SEDIMENTARY FACIES, DEPOSITIONAL ENVIRONMENTS, AND PALEOSOLS OF THE UPPER TERTIARY FORT HANCOCK FORMATION AND THE TERTIARY–QUATERNARY CAMP RICE FORMATION, HUECO BOLSON, WEST TEXAS

by

Thomas C. Gustavson

Final Contract Report

Prepared for

Texas Low-Level Radioactive Waste Disposal Authority
under Interagency Contract Number IAC(90-91)0268

by

Bureau of Economic Geology
W. L. Fisher, Director
The University of Texas at Austin
Austin, Texas 78713

May 1990

CONTENTS

Figures

Tables

Plate (in pocket)

ABSTRACT

The Hueco Bolson is a segment of the Rio Grande Rift, which formed as a result of late Tertiary Basin and Range deformation. The upper Tertiary Fort Hancock Formation and the upper Tertiary–Quaternary Camp Rice Formation compose the basin fill except in the deepest (western) parts of the bolson.

Five lithofacies make up the Fort Hancock Formation: (I) gravel; (II) sand, sandy mud, or sandy silt and gravel; (III) sand, sandy mud, and sandy silt; (IV) clay and sandy clay; and (V) clay, mud, sandy mud, and gypsum. These lithofacies represent the textural gradation from basin margin to basin center of proximal to transitional to distal alluvial fans (lithofacies I through III) to ephemeral lakes (IV) to saline playas (V). In cores from beneath the study area, these same lithofacies are present in a 230-m-thick (700-ft) upward-fining sequence. The sequence records the lacustrine expansion that occurred over basin-margin alluvial fans as the basin filled.

The Fort Hancock Formation is separated from the overlying Camp Rice Formation by a regional unconformity. The unconformity records a period of extensive erosion that marks the integration of the ancestral southern and northern segments of the Rio Grande approximately 2.25 Ma ago.

Fluvial, lacustrine, and eolian sediments accumulated above the unconformity as the Camp Rice Formation. Five lithofacies also make up the Camp Rice Formation: (1) sand and locally derived gravel, which was deposited by tributaries to the Rio Grande; (2) sand and exotic gravel (derived from north of the study area), which was deposited by a through-flowing stream, the Rio Grande; (3) sand, which was deposited as a dune complex; (4) coarse silt and very fine sand, which was deposited as loess, and (5) clay, sandy clay, and gypsum, which was deposited in ephemeral lakes with central playas.

Paleoclimatic conditions can be inferred from both buried soils and from depositional environments. Numerous Stage I and Stage II calcic soils are present in both Fort Hancock and

Camp Rice Formations, indicating that while these sediments were deposited the climate was most likely arid to subhumid. Clayey and muddy facies with local preservation of bedded gypsum, which are interpreted as ephemeral lake and saline playa deposits, are present in both formations. These depositional environments also suggest an arid to semiarid climate.

Paleovertisols, which formed primarily from repeated episodes of expansion and contraction of lacustrine muds and clays caused by precipitation or flooding and desiccation, are common in outcrops and in cores of smectite-rich clay and mud facies of both Fort Hancock and Camp Rice Formations.

INTRODUCTION

The upper Tertiary Fort Hancock Formation and the upper Tertiary–Quaternary Camp Rice Formation are exposed in the Hueco Bolson[1] and underlie a potential low-level radioactive waste disposal site located approximately 64 km (40 mi) southeast of El Paso, Texas, and approximately 18 km (11 mi) northeast of Fort Hancock, Texas (Collins and others, 1988) (figs. 1 and 2). Investigations of the Fort Hancock and Camp Rice Formations are part of a program funded by the Texas Low-Level Radioactive Waste Disposal Authority (TLLRWDA) designed to test the feasibility of isolating low-level nuclear waste in bolson sediments. These formations were studied to reconstruct the environments of deposition and paleoclimatic conditions that prevailed in the Hueco Bolson during the late Tertiary and early Quaternary Epochs and to provide a stratigraphic framework for hydrogeologic studies. Buried soils in these formations belonging to the Vertisol Order were described in detail because they provide important evidence of depositional

[1]The Spanish word "bolson" is generally synonymous with the English word "basin." As originally used by Hill (1900, p. 8), a bolson "is an apparently level valley, usually slightly depressed toward the center and enclosed by mountains usually without a drainage outlet. These plains or 'basins'. . . are largely structural in origin. Bolsons are generally floored with loose unconsolidated sediments derived from the higher peripheral region. Along the margins of these plains are talus hills and fans of boulders, and other wash deposits brought down by mountain freshets. The sediments of some of the bolsons may be of lacustrine origin."

environments and paleoclimatic conditions, and because they have not been previously described in the geologic literature.

Geologic Setting

Tectonic History

The study area for this regional investigation of bolson sediments encompasses the southern half of the Hueco Bolson. The bolson is underlain and bounded primarily by the Lower Cretaceous Campagrande Formation, Bluff Mesa Limestone, Cox Sandstone, and Finlay Limestone (Albritton and Smith, 1965). Locally the Permian Briggs Formation and other unnamed Permian strata, as well as the Jurassic Malone Formation, are present. As a result of early Tertiary Laramide deformation, these rocks were folded and thrusted northeastward toward the relatively undeformed Diablo Plateau. Regional Basin and Range extension further disturbed these rocks during the late Oligocene–Miocene and formed a series of basins, including the Hueco Bolson (Seager and others, 1984). As a result of volcanism during Basin and Range tectonism, various igneous rocks, including basalt, andesite, and trachyte-latite, were intruded into Cretaceous and older strata as a series of volcanic necks, sills, and dikes along the northeastern margin of the bolson (Albritton and Smith, 1965).

The Hueco Bolson, which is a segment of the Rio Grande Rift, extends from about 32 km (20 mi) northeast of El Paso, Texas, toward the south and southeast for approximately 180 km (112 mi) to the Quitman Mountains, Texas (fig. 1). The structure of the basin is not well understood, although Mattick (1967) and Johnson and others (1984) showed that near the New Mexico–Texas border the Hueco Bolson contains as much as 2,728 m (9,000 ft) of bolson sediments. In cross section the basin is asymmetrical and forms a half graben that is deeper along its western and southwestern margin. Basin subsidence continued into the Quaternary, as shown by dip-slip displacement of Quaternary units along the Campo Grande fault (fig. 1) in the study area (Collins and Raney, in press), along the southwestern margin of the basin in Mexico (Muehlberger and others, 1978), and in the Texas–New Mexico border area north of El Paso, Texas (Machette, 1987). Much of the study area, including the potential radioactive waste isolation site, is underlain by a shallow subbasin of the Hueco Bolson. The subbasin is separated from the main Hueco Bolson by a structural ridge, which is expressed at the surface by a northwest-trending series of Cretaceous bedrock outliers, including Campo Grande Mountain.

Physical and Genetic Stratigraphy

A variety of colluvial, fluvial, and lacustrine sediments partly fill bolsons that formed because of Basin and Range deformation. These Tertiary–Quaternary sediments make up the Santa Fe Group throughout much of New Mexico and West Texas (for discussions of this unit, see Bryan, 1938; Kottlowski, 1953; Baldwin, 1956; Hawley and others, 1969; Groat, 1972; and Gile and others, 1981) (fig. 2). The Fort Hancock and Camp Rice Formations compose the middle and upper Santa Fe Group in the region of the study area.

The Fort Hancock and Camp Rice Formations were first described and named by Strain (1966) for outcrops in the Hueco Bolson along Madden and Camp Rice Arroyos near Fort Hancock, Texas. Albritton and Smith (1965) described similar older and younger basin (bolson) sediments from the southern third of the Hueco Bolson. Strain (1966, 1971) interpreted the Fort Hancock Formation as lacustrine clay, silty clay, and crossbedded silt that were periodically subaerially exposed during periods of aridity. Calcic paleosols also formed during periods of exposure. Stuart and Willingham (1984) recognized both lacustrine and fluvial sediments in the Fort Hancock Formation. Clay facies including gypsum beds were thought to be playa lake deposits. Fluvial facies, which consist of mudstone and sandstone, were thought to have been deposited at playa margins or on levees or floodplains, channelized sandstone facies were interpreted as having been deposited in low-sinuosity braided channels, and conglomerates were interpreted as forming lags, alluvial fans, or alluvial aprons along the bolson margin. Riley (1984) described a channel sand with very high-angle, large-scale crossbedding (epsilon crossbedding) that led him to interpret that sandy facies in the type area of the Fort Hancock Formation were deposited by a meandering stream system. Although Riley (1984, p. 25) attributed clayey facies in the type section of the Fort Hancock to deposition by overbank flooding from a meandering stream, he did not completely reject the possibility of deposition of the clayey facies by lacustrine processes. Caliche nodules were recognized as evidence of subaerial exposure and the development of paleosols (Riley, 1984).

Strain (1966) described the Camp Rice Formation as fluvial sediments consisting mainly of channel gravel deposited by a through-flowing stream and sand, silt, and clay deposited as alluvial fans. Volcanic ash beds are preserved locally. Riley (1984) and Stuart and Willingham (1984) suggested that Camp Rice Formation was deposited primarily by a braided stream carrying mostly bed load. They did not distinguish between axial or through-flowing stream deposits and deposits that make up basin-margin alluvial fans or tributary streams.

Age of the Fort Hancock and Camp Rice Formations

Fossil vertebrate remains preserved in the type sections of both the Camp Rice and Fort Hancock Formations compose the Hudspeth local fauna of Blancan Age (Strain, 1966; Vanderhill, 1986; see Riley, 1984, for a review of the vertebrate paleontology of the Camp Rice and Fort Hancock Formations). Strain (1966) recognized the Fort Hancock Formation as probably early Pleistocene (Aftonian) in age on the basis of its vertebrate fauna. He thought that the lower part of the Camp Rice Formation, which also contains a Blancan vertebrate fauna, was Aftonian and that the middle section, which contains an ash bed of the Pearlette family of volcanic ashes, was Kansan. Strain (1966) did not speculate on the age of upper Camp Rice sediments other than to recognize them as Pleistocene. In its present usage the Blancan Land Mammal Age extends from the late Pliocene (4 Ma ago) to earliest Pleistocene (1.5 Ma ago) (Van Eysinga, 1975; Tedford, 1981). The Pearlette ash reported by Strain (1966) is now recognized as the Huckleberry Ridge

Ash of the family of Pearlette ashes and has been dated at 2.01 Ma (Gile and others, 1981; Izett and Wilcox, 1982).

Vanderhill (1986) obtained paleomagnetic data from the Fort Hancock and Camp Rice Formations in the Hueco Bolson and correlated these units with the geomagnetic time scale. He suggested that most of the Fort Hancock and the lower Camp Rice was deposited during the late Gauss epoch, and that the upper part of the Camp Rice was deposited during the Matuyama epoch, possibly during the Olduvai event. Consequently, the Fort Hancock Formation is middle Pliocene in age where it is exposed in the Hueco Bolson, and the Camp Rice Formation is late Pliocene to possibly Pleistocene in age (fig. 2).

Physiographic Evolution

The Hueco Bolson is bounded on the west and southwest by a series of mountain ranges in the Republic of Mexico including Sierra de la Amargosa, Sierra de San Ignacio, and Sierra Del Paso del Norte and by the Franklin Mountains in the United States (fig. 1). On the east and northeast in the United States are the Hueco, Finlay, Malone, and Quitman Mountains and the Diablo Plateau. The Rio Grande flows through the basin and exits the basin where it crosses the Quitman Mountains. The basin is pinched off to the southeast where the Quitman Mountains join the Sierra de la Amargosa but opens to the north into the Tularosa Basin of southern New Mexico.

Major events in the depositional history of the Hueco Bolson have been closely tied to its physiographic evolution since tectonic initiation of the basin during the late Oligocene-Miocene. Sedimentation into a closed basin, but without the contribution of the northern Rio Grande, persisted throughout most of the earlier (Miocene) history of the basin and is reflected in the lower part of 2,500 m (8,250 ft) of sediments preserved near the northern limit of the basin west of the Hueco Mountains (Mattick, 1967; Johnson and others, 1984; Seager and others, 1984). In Pliocene and possibly latest Miocene time, the northern ancestral Rio Grande discharged into the Hueco Bolson, but the basin remained internally drained, as indicated in the predominance of fine-grained clastic sediments near the basin center and coarser clastics near the basin periphery (Fort Hancock Formation of Strain, 1966, Hawley and others, 1969, Riley, 1984, Stuart and Willingham, 1984; older basin deposits of Albritton and Smith, 1965, and Gustavson, 1989a).

Through-flowing drainage in the Hueco Bolson, which is now a segment of the Rio Grande, developed during the late Pliocene, but prior to 2.01 Ma ago (Gile and others, 1981; Seager and others, 1984). Through-flowing streams incised older sediments and deposited coarse sand and gravel, including "exotic" clasts derived from crystalline rocks that crop out only in areas north of the Hueco Bolson (Camp Rice Formation of Strain, 1966, Hawley and others, 1969, Riley, 1984, Stuart and Willingham, 1984, and Gustavson, 1989a; younger basin deposits of Albritton and Smith, 1965).

Although many authors have recognized that the lithologic differences between the Camp Rice and Fort Hancock Formations in the Hueco Bolson reflect different depositional environments and in part different sediment source areas, precisely how this change in depositional environment came about is poorly understood. Strain (1966) did not elaborate on the transition from lacustrine (Fort Hancock) to fluvial (Camp Rice) deposition other than to say that it represented the change from lacustrine sedimentation in a closed basin to sedimentation by a through-flowing stream. Strain (1971) suggested that through-flowing drainage of the Hueco Bolson developed as a result of (1) overflow of Hueco Bolson lake waters (which were part of the larger Lake Cabeza de Vaca), southward into the Red Light and Presidio Bolsons, (2) by headward erosion from the Presidio Bolson, or (3) by combination of the two. Later in the same discussion Strain (1971, p. 169) stated that

> Lake Cabeza de Vaca did not overflow frequently until the holding capacity of the Mesilla, the Hueco, and the Bolson de los Muertos was reduced by filling of the basins with fine sediment brought from New Mexico and Colorado by the "upper" Rio Grande. Late in the early Pleistocene aggradation in the lake basins had reduced their holding capacity to such an extent that the normal volume of the river was sufficient to overflow the lowest barrier impounding the water and develop an outlet to the bolsons to the southeast. The water first spilled over the barrier between the Quitman Mountains and the Sierra del Pinto and into the Red Light Bolson. It probably then spread southward in the valley west of the Sierra de Pilares–Sierra Grande range and joined the Rio Conchos near where it crossed Sierra Grande west of Ojinaga and Presidio.

Hawley and others (1969) suggested that the change from lacustrine sedimentation to fluvial sedimentation developed progressively from the Palomas Basin on the north to the Hueco Bolson on the south, but that before integration with the lower Rio Grande system south of the Quitman Mountains, the upper Rio Grande fed large lakes in several basins in the border region of Texas and New Mexico (Hueco, Mesilla, and Tularosa Bolsons = Lake Cabeza de Vaca of Strain [1971] and the Red Light Bolson). The process whereby the lower Rio Grande system was integrated with upper Rio Grande drainage was not described (Hawley and others, 1969). For additional discussions, see Hawley (1975, 1981) and Gile and others (1981).

Although the Fort Hancock and Camp Rice Formations have filled most of the Hueco Bolson, exposures of these two formations are restricted. Most of the Fort Hancock and Camp Rice Formations are covered by thin veneers of Quaternary alluvium, terrace gravel, fan gravel, calcretes, or eolian sand. Exposures of these two formations are primarily limited to narrow bands along arroyos that are incised through the Quaternary cover. These outcrops only rarely exceed 30 m vertically, and total vertical exposure within a single arroyo does not exceed 100 m. The nature of these exposures is such that individual lithofacies types are easily recognized and examined, but mapping of lithofacies from outcrop to outcrop is difficult because exposures are not continuous. Nevertheless, the easily erodable nature of these sediments and the sparsity of vegetation have provided excellent exposures for study.

Paleosols

Evidence of paleosol development is common in the Fort Hancock and Camp Rice Formations, and most authors mention the presence of calcic soils or caliches but do not describe soil characteristics (Albritton and Smith, 1966; Strain, 1966; Hawley, 1969; Reeves, 1969; Riley, 1984). Gustavson (1989a, b) described the widespread development of buried Vertisols in smectite-rich clay facies of the Fort Hancock and Camp Rice Formations. Paleovertisols are described in detail in this report.

Methods

Approximately 635 m (2,100 ft) of core from 11 stratigraphic and hydrologic test wells and 500 m (1,650 ft) of section in 33 exposures were described, photographed, and sampled (fig. 1, pl. 1).

Cores collected at the study area provide a good record of the Late Tertiary stratigraphy, with the exception that recovery of poorly consolidated sandy sections in the upper parts of each core was limited. Cores (2.5 inches in diameter) and/or cuttings were recovered from 14 hydrologic and stratigraphic test wells. Well locations are shown on plate 1. Most wells were drilled to depths of 150 ft or less and penetrated Quaternary sand and gravel, the Camp Rice Formation where it is present, and the upper Fort Hancock Formation. Three wells were drilled through the Fort Hancock Formation into Cretaceous bedrock.

Core recovery was generally good throughout the Camp Rice and Fort Hancock sections, but it ranged from as little as 64 percent to as much as 95 percent. Average core recovery from TLLRWDA wells was 80 percent. The intervals of core loss were most likely from sections of unconsolidated gravel and sand. These coarse sediments are far less cohesive than the clayey lithofacies, which are stiff and compact and more likely to be lost during standard drilling procedures. Cuttings were collected from most wells for the near-surface intervals where core was not taken.

Although all of the Camp Rice Formation can be seen in outcrop and core, only the upper 280 m (920 ft) of the Fort Hancock Formation was observed in outcrop or core; thus, rocks that represent the early history of infilling of the basin are poorly known. Bed thickness, color, texture, lithology, primary sedimentary structures, and pedogenic structures were described. Core and outcrop samples were analyzed for grain size using sieve and hydrometer methods. Mineralogy of clays preserved in lacustrine sediments and in buried soils was determined by X-ray diffraction, and soil and sediment microstructures were examined using scanning electron microscopy.

FORT HANCOCK FORMATION

The upper Tertiary Fort Hancock Formation unconformably overlies Cretaceous strata. At the TLLRWDA site, the Fort Hancock Formation overlies Cretaceous rocks at depths ranging from 173 m to 217 m (569 ft to 717 ft) (pl. 1). The Fort Hancock is overlain by the upper Tertiary–Quaternary Camp Rice Formation or Quaternary Madden and Ramey Gravels.

Five lithofacies were recognized in the Fort Hancock Formation: (I) gravel; (II) sand, sandy mud, or sandy silt and gravel; (III) sand, sandy mud, and sandy silt; (IV) clay and sandy clay; and (V) clay, mud, sandy mud, and gypsum (table 1). These lithofacies are interpreted to represent primarily downgradient grain-size changes from proximal alluvial fan to evaporative playa lake. Fort Hancock outcrops are predominantly fine-grained (sand-sized and smaller) lithofacies; exposures of coarse-grained (gravel-bearing) lithofacies are limited to narrow outcrops at the basin margins and at contacts with outliers of Cretaceous bedrock. However, 50 m (165 ft) of coarse-grained facies were examined in core. Gravel and finer grained lithofacies in the Fort Hancock Formation are similar to the basin-margin and basin-center facies of Tertiary bolson deposits described by Groat (1972) in the Presidio Bolson.

Gravel Lithofacies

Description

Gravel lithofacies of the Fort Hancock Formation (table 1, lithofacies I), which were encountered in well no. 22 (figs. 3 and 4, pl. 1) between depths of 172 m (569 ft) and 143 m (471 ft), unconformably overlie Cretaceous strata and consist of approximately 29 m (90 ft) of matrix-supported cobble- to boulder-sized limestone gravel/conglomerate. Gravel is poorly cemented with $CaCO_3$. Clasts are primarily Cretaceous Finlay Limestone with a few pebbles of

Cox Sandstone. Gravel, which contains clasts as much as 22 cm (8.6 inches) long, is angular to subrounded and imbricated at some depths. Matrix material is poorly sorted, moderate-brown (5YR 4/4) pebbly sandy mud to muddy sand. Primary sedimentary structures other than rare, weakly expressed horizontal bedding were not recognized. Upward-fining sequences of sediment were recognized only at one depth, 147 m (481 ft). The lack of recognizable sedimentary structures in this part of the Fort Hancock Formation may be an artifact of this sediment being exposed only in narrow (6.5 cm [2.5 inch]) cores.

Gravel lithofacies are also exposed within a deeply incised fan head trench at the base of Sierra de la Amargosa on the southeastern flank of the Hueco Bolson. These sediments, which are poorly cemented by $CaCO_3$, are horizontally bedded, clast-supported, boulder gravel/conglomerate. Clasts are imbricated and measure in length as much as 0.5 m (20 inches). Lateral channel boundaries were not recognized.

Interpretation

Coarse clast-supported, imbricated, horizontally bedded gravel lithofacies of the Fort Hancock Formation exposed adjacent to Sierra de la Amargosa are similar to the proximal alluvial fan facies of the Cambrian (?) Van Horn Sandstone described by McGowan and Groat (1971) and to the proximal incised-alluvial-fan channel-fill facies of the Cretaceous Todos Santos Formation described by Blair (1987). Sedimentary characteristics similar to those described for the Fort Hancock gravel lithofacies as well as for the Van Horn Sandstone are present in fluvial facies of modern proximal alluvial fans described by Bull (1972) and Boothroyd and Ashley (1975).

The nonstratified to poorly stratified matrix-supported Fort Hancock gravel lithofacies observed in core is similar to unstratified basin-filling proximal fan sediments described by Heward (1978) from the Stephanian A and B coalfields of northern Spain. He suggested that scree or colluvial debris was an important constituent of these deposits. Nonstratified, poorly sorted, matrix-supported gravels have also been described as debris-flow deposits (Bull, 1972; Reineck and Singh, 1980).

Gravel lithofacies of the Fort Hancock Formation consists of alluvium and colluvium derived from predominately Cretaceous strata at the Diablo Plateau Escarpment and from the Sierra de la Amargosa and other mountain ranges in Mexico and deposited as proximal alluvial fans. The coarse texture, poor sorting, and high degree of angularity of clasts, their position adjacent to Sierra de la Amargosa and immediately overlying Cretaceous bedrock suggest that these sediments were transported for only short distances. Some of these coarse gravels are clast-supported, imbricated, and horizontally bedded, which indicates fluvial transport by high-energy streams. Those gravels that are nonbedded and matrix supported were probably deposited by mass-wasting processes.

Sand, Sandy Mud, or Sandy Silt and Gravel Lithofacies

Description

The fine-grained part of this lithofacies is composed of sediments that range in grain size from muddy and silty sand to sandy silt and mud. To simplify the following description, these various grain-size classifications are from time to time collectively called sand.

Interbedded sand and gravel lithofacies (table 1, lithofacies II) locally overlie gravel lithofacies or Cretaceous bedrock in core of Fort Hancock sediments (figs. 3 and pl. 1). In outcrop, sections of interbedded sandy mud or sandy silt and gravel lie basinward of proximal alluvial fan gravels exposed along the southwest margin of the Hueco Bolson. This lithofacies consists of beds of gravel, which are similar to the previously described gravel lithofacies, interstratified with beds of muddy sand, silty sand, sandy mud, or sandy silt. Channel margins were not recognized in these sediments. Coarse sediments consist of horizontally bedded, mostly clast-supported, locally imbricated pebble to small cobble limestone gravel. Fine-grained sediments are poorly sorted and moderate brown (10YR 4/4) to yellowish brown (10YR 5/4). Primary sedimentary structures include horizontal laminae, crossbeds, and rare beds of clay/silt rhythmites recognized in the core. In core the sand, sandy mud, or sandy silt and gravel lithofacies fines upward as gravel lenses become thinner and more widely separated higher in the section (fig. 3, pl. 1). $CaCO_3$ nodules as much as 1 cm (0.4 inch) in diameter and $CaCO_3$ filaments are present in most sand and silt beds, especially in those lacking recognizable primary sedimentary structures. Contacts between gravel and sand units are sharp.

Interpretation

Interbedded sand, sandy mud, sandy silt, and gravel lithofacies of the Fort Hancock Formation are generally similar to midfan facies described by McGowen and Groat (1971) and Heward (1978). McGowen and Groat (1971) described midfan sand and gravel facies as being deposited contemporaneously by braided streams or as channel fills. Heward (1978) described midfan facies as the result of debris-flows (gravels) and fluvial transport and deposition (sands). The lack of recognizable sedimentary structures in some sections of the core is partly due to its narrow diameter (~6.4 cm [2.5 inches]), which makes recognition of structures much larger than ripple cross-stratification difficult. Pedogenesis, which includes in situ growth of $CaCO_3$ nodules and filaments and possibly bioturbation (as indicated by $CaCO_3$ and manganese oxide filaments that appear to have formed along former root traces), probably also destroyed original structures.

