire Buffalo Lake section is lightly cemented by calcium carbonate. Carbonate nodules, probably resulting from pedogenic processes, occur throughout the section. Near the base of the section a 2-m- (6-ft-) thick calcrete is present. The calcrete is partly silicified and massive. Although there is minor evidence of brecciation of carbonate clasts and recementation, there are no other characteristics that suggest that this basal Ogallala calcrete is pedogenic in origin. This calcrete is apparently the result of precipitation of calcium carbonate from ground water.

Age

No datable materials were found in this section.

Silverton Section

The Silverton section is exposed on Texas Highway 256 between 18.5 and 19.3 km (11.5 and 12 mi) east of Silverton, Texas (fig. 2). The base of the section is at an elevation of approximately 2,990 ft and extends 38 m (125 ft) to an elevation of approximately 3,100 ft. Ogallala sediments in the Silverton section (fig. 8) unconformably overlie weathered and fractured mudstones of the Triassic Dockum Group.

Facies Descriptions

Locally, narrow, shallow (1- to 1.5-m-deep [3- to 4.5-ft-deep]) channels are filled with sandy carbonate-cemented gravel at the base of this section of the Ogallala Formation. Gravel clasts are up to 13 cm (5 inches) long and are mostly quartzites, vein quartz, metamorphics, and fine-grained igneous rocks. Primary sedimentary structures are not preserved and gravel clasts appear to float in a fine-grained matrix. Carbonate cement in this unit has been locally silicified.

The remaining 36 m (119 ft) of the Silverton section consists of grayish orange pink (5YR 7/2) fine to very fine sand that appears similar to fine and very fine sand sequences in the Buffalo Lake section and in the upper parts of the Ragland and Bellview sections. No primary sedimentary structures were recognized in this section. Well-rounded and frosted sand grains occur throughout the section. The sand contains pinkish-gray carbonate (calcrete) nodules up to 5 cm (2 inches) in diameter throughout much of the section. At least four massive (Stage IV?) pedogenic calcretes (Bachman and Machette, 1979) occur in the lower 17 m (56 ft) of this section. The upper 19 m (63 ft) of this exposure includes 18 paleosols preserved as concentrations of carbonate nodules or as slightly darker (moderate red-brown [10R 4/6] to pale red-brown [10R 5/4]) and slightly clay-rich B soil horizons. Only a few representatives of these paleosols are illustrated in figure 8.

The top 3.5 m (11.6 ft) of the Silverton section is a massive pinkish-gray (5YR 8/1) to grayish orange-pink (5YR 7/2) Stage V calcrete, the Ogallala Caprock caliche. The calcrete is laminated, but does not appear to be brecciated or pisolitic. Large dense areas of carbonate fracture conchoidally.

Facies Interpretations

The shallow, widely separated gravel-bearing channels at the base of the Silverton section represent fluvial deposition, but the lack of preserved sedimentary structures and the sparseness of these deposits precludes additional interpretation.

The upper 36 m (119 ft) of the Silverton section is similar to the Buffalo Lake section and probably represents eolian deposition based on the texture of these sediments

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and on the presence of rounded to subrounded frosted grains. The lack of primary sedimentary structures probably results from bioturbation and in part from the disruption of sediments by soil-forming processes, mainly precipitation of carbonate. The numerous preserved paleosols represent periods of landscape stability followed by influxes of additional eolian sediment. Although only a few root structures are preserved within this section, the landscape stability indicated by development of paleosols also suggests that the Ogallala surface was vegetated. The Caprock caliche that marks the top of the Ogallala Formation is a Stage VI pedogenic calcrete and represents an extended period of landscape stability.

Cementation

The lower 1.5 to 2 m (4.5 to 6 ft) of the Silverton section is a calcrete composed of carbonate-cemented sand and gravel. Gravel clasts appear to float in the fine-grained carbonate matrix. The lack of brecciation and lamination of carbonate deposits, characteristics generally attributable to pedogenic calcretes, suggest that this is a ground-water calcrete. Locally, the calcrete has been silicified. The remainder of the section is moderately to slightly carbonate cemented. For the most part this cement is the result of pedogenic processes and consists of carbonate films along ped faces, carbonate nodules, and pedogenic calcretes.

Age

No datable materials were observed at the Silverton section.

PRELIMINARY INTERPRETATION OF THE DEPOSITIONAL HISTORY OF THE OGALLALA FORMATION

The complex nature of Ogallala sedimentation is reflected in the five stratigraphic sections that have been described (figs 4 through 8). The lower part of the Ragland section (fig. 4) appears similar to the Scott Stream (Boothroyd and Ashley, 1975) or Donjek River (Williams and Rust, 1969) type of gravelly braided-stream deposits (Miall, 1978). The lower part of the Bellview section (fig.5) appears similar to the South

Saskatchewan River (Cant and Walker, 1978) or Bijou Creek (McKee and others, 1967) type of sandy braided stream. The middle part of the Palo Duro Canyon State Park section (fig. 6) is similar to the Platte River (Smith, 1970, 1971) and to Bijou Creek types of sandy braided streams. Within the three sections that contain fluvial deposits, five of the six models commonly used to describe braided-stream deposits (Miall, 1978) can be applied.

Eolian sediments overlie each of the fluvial sequences in the Ragland, Bellview, and Palo Duro Canyon State Park sections and comprise most of the Buffalo Lake and Silverton sections (figs. 7 and 8). The composition of these materials, mainly fine to very fine sand but with a significant silt and clay fraction, and the presence of frosted grains supports the interpretation that these sediments were deposited as eolian sand sheets and loess. Fryberger and others (1979) have described deposition of sand sheets, and recent desert dust deposition and Quaternary loess deposition have been described by McCauley and others (1981), Machenberg (in press), and Miller and others (1984). The lack of preserved sedimentary structures makes it difficult to confirm the mode of deposition.

Calcretes preserved in the fluvial sequences in the Ragland, Bellview, and Palo Duro Canyon State Park sections and at the base of eolian units in the Buffalo Lake and Silverton sections are massive and without the characteristics of pedogenic calcretes (figs. 4 through 8). These and several discontinuous cemented lenses in the fluvial sections were probably formed by precipitation of calcium carbonate from ground water. The time and circumstances of formation of these calcretes is not known.

The calcretes associated with the eolian sequences are characterized as being nodular, laminated, brecciated, or pisolitic. Occasionally, root casts and burrows are preserved and may be opalized. Recent studies by Bachman and Machette (1977) and Gile and others (1981) have led to descriptive classifications of pedogenic calcretes and estimates of the time required to form these features. For example, according to these studies, the Ogallala Caprock caliche would take several hundred thousand years to form. However, a calcrete composed only of a concentration of carbonate nodules could form in several thousand years. Pedogenic development of calcretes is clearly a long, slow

[illegible]

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process, and the presence of numerous pedogenic calcretes in Ogallala eolian sections suggests slow accumulations over a long period of time. The stacked calcretes (paleosols) in the eolian sections of the Ogallala Formation suggest pedogenesis during periods of landscape stability with little or no deposition followed by episodes of eoilan sedimentation.

The distribution of facies within the Ogallala Formation, as reflected in the five described sections, permits a preliminary interpretation of the depositional history of the formation. Examination of the topography on the middle Tertiary erosional surface indicates that broad paleovalleys and paleostream divides were present during pre-Ogallala time beneath the northern part of the Southern High Plains (fig. 2). Basal Ogallala strata within the paleovalleys are fluvial sediments deposited by ephemeral braided streams and are exposed in the Ragland, Bellview, and Palo Duro Canyon State Park sections. Eolian sediments overlie the fluvial deposits in these sections. Eolian sediments and little or no fluvial sediments overlie the paleostream divides and are exposed in the Buffalo Lake and Silverton sections.

The concentration of fluvial sediments in the paleostream valleys suggests that the lower part of the Ogallala Formation was deposited primarily as a valley fill, at least in the areas of the described sections. Valley-fill sequences have also been described by Winkler (1985) for basal Ogallala sediments exposed southeast of Lubbock, Texas and by Diffendal (1984) for Ogallala sediments exposed in southwestern Nebraska.

The abrupt cessation of fluvial sedimentation in the Ogallala Formation suggests a diversion of streams flowing across the Ogallala landscape. This is consistent with Gustavson and Finley's (1985) suggestion that most Ogallala drainage systems were diverted during the Pliocene to form the Pecos and Canadian Rivers.

The thick eolian sections overlying paleostream divides represent a long period of intermittent eolian sedimentation. The eolian sediments in the lower parts of these sections may have been derived from ephemeral, sandy, braided Ogallala streams. However, the upper parts of the eolian sections overlying the interfluves, as well as the eolian portions overlying the paleovalley fills, may have had different source areas because streams on the High Plains had been diverted to form the Pecos and Canadian Rivers.

Machenberg and others (1985) have suggested that the most recent sediments of the Blackwater Draw Formation, which is eolian and overlies the Ogallala Formation, were derived from the floodplains of the Pecos and Canadian Rivers. It may be that the eolian sediments of the upper part of the Ogallala were also derived from the floodplains of the Pecos and Canadian Rivers soon after diversion of Ogallala streams.

The end of deposition of the Ogallala Formation is marked by the development of the massive Ogallala Caprock caliche (calcrete). The development of thick, laminated, brecciated, recemented, pisolitic calcretes such as this requires extended periods of landscape stability (Bachman and Machette, 1977; Gile and others, 1981). According to Bachman and Machette (1977) and Gile and others (1981), calcretes such as the Ogallala Caprock caliche take several hundred thousand years to form. Apparently, neither extensive deposition nor erosion occurred in the High Plains during late Ogallala time.

BLACKWATER DRAW FORMATION

Soil-geomorphic studies were conducted to determine the age and stratigraphic relationships of the surface and near-surface sediments of the High Plains, which, for the most part, comprise the Blackwater Draw Formation. Research on the Rolling Plains has been closely tied to this, in that deposits strikingly similar to the Blackwater Draw have been identified there.

The Blackwater Draw Formation is the principal surficial deposit of most of the High Plains of Texas and New Mexico and supports the lucrative agricultural industry of the region. The unit is a sheet-like body of sediment that varies in texture from sandy in the southwest portion of the region to clayey in the northeast. Considering the extent (roughly 100,000 km^2) and economic importance of the Blackwater Draw Formation, it is suprising that there has been relatively little research on the age and origin of the unit. Frye and Leonard (1957) first formally studied these deposits. They used the informal term "cover sands" for this sediment, and considered it to be of "Illinoisian" age because it apparently was stratigraphically above lacustrine sediments of "Kansan" age (the Tule Formation) and below lacustrine sediments of "Wisconsin" age (the Tahoka Formation). They recognized, however, that the "cover sands ... may include more than one age of deposit" (Frye and Leonard, 1957, p. 28). They also considered the Judkins Formation, an eolian sand deposit identified adjacent to the southwest portion of the Texas High Plains by Huffington and Albritton (1941), to "belong within the complex called 'cover sands.'" They concluded that the "cover sands" were of eolian origin, probably derived from some of the large river valleys, such as the Pecos, to the west and southwest. Frye and Leonard (1964) also recognized a strongly developed soil formed in the upper part of the "cover sands" that they considered a "Sangamon Soil."

Reeves (1976) 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) than the maximum of about 10 m observed by Frye and Leonard (1957). He noted that the term "Sangamon soil" should not be applied to the regional surface soil because of evidence of multiple periods of soil formation.

Several recent investigations shed new light on the age and origin of the Blackwater Draw Formation. Seitlheko (1975) investigated 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 Valley (fig. 9) Allen and Goss (1974) and Hawley and others (1976) recognized that, locally, the Blackwater Draw Formation contains up to seven well-developed soils including the surface soil. This indicates that the unit was deposited episodically. Limited absolute age control suggests that deposition took place throughout much of the Pleistocene (Holliday, 1984; Machenberg and others, 1985). Locally, one of the buried soils in the formation occurs below the 0.6 m.y. Lava Creek ash (formerly Pearlette O), which is within the Tule Formation. Elsewhere, one and possibly two of the buried soils are exposed below the 1.4 m.y. Guaje ash of Izett and others (1972). A preliminary paleomagnetic study of the lowermost of five buried soils in the Blackwater Draw Formation demonstrates that the remnant magnetization, apparently acquired during pedogenesis, is dominantly reversed. This suggests that the soil formed during the last

[illegible]

reversed polarity epoch, which ended about 0.79 m.y. B.P. (E. E. Larson, personal communication, 1984).

With few exceptions, soils provide the only stratigraphic markers within the Blackwater Draw Formation. In any one section, and in a given area, the soils are remarkably similar, although the number of buried soils may vary from none to six within a small area. A detailed investigation of the soils, however, may show subtle pedologic differences useful for correlation purposes. Moreover, the soils may provide information on the age of the Blackwater Draw Formation.

Soils form through time under the influence of climate, parent material, relief, and biota (Jenny, 1941, 1980). If other factors are held constant, or their effects minimized, it may be possible to determine the effects of time on the soils and to use this information to determine the age of the soils (Jenny 1941, 1980; Birkeland, 1984). The only information available on rates of soil formation in the study area are for Holocene soils. Gile (1976) studied soil genesis in the Sand Hills region of Bailey County and Holliday (1982) has investigated rates of soil formation at various localities in valley fills on the Southern High Plains. These investigations are useful because the soils formed in parent materials similar to those of the Blackwater Draw Formation, and are under about the same biotic and climatic circumstances, although the Blackwater Draw Formation soils were probably subjected to some climatic changes. The topographic situations vary somewhat (dunes and draws in contrast to the otherwise broad, flat surface of the High Plains), but significant general comparison of soil development seems possible.

Finally, an attempt at absolute age control was made by using TL dating techniques. TL dating has, at best, accuracy limits of ± 10 percent when applied to suitable deposits such as eolian sediments (Wintle and Huntley, 1982), but can provide valuable minimum age estimates for Quaternary sediments and soils.

METHODS

A number of natural and artificial exposures on the High Plains and Rolling Plains were examined as part of this investigation. On the High Plains, the sites included the

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type locality for the Blackwater Draw Formation (Lubbock County) and Blanco Formation (Crosby County) and an exposure of the Tule Formation and associated ash (the "Tule Basin" site, Swisher County). The Rolling Plains sites included three exposures of the informally named Lingos Formation--two in Briscoe County ("Smith Ditch" and "Henson Ditch") and one in Hall County ("Turkey Railroad Cut") (fig. 1). Soils developed on eolian sediments of the Lingos Formation were compared to and contrasted with soils and sediments of the Blackwater Draw Formation. Most were described using standard soil nomenclature (Soil Survey Staff, 1951, 1975; Guthrie and Witty, 1982) and most horizons were sampled.

The samples were subjected to a variety of physical and chemical analyses (tables 1 through 7) to better characterize pedologic development and to obtain absolute ages. Particle-size distribution (PSD) was determined by sieving sand-sized fractions and by hydrometer analyses of organic matter- and $CaCO_3$-free silt- and clay-sized fractions (Day, 1965). These analyses provide sedimentologic information and data on clay accumulation in the B horizon, an important pedologic characteristic. Determination of organic carbon (OC) content by the Walkely-Black technique (Allison, 1965), and of $CaCO_3$ content by acid-neutralization techniques (U.S. Soil Salinity Laboratory, 1954) were also made. These analyses aid in characterizing A horizon and calcic horizon development, respectively.

Comparisons of certain aspects of the laboratory data, such as carbonate content, can aid in estimating duration of soil development (Machette, 1985). The percent carbonate per horizon is multiplied by the bulk density (gm/cm^3) of that horizon. The result is multiplied by the thickness of the horizon. If other calcic horizons are present a in soil the same procedure is applied and a figure is derived providing total $CaCO_3$ per cm^3 column through the profile. In the study area, these data are available for the Holocene soils (Holliday, 1982) and can be calculated for the surface soils of the Blackwater Draw Formation using bulk density data of Mathers (1963).