The sand, sandy mud, sandy silt, and gravel lithofacies are interpreted as medial alluvial fan deposits, which fine upward from predominantly gravel to predominantly sand and silt, and represent the transition from proximal alluvial fan to distal fan or alluvial plain. Both coarse and fine elements of this facies are stream deposits, but there is insufficient data to determine if these sediments were deposited by braided streams, sheetfloods, or some other process.

The presence of $CaCO_3$ nodules and filaments, which are characteristic of the early stages of development of calcic soils (Machette, 1985), suggests that this alluvial fan or plain was periodically a stable geomorphic surface. $CaCO_3$ filaments and nodules indicate Stages I and II in the development of a calcic soil and are the result of as much as several thousand years of pedogenesis in an arid to subhumid climate (Gile and others, 1966; Bachman and Machette, 1977; Gile and others, 1981; Machette, 1985).

Sand, Sandy Mud, and Sandy Silt Lithofacies

The sand, sandy mud, and sandy silt lithofacies of the Fort Hancock Formation is present in core (fig. 3, pl. 1) and in outcrop (figs. 5 through 9). This lithofacies (table 1, lithofacies III) is probably equivalent to the sand, sandy mud, and sandy silt beds described as part of the midfan lithofacies (table 1, lithofacies II). The primary differences are that this lithofacies contains no gravel and is well exposed throughout the study area, and channel geometry, sequences of channel filling, and primary sedimentary structures are abundant and well preserved.

Description

The sand, sandy mud, and sandy silt lithofacies consists of moderate-yellow-brown (10YR 5/4) to pinkish to yellowish-gray (5YR-5Y 8/1) sand, sandy mud, and sandy silt and less commonly muddy sand or silty mud (figs. 3 and 5 through 8). Sediments coarser than about medium sand were observed only rarely in exposures of this unit. Fine sand, sandy mud, and sandy silt are most commonly present as horizontal laminations, ripple cross-laminations, or ripple-drift cross-laminations (fig. 9). In some sequences clay or mud drapes are present. Gravel-sized lithoclasts or armored mud balls of Fort Hancock Formation sediment are rare. (The term lithoclasts as used in this discussion means a mechanically formed and deposited fragment of rock, usually claystone or mudstone, and is not limited to carbonate rock as defined by Gary and others [1972]). However, sand-sized lithoclasts of Fort Hancock mudstone are common. $CaCO_3$ nodules, $CaCO_3$ films on fractures, and $CaCO_3$-cemented rhizocretions are rare. Contacts between sand and sandy mud and sandy silt beds and overlying clays and sandy clays are typically sharp. Contacts between this lithofacies and underlying clays and sandy clays are typically gradational and coarsen upward.

Sand, sandy mud, and sandy silt units were never observed to be more than 3 m (10 ft) thick in outcrop (figs. 5 through 9), but they are substantially thicker in core (fig. 3, pl. 1). These units are laterally very persistent, commonly extending for several hundred meters without significant change in thickness. Few channels were recognized, but those that were had low depth-to-width ratios (typically <0.01) (fig. 10). Individual beds within these units are a few centimeters to a few decimeters thick and are also laterally persistent. Planar crossbed sets thicker than approximately 30 cm (1 ft) or channels deeper than approximately 30 cm (1 ft) were not observed. Trough crossbed sets are rare. In both outcrop and core, the sand and sandy mud and sandy silt lithofacies commonly overlie clay and sandy clay lithofacies with preserved paleosols. Preservation of the uppermost buried soil horizon indicates that significant erosion and channelization did not precede deposition of this lithofacies.

The sand, sandy mud, and sandy silt lithofacies occurs as relatively thin laterally extensive beds throughout most of the study area. Locally, however, near the axis of the Hueco Bolson, this lithofacies fills channels with high depth-to-width ratios (~0.2) cut into older Fort Hancock sediments. In the type area of the Fort Hancock Formation in Madden Arroyo and in the southern part of Diablo Arroyo, channels as deep as approximately 5 m (17 ft) and several tens of meters (tens of yards) wide are preserved (figs. 7 and 8). Channels occur at several stratigraphic levels, but their lateral and vertical extent is unknown. Channel-fill sediments commonly fine upward from sand with gravel-sized lithoclasts at the base of the channel fill to sandy silt or sandy mud at the top of the channel fill. Sand-sized lithoclasts are common and, like the gravel-sized lithoclasts at the base of the channel fill, are composed of lithoclasts and carbonate nodules eroded from older Fort Hancock Formation strata.

The scale of sedimentary structures in channel fills decreases upward from large trough cross-stratification at the channel base to horizontal laminations and ripple-drift cross-laminations with clay drapes toward the top of channel fills (figs. 7 and 8). In a few outcrops epsilon cross-stratification is preserved.

Interpretation

The sand, sandy mud, and sandy silt lithofacies of the Fort Hancock Formation is characterized throughout most of the area by thin laterally extensive sand, mud, and silt beds with a few preserved channels having low depth-to-width ratios. Horizontal stratification and dune and ripple cross-stratification are the most commonly preserved sedimentary structures. Preserved clay drapes indicate that standing water was present locally after water flow ceased. Contacts with underlying clay beds are most commonly gradational and coarsening upward, indicating that sands, muds, and silts prograded onto playa lake mudflats. Collectively, these features suggest that the sand, sandy mud, and sandy silt lithofacies was deposited by shallow braided streams or sheetfloods that covered the very low sloping parts of a distal alluvial fan or fan delta. These strata are similar to distal alluvial fan facies of the Van Horn Sandstone described by McGowen and Groat (1971), to the distal alluvial fan facies of the Stephanian coalfields described by Heward (1978), and in part to distal sheetflood deposits of the Todos Santos Formation described by Blair (1987). In many respects this lithofacies is also comparable to the modern Gum Hollow fan delta described by McGowen (1971) and to other fan deltas described by Sneh (1979) and McPherson and others (1987).

Fossil root traces, although only rarely preserved in the form of rhizocretions, suggest that these alluvial surfaces were at least partly vegetated. The significance of $CaCO_3$ nodules in these strata is difficult to assess. Nodules are rare and are mostly preserved at the contact between sandy or silty facies and underlying mudstones; thus these nodules may have been deposited by shallow ground water instead of by pedogenic processes. Well-preserved sedimentary structures, the general lack of soil carbonate, and lack of evidence of biological activity suggest that the sand, sandy mud, and sandy silt lithofacies was deposited relatively rapidly.

The sand, sandy mud, and sandy silt lithofacies also fills channels with relatively high depth-to-width channels. Epsilon cross-stratification is preserved in some of these channel fills, illustrating the former positions of laterally migrating point bars of meandering streams. Channel fills with upward-fining grain size and an upward decrease in the scale of sedimentary structures also indicate that these sediments were deposited by meandering streams (Bernard and others, 1970; Puigdefábregas, 1973; Jackson, 1976; Walker and Cant, 1979).

Erosion of local fluvial channel systems with high depth-to-width ratios represents an abrupt change in fluvial depositional environment from alluvial fan sedimentation to sedimentation filling channel forms having very low depth-to-width ratios or as sheetflows. High depth-to-width channels contain locally derived gravel-sized lithoclasts of older Fort Hancock strata. Because these channels apparently contain only locally derived sediment, they probably drained only local areas within the Hueco Bolson. Channel fills are also overlain by ephemeral lake sediments (see p. 25) (figs. 7 and 8). Incision of a 5-m-deep (17-ft) channel requires that local base level be lowered by as much as 5 m (17 ft). The presence of thick lacustrine sequences above the channel fills requires that base levels controlled by the elevation of the basin center be reestablished after this episode of channel cutting.

Two processes could lead to a local lowering of base level: evaporation and tectonism. The southern end of the Hueco Bolson was occupied by playa lakes in which meter-thick sequences of laminated mud and silt and decimeter-thick beds of gypsum were deposited (see p. 28). If these lakes evaporated to dryness during periods of drought, the base level for streams draining the southern Hueco Bolson floor might have been lowered sufficiently to allow erosion of 5-m-deep (17-ft) channels. The depth of former playa lakes in the Hueco Bolson, however, is unknown. Meandering channels, which are similar to the channels in the Fort Hancock Formation, have been observed on mudflats that are exposed between the toes of distal alluvial fans and saline playa lakes that recently contracted because of evaporation in northern Africa (Smith, 1968, his fig. 17), Iran (Krinsley, 1970, his fig. 104), and California (Handford, 1982, his fig. 5).

Faulting could also have affected base level within the Hueco Bolson. The axial part of the Hueco Bolson lies within a fault-bounded graben that has experienced Quaternary faulting (Kreitler and others, 1986; Collins and Raney, in press). Furthermore, reflection seismic data indicate that Fort Hancock strata have been affected by faulting between the basin center and the Campo Grande fault (J. A. Raney, personal communication, 1989). Normal faulting contemporaneous with basin filling could have lowered the local base level by 5 m (17 ft) and allowed incision of parts of the lake floor.

Clay and Sandy Clay Lithofacies

Description

The clay and sandy clay lithofacies of the Fort Hancock Formation (table 1, lithofacies IV) is characteristically moderate brown (5YR 4/4) except locally in the beds where the sediments have been reduced to light-olive gray (5YR 8/1) (figs. 3, 5 through 8, and 11). The clay-sized fraction of this unit, analyzed using X-ray diffraction to determine its mineralogy, typically composes more than 50 percent of these facies and consists primarily of smectite clay with lesser amounts of kaolinite and illite (figs. 11 and 12). Additional small amounts of clay-sized quartz and calcite may be present.

The clay and sandy clay lithofacies are very persistent laterally and do not occur as channel fills. Beds of this lithofacies generally do not exceed about 3 m (10 ft) in thickness. Contacts between clay beds and overlying sand and silt beds are mostly gradational and coarsen upward. Contacts between clay beds and underlying sand and silt beds are mostly sharp.

Clay and sandy clay lithofacies commonly do not preserve primary sedimentary structures. In a few areas, however, horizontal laminations were preserved where they were not destroyed by pedogenesis or multiple episodes of desiccation and wetting, and may include thin silt interbeds. Laminations range from approximately 1 mm to as much as several centimeters in thickness. Both massive and laminated clay and sandy clay lithofacies preserve numerous deep desiccation cracks and pedogenic calcium carbonate nodules. Desiccation cracks are common and occur throughout clay and sandy clay units. Desiccation cracks are commonly filled with sand or silt and may reach 1 m in depth and more than 1 cm in width.

Paleosols belonging to the Vertisol soil group are present at the top of nearly every unit of the clay and sandy clay lithofacies. These paleosols are described in detail in a later section, and their characteristics are listed in table 2.

Interpretation

Pedoturbation due to the development of Vertisol soil profiles and to the development of pedogenic $CaCO_3$ nodules as well as multiple episodes of desiccation and expansion of clay destroyed most primary sedimentary structures in the clay and sandy clay lithofacies. The very fine particle size of the clay and sandy clay lithofacies, the presence of thin horizontal laminations in sections unaffected by pedogenesis, and its wide areal distribution collectively suggest that these sediments were deposited in a lacustrine environment. Preserved laminations further suggest that these sediments aggraded as a result of many depositional events. The lateral continuity of clay and silty clay lithofacies and the laterally consistent thickness of these units indicate that these lakes covered much of the basin floor throughout at least the southern half of the Hueco Bolson. Smectite clay makes up a high percentage of these fine-grained sediments and indicates that they have a high shrink-swell potential. Abundant desiccation cracks in the clay and sandy clay lithofacies indicate that periodically lake-floor sediments dried out (Demicco and Kordesch, 1986). More important, one or more buried Vertisol soil profiles are present in most clay and sandy clay units. Vertisols typically develop in expansive clay and sandy clay as a result of numerous episodes of swelling and shrinking following periods of flooding or rainfall and desiccation. Because paleovertisols are nearly ubiquitous at the top of each lacustrine clay unit, the lake basin in which these clays were deposited must have flooded and dried out numerous times. Consequently, clay and sandy clay lithofacies probably accumulated in a broad, shallow ephemeral lake near the axial part of the Hueco Bolson. Similar strata were observed by Demicco and Kordesh (1986) in the Lower Jurassic East Berlin Formation and were interpreted to be the product of dry playa mudflat aggradation in conjunction with rapid expansion and contraction of perennial lakes in a semiarid climate. Hubert and Hyde (1982) interpreted similar strata from the Upper Triassic Blomidon redbeds as playa sediments that accumulated under semiarid conditions.

Deposition of clay and sandy clay lacustrine sediments and soil formation probably occurred nearly concurrently. Thin laminae were deposited during each flood event. As the lake dried out, these sediments desiccated and cracked. This process was repeated many times as lake sediments accumulated. Multiple episodes of desiccation and expansion slowly destroyed lacustrine sedimentary structures and initiated soil development.

Pedogenic $CaCO_3$ nodules, which are present within the paleosols preserved in clay and sandy clay units, are similar to $CaCO_3$ nodules in Stage I or Stage II calcic soils. Gile and others (1981) and Machette (1985) have shown that development of Stage I and II calcic soils takes several hundred to at most a few thousand years. In a crude fashion, paleosol development in clay and sandy clay lithofacies indicates a minimum time interval during which deposition and pedogenesis was active.

Clay, Mud, Sandy Mud, and Gypsum Lithofacies

Description

The interbedded clay, mud, sandy mud, and gypsum lithofacies was observed only at the southeastern end of the Hueco Bolson, in the southeastern part of the study area in exposures between the Quitman Mountains and the Rio Grande (figs. 13 through 15). Clay strata of this lithofacies are similar in texture, mineralogy, and color to clay described in the clay and sandy clay lithofacies. However, clay and mud beds in this part of the Hueco Bolson are commonly laminated and rhythmically interbedded with laminations of fine silt. Beds of clay and mud as much as 2 m (6.6 ft) thick without recognizable primary sedimentary structures are also present. Massive clay and mud beds fracture conchoidally, and some fractures are stained with manganese oxide or hydroxide. Although minor desiccation cracks are present, these sediments are essentially undisturbed.

Gypsum is present as beds of intergrowths of crystals and as small (> 0.2 cm [>0.1 inch] in length), isolated crystals disseminated in clay or mud. Transparent euhedral gypsum (selenite) crystals as long as 5 cm (2 inches) form beds as thick as 0.5 m (1.6 ft). Interstices between the gypsum crystals are clay filled.

Interpretation

Sediments of the clay, mud, sandy mud, and gypsum lithofacies were deposited in the deeper parts of lakes that formed intermittently in the axial part of the Hueco Bolson. Laminated clays were deposited from suspension in standing water. The paucity of mud cracks suggests that this topographically low part of the bolson was not frequently desiccated. Because the Hueco Bolson was an internally drained basin, ground water probably also flowed toward the center of the basin. Ground-water discharge at the center of the basin may have prevented the deeper parts of the basin from desiccating, which would account for the lack of desiccation cracks. Additionally, because deeper parts of the basin would have retained water longer, this part of the lake may have periodically held water for several years within the much larger ephemeral part of the lake basin. Similar units were described by Groat (1972) as basin center facies of Tertiary sediments filling the Presidio Bolson.

Bedded gypsum was deposited as Ca^{++}, and SO_3^{--} ions in lake water and ground water were concentrated by evaporation. Similar conditions are present in the Salt Basin of Texas, which lies northeast of the Hueco Bolson, where ground waters derived from the upland areas surrounding the basin evaporate above the water table, and the gypsum playa surface acts as a broad ground-water discharge area (Boyd and Kreitler, 1986).

Sources of Fort Hancock Sediment

Cretaceous limestones and sandstones, which make up the bulk of strata exposed in the basin margins, were the source of sands and limestone gravels that accumulated along the flanks of the Hueco Bolson. Clay-sized sediments in the southern Hueco Bolson make up a large part of the total thickness of bolson fill. Limestones exposed along the flanks of the basin, however, were probably not major sources of clays and other fine-grained sediment. Thus, a substantial part of the lacustrine sediments in the study area had source areas outside the southern part of the Hueco Bolson. Perhaps more important, the widespread lakes into which these sediments were deposited probably required more water than could have been derived from the limited drainage basin of the Hueco Bolson proper. Strain (1966, 1971), Hawley and others (1969), Gile and others (1981), Seager and others (1984), Riley (1984), and Stuart and Willingham (1984) argued that a substantial part of both the water and fine-grained sediment in ephemeral lakes that occupied the axial part of the Hueco Bolson were derived from farther north in the drainage basin of the northern ancestral Rio Grande. The northern ancestral Rio Grande drainage was established in central and southern New Mexico by about 4 to 3 Ma ago (Bachman and Mehnert, 1978; Seager and others, 1984).

Paleoclimate

Certain qualitative aspects of the paleoclimate of the Hueco Bolson during the middle Pliocene can be deduced from the geologic and pedogenic record preserved in the sediments of the Fort Hancock Formation. Formation of facies tracks that include alluvial fans, widespread ephemeral lakes, and lakes with local evaporating pans in which gypsum was precipitated probably required an arid to semiarid climate. Widespread development of Vertisols with preserved deep desiccation cracks, mulch or nut zones and pedogenic $CaCO_3$ nodules also suggest a subhumid to arid climate. Collectively, this evidence indicates that the climatic conditions that prevailed during the late Pliocene as the Fort Hancock Formation was being deposited were relatively dry and could have ranged from arid to subhumid.

On the basis of macrofossil and fossil pollen data, Wells and others (1982) and Axlerod and Bailey (1986) determined that desert vegetation and arid climatic conditions were not present during the Pliocene in the Basin and Range province and did not appear until 10 to 8 Ka ago. The biologic and geologic evidence of climatic conditions are not necessarily in conflict, but collectively they support an interpretation that the region was dry and semiarid or subhumid rather than arid during the Pliocene.

Rates of Deposition

Did the ancestral northern Rio Grande provide most of the sediments preserved in at least the upper part of the Hueco Bolson fill? Could as much as 2,000 m (6,000 ft) of lacustrine basin fill have been transported to the Hueco Bolson during the late Pliocene (4 Ma to 2.25 Ma ago)? Unfortunately, no data are available for the direct reconstruction of rates of sedimentation or lacustrine flooding in the Hueco Bolson during the late Tertiary. Some insight into these issues can be obtained, however, by examining discharge and solute load data for the Rio Grande (International Boundary and Water Commission, United States and Mexico, 1975). Although the Hueco Bolson was a closed basin during the time that at least the upper Fort Hancock Formation was being deposited, it was the reservoir into which the northern ancestral Rio Grande discharged in early to middle Pliocene time. During this same time period, fluvial systems occupied upstream basins (Mesilla, Palomas, and San Marcial) (Lozinsky and Hawley, 1986; Lucas and Oaks, 1986; and Repenning and May, 1986).

River discharge is closely tied to rainfall. Sixty to seventy percent of the average annual rainfall within the upper Rio Grande drainage basin falls between June 1 and September 30, whereas less than 10 percent falls between February 1 and April 30 (International Boundary and Water Commission, United States and Mexico, 1975). Precipitation during the summer months is mostly the result of convective storms and is rapid and intense. Pliocene climate was apparently semiarid to subhumid, suggesting that precipitation was somewhat more plentiful than at present.

Modern discharge of the Rio Grande at El Paso, Texas, which averages 374,000 ac-ft/a, has been radically reduced because of upstream diversion of water for irrigation, storage of water in upstream reservoirs, loss of water stored in reservoirs to evaporation, and loss of water to phreatophytes. Discharge of the Rio Grande below Caballo Dam, New Mexico, which is 170 km (106 mi) upstream from El Paso, averaged 627,495 ac-ft/a between 1938 and 1975 and reached a maximum of 1,795,670 ac-ft/a (1942). An annual discharge of 1,800,000 ac-ft would have filled a lake basin in Hueco Bolson that was 160 km (100 mi) long and 16 km (10 mi) wide to an average depth of 85 cm (2.8 ft). The average annual rainfall (25 cm [10 inches] and annual runoff (5 cm [2 inches] from the basin must be added to the average annual discharge to create a hypothetical lake water depth of 115 cm (3.8 ft). Although these calculations ignore substantial water loss because of evaporation and climatic variations during the late Tertiary, they serve to illustrate that in a closed basin such as the Hueco Bolson, large ephemeral lakes could have existed seasonally as a result of discharge into the basin that was comparable to discharge carried by the present-day Rio Grande.

Total dissolved solids carried by the Rio Grande at El Paso, Texas, have averaged 4.0 × 108 kg (441,000 tons) per year between 1938 and 1975. Included in this total solute load are 0.44 × 108 kg (48,000 tons) of dissolved calcium and 1.3 × 108 kg (144,000 tons) of dissolved sulfate carried by the river per year. If all the sulfate were used to form gypsum and if an appropriate amount of water was utilized in the crystallization process, approximately 2.56 × 108 kg (288,000 tons) of gypsum would be produced as lake waters evaporated. Assuming a density of 2,300 kg/m^3, the annual solute load of the Rio Grande will produce 111,000 m^3 of gypsum, which is equivalent to a 1-cm-thick layer of gypsum covering 11 km^2 (4.3 mi^2). This discussion ignores any solute contribution from ground-water discharge into the basin and ignores the probability that some calcium or sulfate would go to form other minerals if evaporation was carried to dryness. Nevertheless, the volumes of gypsum beds observed in outcrop could easily have been derived from evaporation of water volumes equivalent to from 1 to 10 annual discharges of the Rio Grande.

Suspended load of the Rio Granae silt- and clay-sized sediment at El Paso is only 1.44 × 108 kg/yr (160,234 tons/yr). Suspended sediment load is low because upstream reservoirs behind dams at Elephant Butte and Caballo have acted as sediment traps. Consequently, deposition rates for fine silt and clay cannot be estimated.

These discussions of sedimentation and discharge rates conservatively demonstrate that the lake that episodically covered parts of the floor of the Hueco Bolson and the gypsum deposits within this lake could have been produced by the ancestral northern Rio Grande if it carried an annual discharge and solute load equivalent to that of the present-day Rio Grande.

Depositional History

The block diagram in figure 16 illustrates the interpreted geology and geomorphology of a segment of the southern part of the Hueco Bolson during deposition of the Fort Hancock Formation. Basinal structure is based on regional structural interpretations by Collins and others (1988).

Strata deposited in the subbasin illustrated in figure 16 represents a single more-or-less continuous episode of lacustrine expansion resulting in burial of alluvial fan sediments by a rapidly rising lake floor during the later stages of bolson sedimentation. Alluvial fan gravel, sand, and silt (lithofacies I through III) were derived from the Diablo Plateau and other highlands along the margins of the Hueco Bolson. The relatively low elevation of these highlands and the relatively small area that could have contributed sediment and runoff to the streams that supplied these fans allowed only slow rates of growth.

The southern part of the Hueco Bolson received runoff and sediment from the northern ancestral Rio Grande during the late Tertiary. Deposition of fine-grained lacustrine facies (clay and sandy clay and clay, mud, sandy mud, and gypsum lithofacies) in ephemeral lakes in the basin center resulted in a rising base level. Accretion of fan sediment was exceeded by the rate of accretion of fine-grained ephemeral lake sediments, allowing lacustrine expansion to occur. Deposition also exceeded rates of tectonic subsidence in the basin or the extensive subbasin beneath the study area would not have filled with lake sediments.

As sedimentation proceeded, a broad, flat, lacustrine plain formed. Lacustrine sediments, which have a high smectite clay content, were subjected to many episodes of swelling and shrinking as a result of precipitation or flooding and desiccation. Vertisol soil profiles formed because of the high clay content and numerous shrink-swell episodes. The lacustrine plain, which was apparently nearly planar and horizontal, was periodically flooded, adding a thin (millimeters to a few centimeters) new layer of fine sediment. As lake waters evaporated, sediments desiccated. Repeated episodes of desiccation ultimately resulted in the destruction of most primary sedimentary structures in clayey lacustrine lithofacies. In this fashion sections of clay-rich sediments aggraded without preserved sedimentary structures. Concurrent evaporation of lake waters at the southeastern end of the Hueco Bolson produced brines from which gypsum was deposited. The horizontality and lateral continuity of muddy lithofacies, preserved remnants of laminated clays, muds, and silts in outcrop and core, and abundant evidence of clay and mud desiccation all suggest that the southern part of the Hueco Bolson was occupied by a large ephemeral lake while the upper Fort Hancock Formation was being deposited.

Sand, sandy mud, and sandy silt deposited by shallow braided streams as sheet sands and in very low depth-to-width-ratio channels are interbedded with clayey lacustrine sediments. Sheet sands were probably deposited as distal alluvial fan or alluvial slope sediments, and they were likely derived from both the northeast and southwest flanks of the Hueco Bolson. Additionally, some fine sandy facies may have been derived from alluvial plains building southward from the northern end of the Hueco Bolson (Stuart and Willingham, 1984). When lake waters were high, these alluvial bodies were probably fan deltas. As the bolson filled in the presence of ephemeral lakes, avulsion and lateral shifting of distributaries on fans or alluvial plains along the margins of the bolson resulted in the interbedding of lacustrine and fluvial lithofacies.

Gravel and interbedded gravel and sand lithofacies were deposited by flashy, intermittent braided streams on the proximal and medial parts of alluvial fans.

FORT HANCOCK–CAMP RICE UNCONFORMITY AND THE INTEGRATION OF RIO GRANDE DRAINAGE

A significant part of the late Cenozoic history of the Hueco Bolson can be deduced from examining the unconformity that separates the Fort Hancock Formation from the overlying Camp Rice Formation. This unconformity marks the change from low-energy, predominantly lacustrine deposition to high-energy, predominantly fluvial deposition. It also records a period of significant erosion along the axis of the bolson that occurred as the ancestral southern Rio Grande was integrated with the northern Rio Grande.

Fort Hancock–Camp Rice Unconformity

The unconformity that separates the Fort Hancock and Camp Rice Formations in the southern Hueco bolson was first recognized by Albritton and Smith (1965) and Strain (1966). Hawley and others (1969), Riley (1984), and Stuart and Willingham (1984) recognized the unconformity but did not describe it. Vanderhill (1986, p. 248) described the contact between the Camp Rice and Fort Hancock in the southern Hueco Bolson as "simply the base of the first sandy channel, not a regional disconformity."

Early interpretations of the drainage path of the northern ancestral Rio Grande had the river discharging into a series of lakes near Laguna Guzman and Laguna de Santa Maria in Bolson de los Muertos in northern Chihuahua, Mexico, but not into the Hueco Bolson (Lee, 1907; Bryan, 1938; Kottlowski, 1958). Strain (1966) proposed that during periods of maximum precipitation the separate basins of the Mesilla Bolson, Hueco Bolson, and Bolson de los Muertos flooded and overflowed to form an integrated network of waters he named Lake Cabeza de Vaca. "Huge quantities of clay and silt, which originated to the north in New Mexico and Colorado, settled in the lakes to form well bedded deposits which abutted against the surrounding mountains" (Strain, 1966, p. 10).

Strain (1971) indicated that Lake Cabeza de Vaca may have reached an elevation of 1,295 m (4,250 ft) in the Hueco Bolson. Reeves (1969) stated that the base level of waters in the Hueco Bolson was approximately 1,182 m (3,900 ft) where the Quitman Mountains extended across the present Rio Grande Valley. The highest exposures of Fort Hancock lacustrine sediments in the southern Hueco Bolson are consistently about 1,234 m (4,050 ft). However, these exposures are truncated by erosional surfaces overlain by the Madden Gravel, and it is clear that the Fort Hancock Formation originally extended to higher elevations. Therefore, it seems probable that Fort Hancock lacustrine sedimentation (Lake Cabeza de Vaca) extended above 1,234 m (4,050 ft) and that the base level at the Quitman Mountains that contained the Hueco Bolson arm of Lake Cabeza de Vaca was at least 1,234 m (4,050 ft) in elevation.

The clay and sandy clay lithologies that compose the lacustrine sediments of the Fort Hancock Formation were laid down on a nearly horizontal ephemeral lake floor and aggraded to a level in excess of 1,234 m (4,050 ft). Differences in elevation of the lake bottom depositional surface across the bolson were probably only a few meters. Comparison of the elevation of the eroded upper limit of the Fort Hancock Formation with the lowest available elevation for the erosional contact between the Fort Hancock Formation and the overlying Camp Rice Formation yields an estimate of the minimum amount of erosion that occurred prior to the onset of Camp Rice deposition. The lowest elevations of the contact between the Fort Hancock and Camp Rice

Formations range from about 1,158 m (3,800 ft) in Alamo Arroyo to about 1,111 m (3,645 ft) in Quitman Arroyo at the southeastern or downgradient end of the Hueco Bolson. These exposures lie along the northeast flank of the bolson, and depth of incision could have been greater near the center of the bolson. Although faulting has down-dropped the unconformity by about 28 m (92 ft) near Alamo Arroyo (Collins and Raney, in press) no field evidence is available that indicates faulting of the unconformity in Quitman Arroyo. Erosion, therefore, may account for as much as, or more than, 123 m (408 ft) of relief on the unconformity that separates the Fort Hancock Formation from the Camp Rice Formation along Quitman Arroyo and 48 m (158 ft) of relief along Alamo Arroyo. In addition, local relief on the unconformity in Arroyo Diablo is approximately 35 m (116 ft), and beneath the TLLRWDA site, relief on the unconformity is about 30 m (100 ft) (pl. 1). Clearly, the Fort Hancock Formation was eroded to an approximate maximum depth of 130 m (430 ft) before deposition of the Camp Rice Formation began.

The elevation of the unconformity between the Fort Hancock and Camp Rice Formations is known from exposures in arroyos that drain the northeast flank of the Hueco Bolson. On the basis of the elevations of these exposures, the interpreted regional southeast slope of the unconformity can be calculated for several segments of the bolson. For example, the elevations of the unconformity in Alamo and Quitman Arroyos near the downstream ends of these arroyos are approximately 1,158 m (3,800 ft) and 1,111 m (3,645 ft), respectively (fig. 1). The elevation of the unconformity at Alamo Arroyo, however, may have been dropped by approximately 28 m (92 ft) due to faulting. The distance between Alamo and Quitman Arroyos is about 49 km (31 mi). As determined from these data, the unconformity slopes about 1 m/km between Alamo and Quitman Arroyos if an elevation of 1,158 m is used, or the unconformity slopes about 1.5 m/km if the elevation is corrected for possible fault movement.

Boothroyd and Ashley (1975) and Church and Gilbert (1975) both showed that clast size is roughly proportional to surface slope for large glacial outwash fans. Although relationships between slope and clast size are very imprecise, a slope of approximately 1 m/km to 1.5 m/km is associated with sand-sized material and pebbles with a long axis of as much as 2 cm (0.8 inch)

(Boothroyd and Ashley, 1975, their figs. 8 and 9). This is approximately the size distribution of sediments in the Camp Rice Formation, mostly sand with a few small pebbles, that overlie the unconformity. These relations suggest that, where the unconformity is exposed in the southern part of the Hueco Bolson, the slope of the unconformity is comparable with slopes required to transport sand and gravel of the overlying Camp Rice Formation.

The erosional unconformity at the top of the Fort Hancock Formation is the earliest and most compelling evidence of the integration of the ancestral northern Rio Grande to the ancestral southern Rio Grande. Relief on the unconformity, which probably exceeds 130 m (430 ft), could not have developed without lowering base level along the axis of the Hueco Bolson by at least an equal amount. This radical change in base level most likely resulted because the southern end of the Hueco Bolson was breached by overtopping a low divide at the southern end of the bolson by waters of the playa lake that occupied the basin or because of headward erosion of the southern ancestral Rio Grande (Strain, 1966; Reeves, 1969). Breaching the divide at the southern end of the Hueco Bolson eliminated the topographic basin occupied by playa or ephemeral lakes and allowed the northern ancestral Rio Grande to flow through the bolson and to integrate with the southern ancestral Rio Grande. No recognizable evidence to support either hypothesis remains where the Rio Grande cuts through the Quitman Mountains at the southeastern end of the Hueco Bolson near Indian Hot Springs, but it seems likely that both processes played a role in the integration of the Rio Grande. The role of faulting is also unknown, but it is possible that seismicity played a part in the early breaching of the Quitman barrier.

In order to bring the northern Rio Grande into grade with the southern Rio Grande and to provide the slope necessary to transport a coarse sediment load, the Hueco Bolson was deeply incised. Only after the integrated Rio Grande system increased the stream gradient through the Hueco Bolson by erosion was there sufficient flow velocity in the Rio Grande to transport coarse sand and gravel. The unconformity represents a considerable period of time during which the Rio Grande adjusted its slope to carry available discharge and sediment by incising the Fort Hancock Formation.

Ages of the Fort Hancock–Camp Rice Unconformity and the Integration of Rio Grande Drainage

The Camp Rice Formation, which overlies the unconformity, contains the Huckleberry Ridge Ash, which at 2.01 Ma old is the oldest of the Pearlette family of ashes (Izett and Wilcox, 1982). Prior to the work of John Boellstorff and Glenn Izett in the early 1970's, estimates of the age of the integration of the northern and southern segments of the Rio Grande were clouded by the widely held but erroneous belief that there was only a single middle Pleistocene volcanic ash, the Pearlette Ash, preserved throughout the Midcontinent and southwestern United States. The presence of a Pearlette Ash in the Camp Rice Formation required that the formation be middle Pleistocene in age and that integration of the northern and southern segments of the Rio Grande occurred previously, during the early to middle Pleistocene (Strain, 1966; Hawley, 1969; Hawley and others, 1969; Reeves, 1969). Stuart and Willingham (1984) and Taylor (1987) agreed that the integration of Rio Grande drainages was a middle Pleistocene event but offered no supporting evidence. Recognizing the correct age of the ash has allowed a more accurate estimate of the timing of the integration of Rio Grande drainage.

The northern ancestral Rio Grande became a through-flowing system in northern New Mexico about 3.0+ Ma ago (Bachman and Mehnert, 1978). In central and southern New Mexico the Rio Grande became a through-flowing stream about 4 to 3.5 Ma ago (Seager and others, 1984).

The precise timing of integration of the northern and southern ancestral Rio Grande drainage systems is unknown; however, some inference regarding age can be made. The lower Camp Rice Formation contains a lens of the Huckleberry Ridge Ash, which Izett and Wilcox (1982) correlated using trace element chemistry with ash from an eruption that occurred in the Yellowstone National Park area of Wyoming at 2.01 Ma. The ash crops out at an approximate elevation of 1,189 m (3,900 ft). The base of the Camp Rice Formation in the study area is approximately 1,143 m (3,750 ft). Consequently, in addition to erosion of possibly 130 m (430 ft) of Fort Hancock sediments, approximately 46 m (150 ft) of Camp Rice strata were deposited between the time that drainage integration occurred and deposition of the Huckleberry Ridge Ash.

Upper Fort Hancock strata contain a Blancan Land Mammal Age Fauna (Hudspeth Local Fauna) (Strain, 1966): thus, these strata are less than 4.5 Ma old (Tedford, 1981; Repenning and May, 1986). Recently, Vanderhill (1986) suggested that the upper Fort Hancock strata at the type section of the formation were nearly 2.48 Ma old and possibly as old as 3.4 Ma on the basis of paleomagnetic and paleontologic evidence. The elevation of the top of this Fort Hancock section is only about 1,184 m (3,815 ft), requiring that about 50 m (165 ft) of Fort Hancock sediments, which are typically present to an elevation of 1,234 m (4,050 ft), were eroded prior to deposition of the Camp Rice Formation. These stratigraphic and geomorphic arguments indicate that the construction of the regional unconformity between the Camp Rice and Fort Hancock Formations and integration of the northern and southern segments of the Rio Grande occurred after 2.48 Ma and well before 2.01 Ma, probably about 2.25 Ma ago.

CAMP RICE FORMATION

The upper Tertiary–Quaternary Camp Rice Formation unconformably overlies the Fort Hancock Formation throughout much of the study area. The Camp Rice is present beneath the eastern part of the TLLRWDA site and missing to the west (pl. 1). No Camp Rice sediments were recognized in exposures in Alamo Arroyo west of the TLLRWDA site. In the sections described in this report, the Camp Rice Formation is truncated by the Quaternary Madden Gravel. The Madden Gravel is mostly thin pediment gravels derived from Tertiary intrusive rocks, Cretaceous limestones and sandstones, and older rocks exposed at the margins of the Hueco Bolson (see Albritton and Smith, 1965, for description of these units).

Lithofacies groups of the Camp Rice Formation comprise: (1) sand and gravel; (2) sand and exotic gravel; (3) sand; (4) coarse silt and very fine sand; and (5) clay, sandy clay, and gypsum (table 3). Collectively, these lithofacies represent deposition by axial streams flowing through the

Hueco Bolson (lithofacies 2), by streams draining the margins of the bolson (lithofacies 1), by eolian processes (lithofacies 3 and 4), and in ephemeral lakes (lithofacies 5). The Camp Rice Formation, which has been mostly attributed to fluvial sedimentation (for example, Strain, 1966, and Stuart and Willingham, 1984), represents a far more diverse set of depositional environments than previously recognized.

Sand and Gravel Lithofacies (with common locally derived lithoclasts)

Description

Sand and gravel lithofacies comprise primarily sand- and gravel-sized sediment including $CaCO_3$ nodules and numerous mudstone lithoclasts derived from the Fort Hancock Formation (figs. 17 and 18; table 3, lithofacies 1). This facies is preserved in broad shallow channels and lies directly on eroded Fort Hancock strata. Mudstone lithoclasts measure as much as to 20 cm (7.9 inches) in diameter and are only rarely armored with pebbles or sand. $CaCO_3$ lithoclasts do not exceed 3 cm (1.2 inches) in diameter. Gravel-sized clasts in this lithofacies are limited to lithoclasts and nodules derived from the Fort Hancock Formation and do not include gravel-sized limestone clasts from the Diablo Plateau or gravel-sized igneous or metamorphic clasts derived from outside the Hueco Bolson.

Primary sedimentary structures range from ripple-drift cross-lamination to large-scale trough cross-stratification, and horizontal bedding, reflecting multiple episodes of channel cutting and channel filling by migrating bars, dunes, and ripples (figs. 7, 17, and 19). Bases of channels are commonly marked by accumulations of moderate-brown gravel-sized mud and clay lithoclasts. Channel fills commonly fine upward from sand- and gravel-sized to mostly sand-sized sediment. Bed thickness and the scale of sedimentary structures also decrease upward.

Sand and gravel lithofacies are preserved in south-southeast-oriented channel complexes in which paleoflow was generally to the southeast. Channel complexes lie between the belt of sand

and exotic gravel lithofacies (described in following section), which occupies the axial part of the basin and the northeastern basin margin.

Interpretation

The sand and gravel lithofacies records the onset of fluvial sedimentation that marks the change from Fort Hancock to Camp Rice deposition. This lithofacies is characterized by numerous cycles of cutting and filling, with channel fills in which grain size, bed thickness, and the scale of sedimentary structures decrease upward. These sediments were deposited by a braided stream and are similar to the gravelly to sandy braided fluvial facies described by Williams and Rust (1969), Miall (1977), and Cant and Walker (1978). The sand and gravel lithofacies fills channels that are oriented at a high angle to the Rio Grande and clearly contains primarily sediment eroded from Fort Hancock strata. Consequently, the sand and gravel lithofacies is interpreted as consisting predominantly of sediments laid down by short tributaries of the axial drainage of the Hueco Bolson, the ancestral Rio Grande.

Sand and Exotic Gravel Lithofacies

Description

The sand and exotic gravel lithofacies consists primarily of sand and gravel with secondary amounts of interbedded sand (figs. 6 and 19; table 3, lithofacies 2). Lithoclasts and armored mud balls derived from clays and sandy clays and muds of the Fort Hancock Formation are locally present at the base of channels. Gravel, which is primarily composed of locally derived limestone, includes exotic clasts of obsidian, vein quartz, rhyolite, and other igneous, volcanic, and metamorphic clasts. These rock types, which are absent in the study area, were derived from the

Rio Grande drainage north of the study area. This facies is confined to the axial part of the Hueco Bolson (fig. 1).

Gravels are mostly horizontally bedded to planar to trough crossbedded. Sands are horizontally to planar crossbedded or ripple cross-laminated. In some sections sequences that fine upward from primarily gravel to primarily coarse to medium sand are common.

Interpretation

Sand and exotic gravel lithofacies were probably deposited by braided, possibly intermittent streams. These gravelly and sandy facies are similar to Recent braided fluvial deposits described by Williams and Rust (1969), Miall (1977), and Cant and Walker (1978). Exotic gravel, which was derived from north of the study area and probably largely outside of the Hueco Bolson, indicates that these sediments were laid down by the through-flowing ancestral Rio Grande along the axis of the Hueco Bolson (Albritton and Smith, 1965; Strain, 1966).

Sand and exotic gravel deposits are primary evidence of the integration of the northern and southern ancestral segments of the Rio Grande. Sand and gravel lithofacies, both with and without exotic gravel, provide a record of the early development of a through-flowing stream and its tributaries in the Hueco Bolson.

Sand Lithofacies

Description

In Alamo Arroyo, approximately 1 km (0.63 mi) west-northwest of Cavette Lake, a 1- to 1.5-m-thick (3.3- to 5-ft) bed of well-sorted planar crossbedded medium sand is exposed over a distance of about 1 km (0.63 mi) at the base of the Camp Rice Formation (table 3, lithofacies 3). Transport direction was to the south-southeast.

Interpretation

The well-sorted texture of these sediments, the bed thickness, the grain size, the sedimentary structure, and the consistent transport direction collectively suggest that transport and deposition were by eolian processes. These sediments are similar to eolian sediments in active dunes that are present in the study area. The sand lithofacies differs significantly from fluvial sediments in both the Fort Hancock and Camp Rice Formation in that these sands are better sorted, do not contain gravel, and record the movement of a thick sand body with a constant transport direction. These well-sorted sands represent the migration of a single dune complex across the erosional surface that developed on the Fort Hancock Formation.

Coarse Silt and Very Fine Sand Lithofacies

Description

Near the type section of the Camp Rice Formation (Strain, 1966), which lies south of Campo Grande Mountain on the east side of Campo Grande Arroyo, approximately 10 m (33 ft) of clayey to muddy, fine to very fine sand is exposed (table 3, lithofacies 4). No primary sedimentary structures are preserved in this lithofacies. Five cycles of sedimentation and soil development are present. Each cycle consists of very pale orange (10YR 8/2), very fine sand with rare to common $CaCO_3$ nodules overlain by light-brown (5YR 5/6–4/6), angular, blocky to prismatic-fracturing muddy sand with common $CaCO_3$ nodules. Calcium carbonate-filled root tubules (rhizocretions) are rare to common. Strain (1966) described sediments of similar color at the type section of the Camp Rice Formation, which also contain $CaCO_3$ nodules and lack primary sedimentary structures.

Interpretation

Each cycle of very pale orange fine sand to light-brown muddy sand apparently represents an episode of eolian loess sedimentation on a stable vegetated surface. The upper light-brown muddy sand is interpreted as a buried illuvial B soil horizon on the basis of increased clay and $CaCO_3$ content. Illuvial clay horizons as well as the $CaCO_3$ nodules developed during periods of landscape stability. The stacked paleosols show no evidence of erosion between cycles of soil development, even though there are no recognizable A horizons. Downward-branching $CaCO_3$-cemented tubules and $CaCO_3$ filaments are evidence of roots, and they indicate that the landscape was vegetated, most likely by small shrubs or grasses.

Development of illuvial clay horizons and pedogenic $CaCO_3$ nodules requires long periods of landscape stability, during which pedogenic processes would have a chance to operate. Pedogenic $CaCO_3$ nodules form in arid to subhumid climates (Machette, 1985). Absence of sedimentary structures also suggests bioturbation, or that sedimentary structure never developed because of slow sedimentation on a vegetated surface. Fryberger and others (1979) and Kocurek and Neilson (1986) suggested that vegetation, particularly grass, plays a significant role in stabilizing eolian sediments. The texture, color, pedogenic structures, $CaCO_3$-cemented root tubules, and lack of primary sedimentary structures in these sediments are similar to eolian loess sections of the Miocene–Pliocene Ogallala Formation and Quaternary Blackwater Draw Formation of northwest Texas and eastern New Mexico described by Gustavson and Holliday (1988), Gustavson and Winkler (1988), Holliday (1989), and Gustavson (in press).

Clay, Sandy Clay, and Gypsum Lithofacies

Description

The clay, sandy clay, and gypsum lithofacies of the Camp Rice Formation is exposed by incision of Alamo Arroyo and its tributaries over much of the area north of Alamo Reservoir No. 3 and south of Cavette Lake (fig. 19, 23 to 29 m; table 3, lithofacies 5). These strata, which overlie fluvial sand and gravel of the Camp Rice Formation that contain exotic gravel, are very similar to the clay and sandy clay and sand, sandy mud, and sandy silt lithofacies of the Fort Hancock Formation (see descriptions of sand, sandy silt, and sandy mud lithofacies and clay and sandy clay lithofacies of the Fort Hancock Formation for details). Similar texture, color, and shrink-swell properties suggest that Camp Rice clays also contain a high percentage of smectite clay. Sandy silt composes a single thin, horizontally bedded unit. The clay, sandy clay, and gypsum lithofacies lacks primary sedimentary structures where it was observed in the Camp Rice Formation. However, a single, horizontal, nearly 7-cm-thick (2.5-inch) bed of coarsely crystalline gypsum is present approximately 2 m (6.6 ft) above the base of this unit (fig. 19, at 24.5 m). Several buried Vertisol soil profiles (see section on paleovertisols and table 2) are present and identify a planar nearly horizontal stratigraphy exposed over distances of several kilometers. Vertisols develop as a result of numerous episodes of swelling and shrinking following periods of rainfall or flooding and drying. Small gypsum crystals (<5 cm [2 inches] long) and pedogenic $CaCO_3$ nodules are scattered throughout certain zones of these Vertisols.

Interpretation

The similarities in color, texture, stratigraphy, and pedogenic characteristics between clay and sandy clay lithofacies of the Camp Rice Formation and the Fort Hancock Formation strongly suggest that like the clay and sandy clay lithofacies of the Fort Hancock Formation the clay and sandy clay lithofacies of the Camp Rice Formation were deposited in ephemeral lakes. The thin gypsum bed suggests that this basin also held a saline playa for a brief time.

Depositional History

The Camp Rice Formation contains a complex of lithofacies that were deposited in a wide variety of environments (fig. 20). Sand and gravel lithofacies containing exotic gravel derived from north of the Hueco Bolson were deposited along the axis of the Hueco Bolson by a through-flowing stream, the ancestral Rio Grande. The presence of mud balls, a broad shallow channel, coarse sediment texture, and common large-scale trough cross-stratification suggest that these sediments were deposited by a braided stream. A second sand and gravel lithofacies containing numerous lithoclasts locally derived from the Fort Hancock Formation and exposed mostly along the margins of the Hueco Bolson was probably deposited by short tributaries of the ancestral Rio Grande. These deposits, which are characterized by broad shallow channels, few clay or mud drapes, common large-scale trough crossbeds, coarse sediment texture, and abundant lithoclasts and mud balls, were deposited by intermittent braided streams.

Eolian sediments in the form of locally preserved dune sand and loess were deposited between sites of fluvial sedimentation. Loess sedimentation was prevalent locally in areas protected from fluvial erosion and sedimentation. Intermittent streams, which likely deposited the sand and gravel lithofacies, would have provided a local source of eolian sediment.

Ephemeral lakes developed locally in areas that were affected by neither fluvial deposition nor erosion. Whether these lake basins developed as a result of localized tectonic subsidence, differential compaction of underlying sediments, or by some other process is unknown. Sediments deposited in ephemeral lakes were subjected to periodic desiccation, which destroyed most sedimentary structures. Slow sedimentation in the stable lake basin allowed Vertisols to form.

Paleoclimate

As in the Fort Hancock Formation during the early Pliocene, the paleoclimatic conditions that prevailed in the Hueco Bolson during the late Pliocene and early Pleistocene as the Camp Rice Formation was being deposited can only be described in general terms. Fluvial systems that deposited the Camp Rice Formation were deposited by braided locally intermittent streams. Lacustrine sediments including discontinuous beds of gypsum were deposited in small ephemeral lakes. Eolian dunes and loess deposits were recognized locally. Several cycles of buried calcic soils in loess and buried Vertisols with pedogenic $CaCO_3$ nodules are preserved in the Camp Rice Formation and are indicative of subhumid to arid climates (Machette, 1985). Collectively, this evidence suggests that an arid to subhumid, but probably dominantly semiarid, climate prevailed in the Hueco Bolson during the late Pliocene to early Pleistocene.

PALEOVERTISOLS

Paleovertisols are common in outcrops and in core of smectite-rich clay and mud facies (clay and silty clay soils) of the Fort Hancock Formation and do not occur in coarser grained facies (fig. 10). Throughout the middle and northern parts of the study area, paleovertisols or paleosols with some vertic properties are present in nearly every exposed clay or mud bed (figs. 5 through 8 and 19). Buried Vertisols and soils with vertic properties are also present in most clay and mud facies in core to a depth of approximately 67 m (220 ft) but were not recognized in clay and mud facies below that depth (fig. 3). Paleovertisols were also not observed in lacustrine clays and muds interstratified with either massive gypsum beds or beds of dispersed gypsum crystals (figs. 14 and 15).

Paleovertisols have seldom been described in the literature even though modern Vertisols are commonly present in clayey sediments and account for more than 3.2×10^6 km^2 (1.25×10^6 mi^2), or 2.4 percent, of the Earth's land surface (Dudal and Eswaran, 1988). Some published examples of paleovertisols and buried soils with some vertic properties include descriptions of (1) pedogenic slickensides that developed in fine-grained facies of Paleozoic redbeds of the Bloomsburg, Catskill, and Mauch Chunk Formations in the central Appalachian Mountains (Gray and Nickelsen, 1989); (2) buried Vertisols in the Pennsylvanian Monongahela Formation (Blodgett, 1985 a, b); (3) paleosol microrelief features in the Mishor and Ardon Formations, Israel (Goldbery, 1982); and (4) compressional structures associated with pattern ground developed in the Devonian Old Red Sandstone (Allen, 1973).