A number of peds were taken from the soil profiles for thin-section preparation and micromorphological characterization of the soils (following the terminology of Brewer, 1976). This analysis further characterizes and quantifies clay and carbonate accumulation

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in the soils which was accomplished using a technique developed by Holldiay (1982). Point counts, usually 200, were made for each thin section. Presence or absence of clay films (a pedogenic feature) around each counted quartz sand grain was recorded. Where the clay film was present the percent of grain perimeter coated was estimated. Thickness of the clay film was also determined by scanning across the slide and measuring a random sample of 20 clay films. Weighted means were calculated for the percent of the grains with argillans (clay films), the percent of the grain perimeter coated with clay, and the clay film thickness for each soil. Particles of pedogenic carbonate were also counted.

Field data collected from the profiles were manipulated to quantify profile development. The field morphology rating scale of Bilzi and Ciolkosz (1977) was used and the resulting values referred to as B-C values. This approach characterizes each horizon, by color, texture, structure, and boundary characteristics. A single value is obtained for each soil and better developed profiles have higher numbers. The B-C values from the soils of the Blackwater Draw Formation can be compared with B-C values from well-dated Holocene soils (Holliday, 1982) to estimate ages.

The various approaches to estimating duration of pedogensis involving total $CaCO_3$ content, clay film characteristics, and the B-C values provide only minimum ages for the soils. There are several reasons for this. Many of the soils are sufficiently well developed that they may have arrived at a "steady state" condition (Birkeland, 1984), whereby they would show little change in their properties even though pedologic processes are continuing. For example, through time more sand grains will acquire clay films until all grains are completely coated. Clay will continue to accumulate in the B horizon, but this may only be manifested in clay-film thickness or total clay content. Total carbonate content provides a minimum age because the field data show that the surface soils of the Blackwater Draw Formation had carbonate leached to considerably greater depth than the position at which the $CaCO_3$ is presently accumulating. Rates of Holocene carbonate accumulation can only provide an estimate of the time since $CaCO_3$ began to accumulate in the surface soils of the Blackwater Draw Formation. Moreover, carbonate may have accumulated faster in the late Holocene than in the middle Holocene

(Holliday, 1982). Finally, the B-C values provide minimum ages because, in addition to the steady state effect, the Holocene soils with which the comparisons are made developed in a valley, and concentration of water in the drainage probably enhanced rates of pedogenesis. In addition, the B-C values are best applied to complete soil profiles and many of the soils of the Blackwater Draw Formation are incomplete. The A horizons are missing from all but the surface soils and C horizons are seldom observed; most sections are a series of B horizons stacked one on top of another. The B-C value is in part dependent on the number of horizons present. Soils with incomplete profiles will have lower B-C values than if complete profiles were present.

Samples for TL dating of the Blackwater Draw Formation were also secured. In order to determine the suitability of TL techniques for dating these sediments, control samples were collected from radiocarbon-dated eolian sediment, and from the Blackwater Draw Formation immediately below these dated sediments, at a locality in Lubbock. A series of TL samples were then collected from the type locality for the Blackwater Draw Formation. The samples were submitted to Alpha Analytic, Inc., a commercial TL lab. Particles in the 4 to 11 micron range were extracted from the samples and analyzsed. Because much of the material in this size range is illuvial (due to pedogenesis), resulting ages are minima for the dates of burial by the overlying sediments.

SOIL STRATIGRAPHY

The soil stratigraphy of each of the examined sections is described in the following portion of this report. Individual buried soils are referred to based on their stratigraphic position below the surface following the designation of the descriptions (e.g., b1, b2, b3, etc., tables 1 through 7). The discussion of the soils and their stratigraphic significance is presented first for the High Plains and then for the Rolling Plains.

High Plains

Three localities were examined on the High Plains of which two, the Blackwater Draw type section and the Tule basin exposure, were described pedologically and sampled for laboratory analysis. The Blackwater type section was described because this

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was not done when the formation name was proposed (Reeves, 1976), and because there appeared to be at least several buried soils in the section. Exposed at the Tule basin site are Tule Formation lacustrine sediments, the 0.6 m.y. Lava Creek ash, and terrestrial sediments with a soil buried by the ash. At the Blanco Formation type section, the 1.4 m.y. Guaje ash overlies terrestrial sediments with a soil. Both the sediments and the soil are identical to the sediments and soils exposed at the type section of the Blackwater Draw Formation. The Tule and Blanco sites, then, are important to the geochronology of the Blackwater Draw Formation.

Blackwater Draw Formation Type Locality

The type section of the Blackwater Draw Formation is in northern Lubbock County, due north of the city of Lubbock along a roadcut "on the west side of Blackwater Draw north[west] of [the town of] New Deal at approximately N33°46', W101°52'30"" (Reeves, 1976, p. 219) (fig. 1). The exposure is about 10 m thick, with the modern High Plains surface at the top and the Ogallala "caprock caliche" at the base (fig. 10, table 1).

There are two striking features about the type section: its general homogeneity and the presence of a number of strongly developed buried soils. The overall color, texture, and structure of the section is relatively uniform. On close inspection, however, it is apparent that the section is composed of at least four buried soils in addition to the modern surface soil (fig. 10). The overall homogeneity of the section is because all of the soils have about the same degree of pedogenic expression: reddish-brown color (5YR hues), moderate to strong prismatic structure with common films of illuvial clay on the ped faces, and Stage II to III calcic horizons (after Gile and others, 1966). No A or C horizons are apparent other than the A horizon of the surface soil. Pedologically, the section is identical to the well-developed, regional surface soils of the central portion of the Southern High Plains: Paleustalfs and Paleustolls of the Amarillo-Acuff-Mansker soil association (Godfrey and others, 1973). The soil has a thick reddish-brown (5YR hues) argillic horizon (50 to 149 cm) and dominantly coarse prismatic structure. Clay films are apparent on ped faces and very common in thin section. Below the argillic horizon is a Stage III calcic horizon (149 to 290 cm). The boundary between these horizons is very

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abrupt and subhorizontal, similar to a stratigraphic contact. Such an abrupt boundary is typical of the regional surface soils and is considered to be pedogenic. All characteristics of thia higher indicate a very well developed soil.

Morphologically, the buried soils in the section are more strongly developed than the surface soil. At least some portions of each profile exhibit 2.5 YR hues, more continuous clay films on ped faces, higher percentage of clay films in thin section, and an angular blocky structure. The blocky structure is apparently due to higher illuvial clay content (suggested by clay film content).

The morphologies of the calcic horizons in the buried soils are somewhat similar to one another but distinctly different from that in the surface soil. The buried calcic horizons are expressed as either patchy films and coats on ped faces, generally the vertical faces, or as vertically oriented, root-like nodules about 1 cm thick. These nodules appear to follow the joints between prismatic peds and this general morphology is sometimes informally referred to as "ladder structure" carbonate. There is evidence that calcic horizons in the buried soils were more extensive but underwent dissolution. The upper boundary of the ladder-structure calcic horizons is commonly and nearly always horizontal and abrupt. This suggests that the horizon was originally similar to the surface-soil calcic horizon but was subsequently subjected to dissolution with concentration of the carbonate along veins (ped faces?) and as nodules. Illuvial clay is very common in and on peds between carbonate nodules in the ladder-structure horizons, but such clay is not apparent in the surface-soil calcic horizon. This would further suggest that clay illuviation accompanied carbonate dissolution.

Two K horizons were identified at the bottom of the section. The K2m is a silicified petrocalcic horizon, probably the "caprock caliche" at the top of the Ogallala Formation. The K1 above the K2m is a massive, nonindurated calcic horizon, probably representing a build-up of carbonate due to the impermeable nature of the underlying pedogenic calcrete.

There is one exception to the strong pedogenic expression in the type section. At the east end of the roadcut (Profile 5, fig. 10, table 1), on the floor of Blackwater Draw, the surface soil is weakly developed, exhibiting an A-Bw-Btk profile with some clay films apparent in thin section. Although the hues in this soil are 7.5 YR to 5 YR, it is not as well developed as the others in the section because there are no clay films on ped faces and the structure is weak, subangularm, and blocky.

Tule Basin Locality

This site is in Swisher County, 12 mi east-southeast of Tulia, on the south side of Tule Canyon (fig.1). The locality is along a roadcut of FM 2301 and exposes fine-grained, apparently eolian sediments containing the 0.6 m.y. Lava Creek (formerly Pearlette 0) volcanic ash (Izett and Wilcox, 1982) overlying lacustrine sediments of the Tule Formation (Schultz, 1977). The eolian sediments containing the ash are considered to be the Blackwater Draw Formation. By original definition, the "cover sands" (Frye and Leonard, 1957) or Blackwater Draw Formation (Reeves, 1976) are those eolian sediments overlying the Tule Formation.

The Blackwater Draw Formation is more than 4 m thick in this exposure (table 2). The upper 1.47 m of the section contain the well developed modern surface soil (a-Bt-Bk horizonation with reddish-brown (7.5 YR) hues, moderate structural development, and a Stage III calcic horizon). There is also evidence of either a buried soil or a formerly deeper surface profile from 67 to 147 cm (Btk2 horizon), suggested by well-expressed Bt material below the calcic horizon. Soil development in the 170 to 275 cm zone, related to either the surface soil or to the possibly buried soil noted previously, occurred in material that probably contained abundant volcanic ash. This is indicated by low bulk density, massive structure, and some silica coatings. The zone of pure ash underlies the soil and varies in thickness from a feather edge to about 30 cm. The ash buried about 90 cm of Blackwater Draw Formation, which also has a well-developed soil with a Bt horizon, 7.5 YR hues, moderate structural development, and a thin Stage III calcic horizon.

Blanco Formation Type Section

The type section for the Blanco Formation is in northern Crosby County on the west side of Blanco Canyon (which contains the White River). The locality is in a roadcut of State Highway 193, about 1.2 km west of the intersection with State Highway 651 (fig.1). The Blackwater Draw Formation is about 5 m thick and rests on the lacustrine sediments and pedogenic calcrete of the Blanco Formation. The 1.4 m.y. Guaje ash is exposed about 4 m below the surface within sediments considered to be the Blackwater Draw Formation (fig. 11).

Several soils are present in the Blackwater Draw Formation at this section. Above the ash there is the modern surface soil and apparently two buried soils. The surface soil, at the west end of the roadcut away from the edge of the Blanco Canyon, is the typical well-developed surface soil of the region with a Bt horizon, 5 YR hues, prismatic structure, thin clay films commonly present on ped faces, and a Stage III calcic horizon. The upper boundary of the calcic horizon, which is abrupt and somewhat erosionally resistant, persists toward the eastern end of the section where the the upper part of the profile is eroded and the calcic horizon of the first buried soil is exposed as a ledge former near the surface (fig. 11). The two buried soils above the ash are composed of Bt and Stage III calcic horizons with morphologies identical to the surface soils. The calcic horizon of the surface soil apparently developed in the upper Btb1 of the first buried soil, the calcic horizon of the b1 formed in the Btb2. The calcic horizon of b2 developed in the upper portion of the volcanic ash. The calcic horizons of these two buried soils appear to have undergone some leaching. This leaching of the calcic horizons and the overlapping or "welded" nature of the buried soils above the ash at this locality is very similar to that observed at the type section of the Blackwater Draw Formation. The Guaje ash buries a soil with a Bt and K horizon. The Bt horizon has field properties identical to those overlying the ash. The K horizon is strongly indurated and forms a prominent ledge along the lower portion of the roadcut. This zone formed in the highly convoluted, calcareous silt and clay of the Blanco Formation or in pinkish (5YR 8/2) sand that occurs in broad, subtle synclines in the upper part of the Blanco Formation (fig. 11). This pink sand may represent relatively unaltered Blackwater Draw Formation.

Rolling Plains

Three exposures of the informally named Lingos Formation were studied on the Rolling Plains (fig. 1) for comparison to the Blackwater Draw Formation. Exposed sections were described pedologically and sampled for laboratory analyses. Two sections were described in the long, artificial exposure referred to as "Henson's Ditch." One of the sections (15B in Baumgardner and Caran, 1984a) contains what is apparently a sequence of Pleistocene soils and the other section (15D) contains a Holocene sequence. Two sections also were described at the "Turkey Railroad Cut" (Baumgardner and Caran, in press b), an apparent Pleistocene section and an apparent Holocene section. A sequence of late Quaternary soils and sediments was also described at the artificial exposure known as "Smith's Ditch" (Caran and Baumgardner, in press). These localities contain some of the longest and best exposed Holocene and Pleistocene sections in the Rolling Plains.

Henson's Ditch

This long, north-south-trending artificial cut is about 3 km southwest of the town of Quitaque and is described by Baumgardner and Caran (in press a) (fig. 1). Section 15B (BEG sample locality 83040601) is in about the middle portion of the ditch and 15D (BEG sample locality 83040909) is at the northern end of the cut. The section at 15B is about 10 m thick and contains several buried soils (table 3). Only the upper 7 m were described; the lower 7 m of the Tule section were obscured by talus. Five buried soils were described in addition to the modern surface soil and the several zones that apparently had not undergone pedogenic alteration. All of the soils are strongly developed with Bt horizons containing common clay films on ped faces, hues of 5YR, and prismatic structure. None of the buried soils have preserved A horizons but several have C horizons. Several zones (e.g., 320 to 434 cm) had strong, angular blocky structure, abundant clay films, and 2.5YR hues, but these units are composed of clay and the morphological characteristics are considered to be primarily due to the parent material. The origin of the strong red color is uncertain, but the color may be the result of post-burial oxidation. The abrupt upper and lower boundaries also argue against a pedogenic origin for these zones.

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The section at 15D exposes what appear to be eolian sediments overlain by lacustrine sediments. The modern surface soil is developed on the lacustrine sediments (table 4). Pedologic descriptions for 15D were made several hundred meters north of 15D by Caran and Baumgardner (1985). This sequence appears to be stratigraphically above the section at 15B, although it was not possible to continuously trace strata from 15B to 15D. The soil in the upper 3.5 m at 15B is moderately well developed (A-Btk horizonation) with only some suggestion of clay illuviation, weak prismatic and subangular blocky structure, and 5YR hues. The unit with the soil rests on a thin deposit of highly calcareous, friable, apparently lacustrine sediment. This zone in turn overlies a unit that varies from a feather-edge to more than 2 m thick, is dark in chroma, and has abrupt upper and lower boundaries The unit appears very similar to deposits found in playa lake basins on the High Plains and is considered to be lacustrine. Below this dark material is a buried soil with color, structure, texture, and clay-film morphology identical to that seen in the soils at 15B.

There are a number of radiocarbon ages available from exposures along Henson's Ditch (Caran and Baumgardner, 1985). At section 15B three dates have been determined. The A horizon of the surface soil, locally buried by recent eolian sediment, has a date of less than 180 yr B.P. (66-72 cm; Unit 2 of Baumgardner and Caran, in press a). Organic material in the 2Btkb2 horizon yielded an age of 1,880 ± 70 yr B.P. (325-329 cm; Unit 4 of Baumgardner and Caran, in press a). Two radiocarbon ages are available from section 15D. A buried A horizon, probably the equivalent of the Ab horizon in the pedologic description, yielded an age of 1,280 ± 60 yr BP. Organic-rich, clayey lacustrine sediments, the equivalent of the upper C2b horizon, were dated to 9,580 ± yr B.P.

Turkey Railroad Cut

This exposure is immediately north of Turkey and is discussed by Baumgardner and Caran (in press b). The soil-geomorphic studies focused on those sediments and soils above the deformed and eroded sediments exposed in the lower part of the cut (fig. 3). At section 1 (BEG sampling locality 83040802) 180 m south of the highway bridge, the youngest sediments and soils in the section were examined (table 5). the sediments fill a shallow swale. In the upper first meter of the section is a well-developed soil containing a Bt horizon with common clay films, 5YR hues, and weak prismatic structure. This soil is buried by modern sediment and overlies a soil with morphological features identical to the well-developed surface soils of the High Plains. This buried soil is also the surface soil at section 2 (BEG sampling locality 83040901) (fig. 12). At section 2 the surface soil has developed in two parent materials (table 6). The A and well-expressed Bt horizon (25 to 153 cm) formed in sandy clay to sandy clay loam sediments very similar to the Blackwater Draw Formation. The Stage II-III calcic horizon formed in gravelly alluvium. The calcic horizon appears genetically related to the upper portion of the soil. Similar soils in the region typically have such calcic horizons, as noted at other exposures described above. The abrupt boundary between the Bt and the calcic horizon is not unusual, as noted elsewhere, and the parent material change may enhance the abruptness.