Vertisol Characteristics

Vertisols are clayey soils that develop one or more of the following characteristics: (1) gilgai (surface microtopography); (2) deep, wide desiccation cracks (≥1 cm [0.4 inch] wide at a depth of 50 cm [20 inches]) at some time of year; (3) high bulk density when dry; (4) very slow hydraulic conductivity when moist; (5) slickensides on ped faces close enough to intersect at some depth between 25 cm and 1 m; or (6) wedge-shaped structural soil aggregates whose long axes dip between 10° and 60° from 25 cm to 1 m below the soil surface (Soil Survey Staff, 1975). Montmorillonite, which is a member of the smectite family of clay minerals with a high coefficient of linear extensibility, commonly composes at least 30 percent of these soils (Dudal and Eswaran, 1988). Mixtures of equal amounts of kaolinite and montmorillonite and kaolinite-rich, fine-clay (>0.2 μm) soils also have properties similar to those of montmorillonite alone (Yerima and others, 1985, 1987; Smith and others, 1985) and may compose Vertisols.

The characteristic shrink-swell property of smectite clays has commonly been attributed to an ability to take up water or organic liquids between their structural layers. However, Wilding and Tessier (1988) suggested that shrink-swell properties of smectite clays result mostly from water loss and gain between clay particles and, to a lesser extent, from water loss and gain between structural layers. Mielenz and King (1955) showed that free-swelling Ca montmorillonite can expand 45 to 145 percent. The percentage of free swelling is decreased for synthetic mixtures of montmorillonite, kaolinite, and sand. Furthermore, expansion increases as original density increases. Hydration or swelling pressures in montmorillonite clays are in the order of 1 to 6 kg/cm^2 (14.2 to 65.2 $lb/inches^2$) (Mielenz and King, 1955; Komornik and Zeitlin, 1970). The ability of smectite clays to take up water between their structural layers and between clay particles is the fundamental property that leads to the development of Vertisols.

Paleovertisol Properties

Paleovertisols developed in clay and mud facies of the Fort Hancock and Camp Rice Formations, which contain more than 45 percent clay-sized material ($\geq 8\phi$ or 3.9 μm). As sediments these units are classified as clays, muds, sandy clays, or sandy muds (Folk, 1968); as soils they are classified as clays or silty clays (sand 2 to 0.05 mm, silt 0.05 to 0.002 mm, clay $\geq$ 0.002 mm) (Soil Survey Staff, 1975) (fig. 11).

The mineralogy of selected samples of clay-rich facies of the Fort Hancock Formation, many of which contain paleovertisols, was determined using X-ray diffraction. Whole-rock samples were analyzed from 10° to 60° 2 theta using a 35 kv copper X-ray tube. In addition both coarse (2 to 4 μm) and fine (< 2 μm) clay-size fractions were analyzed from 2° to 16° 2 theta. Clay facies of the Fort Hancock Formation are composed primarily of smectite (montmorillonite) with lesser amounts of kaolinite, illite, and quartz (R. S. Fisher, written communication, 1989) (fig. 12).

The microstructure of clay facies is illustrated in figure 21. Thin sheetlike clay particles lie subparallel to each other and are crudely laminated. According to Wilding and Tessier (1988), absorption and loss of water in the pores between clay particles such as these is largely responsible for expansion and contraction of clay facies.

Structures in Paleovertisols

Soil structures in buried Vertisols of the Fort Hancock and Camp Rice commonly include (1) mulch or nut zones, (2) near-vertical desiccation cracks, (3) intersecting fractures with slickensides that bound small blocky soil aggregates and large wedge-shaped soil aggregates, (4) manganese oxide or hydroxide films on fracture faces, and (5) $CaCO_3$ films or nodules (figs. 22 and 23). Mulch or nut zones mark the former surface layer of buried Vertisols and comprise compacted angular, blocky granules. These compacted granules were derived from an original surface layer of loose, puffy aggregates (popcornlike texture) or of a layer broken by numerous small desiccation cracks (fig. 24).

Large desiccation cracks may be as much as 150 cm (60 inches) deep and 1.5 cm (0.6 inches) wide. Formerly open desiccation cracks in buried Vertisols are recognizable when they contain material of a different texture or color than the main body of the soil (fig. 25). Desiccation cracks may be filled with sand and silt that was deposited in the crack from above by either eolian or fluvial processes. Other desiccation cracks are filled with granules of soil that fell into the cracks from the overlying mulch zone. Sand that fills desiccation cracks is commonly cemented with $CaCO_3$ and in plan view may outline an irregular polygonal fracture pattern (fig. 26).

Both small blocky and large wedge-shaped soil aggregates are bounded by intersecting fractures with slickensides. Blocky soil aggregates are normally less than 20 cm (9 inches) on a side. Blocky aggregates occur below the mulch zone and commonly contain many small intersecting fractures with slickensides (fig. 27). Intersecting fractures with slickensides also bound large (0.3- to 3.0-m [1- to 3-ft]) wedge-shaped soil aggregates. Fractures that bound wedge-shaped soil aggregates are commonly slightly concave upward and dip from 10° to 60° (fig. 28). Displacement across fractures bounding large wedge-shaped soil aggregates may exceed several centimeters.

A micrograph (fig. 29) of the slickenside-covered surface of a soil fracture in the clay-rich facies of the Fort Hancock Formation indicates that movement along the fracture to create the slickensides has apparently macerated and smeared out clay particles to produce a compact, thin, very fine grained layer.

Black manganese oxide or hydroxide films are present on some slickenside-covered fracture faces in buried Vertisols in the Fort Hancock and Camp Rice Formations. Manganese films on fracture faces suggest that shallow ground waters flowed along fractures and through these sediments during or after soil formation. Pedogenic $CaCO_3$ filaments and nodules are also present in some paleovertisols. Carbonate filaments tend to follow vertical fractures, and $CaCO_3$ nodules, which may be as large as 10 cm by 3 cm (3.3 inches by 1.2 inches), are commonly vertically elongated. In most buried Vertisols, carbonate nodules are relatively widely separated from each other (<10 cm [3.3 inches]) (fig. 22) and clearly occur well below the mulch zone. Vertically elongate nodules may grow preferentially in buried desiccation cracks. These nodules should not be confused with rhizocretions because they are not downward branching and show no indication of having formed around a former root.

Models for Vertisol Pedogenesis

Wilding and Tessier (1988) critically reviewed models of Vertisol development that emphasize the effects of pedoturbation and differential loading. Citing new evidence from Ahmad (1983), Wilding (1985), and Dasog and others (1987) that suggests that many Vertisols do not undergo extensive mixing, especially in the upper soil horizons, Wilding and Tessier (1988) argued that structures and soil horizons in Vertisols result from inherent mechanical properties of the soil. These models for Vertisol pedogenesis are briefly described and their application to the genesis of buried Vertisols in the Fort Hancock and Camp Rice Formations is evaluated.

Pedoturbation

The pedoturbation model of Vertisol development was first described by Hilgard (1906) as a mechanism by which gilgai (microtopographic surface expression of Vertisols) form. He inferred that deep cracks in soils became partly filled by material falling in from the surface and from the sides of the cracks. When the soil became wet and expanded, desiccation cracks could not close because of the surplus material in them. Soil near the cracks was forced away and upward from the cracks resulting in large wedge-shaped soil aggregates bound by fractures with slickensides in the subsurface, and in microtopographic highs (gilgai) at the surface. Development of pedogenic horizons would be slowed or prevented by soil mixing or pedoturbation.

Wilding and Tessier (1988) noted that in some Vertisols systematic soil-property depth functions, eluvial-illuvial horizonation, and only slightly disturbed stratigraphic horizons suggest that soil mixing was not as active as previously thought. They recognized that filling of desiccation cracks occurs but is only partly responsible for formation of slickensides, gilgai, and cyclic horizonation.

Differential Loading

Paton (1974) suggested that gilgai were formed by a process of differential loading where clays moved from areas of high-confining pressure to areas of low-confining pressure. Paton (1974) drew analogies between gilgai and sedimentary structures and mudlump islands from the Mississippi delta (see Morgan and others, 1968). Gustavson (1975) argued that Paton's application of the process by which sedimentary load structures and mudlump islands occurs to the formation of gilgai is questionable. Marked density differences exist between deltaic sands and uncompacted water-saturated muds, but similar density differences have not been observed in adjacent soil horizons. Furthermore, sedimentary load structures on delta front slopes tend to be elongated transverse to slope direction. Gilgai, when they occur on slopes greater than 1 percent, are elongated ridges and troughs aligned roughly parallel to the slope direction. Blokhuis (1982) noted that the regular pattern of gilgai microtopography was not compatible with patterns of sediment density differences arising from recognized depositional processes.

Soil Mechanics

Wilding and Tessier (1988) proposed a model of Vertisol pedogenesis based on the mechanical behavior of expansive clay sediment or soil. They recognized that soil wetting takes place downward from the surface mulch zone and upward or inward from desiccation cracks filled with water during precipitation events (Howard, 1932; Blake and others, 1973). Swelling and expansion of near-surface clays following absorption of water results in uplift of surface material. Water absorption and clay expansion in the subsurface where vertical and lateral soil movement is confined result in crack closure and eventually in swelling pressures that exceed soil shear strength. Swelling pressures in Vertisols are approximately 1 to 6 kg/cm^2 (Mielenz and King, 1955; Komornik and Zeitlin, 1970), but probably do not exceed 1 kg/cm^2 at moisture levels where failure is most likely (Wilding and Tessier, 1988). Failure by shearing results in small faults or fractures with slickensides. Fractures tend to radiate outward and upward from beneath gilgai microdepressions, forming bowl-like structures (Dudal and Eswaran, 1985; Wilding, 1985). The soil mechanics model accommodates formation of slickensides and pedogenic structure and is compatible with systematic depth functions recognized in Vertisols (Wilding and Tessier, 1988).

Field observations of buried Vertisols reveal characteristics that support both the pedoturbation and soil mechanics models. Fractures (microfaults) with slickensides are mostly concave upward and dip less than 60° (fig. 18). Slickensides on fractures appear to be similar to those produced experimentally on stiff wax by Means (1987). This style of slickensides, which is characterized by nested troughs and ridges on opposing fracture faces, was produced by approximately 2 cm (0.8 inch) of displacement and suggests that slickensides in soils can be produced with relatively little displacement.

Deep desiccation cracks are commonly preserved in buried Vertisols of the Fort Hancock and Camp Rice Formations. These cracks are recognizable because they are filled with sand or silt from an overlying unit or with clayey soil aggregates from an overlying mulch zone. Clearly, significant volumes of sediment can be contributed to desiccated clay facies as crack fillings. In rare instances crack fillings composed of sand and mud or clay lithoclasts may reach 10 cm (4 inches) in width. Small-scale reverse faulting is commonly associated with fracture surfaces bounding large wedge-shaped soil aggregates. Displacement of filled desiccation cracks and $CaCO_3$ nodules across these fractures rarely exceeds 10 cm. However, the fact that crack fillings and large fracture planes are preserved suggests that pedoturbation was a slow process. Soil movement in the buried Vertisols of the Hueco Bolson was more of a jostling of soil aggregates than a turbulent overturn. Vertisol development in the Fort Hancock Formation is probably better described by the soil mechanics model of Wilding and Tessier (1988), but it clearly retains features described by the pedoturbation model of Hilgard (1906).

The mulch or nut zone that characterizes the upper 10 to 20 cm (4 to 8 inches) of a Vertisol developed in a smectite-rich clay in an arid or semiarid climate consists of small, loose angular soil aggregates. Deposition of fine-grained sediments of the Fort Hancock and Camp Rice Formations occurred primarily from settling out from suspension in playa lakes or locally as overbank deposits. Preserved sedimentary structures in these environments are rare, but preserved structures are primarily thinly laminated clays and interlaminated thin silts and clays. These structures suggest that ephemeral lake deposits were built up over a long period of time by numerous depositional events, each of which contributed a small increment of sediment. Laminations were preferentially preserved where playas remained flooded or where playa surfaces remained wet at ground-water discharge points. Where playa sediments were exposed after flood events, desiccation occurred and mud cracks as deep as a meter formed. Desiccation cracks disrupted lamination. The next flooding event wet the soil, washed mud chips into cracks, and caused cracks to close. Desiccation followed and the process of cracking was repeated. Sand, silt, or small mud flakes were blown into cracks. As lacustrine sediments slowly accumulated, numerous cycles of deposition followed by desiccation obliterated sedimentary structures and resulted in the massive clay and sandy clay beds that are as much as 2 m (6.6 ft) thick in the Fort Hancock and Camp Rice Formations. Although many cycles of shrink/swell occurred, the destruction of primary sedimentary structures was mostly accomplished by repeated episodes of wetting and desiccation at the surface, not by turbulent overturn of the soil.

Degree of Buried Vertisol Development

The degree of soil development ranges from (1) undisturbed laminated playa lake deposits to (2) lacustrine laminae with desiccation cracks to (3) 2-m-thick clay beds having all the characteristics of a preserved Vertisol and a few remnants of disturbed blocks of laminated lake clays to (4) Vertisols with no preserved primary sedimentary structures. Most commonly, no sedimentary structures are preserved. The degree of development of buried Vertisols in sediments of the Fort Hancock and Camp Rice Formations probably depended on several factors, including clay content and mineralogy, duration of surface exposure, the frequency of flooding or rainfall events to which these sediments were subjected, degree of desiccation, and to some extent the rate of burial by later sedimentation. Recognizable buried Vertisol horizons are present only in clay, mud, sandy clay, and sandy mud facies containing more than 45 percent clay.

Age of Paleovertisols

The time required to generate Vertisols such as those typical of the buried soils preserved in the Fort Hancock Formation is difficult to assess. No recognized chronosequences have been described for Vertisols that formed in a desert basin under semiarid climates. Furthermore, Vertisols form under a variety of climatic conditions, ranging from humid to arid and tropical to temperate. Swelling and desiccation of clays is an integral part of the formation of Vertisols, and the frequency of shrink-swell cycles to which a soil is subjected is directly tied to climate and depositional setting. Shrink-swell cycles might be expected to be more frequent in a subhumid temperate climate than in a humid tropical climate, where soils remain wet most of the year, or in an arid or cold climate where soils remain dry or frozen for much of the year. Consequently, Vertisols are likely to form at different rates under different climatic conditions.

Gilgai and pedogenic structures such as slickensides have been reported to have formed in time intervals as short as 5 to 200 yr (White, 1967; Parsons and others, 1973; Yaalon and Kalmar, 1978; Wilding and Tessier, 1988). However, even though some soil structures can form in these short time periods, newly deposited sediment cannot be transformed to a mature Vertisol in as few as 5 yr. Certain structures such as gilgai (microtopography), however, can reform in as little as 5 yr after being leveled.

Pedogenic structures associated with calcic soils such as $CaCO_3$ nodules and filaments are commonly observed in clay and sandy clay lithofacies (ephemeral lake clay) in the Fort Hancock Formation but are only rarely seen in coarser grained facies except as lithoclasts. In the Camp Rice Formation, pedogenic $CaCO_3$ nodules and filaments developed in the coarse silt to very fine sand (loess) lithofacies and the clay and sandy clay lithofacies (ephemeral lake clay). $CaCO_3$ nodules in loess were accompanied by the development of illuvial clay horizons.

$CaCO_3$ in calcic soils is derived from several potential sources, including eolian $CaCO_3$ dust, $CaCO_3$ dissolved in rainfall, and dissolving surface or near-surface carbonate rocks. Precipitation or surface runoff carrying small amounts of dissolved $CaCO_3$ commonly infiltrates only near-surface sediments. Some of this water is lost to evaporation, and solutes such as $CaCO_3$ are left behind. Usually this process takes place in the upper 1.5 m (5 ft) of near-surface sediments. Clay-sized sediments carried in suspension are also left behind as near-surface waters evaporate.

Studies by Bachman and Machette (1977), Gile and others (1981), and Machette (1985) have provided considerable insight into the processes and rates of $CaCO_3$ accumulation and characteristic structures associated with the development of calcic soils and calcretes. For example, development of $CaCO_3$ nodules and filaments are characteristic features in the early stages (I and II) of development of calcic soils. Gile and others (1981) suggested that Stage I calcic soils form in 100 to 7,000 yr and that Stage II calcic soils form in 8,000 to 15,000 yr in nongravelly, sandy, low-clay content material in the Basin and Range area of southern New Mexico.

Although $CaCO_3$ nodules and filaments are present in most buried Vertisols, the filaments and nodules are widely dispersed. The fact that only a few dispersed nodules are present in clayey facies of the Fort Hancock Formation suggests that the soil age relations described by Gile and others (1981) for coarser sediments may not be applied directly to desiccated clays. For example, surface water probably infiltrated along desiccation cracks instead of infiltrating the soil on a broad front. Consequently, solute loads were concentrated in desiccation cracks as evaporation occurred, and these widely dispersed nodules were able to grow more rapidly than in coarser sediment. If this is correct, then the few dispersed $CaCO_3$ nodules that characterize many buried Vertisols could have developed in a shorter timeframe than 7,000 to 15,000 yr—perhaps only a few thousand years.

In summary, the time required to develop a Vertisol can only be grossly estimated on the basis of times required to regenerate soil microtopography and on times required to form soil structures such as $CaCO_3$ nodules and filaments. On the basis of these arguments, Vertisols in the Fort Hancock and Camp Rice Formations probably formed in several hundred to several thousand years.

SUMMARY

During the late Tertiary the southern Hueco Bolson was an internally drained basin filling with fluvial and lacustrine sediment of the Fort Hancock Formation. Proximal, transitional, and distal alluvial fan sediments (gravel, gravel and sandy silt, sandy silt, and sandy mud lithofacies) were derived from the Diablo Plateau and other highlands along the margins of the Hueco Bolson. The basin also received runoff and sediment, albeit mostly suspended sediment, from the northern ancestral Rio Grande. Rapid deposition of fine-grained lacustrine sediments (clay and sandy clay and clay, mud, sandy mud, and gypsum lithofacies) in ephemeral lakes in the basin center resulted in a rapidly rising base level. Deposition exceeded rates of tectonic subsidence in the basin, and through-flowing drainage began as the confining barrier at the southern end of the basin was breeched.

Depositional environments in the Fort Hancock Formation included alluvial fans and ephemeral lakes, which suggest an arid to semiarid climate during deposition. Paleosols preserved in the Fort Hancock Formation include calcic soils and Vertisols. Calcic soils form most commonly in subhumid to arid climates and, in conjunction with the stratigraphic evidence, indicate that arid to semiarid climates prevailed as the upper Fort Hancock Formation was being deposited.

Breeching of the drainage divide at the southern end of the Hueco Bolson initiated a long period of erosion during which the newly integrated Rio Grande drainage was incised more than 130 m (430 ft) into Fort Hancock sediments in the southern part of the Hueco Bolson. This event cannot be precisely dated but probably occurred about 2.25 Ma ago.

The Pliocene–Pleistocene Camp Rice Formation unconformably overlies the Fort Hancock Formation and contains a complex of lithofacies that were deposited in a wide variety of environments. Sand and gravel lithofacies containing exotic gravel derived from north of the Hueco Bolson were deposited along the axis of the bolson by a through-flowing stream, the ancestral Rio Grande. A second sand and gravel lithofacies containing numerous lithoclasts derived from the Fort Hancock Formation was most likely deposited by short tributaries of the Rio Grande. Locally preserved eolian dune sand and loess were deposited between sites of fluvial sedimentation. Lacustrine sediments accumulated in ephemeral lakes that developed locally in areas affected by neither fluvial deposition nor erosion. Sediments deposited in ephemeral lakes were subjected to periodic desiccation, destroying most primary sedimentary structures. Slow sedimentation in the stable lake basin allowed Vertisols to form.

Fluvial systems that deposited the Camp Rice Formation were largely ephemeral braided streams, suggesting arid to subhumid conditions. Lacustrine sediments including discontinuous beds of gypsum were deposited in ephemeral lakes, and most likely indicate an arid or semiarid climate. Pedogenic $CaCO_3$ nodules are common in buried soils in the Camp Rice Formation and also suggest subhumid to arid climates. Soil, stratigraphic, and fossil evidence indicate that climatic conditions in the Hueco Bolson from the late Tertiary to the early Quaternary were semiarid to subhumid.

Paleovertisols commonly developed on the smectite-rich clayey sediments deposited in ephemeral lakes of both the Fort Hancock and Camp Rice Formations. These paleosols are characterized by mulch zones, deep desiccation cracks, intersecting fractures with slickensides, manganese oxide or hydroxide stains on fractures, and $CaCO_3$ nodules. Vertisols formed in ephemeral lake clays as a result of numerous episodes of shrinking and swelling because of flooding or precipitation and desiccation.

ACKNOWLEDGMENTS

This work was supported by the Texas Low-Level Radioactive Waste Disposal Authority under Interagency Contract Number IAC(90-91)0268. The conclusions presented in this report are not necessarily endorsed or approved by the Authority.

This report was reviewed by Robert Blodgett, John Hawley, Tucker F. Hentz, Richard Langford, and Jay Raney. Their comments, which significantly improved this report, are appreciated. X-ray diffraction analyses were prepared under the supervision of S. W. Tweedy. R. S. Fisher interpreted the X-ray diffraction patterns. Sediment and soil textural analyses were prepared under the supervision of Robert Brinkman of the University of Wisconsin–Milwaukee Soils Laboratory. Figures were drafted by Yves Oberlin under the supervision of Richard L. Dillon. The text was edited by Bobby Duncan and assembled by Jamie H. Coggin. Word processing was by Melissa Snell.

REFERENCES

Ahmad, N., 1983, Vertisols, *in* Wilding, L. P., Smeck, N. E., and Hall, G. F., eds., Pedogenesis and soil taxonomy II, the soil orders: Amsterdam, Elsevier, Developments in Soil Science IIB, p. 91–123.

Albritton, C. C., Jr., and Smith, J. F., Jr., 1965, Geology of the Sierra Blanca area, Hudspeth County, Texas: U.S. Geological Survey Professional Paper 479, 131 p.

Allen, J. R. L., 1973, Compressional structures (patterned ground) in Devonian pedogenic limestones: Nature, Physical Science, v. 243, p. 84–86.

Axelrod, D. I., and Bailey, H. D., 1976, Tertiary vegetation, climate, and altitude of the Rio Grande depression, New Mexico–Colorado: Paleobiology, v.2, p. 235–254.

Bachman, G. O., and Machette, M. N., 1977, Calcretes: U.S. Geological Survey Open-File Report 77-794, 162 p.

Bachman, G. O., and Mehnert, H. H., 1978, New K-Ar dates and the late Pliocene to Holocene geomorphic history of the central Rio Grande region, New Mexico: Geological Society of America Bulletin, v. 89, p. 283–292.

Baldwin, Brewster, 1956, The Santa Fe Group in north-central New Mexico: New Mexico Geological Society Guidebook, Seventh Annual Field Conference, Southeastern Sange De Cristo Mountains, p. 115–121.

Bernard, H. A., Major, C. F., Jr., Parrott, B. S., and LeBlanc, R. J., Sr., 1970, Recent sediments of southeast Texas—a field guide to the Brazos alluvial and deltaic plains and the Galveston barrier island complex: The University of Texas at Austin, Bureau of Economic Geology Guidebook No. 11, 16 p.

Blair, T. C., 1987, Tectonic and hydrologic controls on cyclic alluvial fan, fluvial, and lacustrine rift-basin sedimentation, Jurassic-Lowermost Cretaceous Todos Santos Formation, Chiapas, Mexico: Journal of Sedimentary Petrology, v. 57, p. 845–862.

Blake, G., Schlichting, E., and Zimmerman, E., 1973, Water recharge in a soil with shrinkage cracks: Soil Science of America Proceedings, v. 37, p. 669–672.

Blodgett, R. H., 1985a, Field guide to upper Pennsylvanian and lower Permian (?) rocks of southeastern Ohio and western West Virginia, *in* Haban, S. M., ed., Carboniferous of eastern Kentucky: Field Excursion 6, Guidebook, Sixth Gondonwana Symposium, Ohio State University Institute of Polar Studies Miscellaneous Publication #228, p. 1–20.

——— 1985b, Paleovertisols—their utility in reconstructing ancient fluvial floodplain sequences (abs.): Third International Fluvial Sedimentology Conference Abstracts, p. 10.

Blokhuis, W. A., 1982, Vertisols and rice soils of the Tropics: New Delhi, India, Symposia Papers II, 12th International Congress of Soil Sciences, p. 23–47.

Boothroyd, J. C., and Ashley, G. M., 1975, Processes, bar morphology, and sedimentary structures on braided outwash fans, northeastern Gulf of Alaska, *in* Jopling, A. V., and McDonald, B. C., eds., Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication No. 23, p. 193–222.