Below the surface soils are undisturbed lacustrine sediments that bury older terrestrial sediments and soils. At section 2 the lake deposits overlie a soil with features typical of the well-developed soils of the region, including a Bt horizon with common clay films, 5YR hues, and prismatic structure. Limonite and manganese patches are also common.

Several radiocarbon ages are available from this section (Caran and Baumgardner, 1985). Four ages were determined on organic material from section 1: 660 ± 70 yr. B.P. (upper A horizon, 38 to 43 cm); 1,070 ± 130 yr B.P. (lower A horizon, 47 to 50 cm) (both samples from Unit 2 of Caran and Baumgardner, 1985); 4,070 ± 110 yr B.P.(lower Bt horizon, 85 to 90 cm); 6,490 ± 130 yr B.P. (Ab horizon, 110 to 115 cm) (the two latter samples from Unit 4 of Caran and Baumgardner, 1985). At section 2, a date of 18,680 ± 260 yr B.P. was determined on carbonate in the upper portion of the calcic horizon of the surface soil (2Bkt horizon, 170 to 180 cm; Unit 10 of Baumgardner and Caran, in press b)

Smith's Ditch

This large gully is located about 6 km southwest of Quitaque and is described by Caran and Baumgardner (in press) (fig. 1). One section was described at the north end of the gully (fig. 13, table 7), north of the deformed and faulted terrestrial and lacustrine sediments discussed by Caran and Baumgardner (in press) Another section (BEG sampling locality 84071001) (fig. 13) at about the middle reach of the gully and near BEG locality 83062401 of Caran and Baumgardner (in press), was also briefly examined. At the north end several soils are exposed in the gully. At the top of the section are recent eolian sediments locally up to 80 cm thick. The unit is highly variable in thickness and lithology with several laterally discontinuous units, including two weakly developed A horizons. The unit is quite young as indicated by fencing buried by the deposit. This part of the section was not described. Below the recent eolian material is a moderately developed soil that includes a Bt horizon with 7.5YR hues, clay films (in thin section), and weak prismatic structure. Below this soil is a thick, well-developed buried soil with 7.5YR to 5YR hues, common clay films on ped faces, and prismatic structure. This soil appears to correlate with one identified near the surface in the exposure examined along the middle reach of the gully. This is possibly Unit 2 of Caran and Baumgardner (in press) The soil examined at this section is well developed, though morphologically it is slightly weaker than the soils of the Blackwater Draw Formation. The soil also has formed under a surface sloping in toward the gully. This soil overlies lacustrine sediments more than 10 m thick (Units 3 through 10 of Caran and Baumgardner, 1984).

Two radiocarbon ages are available from Unit 2 of the section studied by Caran and Baumgardner (in press) A date of 1,000 ± 70 yr B.P. was secured from the top of the soil in the unit and a date of 2,970 ± 70 yr B.P. was determined on material from near the base of the soil. As noted, however, it is unclear how this unit relates to the

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soil in the upper portion of the middle reach of the gully. Caran and Baumgardner (1985) report four radiocarbon ages on sediment samples taken from the thick lacustrine deposits exposed along the middle reach of Smith Ditch. From the top down, the dates are: 14,920 ± 490 yr B.P. (Unit 5); 11,560 ± 990 yr B.P. (Unit 6); 18,650 ± 1,350 yr B.P. (Unit 8); and 23,240 ± 2,330 yr B.P. (Unit 9).

DISCUSSION

A number of observations can be made concerning the soil-stratigraphic relationships of the units investigated as part of this study. On the High Plains the Blackwater Draw Formation is clearly composed of a number of individual deposits, each strongly modified by pedogenesis. The original thickness and total number of these units in the Blackwater Draw Formation is difficult to determine. All of the buried deposits have unconformable contacts with adjacent units, indicating erosion between periods of deposition. This also is suggested by the varying number of buried units in the different exposures of the Blackwater Draw Formation. Seven units, denoted by six buried soils and the surface soil, have been identified in an exposure near Amarillo (Allen and Goss, 1974), suggesting a minimum number of depositional events for the Blackwater Draw Formation. It is noteworthy that although the number and thickness of buried units in the formation may vary from section to section, morphology of the soil in the surface unit is generally similar in any given area. The soil tends to be 1.5 to 2.0 m thick, if not eroded, and to have a very well-developed Bt horizon with 5YR hues, common clay films on ped faces, prismatic structure, and a Stage III calcic horizon. The upper boundary of the calcic horizon is commonly abrupt. This is apparent in many other exposures described for this project, and is also suggested by the county soil surveys. There is no known site where the surface soil of the Blackwater Draw Formation is less than about one meter or is observed to pinch out against an identical unit. This suggests that uppermost deposits of the Blackwater Draw Formation may be continuous across the High Plains.

The Quaternary stratigraphy of the Rolling Plains contrasts with that of the High Plains because in the Rolling Plains some strata are deformed owing to subsidence, and

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lacustrine and alluvial sediments are present in addition to eolian material. Buried and surficial eolian deposits of both regions, however, are similar texturally and pedologically.

Available data suggest that the following general model of the Quaternary geologic history of the Southern High Plains is also applicable to the Rolling Plains in the study area. The geologic history of the area seems to be cyclic. Each cycle begins with eolian deposition, is followed by nondeposition with landscape stability and soil formation, and ends with erosion. Wind has probably been the dominant geomorphic and sedimentologic agent of the region throughout the late Cenozoic; however, at any given time wind erosion and sedimentation probably operated together along with pedogenic processes, as is happening today. During the course of a single cycle, however, different processes would dominate from time to time. During deposition, material derived from the Pecos Valley would blow onto the High Plains surface and out across the western Rolling Plains at a rate faster than erosion or pedogenesis. The result would be the deposition of a more or less continuous sheet of eolian sediment across the area. Sedimentation would then slow and erosion would be minimal. During this period of landscape stability a soil would form in the eolian sheet. Locally, during phases of landscape stability, lacustrine sediments would accumulate in depressions on the surface. Enough time would elapse to allow formation of a well-developed soil similar to the surface soil of the area. Erosion by wind deflation would follow, destroying the lateral continuity of the eolian sediment in many areas. In other places the more easily eroded A horizon would be removed down to the more resistant Bt horizon. The erosion would occur immediately before or perhaps be coeval with early stages of the subsequent depositional event. Deflation in one region of the Southern High Plains could result in deposition in a downwind area. After several such cycles the result would be a stack of sedimentary units disconformably overlying one another, varying in number from one section to the next, but with each unit exhibiting similar pedologic properties. At the present time the Southern High Plains is well into the phase of the cycle dominated by landscape stability and soil formation, following at least six complete cycles.

On the western Rolling Plains the above-described model probably operates, although modified by several local factors. The region had a high degree of relief relative to the

High Plains during the Quaternary, resulting in stream sedimentation, erosion, and the interfingering of alluvial sediments with eolian material. Dissolution of evaporites in the bedrock has also resulted in the deformation of the Quaternary deposits, locally producing basins that accumulated lacustrine deposits.

AGE ESTIMATES: PEDOLOGIC FEATURES AND THERMOLUMINESCENCE PROPERTIES

To provide some estimate of the age of the upper portion of the Blackwater Draw Formation, pedologic data from the unit were compared with rates of Holocene pedogenesis and samples were dated by TL techniques The pedologic development of the surface soil at the Blackwater Draw type section was compared with late Holocene soils at the Lubbock Lake archaeologic site. Comparisons were made on the basis of B-C values, $CaCO_3$ content expressed as gm/cm^3/calcic-horizon thickness, and characteristics of clay-film coatings observed in thin section. The calculations from the type section were plotted along regression lines calculated by Holliday (1982) for the late Holocene soils (fig. 14). These plots provide an estimate of the minimum length of development of the surface soil at the type section for reasons discussed earlier. The results suggest that the surface soil at the type section has been forming for a minimum of 10,000 years.

Five TL ages have been determined from sediments of the Blackwater Draw Formation thus far, with ambiguous results. Two TL analyses were run on samples whose approximate ages are known. The samples are associated with a dune 2 km north of the Lubbock Lake site. Organic material from the A horizon of the lowermost of a sequence of buried soils in the dune yielded a radiocarbon age of 33,750 ± 3600 yr B. P. (Holliday, 1985a), which is in good agreement with other dates from the dune. A TL sample from the same horizon yielded an age of 42,720 ± 470 yr B.P. (Alpha 806). The TL method seems to work well on these eolian sediments. However, a TL sample from Blackwater Draw buried by the dune yielded an age of 28,600 ± 4000 yr B.P. (Alpha 918). Judging by the radiocarbon ages and pedologic development of soils in the dune, the Blackwater Draw Formation was buried by the dune 40,000 to 50,000 yr B.P.

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Interpreting the results of just two analyses is difficult, but one interpretation could be that the dune material provides more reliable TL ages than the Blackwater Draw Formation. Nevertheless, the TL dates seem to provide the correct order of magnitude of the ages.

Three samples for TL dating were taken at the Blackwater Draw Formation type section. The provenance of the first sample is uncertain. It probably came from soil b4 and was taken relatively near the surface. The sample yielded an age of 90,000 ± 12,000 yr B.P. (Alpha 919). A sample from the Btk1b1 horizon yielded an age of 118,000 ± 14,000 yr B.P. (Alpha 1750) and a sample from the Btkb2 horizon was dated at greater than 270,000 yr (Alpha 1751). The date of 90,000 yr B.P. is considered questionable because of its uncertain provenance and because of the possibilities of young fine-grained material being translocated into the soil from the surface. The older TL age estimates may be reasonable minimal dates and are evaluated in the following section.

GEOCHRONOLOGY

Data derived from this study combined with other information allows for some initial estimates of both the ages of the Quaternary sediments described in this report and the duration of certain geologic events or processes. On the Southern High Plains it is now clear that the extensive eolian deposit that blankets the region, the Blackwater Draw Formation, has been accumulating during much of the Quaternary. At the Blanco Formation type section at least one cycle of eolian sedimentation and soil formation occurred prior to deposition of the 1.4 m.y. Guaje ash. At least two full cycles occurred after this time. Data from the Tule Basin locality demonstrates that at least one cycle occurred before 0.6 m.y. and probably at least one full cycle occurred later.

The duration of each cycle of deposition-pedogenesis-deflation is difficult to determine. It seems reasonable to assume that all cycles were of approximately the same duration because of the relatively uniform thickness of each deposit and the remarkable similarities between soils formed in each deposit. The two TL ages from the first two buried soils at the Blackwater Draw type section suggest that each cycle may

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Matuyama ~750 ka

Malmarvel cycles — NOTE

last on the order of 100,000 years. Further evaluation of these dates and their geologic implications cannot be attempted until more data are available.

Some understanding of the length of the depositional-pedological cycles can be gained from estimates of the time elapsed since the last major depositional episode, which produced the sediments at the surface of the region. There are several lines of evidence for this. The pedologic data from the surface soil at the Blackwater Draw type section suggest that pedogenesis has taken place for at least 10,000 years. Radiocarbon ages from the dune north of the Lubbock Lake site (Holliday, 1985a), which rests on the Blackwater Draw Formation, indicate that the formation was buried as much as 50,000 yr ago. Finally, lake sediments at a site north of Lubbock, which unconformably overlie the Blackwater Draw Formation, and associated pedologic features have been dated to about 10,000 yr B.P. The basin containing the sediments was eroded into the Blackwater Draw Formation after considerable development of soil in the surface of the unit. If the upper several meters of the Blackwater Draw Formation on the central Llano Estacado is a single, laterally discontinuous deposit, the above data indicate that it has been in place at least several tens of thousands of years and perhaps as much as 50,000 years. This and the limited TL information further hint that a complete cycle of deposition-pedogenesis-erosion, at least for the upper units of the Blackwater Draw, may last 100,000 years.

bld on soils?

On the Rolling Plains the only direct age-control available is from the radiocarbon dates of Caran and Baumgardner (1985) listed earlier. Some age-estimates can also be derived from the soils described in the area. The thick sequences of eolian sediments and respective soils are probably related to the Blackwater Draw Formation. Therefore, the soils formed in at least the upper portion of the eolian sediments on the Rolling Plains are probably of similar age to those previously discussed for the High Plains. This provides a gauge with which to evaluate the radiocarbon dates from the sections described in the Rolling Plains.

One of the most recent sedimentary sequences studied on the Rolling Plains is that at Henson's Ditch, section 15D. This entire sequence and the pedologic characteristics of the zone from 190 to 360 cm are remarkably similar to Holocene sediments in the

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valley fills on the High Plains. Both are characterized by clayey, organic-rich early Holocene eolian sand with a moderately developed soil (Holliday, 1985 a, b). The two radiocarbon dates further corroborate this interpretation. The age of about 1,300 yr B.P. from deep in the buried A horizon in the upper section is similar to ages from the buried A horizon of the late-Holocene Lubbock Lake soil at the Lubbock Lake site (Holliday and others, 1983), and the date of about 9,600 yr B.P. from the organic-rich lacustrine sediments is in the middle of the range of numerous ages of similar, very early Holocene deposits at Lubbock Lake (Holliday and others, 1983). Locally, there appears to have been erosion in the late Pleistocene followed by lacustrine sedimentation in the channels in the early and middle Holocene. Eolian deposits then covered the area in the late Holocene.

At section 15B, the two dates of less than 180 and about 850 yr B.P. are to be expected from the A horizons of surface or very recently buried soils in the region regardless of the length of pedogenesis (Martel and Paul, 1974; Holliday, 1982; Evans, 1985). The date of about 1,900 yr B.P. on the 2Btkb2 horizon, however, is entirely inconsistent with the pedologic evidence. Above this zone are two soils, the surface soil and b1, that are strongly developed, similar to the soils of the upper Blackwater Draw Formation, and have undoubtedly had more than a few thousand years to form. It is unclear what organic fraction of this sample was dated. In the field the horizon did not appear to have much organic matter, a conclusion confirmed by a determination of 0.7% organic carbon content.

At the Turkey railroad cut the four radiocarbon ages from section 1 are in agreement with the pedologic data. The parent material for the upper soil began to fill the shallow swale sometime after about 6,500 yr B.P. Soil formation probably began as the sediments slowly aggraded throughout the middle and late Holocene. The dates of about 660 and 1,100 yr B.P. from the upper and lower portions of the A horizons, respectively, are, again, the sorts of ages expected from A horizons of surface or recently buried soils.

The date of about 18,700 yr B.P. for the calcic horizon of the surface soil at section 2 of the railroad cut is more problematic. Radiocarbon ages on pedogenic carbonate are almost always questionable (Evans, 1985), a point noted by Caran and Baumgardner (1985). This is particularly a problem in places where the parent material for a soil or the ground water has older carbonate. This does not appear to be a problem at this site; rather, the date was probably obtained on a mixture of carbon representing the total period of carbonate accumulation. In a surface soil such a date provides a minimum age for the duration of soil formation. This interpretation is consistent with the pedologic properties of the surface soil, which indicate that its age is of the same order of magnitude as the surface soil of the Blackwater Draw Formation.

At Smith Ditch, two prominent soils are exposed at the north end of the gully. The upper soil buried by historic eolian sediment has morphologic similarities to the Lubbock Lake Soil at the Lubbock Lake site (Holliday, 1985c), which formed throughout most of the late Holocene. The upper soil at Smith Ditch, therefore, is considered to have developed during a significant portion of the Holocene. The lower, buried soil at the north end of the gully is morphologically much better developed than the upper soil and has probably had a considerably longer time to develop. Morphologically it is slightly weaker than the soils of the Blackwater Draw Formation. This could indicate that the soil is somewhat younger than the surface soils of the High Plains or that the parent material is of the same age, but the soil is not as strongly developed because it is forming under a sloping surface. In either case the soil probably began forming in the late Pleistocene. This indicates that the radiocarbon ages of about 1,000 and 3,000 yr B.P. from what appears to be the same soil along the middle reach of the gully are falsely young. As noted, however, the exact relationship of the radiocarbon samples to the sections examined as part of this study remains unclear. Evaluating the dates from the lake sediments is also difficult because the dates are not in proper stratigraphic order and because of the possibility that the soil above the lake beds is the equivalent of the surface soil of the Blackwater Draw Formation. These radiocarbon ages may be minimal ones.

The age estimates from the Rolling Plains indicate that deformation of the beds underlying the thick lacustrine sections observed at the Turkey railroad cut and Smith Ditch occurred by at least the late Pleistocene and perhaps earlier. The lacustrine

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sedimentation took place prior to the last significant phase of eolian sedimentation, occurring in the late Pleistocene. This event probably related to the last of such events on the High Plains, left a blanket of fine-grained deposits across the western Rolling Plains, and provided the parent material for the well-developed surface soils of the region.

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Table 1. Soil descriptions, Blackwater Draw Formation type section (fig. 1).

Profile Bw. Dr. Fm. Type Section Profile 1

Page 1 of 1

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
Fill	0-33										
A	33-50	5YR3/4	5YR3/3	SC (SCL+)	2csbk		f		non	cw	
BAt	50-63	5YR3/4	5YR3/3	SC (SCL++)	1cpr 2csbk	h			non-se	cw	
Btk1	63-95	5YR3.5/6 5YR7/4 (ped faces with carb.)	5YR3/4 5YR4/4	SCL	2cpr 2cabk	h			se es	cw	common v. fine films and threads of carb.; many thin clay films.
Btk2	95-127	5YR+3/6	5YR+3.5/4	SCL	2cpr 2cabk	h			non-se es	cw	Few threads and films of carb.; many thin clay films.
Btk3	127-149	5YR+3/8	5YR+3/6	SCL	3cpr 2cabk	h			non-se ev	aw	V. few threads and films; common thin clay films.
Bk1	149-215	5YR6/4 (matrix) 7.5YR8/2 (max. carb.)	5YR5/6 (matrix) 7.5YR7/4		m	h			ev ev	gw	Stage III; 60% carb. bodies and concretions; few burrows.
Bk2	215-242	7.5YR+5/8 (matrix) 7.5YR8/3 (carb.)	5YR5/7 7.5YR7/4	L	1csbk		f		ev	cw	30% carb. bodies (no thin sections).
Bk3	242-290	7.5YR+5/8 (matrix) 7.5YR8/3 (carb.)	5YR5/7 7.5YR7/4	L	1csbk		f		es	gw	Less than 20% carb. bodies and concretions; groups of carb. bodies and concretions occur in distinct zones.

NOTE: c. 5-10 m east of this profile; carb. in Bk2 and Bk3 occurs as distinct bodies 5-10 cm vert. and 2-5 cm horiz. Bodies equal 20-30% of horizon.

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Table 1(cont.) Soil descriptions, Blackwater Draw Formation type section (fig. 1).

Profile Bw. Dr. Fm. Type Section Profile 2

Page 1 of 1

Horizon	Depth cm	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
equiv. of lower profile 1.	0-110										
Btk1b1	110-155	2.5YR-3/6 (matrix) 5YR8/3 (carb)	2.5YR3/4 5YR7/4	SC (SCL+)	3cabk m	h			e ev	ci	Max. carb. 119-121 cm; w/tongues of max carb producing irreg. boundaries; Stage III: Carb. is massive(same area); common thin clay films.
Btk2b1	155-200	2.5YR-3/6 (matrix) 5YR8/3 (carb.)	2.5YR3/4 5YR7/4	SC (SCL+)	1mpr 3mabk	h			e ev	cw	Stage II-III. Carb. (50%) as large (50-70mm) patches and bodies; many fine clay films; very few 1-2mm Mn? patches.
Btk3b1	200-220	5YR+4/8 (matrix) 5YR8/2 (carb.)	5YR+3/6 5YR7/4	SCL	2cabk	h			e ev	ci	Stage II.; carb. occurs as 30-50% (20-50mm) patches and bodies.
Btk1b2	220-295	2.5YR3/6 (matrix) 5YR8/2 (carb.)	2.5YR3/6 5YR7/4	SC (SCL+)	3mabk m	h			non-slight ev	aw	Carb. occurs as veins 5-15 cm wide and up to 50cm deep from overlying horizons; also few sub horiz veins 1 cm thick; massive carb; many to cont. clay films; few 1-4 m dendritic Mn?

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Table 1(cont.) Soil descriptions, Blackwater Draw Formation type section (fig. 1).

Profile Bw. Dr. Fm. Type Section Profile 3

Page 1 of 1

Horizon	Depth cm	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
0 equiv. to base #2?											
Btk1b3	0-27	5YR+5/8 (matrix) 5YR8/4 (carb.)	5YR+5/8 5YR7/4	SCL	1mpr 2msbk	h			e-es ev	cw	
Btk2b3	27-57	2.5YR-4/8 (matrix) 5YR8/3 (carb.)	2.5YR-4/8 5YR7/4	SCL	1mpr 2msbk	h			e-es ev	cw	
Btk3b3	57-110	5YR8/4 (matrix) 5YR9/1 (carb.)	5YR8/4 5YR7/6	SCL	1mpr 2msbk	h			e-es ev	cs	
Btk4b3	110-164	5YR5/8 (matrix) 5YR8/3 (carb.)	5YR5/8 5YR7/4	SCL	1mpr 1msbk	h			s-es ev	cs	
Btk5b3	164-195	5YR5/8 (matrix) 5YR8/4 (carb.)	5YR5/8 5YR8/4	SCL	1mpr 1msbk	h			s-es ev	gw	
Bktb3	195-250	5YR9/1	7.5YR8/3	carb	m	h			ev	cw	Stage III; only locally present.
Btb4	250-315	5YR+4/8	5YR+4/8	SCL	1mpr 2sbk	h			pedfaces s ped int. none		Very few carb. bodies 2.5 cm diam. Rare Mn nodules on ped. faces. Thin section collected.

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Table 1(cont.) Soil descriptions, Blackwater Draw Formation type section (fig. 1).

Profile Bw. Dr. Fm. Type Section Profile 4

Page 1 of 1

Horizon	Depth cm	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
Top of		probable equiva~~lent~~of Btb4 at profile 3.									Most carb. coats and films are on ped faces
Btk1b~~5~~4	0-75	5YR4/8 (matrix) 5YR8/2 (carb.)	5YR3/6 5YR7/3	SCL	1cpr 2cabk	h			non-se ev	cw	30% carb films and coatings, few 1-5 cm diameter nodules. Stage II. Many to continuous thin clay films on ped faces.
Btk2b~~5~~4	75-110	5YR+4/8 (matrix) 5YR8/1 (carb.)	5YR3/6 5YR7/3	SCL+	2cpr 3cabk	h			non-se ev	cw	20% patches and threads carb. Stage I-II Cont. thin clay films.
Btk3b~~5~~4	110-155	5YR+4/8 (matrix) 5YR8/1 (carbl)	5YR3/6 5YR7/3	SCL+	2cpr 2csbk	h			non-se ev	cw	10% carb. films on ped faces. Many thin clay films on ped faces.
Btk4b~~5~~4	155-225	5YR+4/8	5YR3/6	SCL	1cpr 2csbk	h			non-se		Less than 10% carb films and threads on ped faces.
Auger		NOTES:	~40cm below profile, sandy, C horizon? ~90cm, buried Bt? ~100cm, sandy and paler in color 120-130cm, pale brown medium sand 130-145cm, buried Bt?								

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Table 1(cont.) Soil descriptions, Blackwater Draw Formation type section (fig. 1).

Profile Bw. Dr. Fm. Type Section Profile 5

Page 1 of 1

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
A	0-26	7.5YR3/4	7.5YR2/3	fSL	1msbk g 2mg	so			e	cs	
BA	26-51	7.5YR3.5/4	7.5YR3/4	fSL+	1csbk	sh			e	cs	Some very weak prisms.
Bw	51-75	7.5YR+4/4	7.5YR+3/4	fSL+	1mpr 2msbk	sh			es	cw	Few 1-2 mm clasts of carb., probably slope wash.
Btk1	75-101	5YR5/6	5YR4/6	SCL	1msbk	sh			ev	cw	10% threads of carb. common 1-3 mm clasts of carb.; some with coating of secondary carb.; weak Stage I.
		↖ These two may be one thick horizon. ↙									
Btk2	101-120	5YR4/6 (matrix)	5YR4/6 (matrix)	SCL	1msbk	sh			ev	ci	Weak Stage I. 10% threads of carb.; common 1-3 mm clasts of carb., some w/ coatings of 2ndary carb.
2Btk3	120-155	5YR4/6 (matrix) 5YR8/3 (carb.)	5YR4/6 5YR6/4	SCL+	1msbk			f	ev	ci	Many films and threads of carb.; v. common pockets & lenses of 1-5mm carb. clasts, commonly coated &/or cemented by 2ndary carb.; weak Stage II.
		NOTE: Horizons 75-155 dip to east (towards Blackwater Draw). Soil 0-155 is probably Holocene Valley fill. ≈Lubbock Lake soil.									
3Btkb4	155-225	5YR+4/8 (matrix) 5YR9/1 (carb.)	5YR+3/6 (matrix) 5YR8/3 (carb.)	SCL+	1cpr 2csbk		firm		nonse ev	aw	Blackwater Dr. Fm.; Stage I carb., ~20% films, threads along ped faces.
K1b4	225-385	5YR9/1	5YR8/2		m				ev	ai	Upper ±10cm has some laminar structure; common 2-5 mm carb. concretions.
K2mb4	385+										Ogallala Caprock?

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Table 2. Soil descriptions, Tule basin (fig. 1).

Profile Tule Basin Section Profile 2

Page 1 of 1

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
2C		7.5YR8/1	7.5YR7/3		m						Ash layer, varies in thickness from a feather edge to ~30cm Ash occurs in irregular masses; weathered
3Bt1b	0-50	7.5YR6/3	7.5YR4/4	SiL	1cpr 3cabk	h			non	cs	Structure is coarsest near the top. Few very thin clay films on ped faces (maybe bleached out A?)
3Bt2b	50-75	7.5YR5/5	7.5YR4/6	SiL	1fpr 3msbk	h			non	cw	Less than 10% threads and film of silica on ped faces and lining root channels. Probably a mixture of Tule Fm. lake beds and 2ndary carb.. Common thin clay films on ped faces.
3Ck	75-90	7.5YR7/4	7.5YR7/4	SiC	m	h			ev	d	Stage VI

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Table 2 (cont.) Soil descriptions, Tule basin (fig. 1).

Profile Tule Basin Section Profile 1

Page 1 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
A	0-17	7.5YR5/3	7.5YR3/3	SiCL	1msbk 3fgr	sh			es	cs	10-20% granules are pinkish in color as if brought up from the B horizon. (Bioturbation?)
B/A	17-40	7.5YR6/3	7.5YR4.5/4	SiC	1msbk 3fgr	sh			es	cs	Very weak prisms evident; granules seem to be a mixture of overlying A and underlying B.
Btk1	40-67	7.5YR5/6 (matrix) 7.5YR9/1 (carb.)	7.5YR4/6 (matrix) 7.5YR7/4 (carb.)	SiC	1mpr 2msbk	sh			es ev	ci	20% 1-20cm bodies soft $CaCO_3$; $CaCO_3$ films on ped faces and lining root channels (profile is benched at 67 cm.)
Btk2(b?)	67-147	7.5YR4/6 (matrix) 7.5YR9/1 (carb.)	7.5YR4/6 (matrix) 7.5YR8/3 (carb.)	CL	1msbk m (pockets of granular material)	h sh			e ev	cw	Massive Stage III carb with tongues of B material occurring in zones 10-30 cm wide and up to 70 cm deep; in some areas of roadcut massive caliche begins as high as B/A horizon; tongues of B material begin at Btk1; few very thin clay films. ~50% of tongues of B material connect w/underlying B horizon.
Btk3(b?)	147-170	7.5YR5.5/4 (matrix) 7.5YR9/1 (carb.)	7.5YR4/4 (matrix) 7.5YR8/2 (carb.)		2mpl m	vh eh			non ev	ai	Similar to B horizon above but only 30-40% carb. here, in masses up to 40 cm across; common thin Mn coats. 30-40% 1-2 mm granules of carb. throughout B horizon.

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Table 2 (cont.) Soil descriptions, Tule basin (fig. 1).

Profile Tule Basin Section Profile 1 continued

Page 2 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
Bk (b?)	170-208	7.5YR6/4 (matrix) (plate interior)	7.5YR5/6 (matrix)		3cpl	eh			non	ai	Carb. occurs as continuous lens 1-2 mm thick all across plate; low bulk density material (ash).
2Bw (b?)	208-275	7.5YR7/3	7.5YR4/6	fSL no clay	m	sh-h			non	ai	Low bulk density, contains some volcanic ash; very weakly sbk. 10% silica threads along root channels and as veins. *2 platy zones together occur across the outcrop face in a broadly undulating zone.

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Table 3. Henson's farm, soil descriptions (fig. 1)

Profile Henson's farm, BEG Site No. 83040601 (stop 15B)

Page 1 of 3

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
	0-37										Historic eolian material.
A	37-65	5YR3/4	5YR3/3	SCL	2msbk	sh			non	cs	Radiocarbon-dated: top, bottom.
Bt	65-81	5YR3/6	5YR3/4	SCL+	1mpr 2msbk	h			e	cw	Many thin clay films.
Btk1	81-122	5YR3/6 (poor match)	5YR3/6		1cpr 2msbk	h			Matrix e Carb. es	cw	Few films, threads of carb. Many thin clay films.
Btk2	122-141	5YR6/4 (matrix) 5YR8/3 (carb.)	5YR3/6 (matrix) 5YR7/4 (carb.)	No texture	mass.	h			Matrix es Carb. ev	cw	Many small bodies of carb. Stage II; many thin clay films.
Btk3	141-162	5YR5/6 (matrix) (carb. not done.)	5YR3/6 (matrix) (carb. not done.)	fSL	mass.	h			Matrix e Carb. ev	cw	Few small bodies of carb. Stage I; many thin clay films.
Btk4	162-240	5YR6/4 (matrix) 5YR9/1 (carb.) (Maximum color range. some laminae intermediate.)	5YR4/6 (matrix) 5YR8/3 (carb.)	not done	mass.	h			Matrix es Carb. ev	aw	Many bodies and coats of carb. Stage II. Faint horizontal laminae, 1-2 cm thick.
C	240-262	5YR6/6	5YR4/8	fS	1msbk	sh			es	cw	TL and bulk samples collected.
Btkb1	262-320	5YR+4/8 (matrix) 5YR9/1 (carb.)	5YR3/6 (matrix) 5YR8/3 (carb.)	CL	1cpr 1msbk	h			Matrix e Carb. es	aw	Stage I. Few bodies; coats of carb. Many v. thin clay films.
2Btkb2	320-375	2.5YR4/4 (matrix) 2.5YR9/1 (carb.)	2.5YR3/4 (matrix) 2.5YR7/4 (carb.)	C	2mpr 3mabk	h			Matrix e Carb. ev	cw	Radiocarbon dated:top. "Purple zone". Structure and clay films probably from pm. Clay films pervasive. Common carb. nodules. Bulk sample collected.

Table 3(cont.) Soil descriptions, Henson's farm (fig. 1).

Profile Site No. 83040601 continued.

Page 2 of 3

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
3Cb2	375-434	2.5YR4/4 (clay) 5YR4/8 (sand)	2.5YR3/4 (clay) 5YR3/6 (sand)	C	S:sg C:1cly abk (some peds contorted)	S:1 C:h			S:non Cl: non-se carb. ev	ai	Few carb. nodules in clay.
4Cb2	434-470	5YR5/6	5YR4/6		sg-v1mpr	sh			non-e	cw	Bulk sample taken; also TL 3,6 sample.
4Btk1b3	470-497	5YR5/6	5YR4/6	SCL	1mpr 2msbk	h			non	gs	Few threads and bodies of carb; bulk sample taken; many,v.thin clay films.
4Btk2b3	497-527	5YR6/6	5YR5/6	L	M-1mpr	h			non-es	cw	Pervasive finely divided carb. and few carb. bodies; bulk sample taken; common v. thin clay films.
4Btk1b4	527-560	5YR5/6	5YR4/6	SCL	1mpr 2msbk				es	cw	Common small bodies of carb. Stage I; bulk samples taken; common, thin, clay films.