Boyd, F. M., and Kreitler, C. W., 1986, Hydrology of a gypsum playa, northern Salt Basin, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 158, 37 p.

Bryan, Kirk, 1938, Geology and ground-water conditions of the Rio Grande depression in Colorado and New Mexico, *in* Rio Grande joint investigation in the Upper Rio Grande Basin in Colorado, New Mexico, and Texas: Natural Resources Commission, Regional Planning, pt. 6, p. 196–225.

Bull, W. B., 1972, Recognition of alluvial fan deposits in the stratigraphic record, *in* Rigby, J. K., and Hamblin, W. K., eds., Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists Special Publication 16, p. 63–83.

Cant, D. J., and Walker, R. G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625–648.

Church, Michael, and Gilbert, Robert, 1975, Proglacial fluvial and lacustrine environments, *in* Jopling, A. V., and McDonald, B. C., eds., Glaciofluvial and glaciolacustrine sedimentation: Society of Economic Paleontologists and Mineralogists Special Publication No. 23, p. 1–100.

Collins, E. W., and Raney, J. A., in press, Neotectonic history and structural style of the Campo Grande fault, Hueco Basin, Trans-Pecos Texas: The University of Texas at Austin, Bureau of Economic Geology Geological Circular.

Collins, E. W., Raney, J. A., Gustavson, T. C., and Henry, C. D., 1988, Geologic studies for potential sites for a low-level radioactive waste repository, Trans-Pecos, Texas (abs.): Geological Society of America Abstracts with Programs, v. 20, p. A279.

Dasog, G. S., Acton, D. F., and Mermut, A. R., 1987, Genesis and classification of clay soils with vertic properties in Saskatchewan: Soil Science Society of America Journal, v. 51, p. 1243–1249.

Demicco, R. V., and Kordesch, E. G., 1986, Facies sequences of a semi-arid closed basin: the lower Jurassic East Berlin Formation of the Hartford Basin, New England, U.S.A: Sedimentology, v. 33, p. 107–118.

Dudal, R., and Eswaran, H., 1988, Distribution, properties, and classification of Vertisols, *in* Wilding, L. P., Puentes, R., eds., Vertisols: their distribution, properties, classification and management: Texas A&M University, College Station, Texas, p. 1–22.

Folk, R. L., 1968, Petrology of sedimentary rocks: Austin, Texas, Hemphill's, 170 p.

Fryberger, S. G., Ahlbrandt, T. S., and Andrews, S., 1979, Origin of sedimentary features and significance of low-angle eolian "sheet sand" deposits, Great Sand Dunes National Monument and vicinity, Colorado: Journal of Sedimentary Petrology, v. 49, p. 733–746.

Gary, Margaret, McAfee, Robert, Jr., and Wolf, C. L., 1972, eds., Glossary of geology: Washington, D.C., American Geological Institute, 805 p.

Gile, L. H., Peterson, F. F., and Grossman, R. B., 1966, Morphological and genetic sequences of carbonate accumulation in desert soils: Soil Science, v. 101, p. 347–360.

Gile, L. H., Hawley, J. W., and Grossman, R. B., 1981, Soils and geomorphology in the Basin and Range area of southern New Mexico—guidebook to the Desert Project: New Mexico Bureau of Mines and Mineral Resources Memoir 39, 222 p.

Goldbery, R., 1982, Structural analyses of soil microrelief in paleosols of the Lower Jurassic "Laterite Derivative Facies" (Mischor and Ardon Formations), Makhtest Ramon, Israel: Sedimentary Geology, v. 31, p. 119–140.

Gray, M. B., and Nickelsen, R. P., 1989, Pedogenic slickensides, indicators of strain and deformation processes in redbed sequences of the Appalachian foreland: Geology, v. 17, p. 72–75.

Groat, C. G., 1972, Presidio Bolson, Trans-Pecos Texas and adjacent Mexico: Geology of a desert aquifer system: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 76, 46 p.

Gustavson, T. C., 1975, Microrelief (gilgai) structures on expansive clays of the Texas Coastal Plain—their recognition and significance in engineering construction: The University of Texas at Austin, Bureau of Economic Geology Geological Circular 75-7, 18 p.

———— 1989a, Sedimentary facies, depositional environments, and paleosols of the upper Tertiary Fort Hancock Formation and the Tertiary–Quaternary Camp Rice Formation, Hueco Bolson, West Texas: The University of Texas at Austin, Bureau of Economic Geology, draft report prepared for the Texas Low-Level Radioactive Waste Disposal Authority under Interagency Contract Number IAC(88-89)-0932, 94 p.

———— 1989b, Paleovertisols of the late Tertiary Fort Hancock Formation and the Tertiary–Quaternary Camp Rice Formation, Hueco Bolson, West Texas (abs.): Geological Society of America, Abstracts with Programs, v. 21.

———— in press, ed., Tertiary and Quaternary stratigraphy and vertebrate paleontology of parts of northwestern Texas and eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology Guidebook.

Gustavson, T. C., and Holliday, V. T., 1988, Depositional and pedogenic characteristics of the Quaternary Blackwater Draw and Tertiary Ogallala Formations, Texas Panhandle and eastern New Mexico: The University of Texas at Austin, Bureau of Economic Geology, final contract report prepared for the U.S. Department of Energy Salt Repository Project Office under contract no. DE-AC97-83WM46651, 112 p.

Gustavson, T. C., and Winkler, D. A., 1988, Depositional facies of the Miocene–Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico: Geology, v. 16, p. 203–206.

Handford, C. R., 1982, Sedimentology and evaporite genesis in a Holocene continental-sabkha playa basin—Bristol Dry Lake, California: Sedimentology, v. 29, p. 239–254.

Hawley, J. W., 1969, Notes on the geomorphology and late Cenozoic geology of northwestern Chihuahua, *in* Cordoba, D. A., Wengerd, S. A., and Shomaker, J., eds., The border region: New Mexico Geological Society, 20th Annual Field Conference Guidebook, p. 131–142.

———— 1975, Quaternary history of the Dona Ana County region, south-central New Mexico: New Mexico Geological Society, 26th Annual Field Conference Guidebook, Las Cruces Country, p. 139–150.

———— 1981, Pleistocene and Pliocene history of the International Boundary area, southern New Mexico, *in* Geology of the border, southern New Mexico–northern Chihuahua: El Paso Geological Society, Field Trip Guidebook, p. 26–32.

Hawley, J. W., and Kottlowski, F. E., 1969, Quaternary geology of the south-central New Mexico border region, *in* Kottlowski, F. E., and Lemone, D. V., eds., Border Stratigraphy Symposium: New Mexico Institute of Mining and Technology, New Mexico Bureau of Mines and Mineral Resources Circular 104, 123 p.

Hawley, J. W., Kottlowski, F. E., Seager, W. A., King, W. E., Strain, W. S., and LeMone, D. V., 1969, The Santa Fe Group in the south-central New Mexico Border Region, *in* Kottlowski, F. E., and Lemone, D. V., eds., Border Stratigraphy Symposium: New Mexico Institute of Mining and Technology, New Mexico Bureau of Mines and Mineral Resources Circular 104, p. 52–76.

Heward, A. P., 1978, Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Cinera—Matallana and Sabero) coalfields, northern Spain: Sedimentology, v. 25, p. 451–488.

Hilgard, E. W., 1906, Soils: New York, Macmillan, 593 p.

Holliday, V. T., 1989, The Blackwater Draw Formation (Quaternary): a 1.4-plus–m.y. record of eolian sedimentation and soil formation on the Southern High Plains: Geological Society of America Bulletin, v. 101, p. 1598–1607.

Howard, A., 1932, Crab-hole, gilgai, and self-mulching soils of the Murrumbidgee irrigation area: Pedology, v. 8, p. 14–18.

Hubert, J. F., and Hyde, M. G., 1982, Sheet-flow deposits of graded beds and mudstones on an alluvial sandflat-playa system: upper Triassic Blomidon redbeds, St Mary's Bay, Nova Scotia: Sedimentology, v. 29, p. 457–474.

International Boundary and Water Commission, United States and Mexico, 1975, Flow of the Rio Grande and related data: Water Bulletin Number 45, 154 p.

Izett, G. A., and Wilcox, R. E., 1982, Map showing localities and inferred distributions of Huckleberry Ridge, Mesa Falls, and Lava Creek ash beds (Pearlette Family ash beds) of Pliocene and Pleistocene age in the western United States and southern Canada: U.S. Geological Survey Miscellaneous Map Series, Map I-1325.

Jackson, R. G., 1976, Depositional model of point bars in the lower Wabash river: Journal of Sedimentary Petrology, v. 46, p. 579–594.

Johnson, W. D., Jr., Hawley, J. W., Stone, W. J., Kottlowski, F. E., Henry, C. D., and Price, J. G., 1984, Geology, *in* Bedinger, M. S., Sargent, K. A., and Langer, W. H., eds., Studies of geology and hydrology in the Basin and Range province, Southwestern United States—characterization of the Rio Grande region, New Mexico and Texas: U.S. Geological Survey Open-File Report 84-740, p. 16–71.

Kocurek, Gary, and Nielson, Jamie, 1986, Conditions favorable for the formation of warm climate sand sheets: Sedimentology, v. 33, p. 795–816.

Komornik, A., and Zeitlin, J. G., 1970, Laboratory determination of lateral and vertical stresses in compacted swelling clay: Journal of Materials, v. 5, p. 108–128.

Kottlowski, F. E., 1953, Tertiary–Quaternary sediments of the Rio Grande Valley in southern New Mexico: New Mexico Geological Society Guidebook, fourth annual field conference, southwestern New Mexico, p. 144–148.

———— 1958, Geologic history of the Rio Grande near El Paso: West Texas Geological Society Fieldtrip Guidebook, Franklin and Hueco Mountains, Texas, p. 46–54.

Kreitler, C. W., Raney, J. A., Nativ, Ronit, Collins, E. W., Mullican, W. F., III, Gustavson, T. C., and Henry, C. D., 1986, Preliminary geologic and hydrologic studies of selected areas in Culberson and Hudspeth Counties, Texas: The University of Texas at Austin, Bureau of Economic Geology, final report prepared for the Low-Level Radioactive Waste Disposal Authority under Interagency Contract Number IAC(86-87)-0828, 184 p.

Krinsley, D. B., 1970, A geomorphological and paleoclimatological study of the playas of Iran: contract report AFCRL-70-0503, part II, prepared for Air Force Cambridge Research Laboratories, U.S. Air Force, Bedford MA, p. 330–486.

Lee, W. T., 1907, Water resources of the Rio Grande Valley in New Mexico and their development: U.S. Geological Survey Water-Supply Paper 188, 59 p.

Lozinsky, R. P., and Hawley, J. W., 1986, Upper Cenozoic Palomas Formation of south-central New Mexico, *in* Clemons, R. E., King, W. E., and Mack, G. H., eds., New Mexico Geological Society Guidebook, 37th field conference, Truth or Consequences, p. 239–248.

Lucas, S. G., and Oaks, Wayne, 1986, Pliocene (Blancan) vertebrates from the Palomas Formation, south-central New Mexico, *in* Clemons, R. E., King, W. E., and Mack, G. H., eds., New Mexico Geological Society Guidebook, 37th field conference, Truth or Consequences, p. 249–255.

Machette, M. N., 1985, Calcic soils of the southwestern United States, *in* Weide, D. L., ed., Soils and Quaternary geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1–22.

——— 1987, Preliminary assessment of paleoseismicity at White Sands Missile Range, southern New Mexico—evidence for recency of faulting, fault segimentation,and repeat intervals for major earthquakes in the region: U.S. Geological Survey Open-File Report 87-444, 46 p.

Mattick, R. E., 1967, A seismic and gravity profile across the Hueco Bolson, Texas: U.S. Geological Survey Professional Paper 575-D, p. D85–D91.

McGowen, J. H., 1971, Gum Hollow fan delta, Nueces Bay, Texas: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 69, 91 p.

McGowen, J. H., and Groat, C. G., 1971, Van Horn Sandstone, West Texas: an alluvial fan model for mineral exploration: The University of Texas at Austin, Bureau of Economic Geology Report of Investigations No. 72, 57 p.

McPherson, J. G., Shanmugam, Ganapathy, and Moiola, R. J., 1987, Fan-deltas and braid deltas: varieties of coarse-grained deltas: Geological society of America Bulletin, v. 99, p. 331–340.

Means, W. D., 1987, A newly recognized type of slickenside striation: Structural Geology, v. 9, p. 385–390.

Miall, A. D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1–62.

Mielenz, R. C., and King, M. E., 1955, Physical-chemical properties and engineering performance of clays, *in* Pask, J. A., and Turner, M. D., eds., Clays and clay technology: California Division of Mines Bulletin 169, p. 196–254.

Morgan, J. P., Coleman, J. M., and Gagliano, S. M., 1968, Mudlumps: diapiric structures in Mississippi delta sediments, *in* Braunstein, Jules, and O'Brien, G. D., eds., Diapirism and diapirs: American Association of Petroleum Geologists, Memoir 8, p. 145–161.

Muehlberger, W. R., Belcher, R. C., and Goetz, L. K., 1978, Quaternary faulting in Trans-Pecos Texas: Geology, v. 6, p. 337–340.

Parsons, R. B., Moncharoen, L., and Knox, E. G., 1973, Geomorphic occurrence of Pelloxererts, Willamette Valley, Oregon: Soil Science Society of America Proceedings, v. 37, p. 924–927.

Paton, T. R., 1974, Origin and terminology for gilgai in Australia: Geoderma, v. 11, p. 221–242.

Puigdefabregas, C., 1973, Miocene point-bar deposits in the Ebro Basin, northern Spain: Sedimentology, v. 20, p. 133–144.

Reeves, C. C., Jr., 1969, Pluvial Lake Palomas northwestern Chihuahua, Mexico, *in* Cordoba, D. A., Wengerd, S. A., and Shomaker, J. E., eds., The border region: New Mexico Geological Society, 20th field conference guidebook p. 143–154.

Reineck, H. E., and Singh, I. B., 1980, Depositional sedimentary environments: New York, Springer-Verlag, 549 p.

Repenning, C. A., and May, S. R., 1986, New Evidence for the age of the lower part of the Palomas Formation, Truth or Consequences, New Mexico, *in* Clemons, R. E., King, W. E., and Mack, G. H., eds., New Mexico Geological Society Guidebook, 37th field conference, Truth or Consequences, p. 257–260.

Riley, Robert, 1984, Stratigraphic facies analysis of the upper Santa Fe Group, Fort Hancock and Camp Rice Formations, far West Texas and south-central New Mexico: The University of Texas at El Paso, Master's thesis, 108 p.

Seager, W. R., Shafiqullah, M., Hawley, J. W., and Marvin, R. F., 1984, New K-Ar dates from basalts and the evolution of the southern Rio Grande: Geological Society of America Bulletin, v. 95, p. 87–99.

Scanlon, B. R., Wang, F. P., and Richter, B. C., 1990, Analysis of unsaturated flow based on physical data related to low-level radioactive waste disposal, Chihuahuan Desert, Texas: University of Texas at Austin, Bureau of Economic Geology, contract report prepared for

Texas Low-Level Radioactive Waste Disposal Authority under Interagency Contract Number IAC(90-91)0268, 43 p.

Smith, C. W., Hadas, A., and Koyumdjisky, H., 1985, Shrinkage and Atterberg limits in relation to other properties of principal soil types in Israel: Geoderma, v. 35, p. 47–65.

Smith, H. T. U., 1968, Photo-interpretation studies of desert basins in northern Africa: Contract Report AFCRL-68-0590, prepared for Air Force Cambridge Research Laboratories, U.S. Air Force, Bedford MA, 79 p.

Sneh, Amihai, 1979, Late Pleistocene fan-deltas along the Dead Sea rift: Journal of Sedimentology, v. 49, p. 541–552.

Soil Survey Staff, 1975, Soil taxonomy, a basic system of soil classification for making and interpreting soil surveys: U.S. Department of Agriculture, Soil Conservation Service Agricultural Handbook No. 436, 754 p.

Strain, W. S., 1966, Blancan mammalian fauna and Pleistocene formations, Hudspeth County, Texas: The University of Texas at Austin, Texas Memorial Museum Bulletin No. 10, 55 p.

———— 1971, Late Cenozoic bolson integration in the Chihuahua tectonic belt, *in* Seewald, K., and Sundeen, D., eds., The geologic framework of the Chihuahua tectonic belt: West Texas Geological Society Publication No. 71-59, p. 167–173.

Stuart, C. J., and Willingham, D. L., 1984, Late Tertiary and Quaternary fluvial deposits in the Mesilla and Hueco Bolsons, El Paso area, Texas: Sedimentary Geology, v. 38, p. 1–20.

Taylor, D. W., 1987, Fresh-water mollusks from New Mexico and vicinity: New Mexico Institute of Mining and Technology, New Mexico Bureau of Mines and Mineral Resources Bulletin 116, 51 p.

Tedford, R. H., 1981, Mammalian biochronology of the Late Cenozoic basins of New Mexico: Geological Society of America Bulletin, v. 92, p. 1008–1022.

Vanderhill, J. B., 1986, Lithostratigraphy, vertebrate paleontology, and magnetostratigraphy of Plio-Pleistocene sediments of the Mesilla Basin, New Mexico: The University of Texas at Austin, Ph.D. dissertation, 305 p.

Van Eysinga, F. W. B., 1975, Geologic time table (3rd ed.): Amsterdam, Elsevier Scientific Publishing Company.

Walker, R. G., and Cant, D. J., 1979, Facies models, pt. 3 of Sandy fluvial systems, *in* Walker, R. G., ed., Facies models: Geoscience Canada, Reprint Series 1, p. 23–32.

Wells, S. G., Bullard, T. F., and Smith, L. N., 1982, Origin and evolution of deserts in the Basin and Range and Colorado Plateau provinces of western North America, *in* The geological story of the world's deserts: Striae, v. 17, p. 101–111.

White, E. M., 1967, Soil age and texture factors in subsoil structure genesis: Soil Science, v. 103, p. 288–298.

Wilding, L. P., 1985, Genesis of Vertisols, *in* Proceedings of the 5th International Soil Classification Workshop, Sudan, 1982: Khartoum, Sudan Soil Survey Administration, p. 47–62.

Wilding, L. P., and Tessier, D., 1988, Genesis of Vertisols: shrink-swell phenomena, *in* Wilding, L. P., and Puentes, Ruben, eds., Vertisols: their distribution, properties, classification, and management: Texas A&M University Printing Center, Soil Management Support Services Technical Monograph No. 18, p. 55–81.

Williams, P. F., and Rust, B. R., 1969, The sedimentology of a braided river: Journal of Sedimentary Petrology, v. 39, p. 649–679.

Yaalon, D. H., and Kalmar, D., 1978, Dynamics of cracking and swelling clay soils: displacement of skeletal grains, optimum depth of slickensides, and rate of intrapedonic turbation: Earth Surface Processes, v. 3, p. 31–52.

Yerima, B. P. K., Calhoun, F. G., Senkayi, A. L., and Dixon, J. B., 1985, Occurrence of interstratified kaolinite-smectite in El Salvador Vertisols: Soil Science Society of America Journal, v. 49, p. 462–466.

Yerima, B. P. K., Wilding, L. P., Calhoun, F. G., and Hallmark, C. T., 1987, Volcanic ash-influenced Vertisols and associated Mollisols in El Salvador: physical, chemical, and morphological properties: Soil Science Society of America Journal, v. 51, p. 699–708.

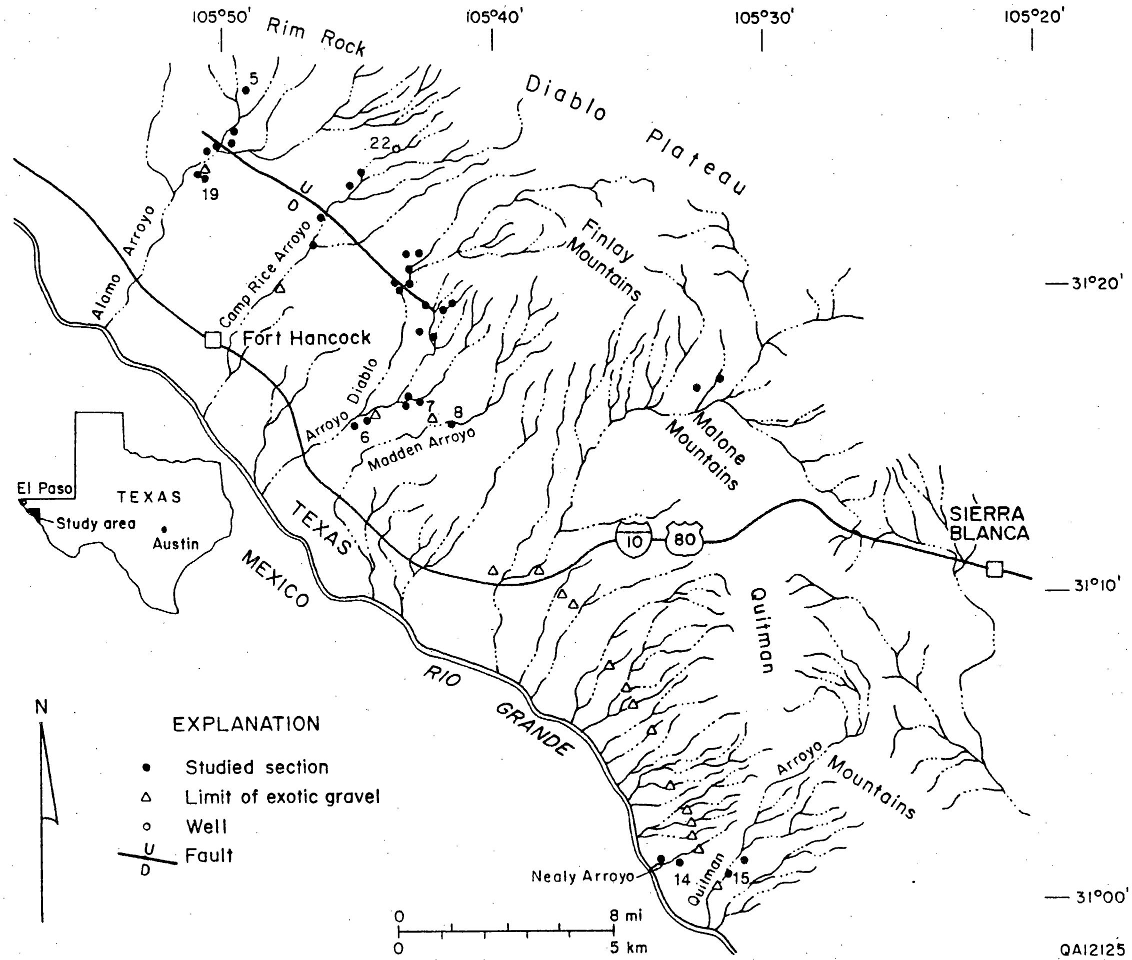


Figure 1. Location map showing described sections, Texas Low-Level Radioactive Waste Disposal Authority hydrologic and stratigraphic test well no. 22, and the northeastern limit of exotic gravel in the Camp Rice Formation (limits of exotic gravel modified from Albritton and Smith, 1965). Numbered sections refer to figure numbers in this report.

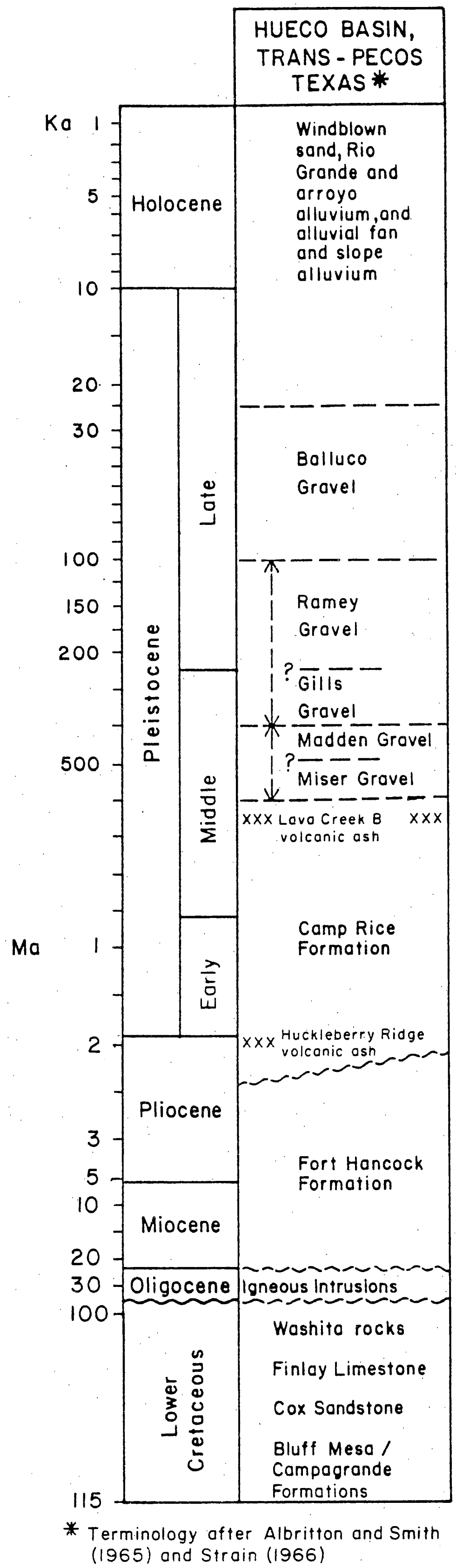


Figure 2. Stratigraphic correlation chart for south-central New Mexico and the Hueco Bolson, Texas.