NOTE: 2Btkb2 and 3Cb2 highly variable in thickness, to 0 cm minimum. Thin beds of sand and clay alternate within 3Cb2, beds 4-6 cm thick (generally). Clayey beds in 3Cb2 contorted, owing to loading or heaving.

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Table 3(cont.) Soil descriptions, Henson's farm (fig. 1).

Profile Site No. 83040601 continued.

Page 3 of 3

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reac-tion	Bound-ary	
		Dry	Moist			Dry	Moist	Wet			
4Btk2b4	560-613	5YR+5/6 (matrix) (poor match) 5YR8/3 (carb.)	5YR+3/6 (matrix) 5YR7/6 (carb.)	C	2fpr-3Fabk	h			Matrix ef Carb. ev	cw	Stage II; common carb bodies; continuous thin clay films. (p. m. ?); bulk sample taken.
		Unit thins markedly within ~40 m to the south, then resumes constant thickness ~15 m farther south.									
4Btk3b4	613-665	5YR6/6 (matrix) 5YR9/1 (carb.)	5YR4/6 (matrix) 5YR7/3 (carb.)	fSL lots Si	1mpr 2msbk	h			Matrix es carb. ev	cw	Stage II; common carb. coats and bodies; bulk sample taken.
4Btkb5	665-684	2.5YR-4/6 (matrix) 2.5YR9/1 (carb.)	2.5YR-3/4 (matrix) 2.5YR7/3 (carb.)	CL	1mpr 2msbk	h			Matrix es carb. ev	cw	Stage II; common carb. bodies; bulk sample taken.

Table 4. Soil descriptions, Henson's farm (Stop 15D) (fig. 1).

Profile Henson's Farm, BEG site no. 83040909 (Stop 15D)

Page 1 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
C	0-190										Largely unconsolidated eolian deposits, perhaps including one or more thin discontinuous A horizons. Includes discontinuous lenses of sand and gravel to the south.
Ab1	190-230	7.5YR3/4	7.5YR2/3	L	1msbk		vf		es	cs	
Bwb1	230-267	7.5YR4/6	7.5YR+3/4	L	1cpr 2csbk	sh			es	cs	Very few faint films and threads of carb.
Btk1b1	267-295	5YR6/4	5YR5/4	L	2cpr 2csbk	sh			es (matrix)	cs	Common faint films and threads of carb.
Btk2b1	295-341	5YR6/4	5YR4/6	fSL	2cpr 2csbk	h			es (matrix)	cw	Common faint films and threads of carb. Bulk and thin section samples collected.
Btk3b1	341-360	5YR6/4	5YR4/4	L	1msbk-m	h			es (matrix)	aw	Common small bodies of carb., and few faint films and threads of carb. Bulk sample collected.
C1b1	360-372	7.5YR7/1 (10YR7/1?)	10YR3/2	SiCL	m-1csbk	sh			none	gw	This zone varies in thickness from 0-20 cm. Common filled (with carb.) and unfilled root channels.

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Table 4 (cont.) Soil descriptions, Henson's farm (Stop 15D) (fig. 1).

Profile BEG site No. 83040909 continued.

Page 2 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
C2b1	372-587	7.5YR5/1	10YR2/2	L	1fpr 3mabk	h			non-se	ci	This zone varies in thickness from 0-220 cm. Common carb. film threads and bodies in upper 20cm. Samples collected from upper 20 cm and lower 20 cm.
Profile continues 15m south.											
Btb2	587+	5YR4/6	5YR4/6	SCL+	2cpr 2cabk	h			non-se		Buried "Amarillo-like" soil, cut-out and filled by pond deposits. Few Mn concretions and many, thin clay films.

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Table 5. Soil descriptions, Turkey Railroad cut (fig. 1).

Profile Turkey R. R. Cut. Site no. 83040802 (ca. 180m S of bridge)

Page 1 of 1

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			10% HCl Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
	0-38										"Recent" eolian material and/or spoil.
A	38-50	7.5YR3/4	7.5YR2/3	SL	1msbk	sh			non	cw	Radiocarbon dated (2).
BAt	50-64	5YR3/4	5YR2/3	CL	1mpr 1msbk	h			non	cw	Common, thin clay films
Bt	64-100	5YR3/6	5YR3/4	CL	1mpr 2msbk	h-vh			non	cw	Many thin clay films. (continuous?)
Ab	100-145	7.5YR3/4	7.5YR2/3	SCL	1mpr 2msbk	h-vh			non	cw	Radiocarbon dated (2).
Btkb	145-255										Very common finely divided carb. best expressed from 180-240 cm depth.
Btb	255-355±										"Typical" Amarillo Bt.

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Table 6. Soil descriptions, Turkey Railroad cut (fig. 1).

Profile Turkey R.R. cut, BEG site no. 83040901 (ca. 25m s of bridge)

Page 1 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
Anthropogenic ?	0-25										'Recent" eolian material and/or spoil.
A	25-43	7.5 YR 3/4	7.5 YR 3/4	fSL	1msbk	h			non	cw	
BA+	43-68	5 YR 3/4	5 YR 2/4	SCL	1mpr 2msbk	h			non	cw	common thin clay films.
Bt1	68-85	5 YR 4/6	5 YR 3/4	CL	1mpr 2mabk	h	f		non	cw	many thin clay films (continuous?)
Bt2	85-118	5 YR 4/6	5 YR 3/4	SCL	2mpr 2msbk	h	f		non	cw	many thin clay films (continuous?)
Btk	118-153	5YR4/8	5YR3/6	SCL-	1mpr 2msbk	h	vf		matrix se threads es	ai	Few threads, films, and bodies of carb; many thin clay films
2Bkt	153-215	5YR7/4 (matrix) 5YR9/1 (carb. bds.)	5YR6/6 (matrix) 5YR 8/4 (carb. bds.)	no texture	m	h			matrix ev carb. ev	ai	Stage II-III. Some areas dominated by carb., other areas 30-50% carb. bodies (1-3 cm diam.). Gravel consists of lithoclasts of caliche, chert, and quartzite. Quartz sand locally abundant, becoming dominant parent material.
2Ck	215-240±			no texture						ai	Quartz sand and lithoclasts of lacustrine clay, with less gravel than in 2Bkt above.

--------------Lacustrine, fluvial deposits--not described (see measured section, Baumgardner and Caran (in press b)---------------

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Table 6 (cont.) Soil descriptions, Turkey Railroad cut (fig. 1).

Profile (cont) BEG site 83040901

Page 2 of 2

Horizon	Depth (cm)	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
4Btk1b2	0-40 cm	5YR5/6 (matrix) 5YR8/3 (carb. beds)	5YR4/6 5YR7/3 (carb. beds)	no texture	1fpr 2msbk	h			matrix e carb ev	cw	Thermoluminescence sample collected, 2-12 cm below top of unit. Common threads of limonite stains and small patches Mn stains. Stage II, 50% carb. beds, elongate. Bulk sample. Common thin clay films.
4Btk2b2	40-79	5YR4/6 (matrix) 5YR9/1 (carb. bds.)	5YR3/6 (matrix) 5YR8/3 (carb. bds.)	SL	1fpr 2msbk	h			matrix e carb ev	ab	Very few Mn, limonite stains. Stage II, 30% carb. beds, elongate w/distinct zone of accumulation in lowest 5 cm. Bulk sample. Common thin clay films.
4Btb2	79-110	5YR4/6	5YR3/6	SL	2msbk	h			e	cw	Bulk sample. Common thin clay films.

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Table 7. Soil descriptions, Smith's ditch (fig. 1).

Profile: Smith Ditch, N end of gully, BEG site no. 84062802.

Page 1 of 1

Horizon	Depth	Color		Texture	Structure	Consistence			Reaction	Boundary	
		Dry	Moist			Dry	Moist	Wet			
	Eolian deposits locally approximately 80 cm thick but highly variable. These deposits include at least two thin, laterally discontinuous buried A horizons, and incorporate strands of barb-wire fencing beneath one or both of these A horizons. Primary sedimentary structures (cross-beds) preserved throughout unit.										
AB	0-28	7.5YR3/4	7.5YR2/3	SL-	m- 1msbk	h			non	gs	Measured from top of AB horizon. Very weak pr on desiccated surf. Better developed pr to south.
Bw(t?)	28-56	7.5YR3/4	7.5YR2/3	SL+	1mpr 1msbk		f		e	gs	
Ab	56-88	7.5YR5/3	7.5YR3/4	fSCL	1mpr 1msbk	h			es (matrix and films)	cs	Common faint carb. threads and films, especially in lower half of horizon.
BAkb	88-126	7.5YR4/3 (matrix) 7.5YR8/1 (carb.)	7.5YR3/3 (matrix) 7.5YR6/3 (carb.)	Cl	1mpr 2msbk	h			es (matrix)	cw	Common, distinct films and threads of carb.
Btk1b	126-151	7.5YR5/4	7.5YR3/4	fSCL+	2fpr 2fsbk	h			se-e (matrix)	cw	Common, distinct films and threads of carb. Many, thin clay films on ped faces.
Btk2b	151-222	7.5YR+5/4	7.5YR+3/4	SCL+	2cpr 2csbk	h			non (matrix)	cw	Many threads and 50% films of carb. on ped. faces. Many thin clay films on ped. faces.
Btk3b	222-292	5YR5/6	5YR4/5	SCL	2cpr 2cabk	h			non (matrix)	ci	Common films and threads of carb. Continuous; thin clay films on ped. faces.

Overlies erosional contact on lacustrine beds.

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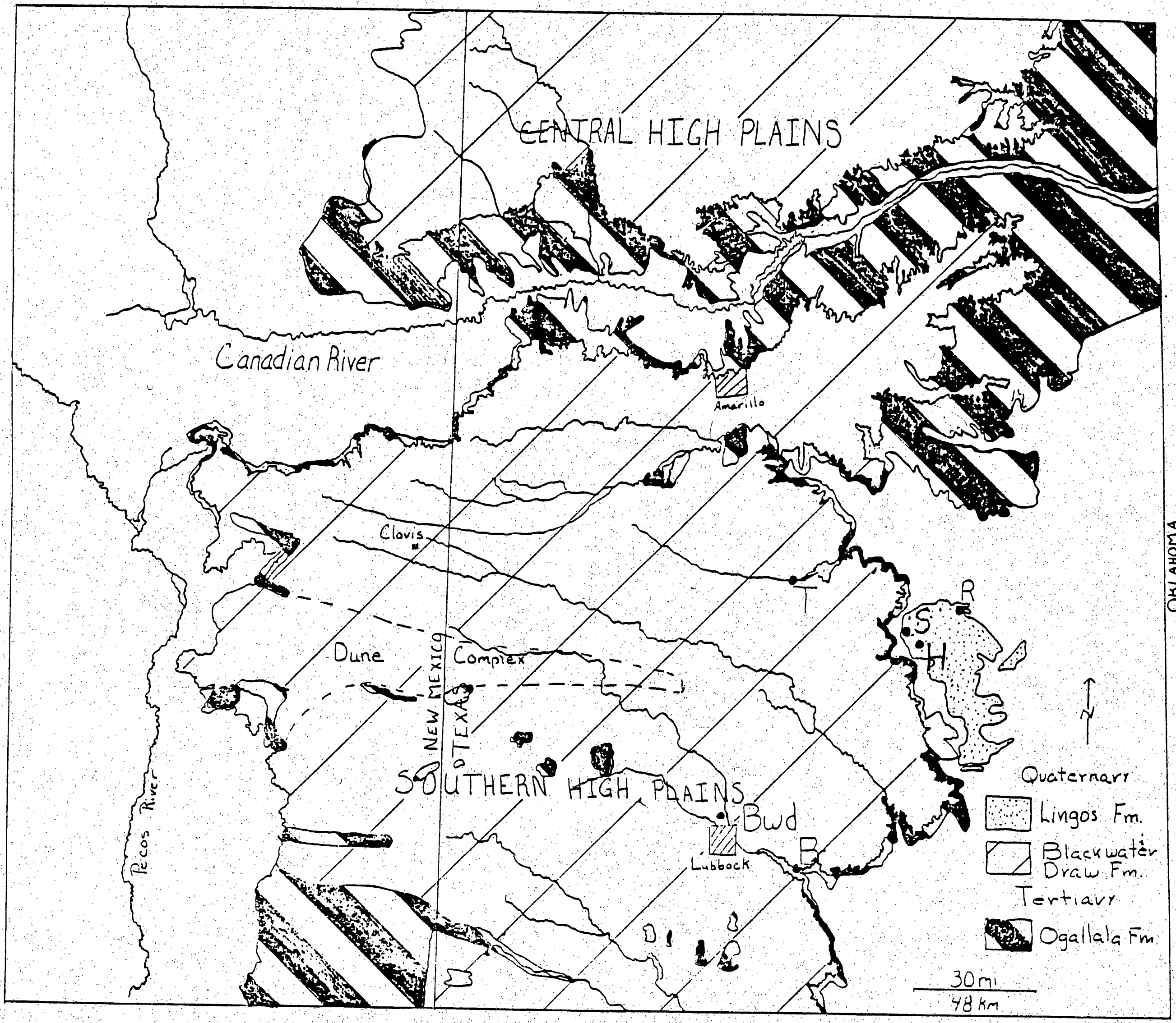

Figure 1. Distribution of the Ogallala and Blackwater Draw Formations in eastern New Mexico and the Texas Panhandle. Physiographic units of eastern New Mexico and the Texas Panhandle are shown. Bwd. locates the Blackwater Draw Formation type section. B. locates the Blanco Formation type section. T. locates tha Tule basin section. H. locates Henson's ditch section. R. locates the Turkey railroad cut section. S. locates Smith's ditch section.

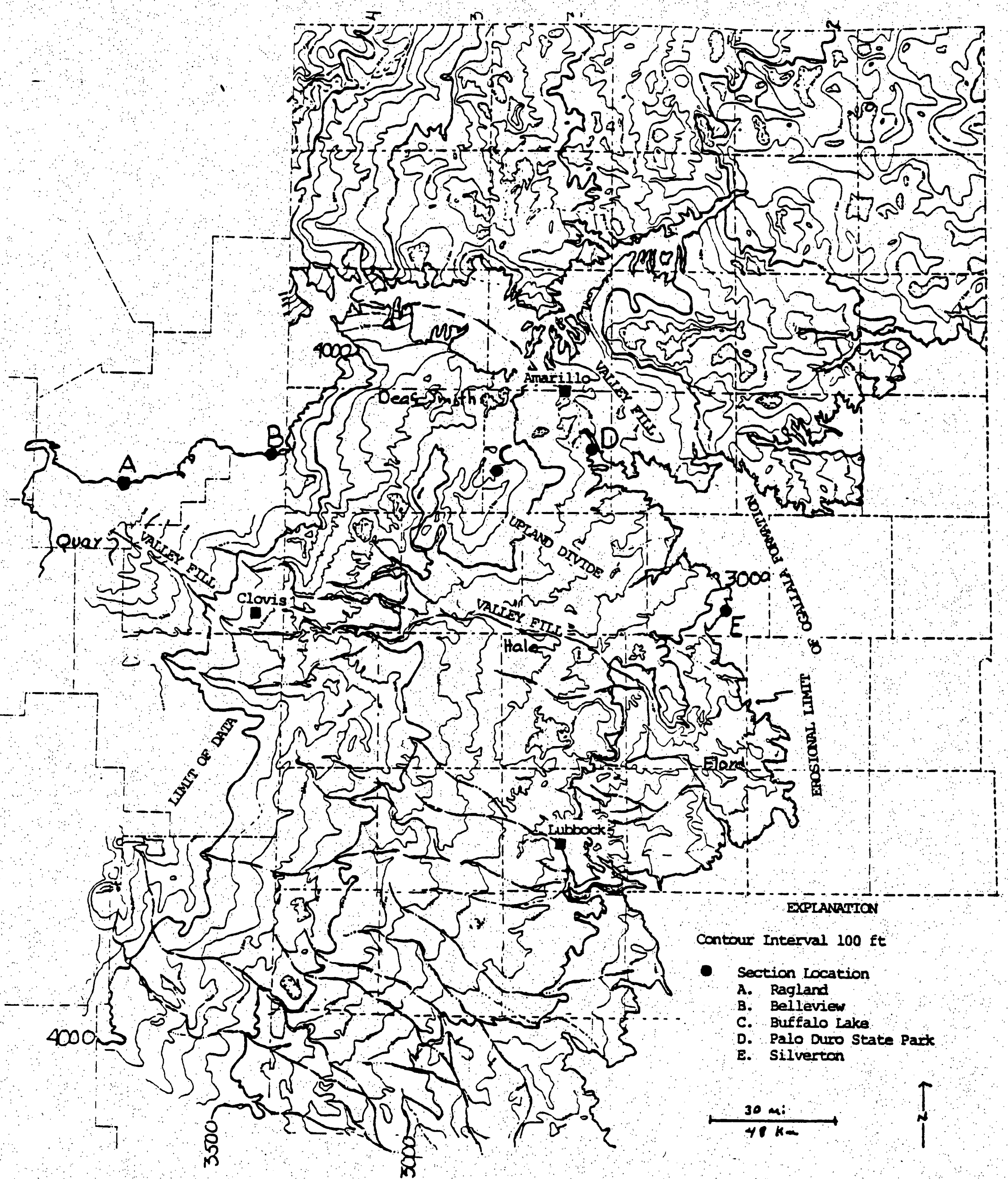

Figure 2. Structure-contour map on the base of the Ogallala Formation. Map derived from Knowles and others (1982) and Cronin (1969).