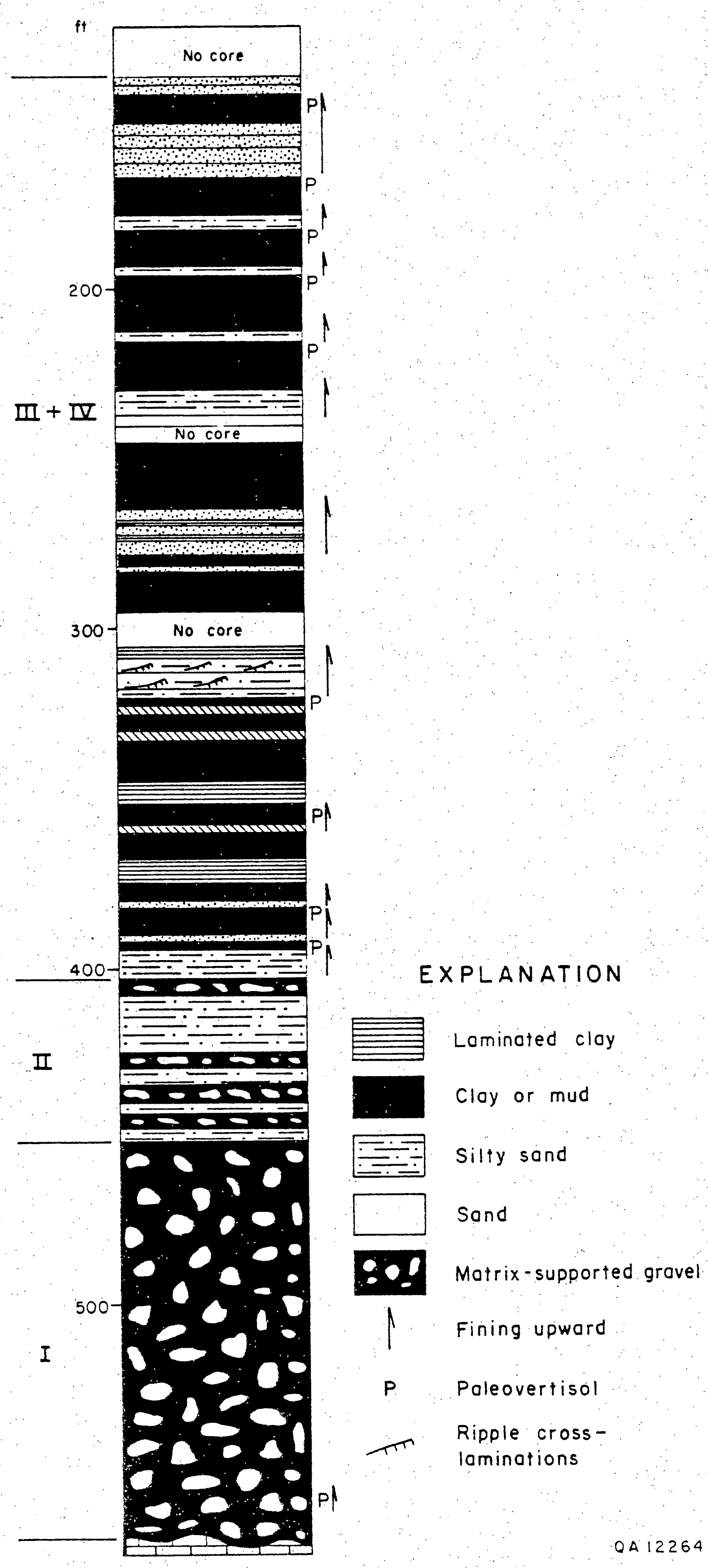


Figure 3. Lithologic diagram interpreted from core of Texas Low-Level Radioactive Waste Disposal Authority well no. 22 (see fig. 1 for location of well no. 22). Section records the transgression of distal alluvial fan and ephemeral lake deposits across proximal alluvial fan deposits. Roman numerals identify lithofacies in the Fort Hancock Formation: I, gravel (proximal alluvial fan); II, sand, sandy mud, or sandy silt and gravel (transitional alluvial fan); III, sand, sandy mud, and sandy silt (distal alluvial fan); IV, clay and sandy clay (ephemeral lake).

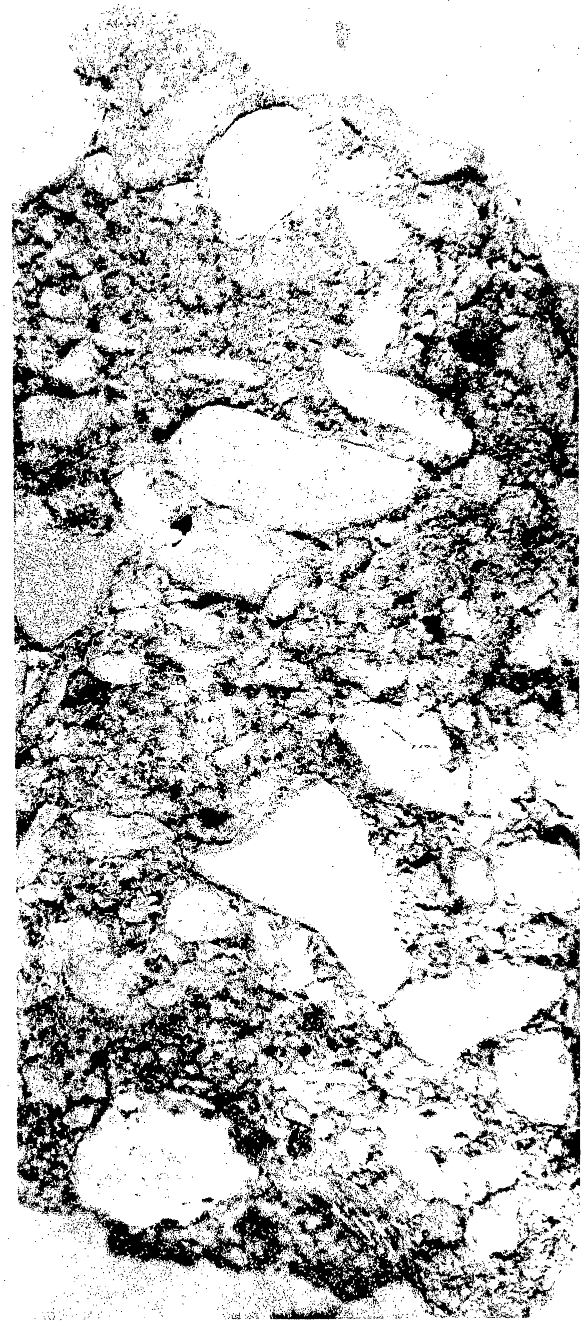


Figure 4. Matrix-supported subangular limestone gravel in core from a depth of 149.6 m (463 ft) from Texas Low-Level Waste Disposal Authority stratigraphic test well no. 22. Matrix-supported gravel is typical of interpreted proximal alluvial fan deposits of the Fort Hancock Formation. Core is 7.7 cm (3 inches) in diameter. See figure 1 for location of well no. 22.

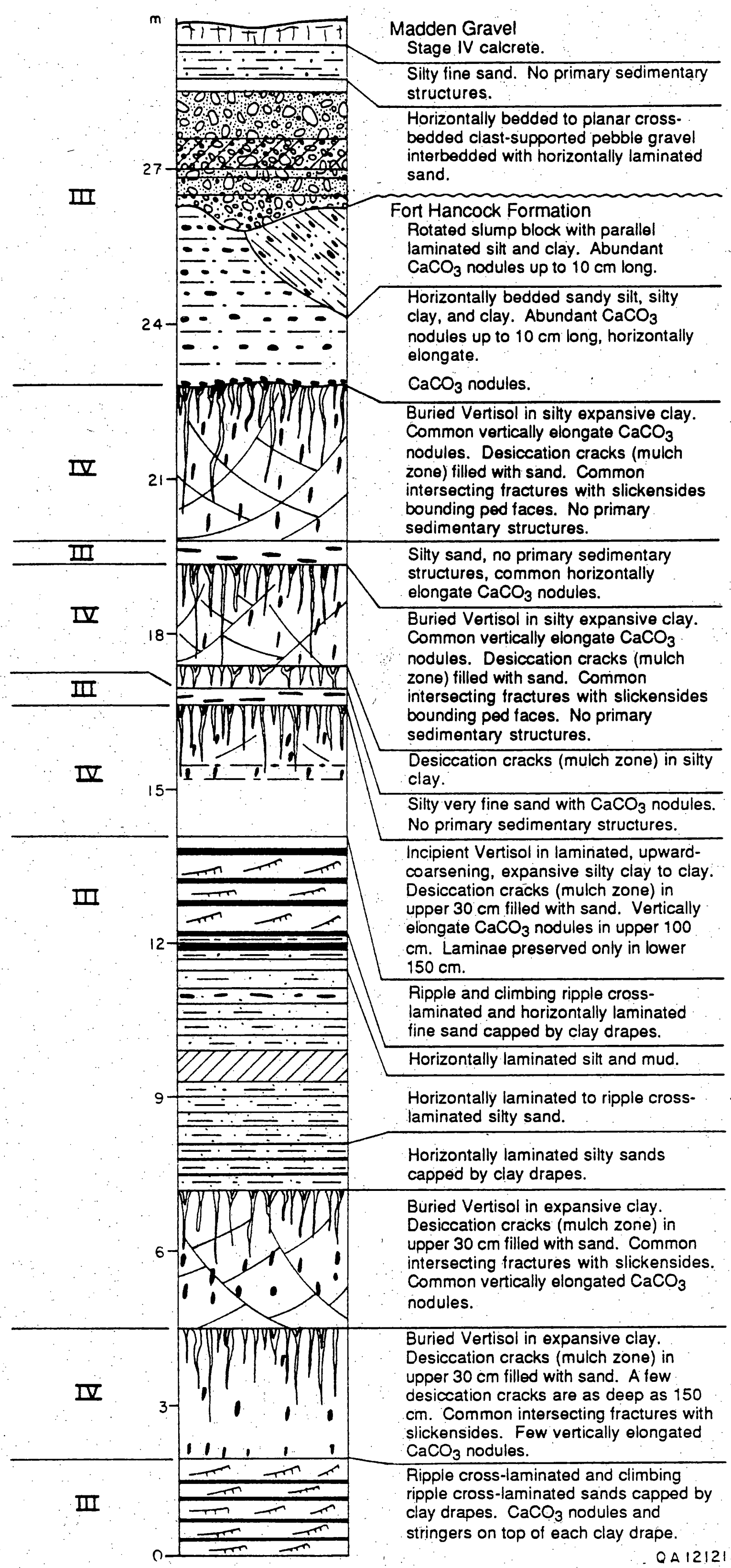


Figure 5. Stratigraphic section of the upper Fort Hancock Formation exposed in the headwaters of Alamo Arroyo (see fig. 1 for location). Elevation of the base of the section is approximately 1,213 m (3,980 ft). Elevation of top of the Fort Hancock Formation is approximately 1,234 m (4,050 ft). Roman numerals identify lithofacies in the Fort Hancock Formation: III, sand, sandy mud, and sandy silt (distal alluvial fan); IV, clay and sandy clay (ephemeral lake).

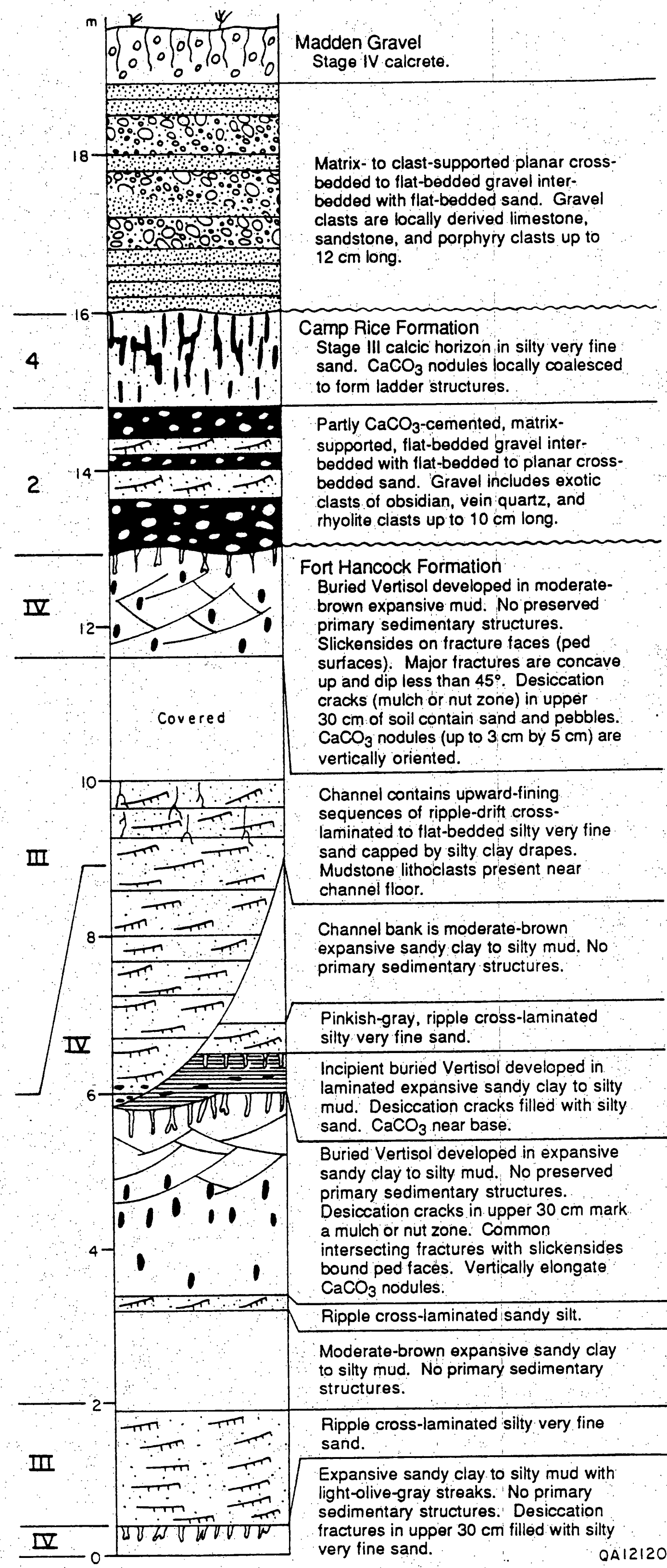


Figure 6. Stratigraphic section of the upper Fort Hancock Formation and Camp Rice Formation exposed in Diablo Arroyo (see fig. 1 for location). Elevation of the base of the section is approximately 1,137 m (3,730 ft). Elevation of the top of the Fort Hancock Formation is 1,155 m (3,773 ft). Roman numerals identify lithofacies in the Fort Hancock Formation: III, sand, sandy mud, and sandy silt (distal alluvial fan); IV, clay and sandy clay (ephemeral lake). Arabic numerals identify lithofacies of the Camp Rice Formation: 2, sand and exotic gravel (braided stream); 4, coarse silt to fine sand (loess).

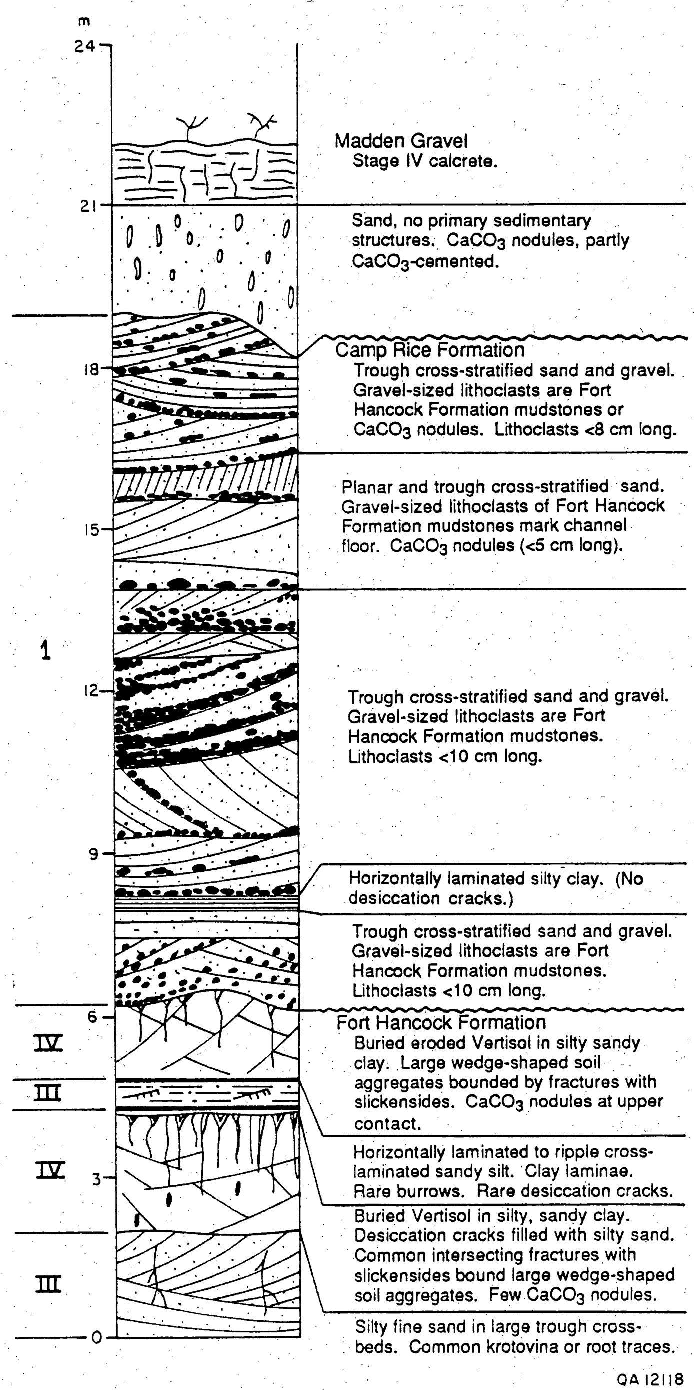


Figure 7. Stratigraphic section of the upper Fort Hancock Formation and Camp Rice Formation exposed in Diablo Arroyo (see fig. 1 for location). Elevation of the base of the section is approximately 1,177 m (3,860 ft). Elevation of the top of the Fort Hancock Formation is approximately 1,183 m (3,880 ft). Roman numerals identify lithofacies in the Fort Hancock Formation: III, sand, sandy mud, and sandy silt (distal alluvial fan); IV, clay and sandy clay (ephemeral lake). Arabic numeral 1 identifies the sand and gravel lithofacies of the Camp Rice Formation.

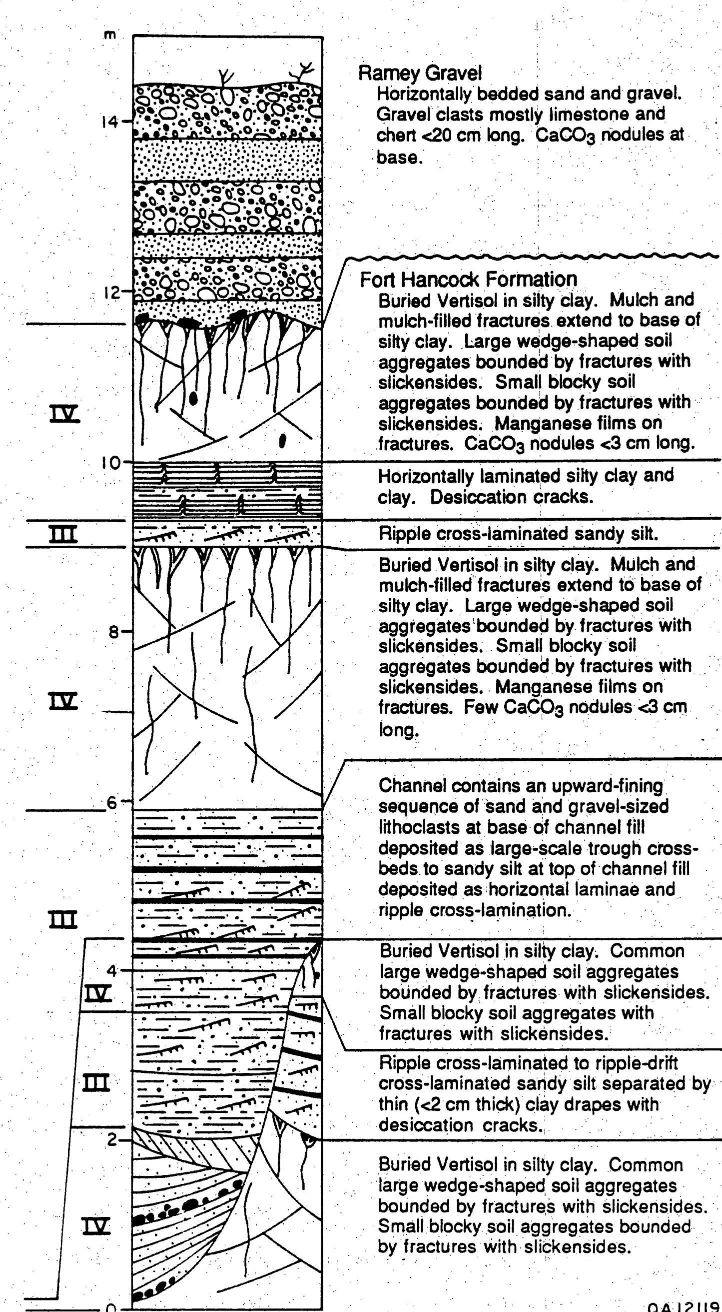


Figure 8. Stratigraphic section of the upper Fort Hancock Formation exposed approximately 0.75 km (0.5 mi) northeast of the type section of the Fort Hancock Formation in Madden Arroyo (see fig. 1 for location). Elevation of the base of the section is approximately 1,143 m (3,750 ft). Roman numerals identify lithofacies of the Fort Hancock Formation: III, sand, sandy mud, and sandy silt (distal alluvial fan); IV, clay and sandy clay (ephemeral lake).

Figure 9. Ripple cross-laminated, silty, very fine sand from core of Texas Low-Level Radioactive Waste Disposal Authority well no. 22 at a depth of 101.2 m (332 ft). Core is 7.7 cm (3 in) in diameter. Silty sand is typical of distal alluvial fan deposits. See figure 1 for well location.

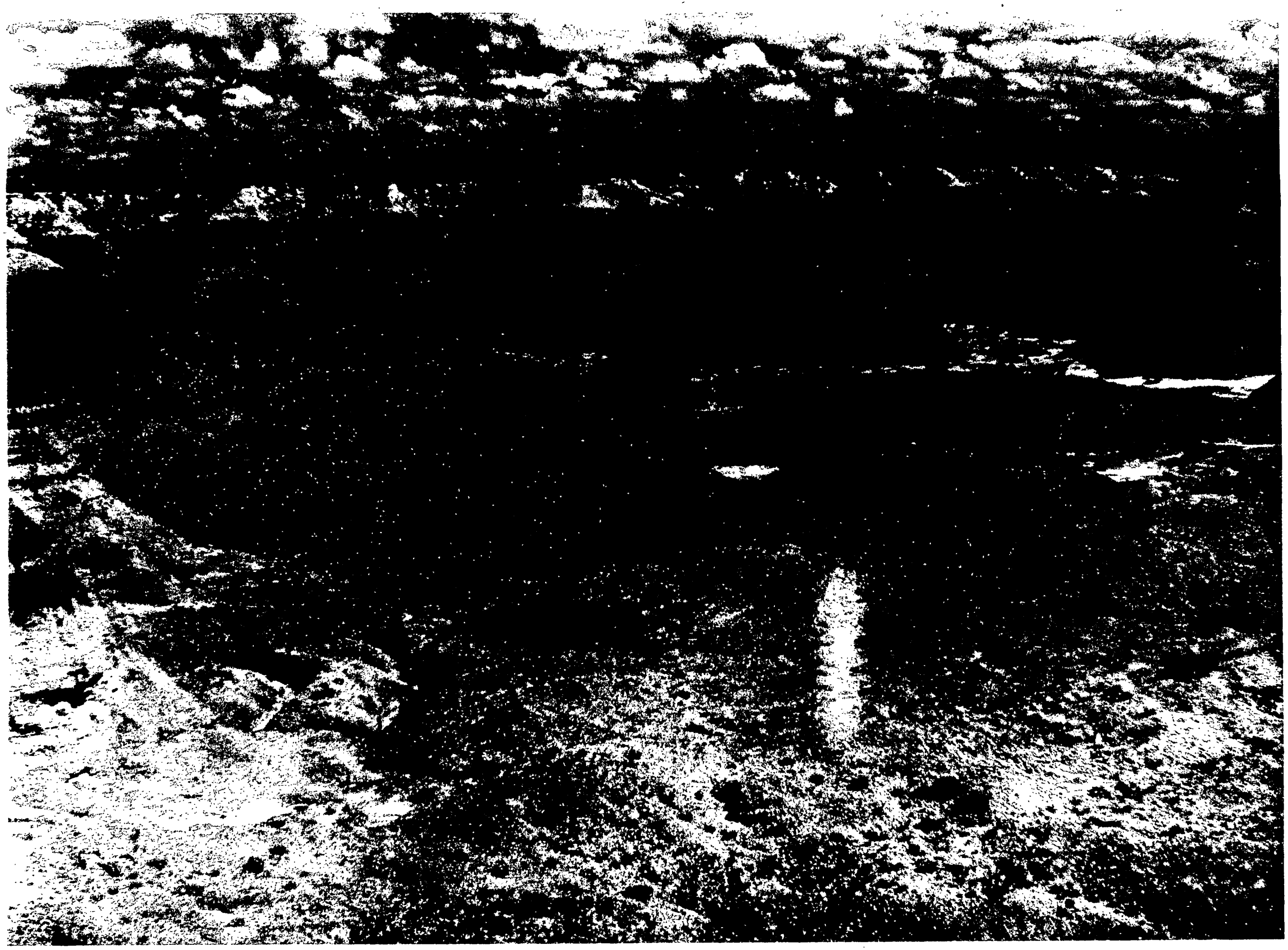


Figure 10. View of upper Tertiary Fort Hancock Formation overlain unconformably by the Quaternary Madden Gravel in the headwaters of Alamo Arroyo. In a general fashion these units fine upward. Increasing clay content results in darker colors. Each clay (dark) unit contains a buried Vertisol. Steep bluffs are approximately 30 m (100 ft) high.

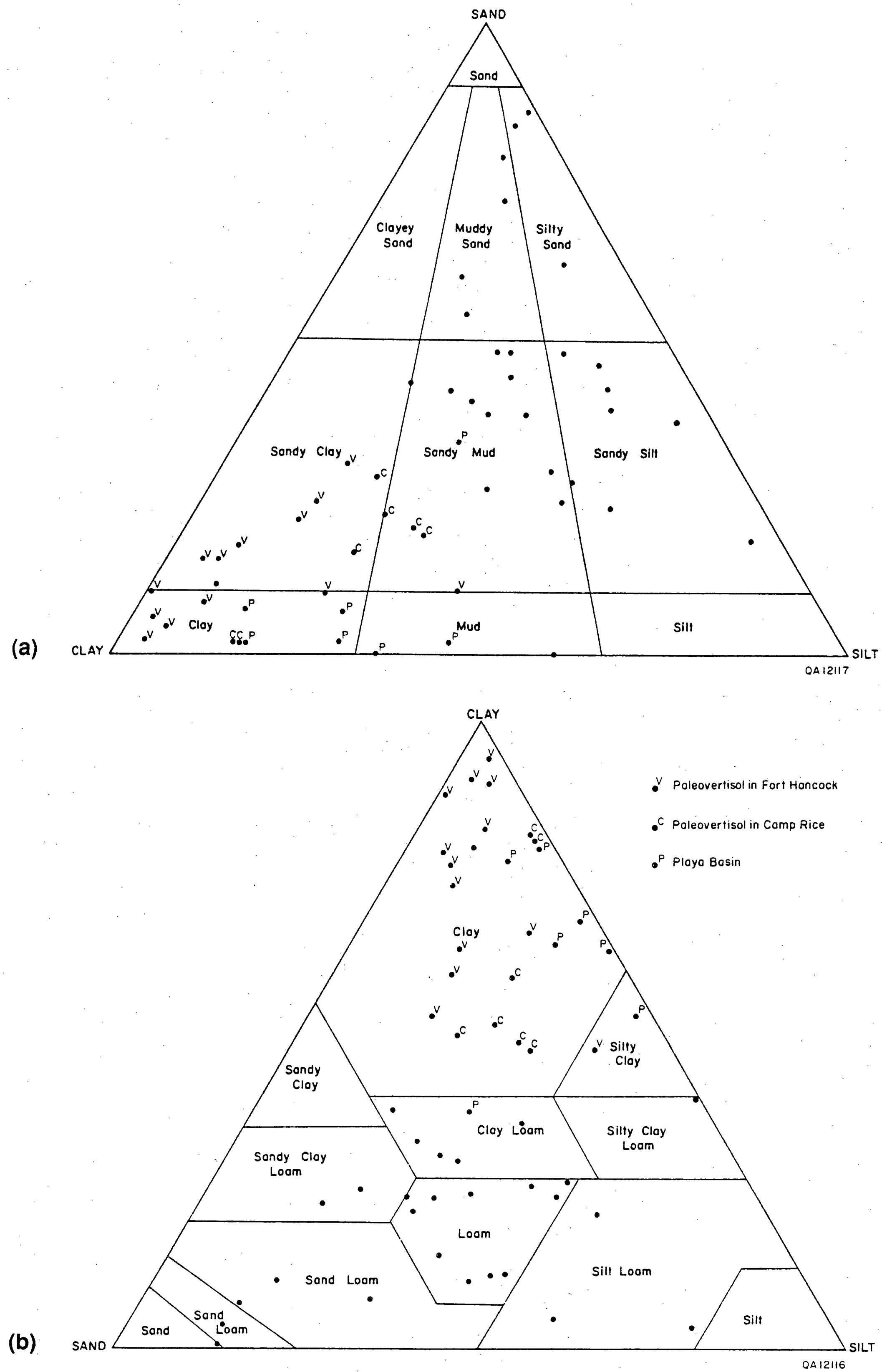


Figure 11. Textural classifications of sediments of Fort Hancock and Camp Rice Formations. (a) Triangular chart showing percentages of sand (2 to 0.0625 mm), silt (0.0625 to 0.0039 mm), and clay (less than 0.0039 mm) (after Folk, 1968). (b) Triangular chart showing percentages of clay (less than 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2 mm) in basic soil textural classes.

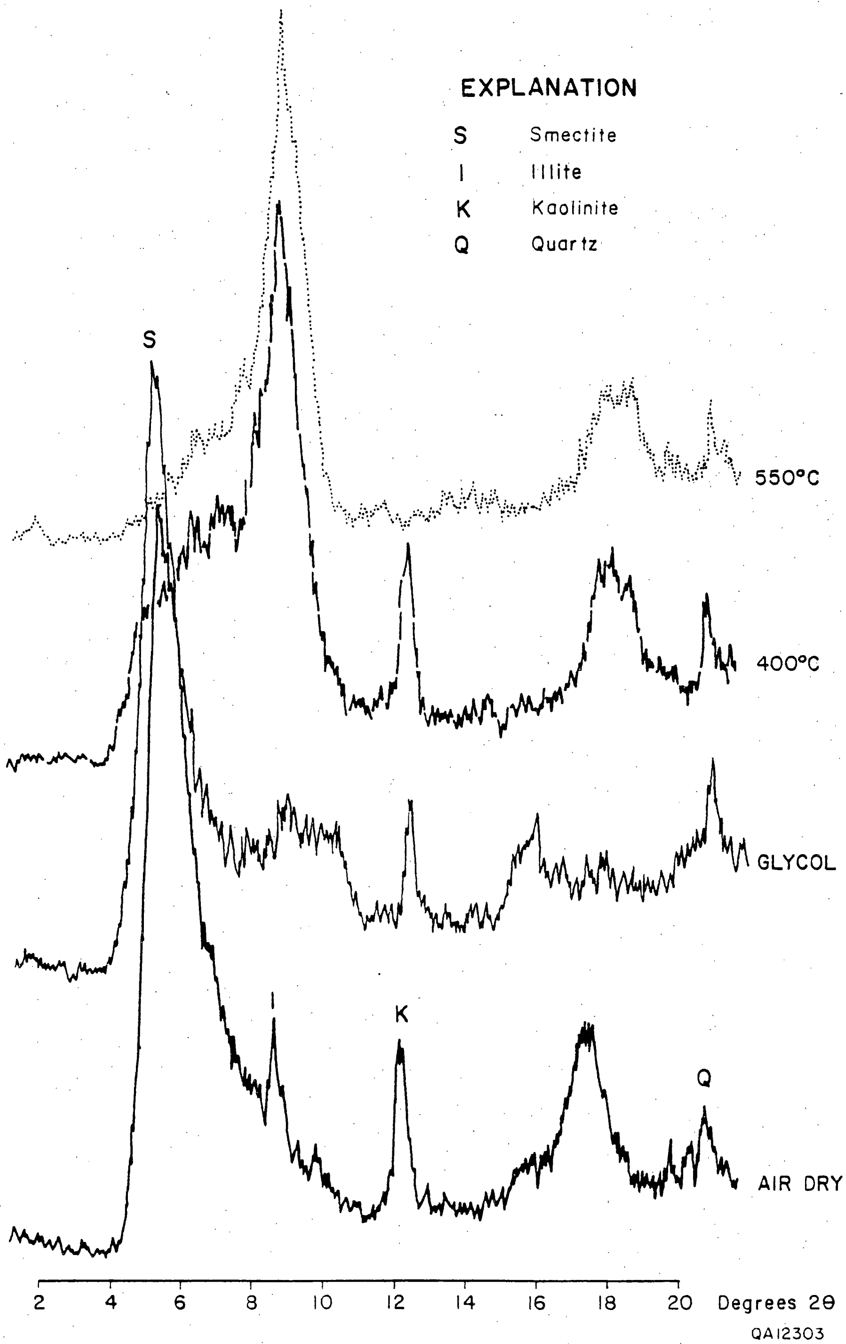


Figure 12. X-ray diffraction diagram for selected samples of Fort Hancock Formation clay and mud facies. Clays are primarily smectite with lesser amounts of illite, kaolinite, and quartz.

Figure 13. Interbedded clay and gypsum of the clay, sandy mud, and gypsum lithofacies (playa lake) of the Fort Hancock Formation exposed along Nealy Canyon. Knife is 9 cm long.

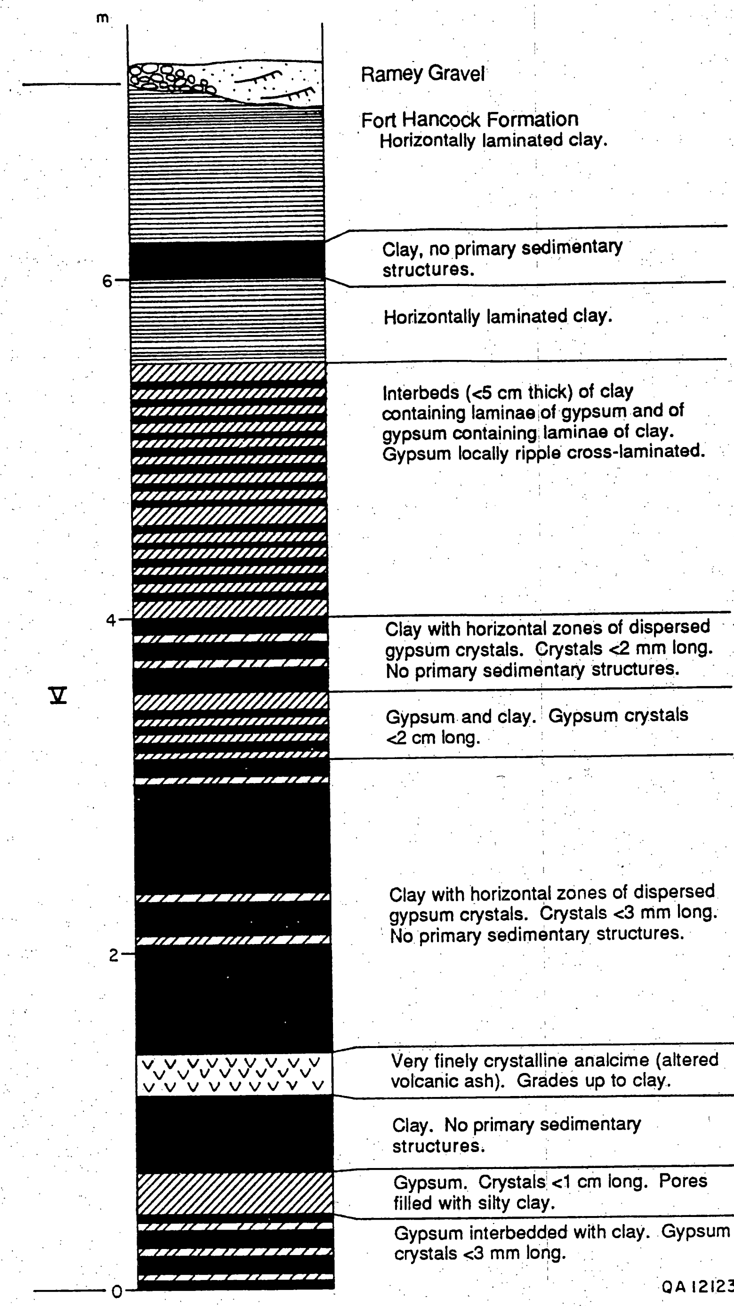


Figure 14. Stratigraphic section of the upper Fort Hancock Formation exposed in Nealy Canyon approximately 1.6 km (1 mi) northeast of the Rio Grande. No paleovertisols were recognized in clayey sediments in this section. See figure 1 for section location. Elevation of the base of the section is 1,061 m (3,480 ft). Roman numeral V identifies the clay, mud, sandy mud, and gypsum lithofacies interpreted to have been deposited in a playa lake.

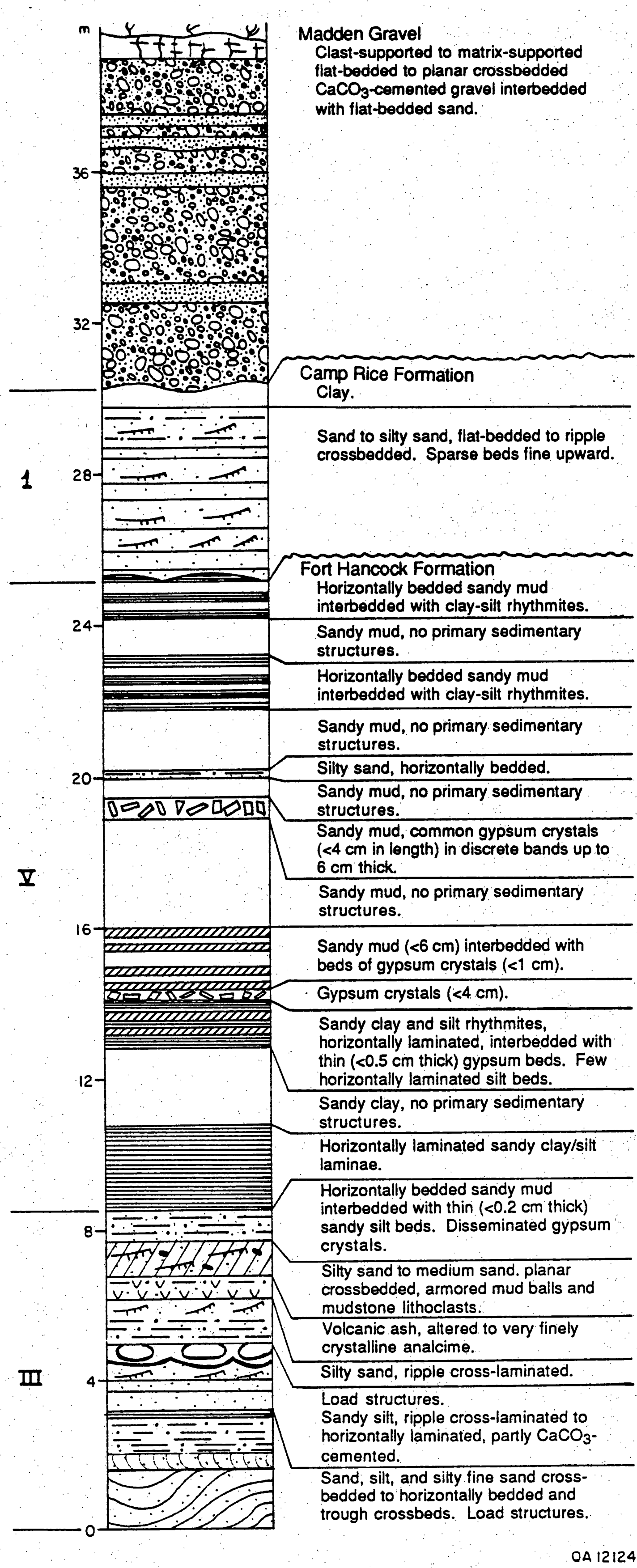


Figure 15. Stratigraphic section of the upper Fort Hancock Formation exposed in Quitman Canyon approximately 3 km (2 mi) northeast of the Rio Grande. See fig. 1 for section location. Elevation of the base of the section is approximately 1,085 m (3,560 ft). Elevation of the top of the Fort Hancock Formation is approximately 1,113 m (3,650 ft). Roman numerals identify lithofacies in the Fort Hancock Formation: III, sand, sandy mud, and sandy silt (distal alluvial fan); V, clay, mud, sandy mud, and gypsum (playa lake). Arabic numeral 1 identifies the sand and gravel lithofacies of the Camp Rice Formation, interpreted to have been deposited by a braided stream.

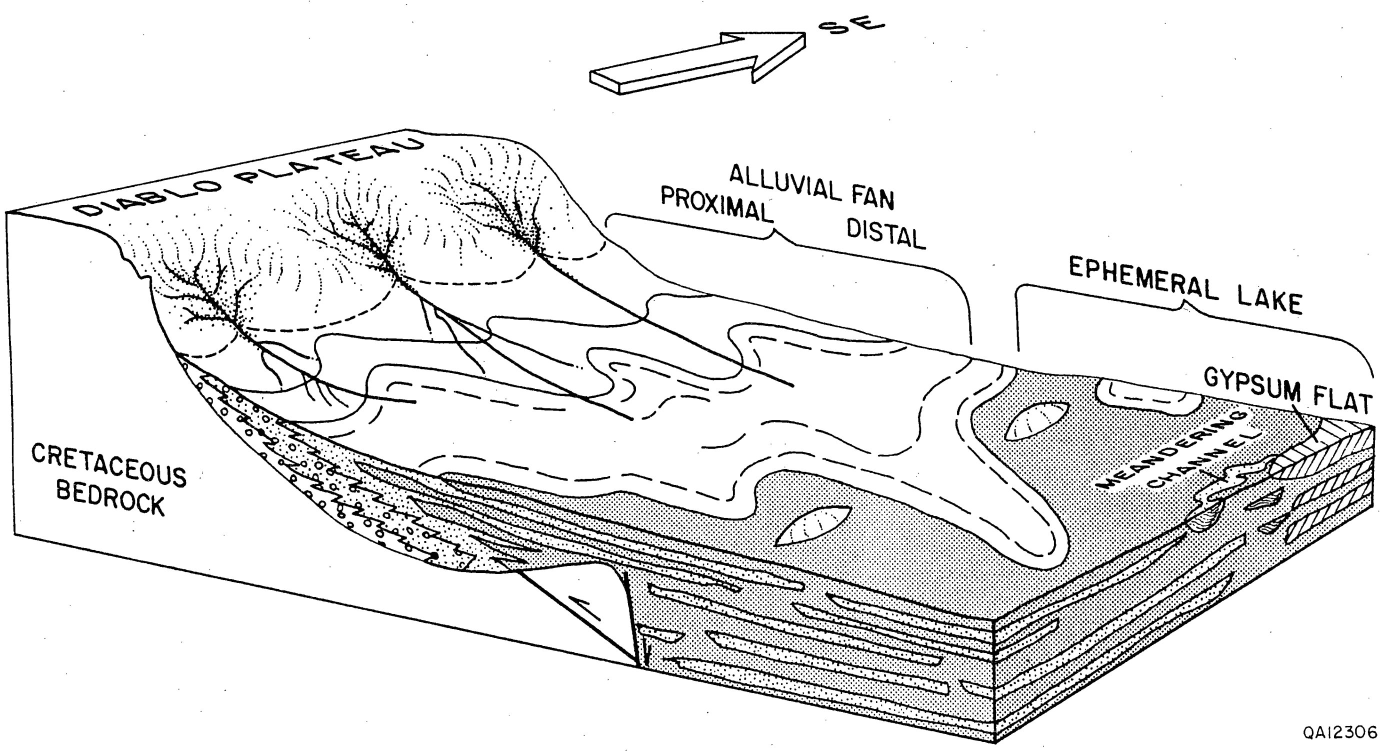


Figure 16. Block diagram showing interpreted depositional environments of the Fort Hancock Formation in the southern Hueco Bolson.

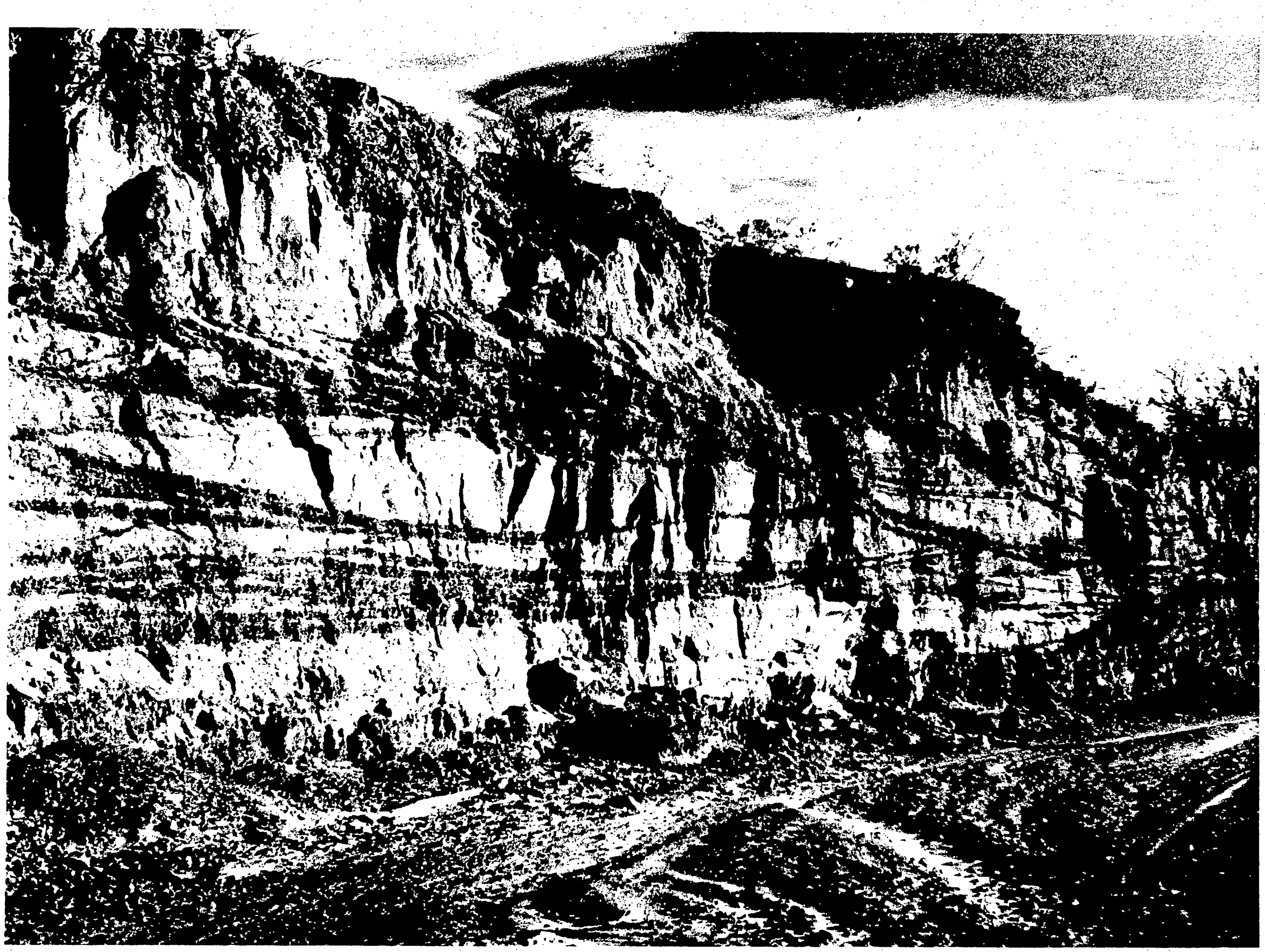


Figure 17. Large-scale trough cross-stratification in sand and gravel lithofacies of the Camp Rice Formation. Bases of channel fills contain gravel-sized lithoclasts derived from Fort Hancock Formation. Fort Hancock Formation is exposed below the erosional unconformity at the base of the Camp Rice section in the left side of the photograph. Bluff is approximately 5 m (17 ft) high.