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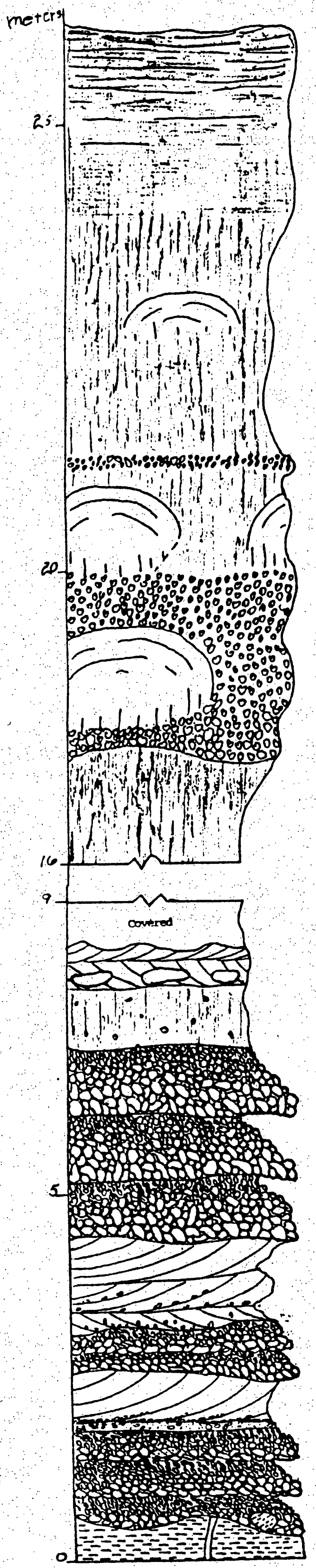

Ogallala Formation. Caprock caliche (calcrete).

Dense, brecciated, pisolitic, laminated Stage VI calcrete. Pinkish gray (5YR 8/1).

Calcrete nodules, uncemented sand, light brown (5 YR 6/4).

Dense calcrete mound, locally pisolitic, and brecciated. Dense part fractures conchoidally.

Nodular calcrete.

Gravel, 5 cm.

Calcrete mound is dense, locally pisolitic and brecciated. Dense part fractures conchoidally.

Nodular calcrete, crude vertical structure.

Calcrete mound is dense, locally pisolitic and brecciated. Dense part fractures conchoidally. Gravel clasts are rare compared to surrounding gravels.

Gravels occur in slightly cemented zones.

Carbonate cementation increases upward. Calcrete nodules in less cemented zones. Heavily cemented zones in part brecciated. Pisolitic, dense. Conchoidal fracturing with chalcedony veins.

Vertical zones of $CaCO_3$ cemented sand with dispersed pebbles.

Covered with slope wash.

Cross-bedded, pinkish gray, vuggy weathering sandstone. Irregular $CaCO_3$ cement.

Gravel, pebbles, cobbles dispersed in a light gray (5YR 5/6) fine sand matrix; case hardened at surface. $CaCO_3$ cement in vertical structure. Cemented (5YR 5/6) or cemented (5YR 4/4).

Pebble-cobble, clast-supported conglomerate. $CaCO_3$ cemented. Cobbles are volcanics, quartzites, schists, and gneisses. Fines are $CaCO_3$ cemented. Some originally open work gravels are partly to entirely filled with $CaCO_3$. Clasts are imbricated. Matrix is mostly pinkish gray (5YR 8/1).

Pinkish gray (5YR 8/1) $CaCO_3$ cemented medium sandstone.

$CaCO_3$ cemented pebble-cobble conglomerate

Low angle, tangential cross sets in pinkish gray (5YR 8/1), pebbly, coarse sand.

Pebble-cobble conglomerate. $CaCO_3$ cemented. Cobbles are volcanics, quartzites, schists, and gneisses. Clast supported Fines are $CaCO_3$ cemented. Some originally open work gravels are partly to entirely filled with $CaCO_3$. Clasts are imbricated. Matrix is mostly pinkish gray (5YR 8/1). Three fining upward sequences occur in this section. Clasts are mostly subrounded to well-rounded. Clasts range up to 20 cm (rare), 10 cm (few), and 7 cm (common). Clasts are not drawn to size.

Triassic Dockum Group. Moderate reddish brown mudstone. Rare clastic dikes filled with $CaCO_3$ cemented Dockum fragments.

Figure 3. Vertical profile of the Ogallala Formation exposed along New Mexico Highway 18 at Ragland, NM. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.

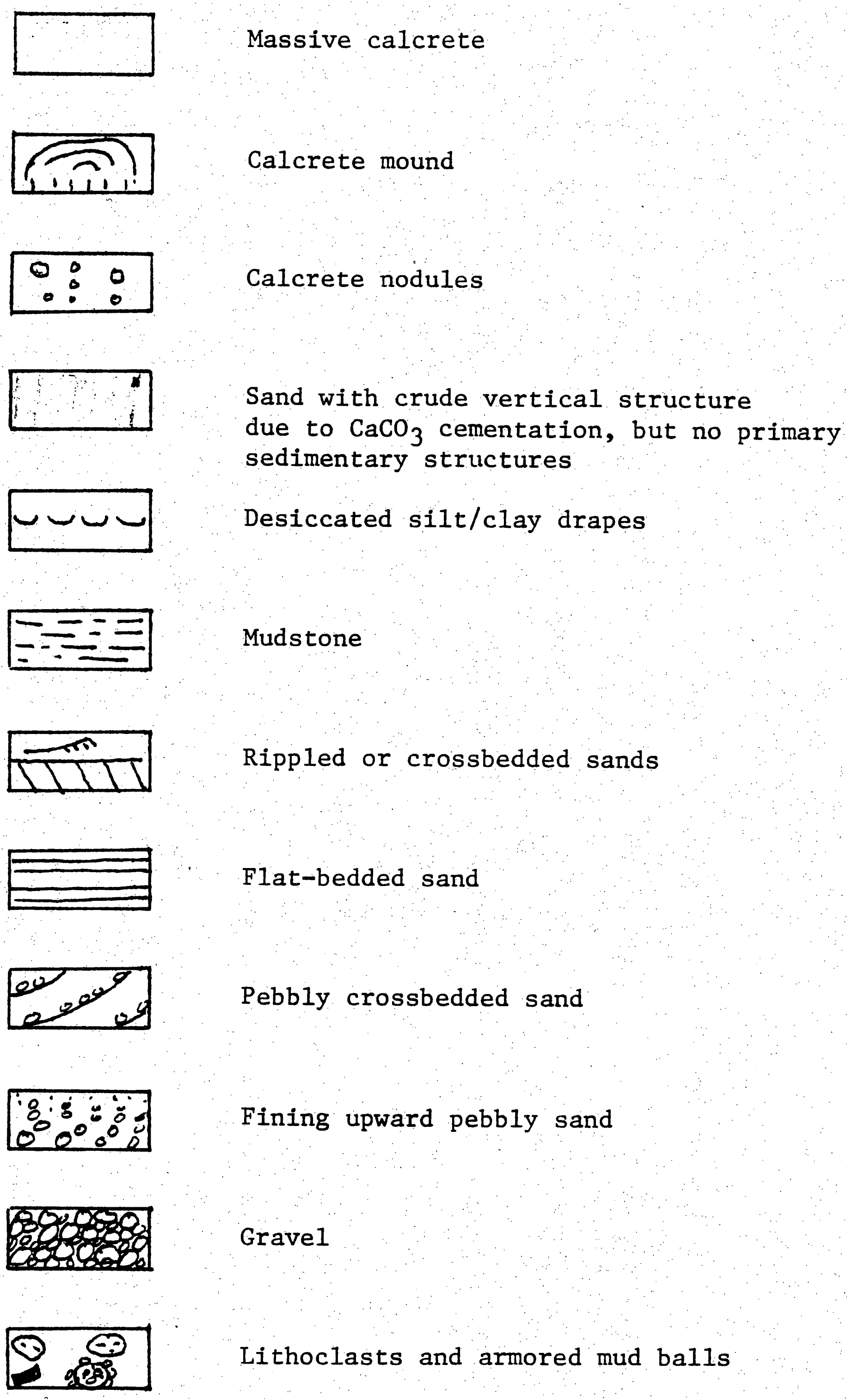

Figure 4. Symbols used in figures 3, 5, 6, 7, and 8.

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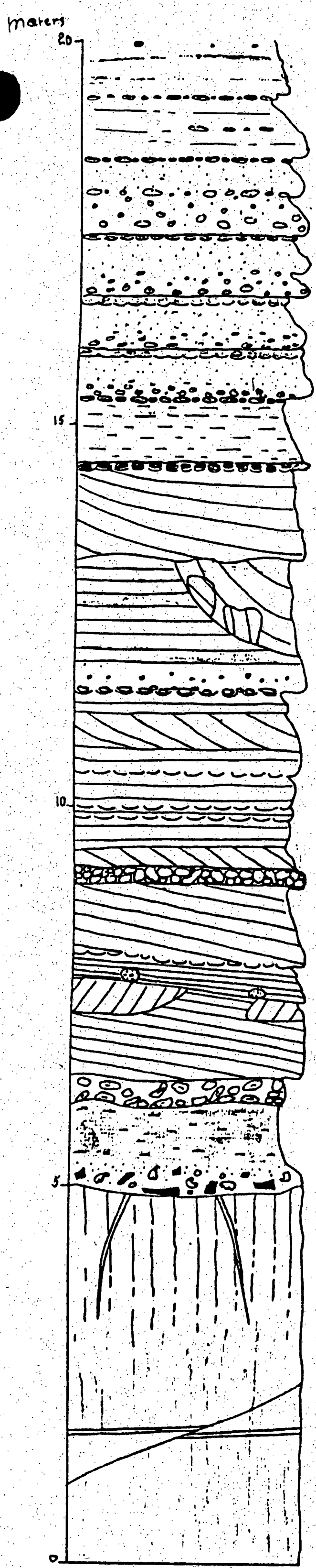

shaded areas — $CaCO_3$ cemented zone.

$CaCO_3$ nodules. Sands with vague horizontal stratification.

$CaCO_3$ nodules.

Fining upward sequence from sand and pebble gravel to clay drape. 10 cm thick $CaCO_3$ nodules form on drape.

Fining upward sequence from sand and pebble gravel at base to clay drape at top. 10 cm $CaCO_3$ nodules at top.

$CaCO_3$ nodules.

Sand fines downward to clay or mud. Stratum is laterally extensive and may represent either overbank or channel fill. Claystone or mudstone appears laminated. 2-6 cm. Numerous $CaCO_3$ nodules.

10 cm thick $CaCO_3$ beds.

Low angle trough crossbeds over flat beds. Iron-stained sandstone.

$CaCO_3$ cement in shaded areas.
Channel cuts flat beds, all sand.
Flat beds contain clay drapes; sands preferentially cemented above drapes with $CaCO_3$. Edge of channel lined with blocks that collapsed from cut bank.

$CaCO_3$ nodules have formed on the top side of clay drape.

Planar beds with mud drapes.

Mud cracks
Mud drapes with mud cracks.
Planar beds

Planar crossbeds

Carbonate cemented gravel.

Flat-bedded, light brown (10YR 6/4) sands, armored mudballs, mudcracks in mud drapes.

Flat-bedded sandstone, pebble conglomerate.

Pebble-cobble gravel composed mostly of lithoclasts of underlying B horizon. Matrix and lithoclasts light brown (5YR 5/6). Clasts include both quartzite and gryphea. Medium to fine sand, moderate clay content, light brown (5YR 5/6) (dry). This represents a B horizon developed on Tertiary colluvium. Coarse clasts above (10 cm) unconformity are mostly angular, hematite and ilmenite, ironstones and gryphea.

Tertiary erosion surface on top of the Triassic Dockum Group. Weathered Dockum is progressively cemented by $CaCO_3$ to a depth of 5 m.

Clastic dikes contain red material from overlying B horizon. Fractures post-date weathering of pre-Ogallala material.

Light greenish gray (5G 8/1) reduced zone transitional upward to oxidized, weathered pale red brown (10R 5/4) mudstone.

Triassic Dockum Group mudstone. Mudstones are weathered showing the beginning of pedogenesis by deposition of $CaCO_3$ coatings in light vertically banded areas which are pale red brown (10R 5/4). Intervening dark areas are unweathered moderate red brown (10R 4/6) mudstones. Light greenish gray (5G 8/1) fractures (reduced contact zone) are offset by east over west thrusts.

Figure 5. Vertical profile of the Ogallala Formation exposed along New Mexico Highway 93, 13 km (8 mi) north of Bellview, NM. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.

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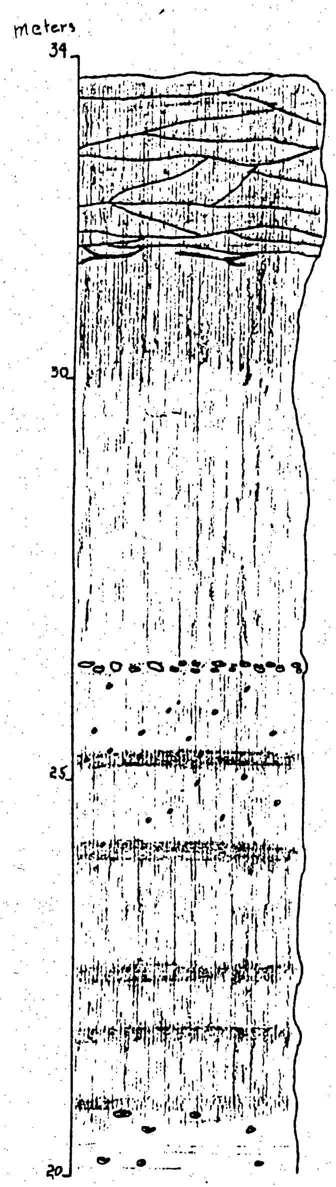

Ogallala Formation. Caprock caliche (calcrete).

Pisolitic, massive, stage VI calcrete.

Chalcedony veins
Massive, very fine sand with numerous $CaCO_3$ nodules.
Pinkish gray (5YR 8/1).

Base of Caprock caliche

Fine sand with $CaCO_3$ nodules. No preserved sedimentary structures. Pinkish gray (5YR 8/1). Nodules are white. Crude vertical structure.

Vertically fractured, very fine sand, $CaCO_3$ nodules, crude vertical structure.

$CaCO_3$ nodules layer

Calcrete

Calcrete

Calcrete

Calcrete

20 cm thick zone of dispersed granules. Looks like mostly ironstone.

Calcrete

Fine sand, no preserved sedimentary structures. Rare dispersed granules and pebbles (quartz). Dispersed $CaCO_3$ nodules and bands. Light brown (5YR 5/6). Possible B horizon.

Fine sand, no preserved sedimentary structures. Rare dispersed granules and pebbles (quartz). Dispersed $CaCO_3$ nodules and bands. Light brown (5YR 6/4).

Figure 5 cont. Vertical profile of Ogallala Formation exposed along New Mexico Highway 93, 13 km (8 mi) north of Bellview, NM. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.

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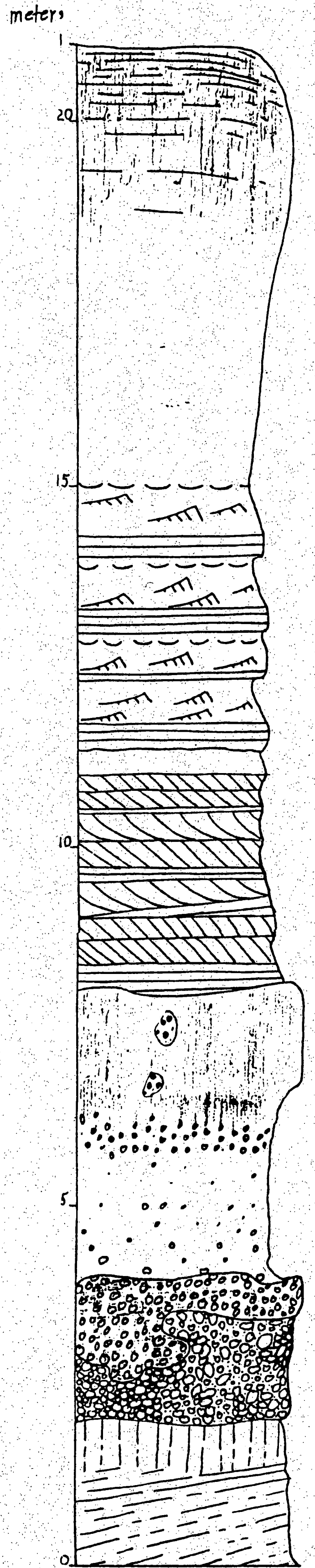


Ogallala Formation Caprock caliche (calcrete).
Calcrete is massive to laminated and brecciated.

Slope mostly covered with calcrete rubble.

Mudcracked clay drapes top repeated fining upwards sequences.

Fine-laminated to ripple-laminated sands.

Irregularly cemented lenses do not follow lithology.

$CaCO_3$ cemented, laminated and ripple laminated sand (fine).

Fine to medium sand, no preserved sedimentary structure, except laminar locally. Porous, mottled.

Medium sand, trough and planar crossbeds. Uncemented except as local calcretes.

Massive, dense, conchoidal fracturing calcrete. Contains enclosures of $CaCO_3$ nodules. Ghosts of $CaCO_3$ nodules preserved. Rare siliceous pebbles float in massive calcrete. Rare opalized zones.

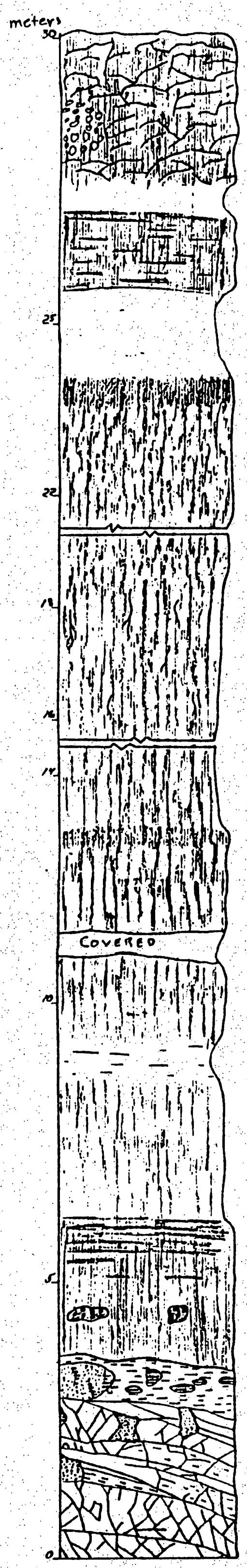
Uncommon, siliceous pebbles and granules in fine sand. No preserved sedimentary structures. Caliche nodules become more numerous upward. Rare siliceous concretions. Grayish orange pink (5YR 7/2). Nodules are pinkish gray (5YR 8/1).

Dispersed siliceous pebbles in fine sand. No preserved sedimentary structures. $CaCO_3$ nodules up to 1.5 cm common. Light brown (5YR 6/4).

Silica-cemented nodular to massive, conchoidal fracturing, conglomerate. $CaCO_3$ nodules have been replaced with silica. Color of siliceous clasts is moderate reddish brown (10R 4/6).
Gravel is locally up to 2 m thick. Irregularly cemented ($CaCO_3$) pebble-cobble gravel (up to 7 cm) composed of quartzites, intrusives, schists -- no volcanics (?). Uncemented zones appear to contain alluviated fines and iron oxides. These areas are moderate brown (5YR 4/4). Caliche nodules are in the cemented zone. Degree of cementation increases upward. No $CaCO_3$ nodules are in the uncemented zone.
Middle Tertiary erosional surface. Upper ½ m is weathered (oxidized) to a yellowish gray (5Y 7/2) and, at the contact, a light brown (5YR 5/6).

Light olive gray (5Y 6/1). Triassic Dockum Group shale.

Figure 6. Vertical profile of the Ogallala Formation exposed at the Caprock Escarpment along the entrance road to Palo Duro Canyon State Park, 26 km (16 mi) east of Canyon, TX. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.



Massive Stage V calcrete with massive cores in fractured blocks.

Brecciated, angular $CaCO_3$ nodules in a $CaCO_3$-cemented fine sand groundmass.

Blocky weathering, pinkish gray (5YR 8/1) calcrete.

Massive grayish orange pink (10YR 7/2) calcrete.

Massive, lightly cemented grayish orange pink (5YR 7/2) calcrete.

Massive grayish orange pink (5YR 7/2) strongly cemented calcrete

Opalized tubules

Mottled appearance due to irregular $CaCO_3$ cementation. Locally massive

Crude vertical prismatic structure. $CaCO_3$ filaments. Vertical opalized, downward branching tubules.

Weakly cemented vertical prismatic structure, light brown (5YR 6/4).

Rubble colluvium cover.

Crude vertical prismatic structure.

From 13-15 m rare, isolated, small, well-rounded siliceous clasts occur (up to 2 cm). Quartzites.

Numerous carbonate concretions.

Strongly cemented, lighter colored zone, pinkish gray (5YR 8/1).

Quaternary colluvium. Tierra Blanca Ck.

Very fine sand is grayish orange pink (5YR 7/2) on exposed surfaces and light brown on fresh surfaces.

No siliceous clasts.

Vague subhorizontal laminations on exposed surface. Not visible on fresh surfaces.

Vertical prismatic structure seen on exposed surface reflects degree of $CaCO_3$ cementation, shaded areas contain more $CaCO_3$

Common $CaCO_3$ nodules throughout.

No siliceous clasts.

Stage I-II vertical structure reflects degree of $CaCO_3$ cementation in an otherwise structureless, very fine sand. Numerous $CaCO_3$ concretions up to 1-1.5 cm.

Massive Stage IV-V calcrete. Internally brecciated, mottled in color, locally silicified. Siliceous nodules post date caliche because silicification boundaries cross cut breccia clasts.

The lower part (50 cm) contains dispersed siliceous clasts.

Fresh faces range from very light gray (N 8) to pinkish gray (5YR 8/1) (clasts of breccia). Matrix is pinkish gray (5YR 8/1).

Top of Dockum Group, middle Tertiary erosional surface. Brecciated red Dockum mudstone interrupted by irregular masses of laminated calcrete.

Laminated calcrete displacing Dockum mudstones.

Olive to red Dockum mudstones and fine sandstones are strongly brecciated. Vein fillings are $CaCO_3$ with included angular fragments of Dockum sediments.

Mudstones are mostly dusky yellow (5Y 6/4) to light olive brown (5Y 5/6).

Redbeds are dark reddish brown (10R 3/4) to moderate brown (5YR 4/4).

Figure 7. Vertical profile of the Ogallala Formation exposed along Texas Highway 168, 5 km (3 mi) south of Umbarger, TX. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.

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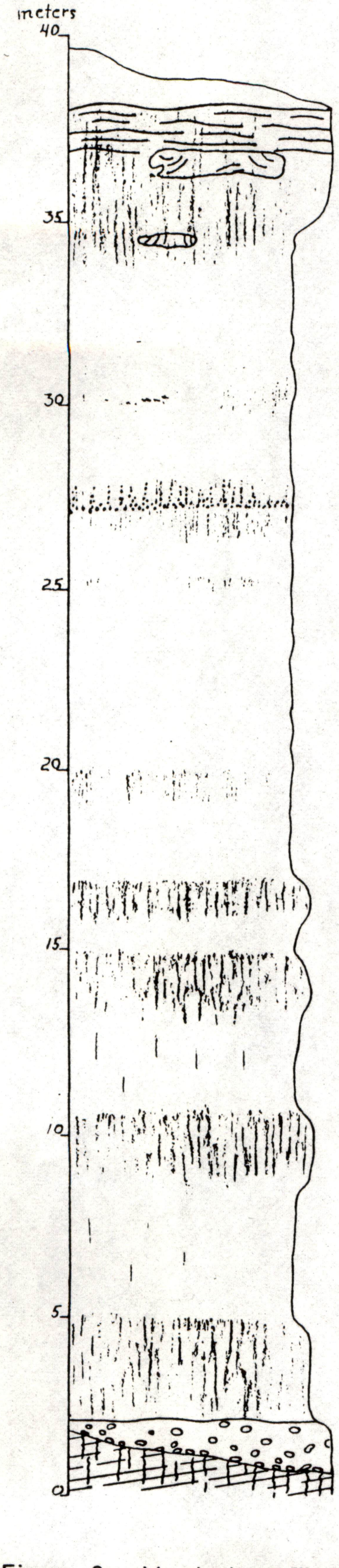

BLACKWATER DRAW FORMATION

Ogallala Formation Caprock caliche (calcrete)
Laminated pinkish gray (5YR 8/1) to grayish-orange pink
(5YR 7/2) -- less calichified areas are darker.
Moderate reddish brown (10R 4/6) to moderate brown (5YR 4
calcrete.

Darker areas may or may not effervesce strongly.
Light areas effervesce strongly.
Dense conchoidal fracturing masses are pinkish gray (5YR

Massive caliche

Base of Caprock Caliche

Bt horizon

Rubbly, strongly cemented calcrete, pinkish gray (5YR 8/

Two possible moderate red brown (10R 4/6) Bt Horizons.
1-2 cm $CaCO_3$ nodules are in upper 40 cm.
Nodules are common in middle 20 cm zone, rare below.

Possible weak Bt
Pale reddish brown (10R 5/4) with nodules of moderate re
brown (10R 4/6).

Nodular calcrete, prismatic structure, $CaCO_3$-filled tubul

Bt horizon

Massive calcrete. Top 10 cm very dense.

Calcrete is nodular with vertical tubules.
Vertical structure.

Massive calcrete.

Weakly cemented — grayish orange pink (5YR 7/2)
Calcrete nodules — pinkish gray (5YR 8/1)

Massive calcrete — rubbly at top, many $CaCO_3$ nodules.
Vertical structure at base due to $CaCO_3$ cement.

Massive, mottled calcrete, vertical prismatic structure.

Gravel clasts appear to float in fine-grained matrix (clast
in silicified zones break across the clasts in some cases).
Moderate red (10R 5/4) is a siliceous matrix that occurs nea
the base. CO_3 cemented section is light brown (5YR 6/4).
Clasts up to 5 inches, quartzite, meta, fine-grained igneou

Triassic Dockum Group weathered
Fractured, calichified mudstone.

Figure 8. Vertical profile of the Ogallala Formation exposed along Texas Highway 86, 19 km (12 mi) east of Silverton, TX. Symbols for sedimentary structures are described in figure 4. Field observations are noted to the right of the column.

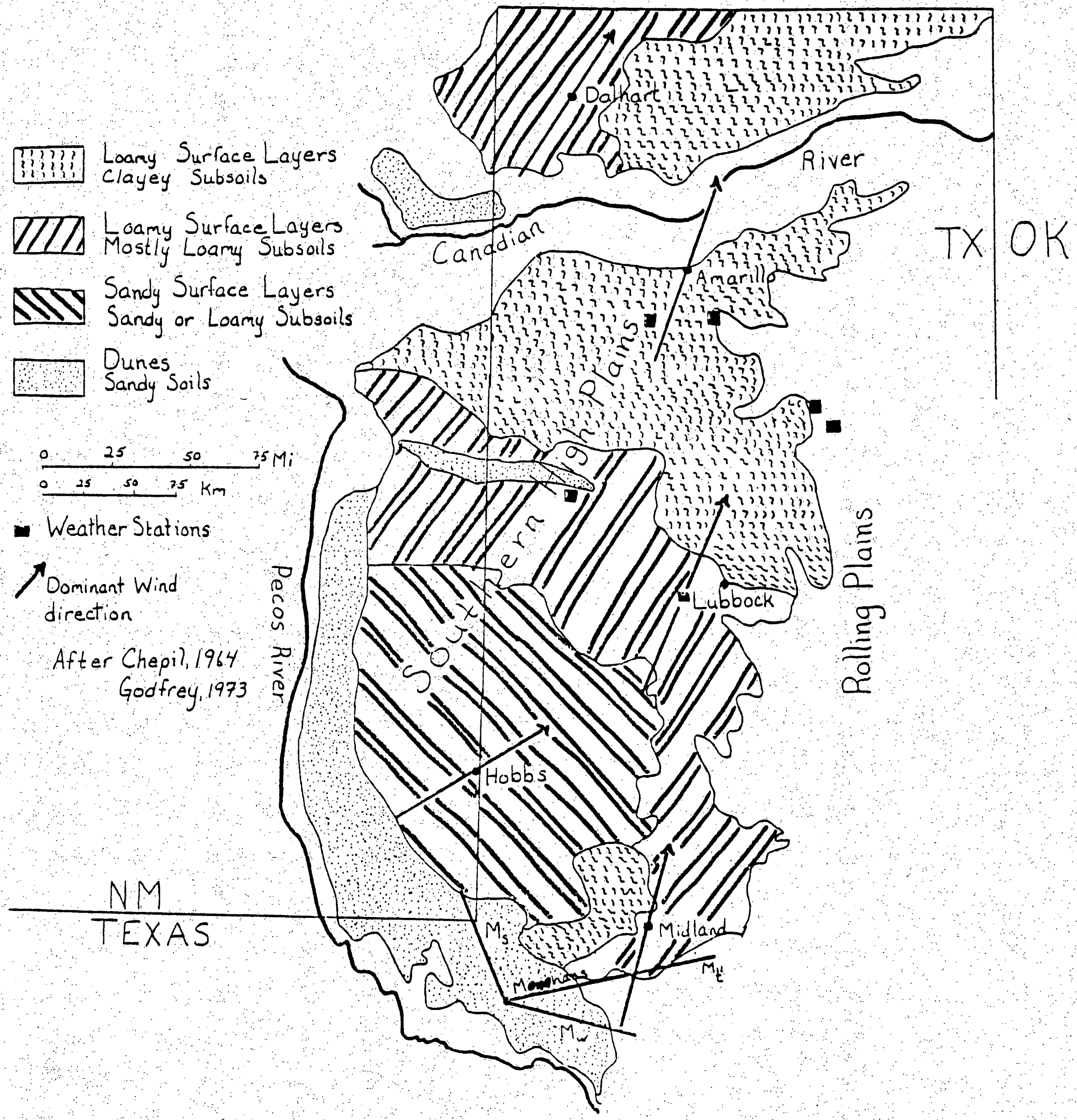

Figure 9. Distribution of the Blackwater Draw Formation showing progressive fining of surface soils to the northeast. Coarsest soils occur east and north of the Pecos and Canadian Rivers suggesting that these may be the source areas for at least the upper part of the Blackwater Draw Formation. Modern dominant wind directions are also shown.

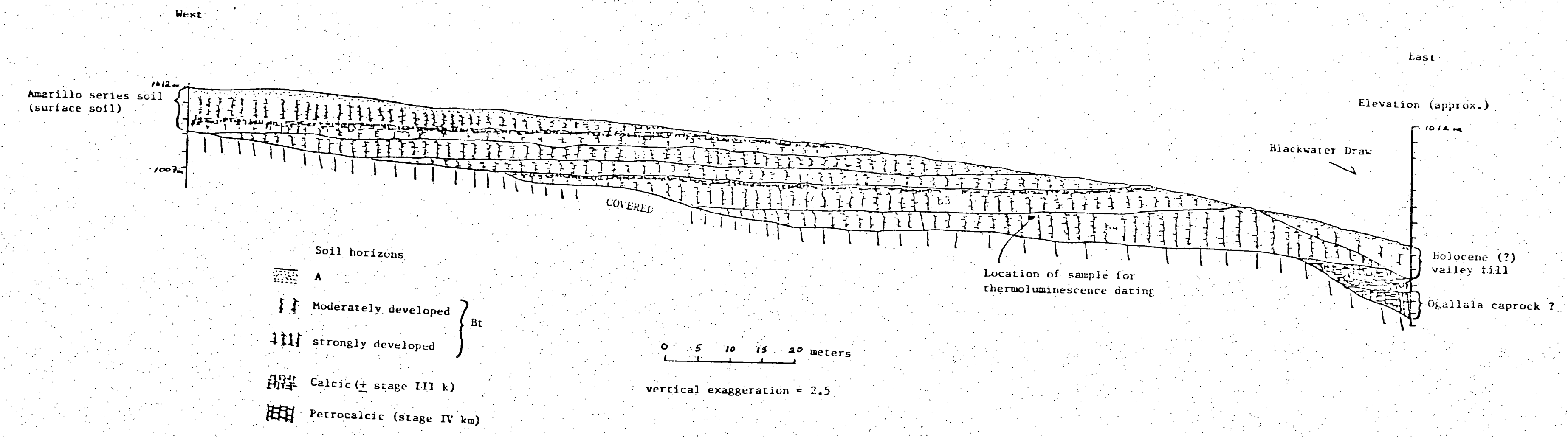

Figure 10. Generalized soil-stratigraphic relationships exposed at the Blackwater Draw Formation type section, Lubbock County. Location of profile descriptions in table 1 are at the ends of the section.

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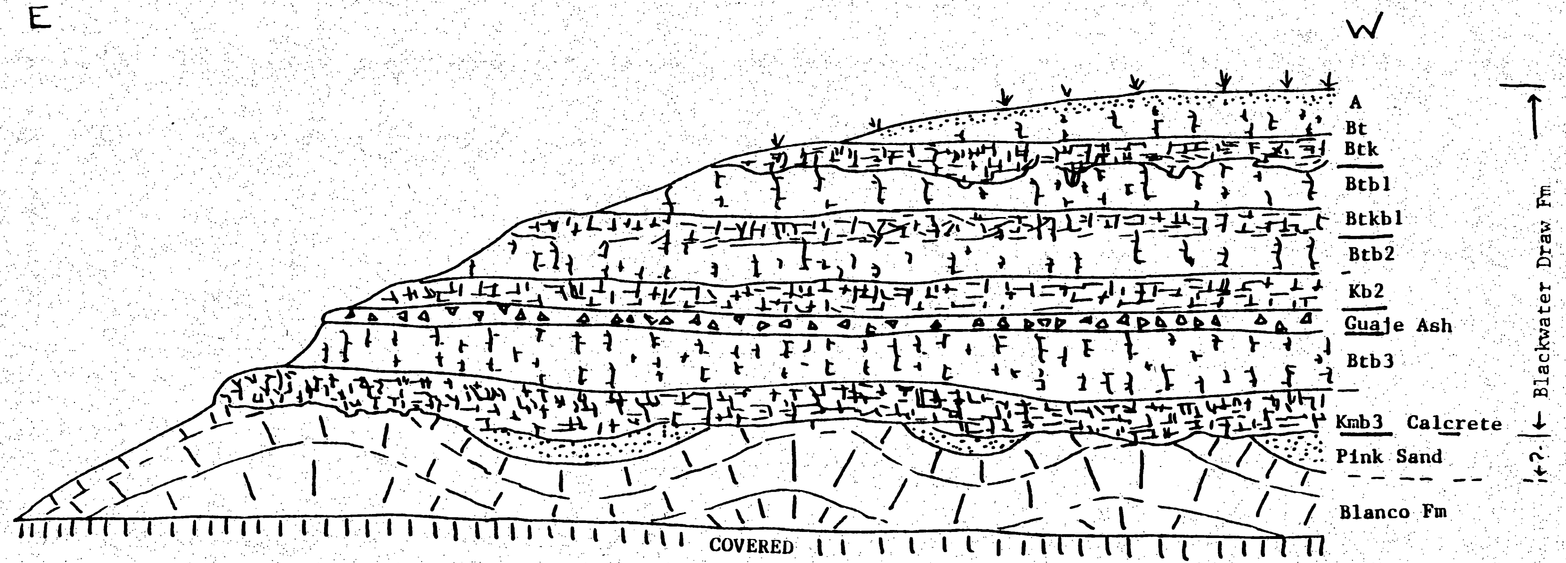

Figure 11. Schematic drawing of the late Cenozoic strata exposed at the Blanco Formation type section, Crosby County (not to scale). Symbols are identified in figure 10.

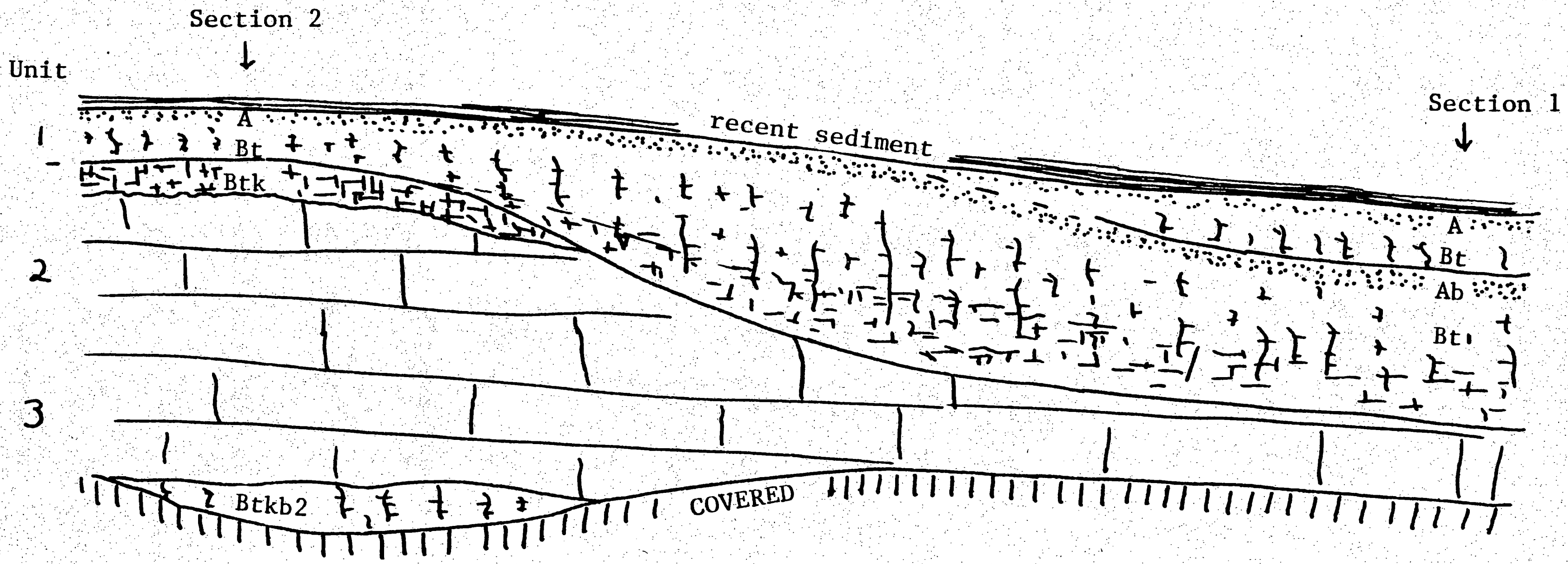

Figure 12. Schematic drawing showing the soil-stratigraphic relationships between sections 1 and 2 described at the Turkey railroad cut (not to scale). Symbols are identified in figure 10.

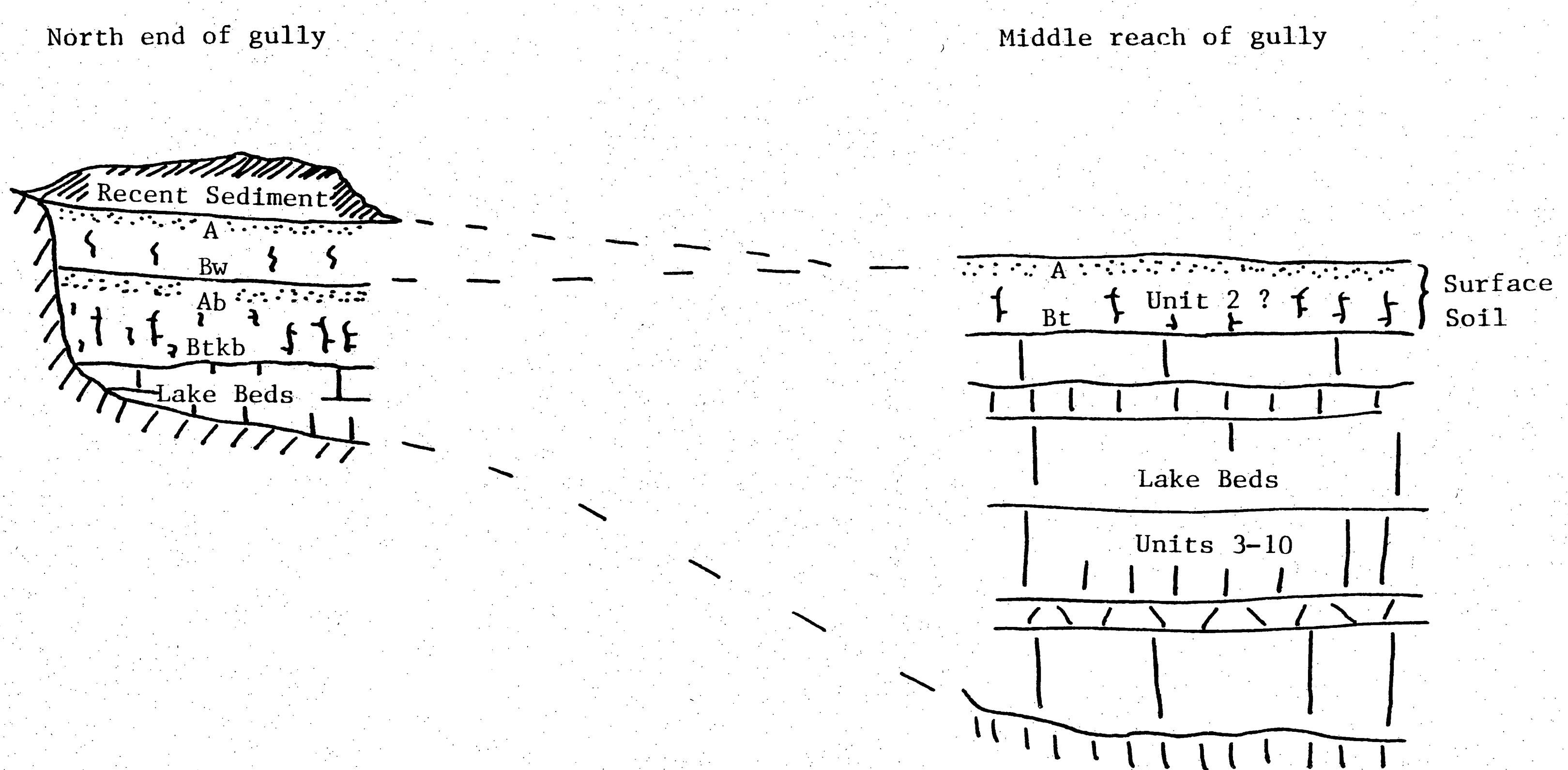

Figure 13. Schematic diagram of stratigraphic relationships of sections examined at Smith Ditch (not to scale). The section at the north end of the gully is described in table 7. Symbols are identified in figure 10.

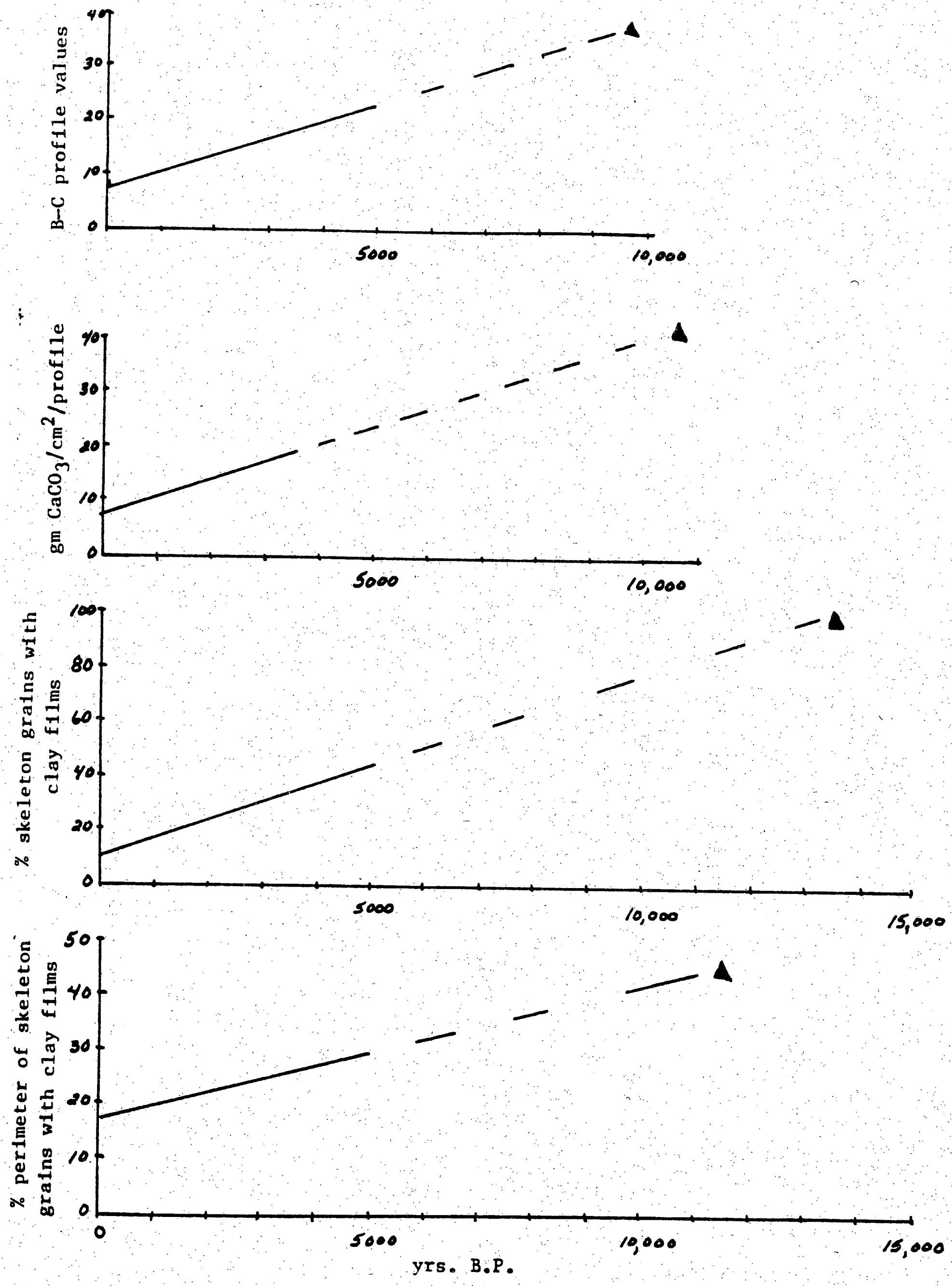

Figure 14. Plots of quantified pedologic characteristics for the surface soil at the Blackwater Draw Formation (triangles) along linear regressions calculated for late Holocene soils at the Lubbock Lake site (Holliday, 1982). Late Holocene regression lines are solid and projections are dashed.