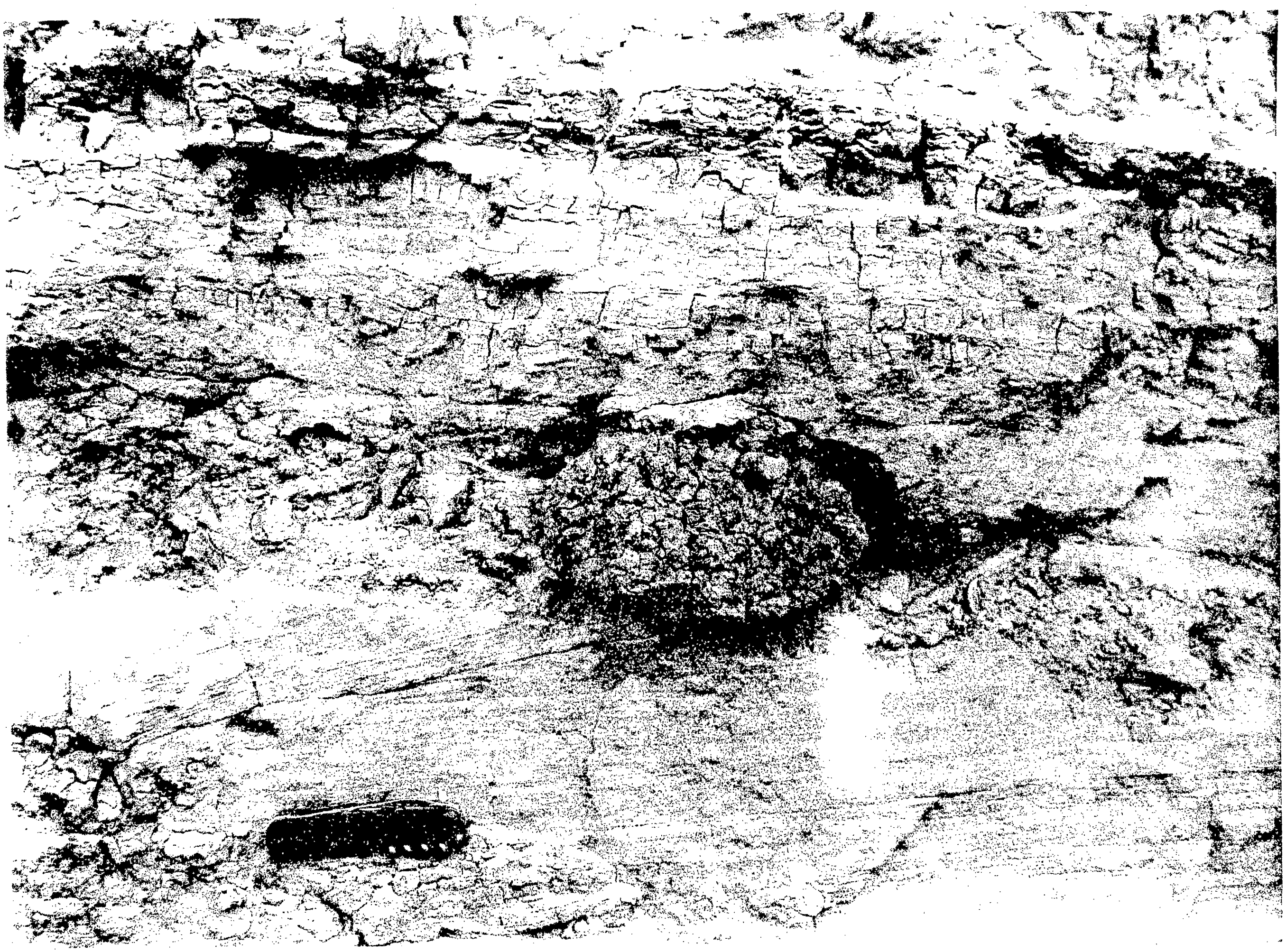


Figure 18. Lithoclasts including a large mud ball in the Camp Rice Formation derived from clayey facies of the Fort Hancock Formation. Mud balls are commonly not armored.

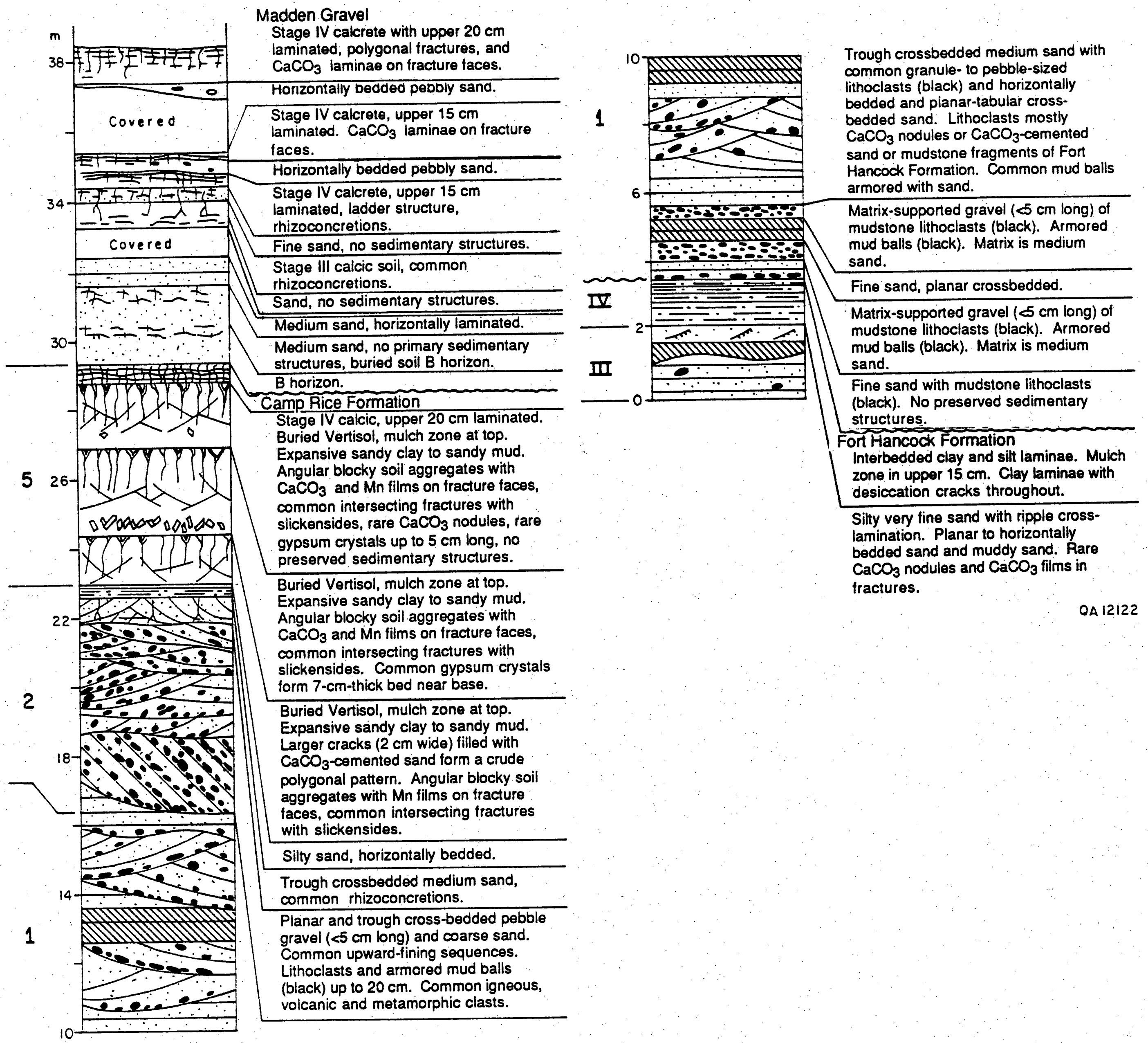


Figure 19. Stratigraphic section of the Fort Hancock and Camp Rice Formations exposed along Alamo Arroyo approximately 7 km (4. 4 mi) northeast of the Rio Grande. Note that nearly 14 m (45 ft) of locally derived sand and gravel lithofacies underlie Camp Rice sand and gravel bearing exotic igneous and metamorphic clasts derived from north of the Hueco Bolson. Arabic numerals identify lithofacies of the Camp Rice Formation: 1, sand and gravel lithofacies (braided stream); 2, sand and exotic gravel (braided axial stream); 5, clay, sandy clay, and gypsum lithofacies (ephemeral lake or playa). Roman numerals identify lithofacies of the Fort Hancock Formation: III, sandy mud, and sandy silt lithofacies (distal alluvial fan); IV, clay and sandy clay lithofacies (ephemeral lake). Elevation of the base of the section is approximately 1,155 m (3,790 ft). Elevation of the top of the Fort Hancock Formation is approximately 1,159 m (3,800 ft).

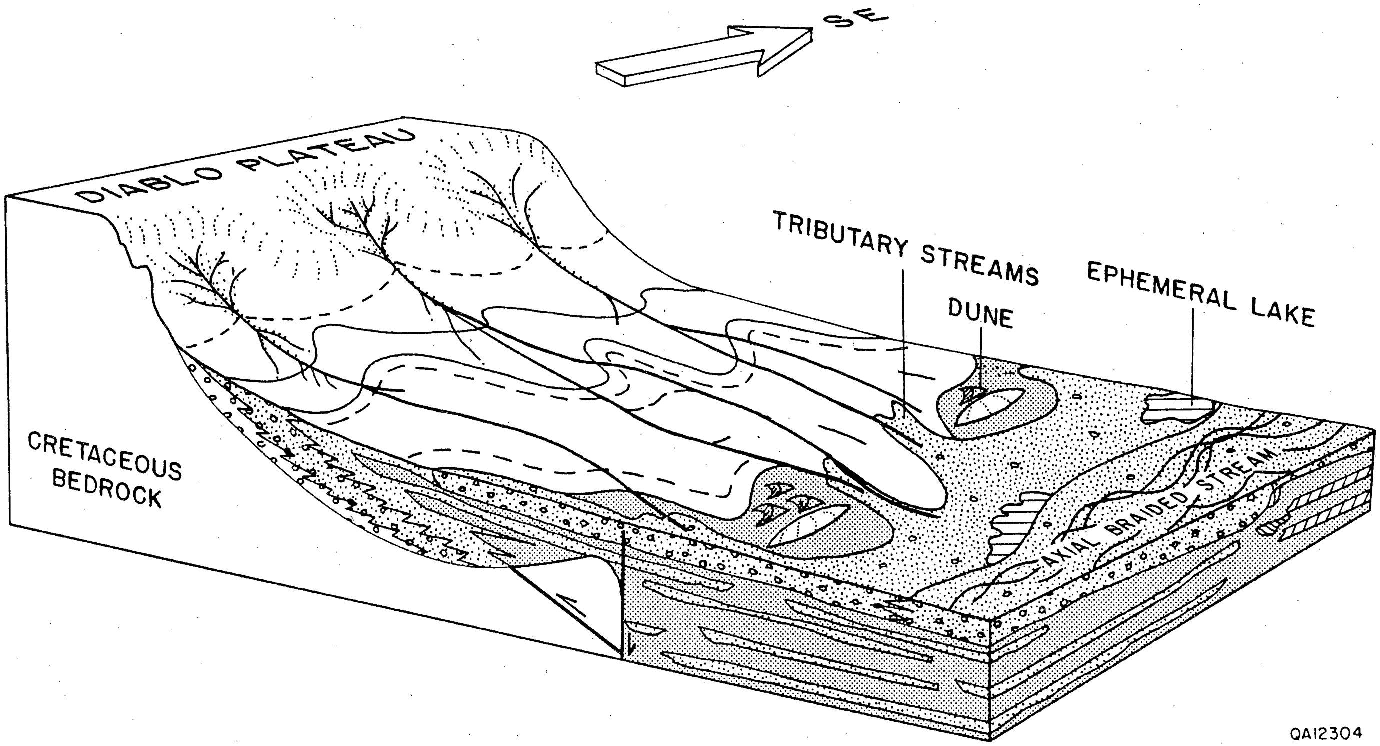


Figure 20. Block diagram showing interpreted depositional environments and lithofacies of the Camp Rice Formation in the southern Hueco Bolson. Primary lithofacies are axial braided stream, gravel-bearing tributaries to the axial stream, and local dune and lacustrine sediments.

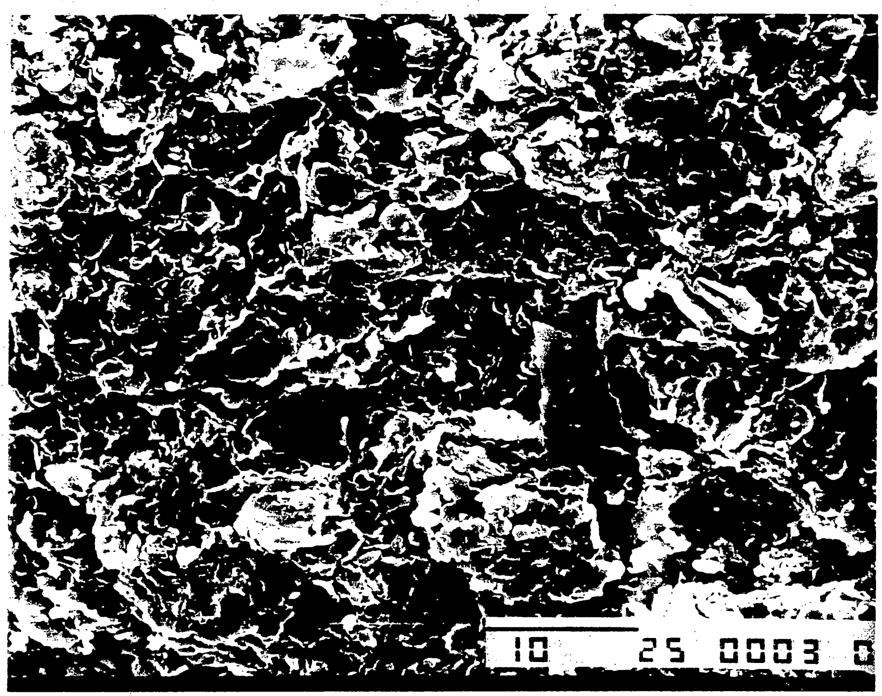


Figure 21. Scanning electron microscope image showing typical microstructure of smectite clays from a buried Vertisol in Fort Hancock Formation. Bar is 10 μm.

Figure 22. Paleovertisol developed in sandy clay of the Fort Hancock Formation. Most inclined fractures intersect. Fracture surfaces are slightly concave up and are covered with slickensides. Mulch zone extends from near the base of the scale to approximately 10 cm (4 inches) above the scale. Near-vertical $CaCO_3$ nodules are present in the lower two-thirds of the exposed soil profile. Top of the soil profile is the irregular surface, approximately 10 cm (4 inches) above the scale, where these clayey sediments are overlain by fluvially deposited sandy silt.

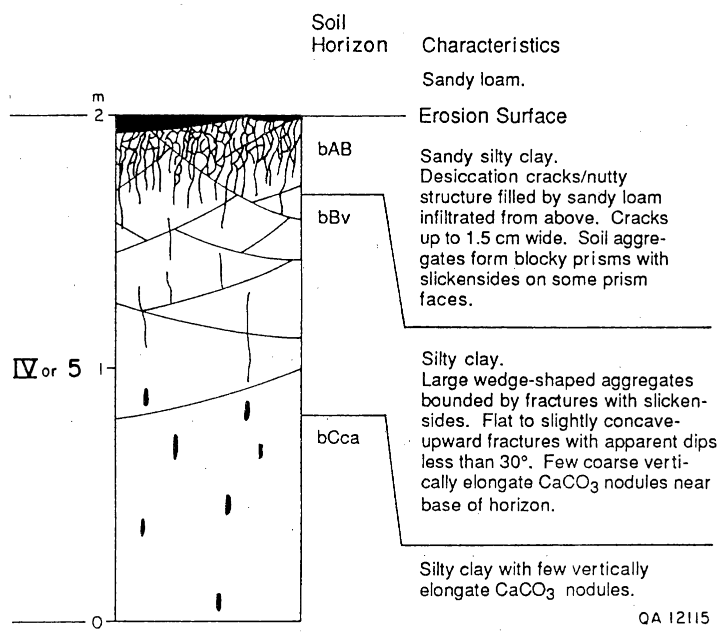


Figure 23. Model illustrating the vertical distribution of the characteristic soil structures of buried Vertisols in clay and sandy clay lithofacies in the Fort Hancock Formation (IV) and Camp Rice Formations (5). See Soil Survey Staff (1975) for discussions of soil horizon identifications.

Figure 24. Surface exposure of a mulch or nut zone (commonly referred to as popcorn texture). This surface soil texture is characteristic of clayey sediments with high shrink/swell properties such as smectites. Pen is 14 cm (5. 5 inches) long.

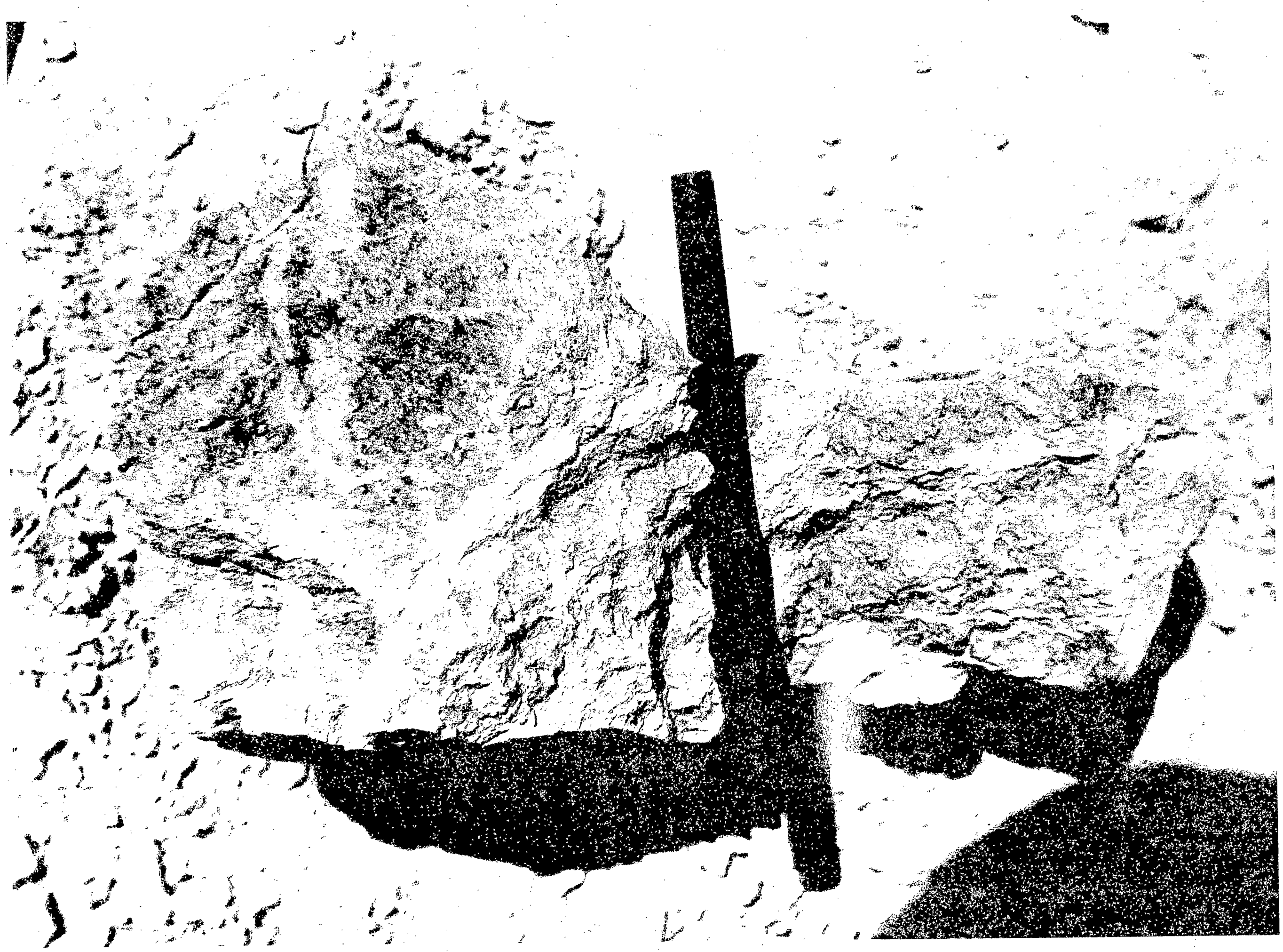


Figure 25. Plan view of desiccation cracks in a block of moderate-gray Fort Hancock sandy clay filled with light-gray sandy silt. The block of sediment is from a buried Vertisol, Fort Hancock Formation. Pen is 14 cm (5. 5 inches) long.

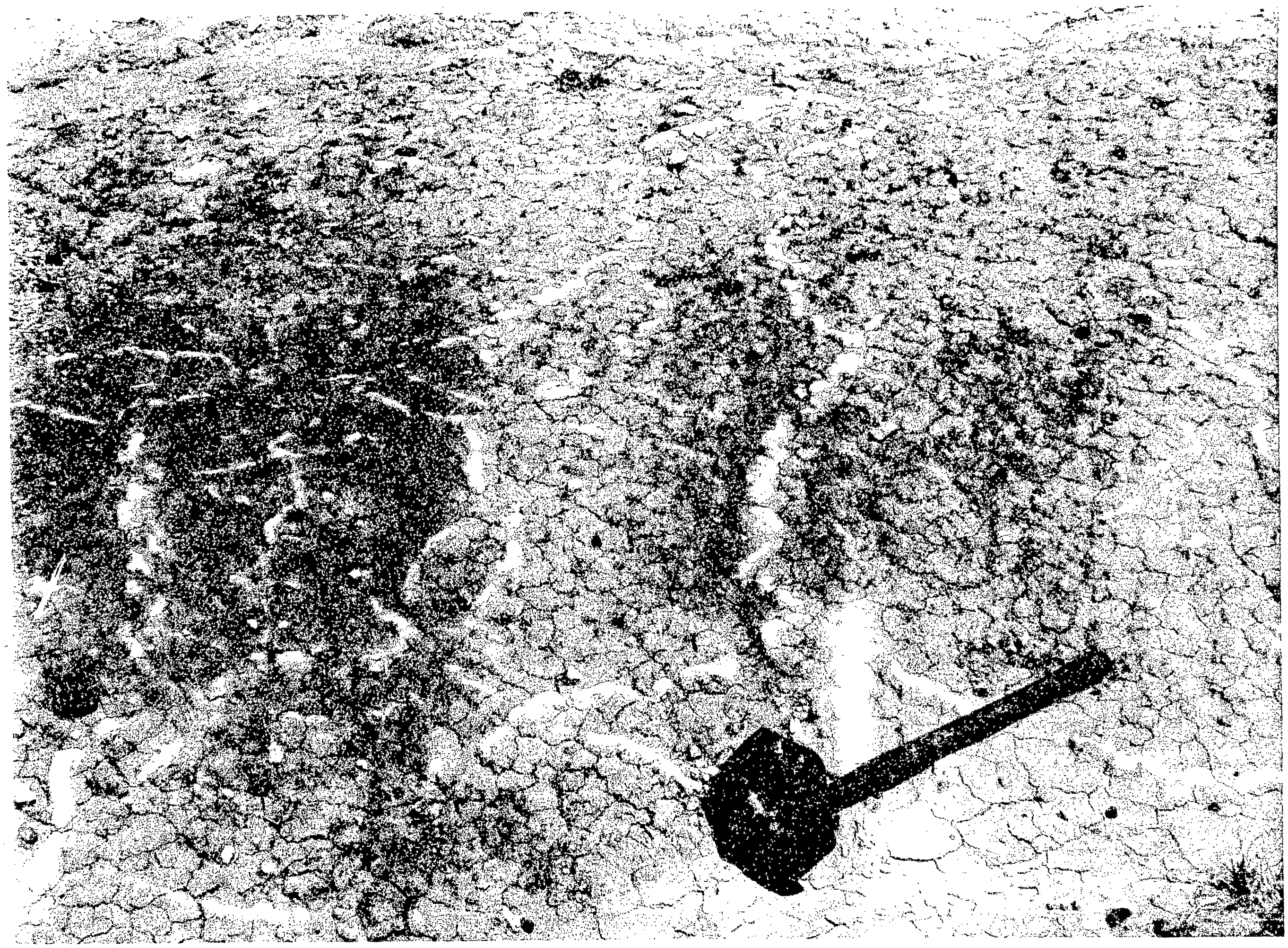


Figure 26. $CaCO_3$-cemented sandy silt fills desiccation cracks in a buried Vertisol developed in sandy clay of the Fort Hancock Formation.

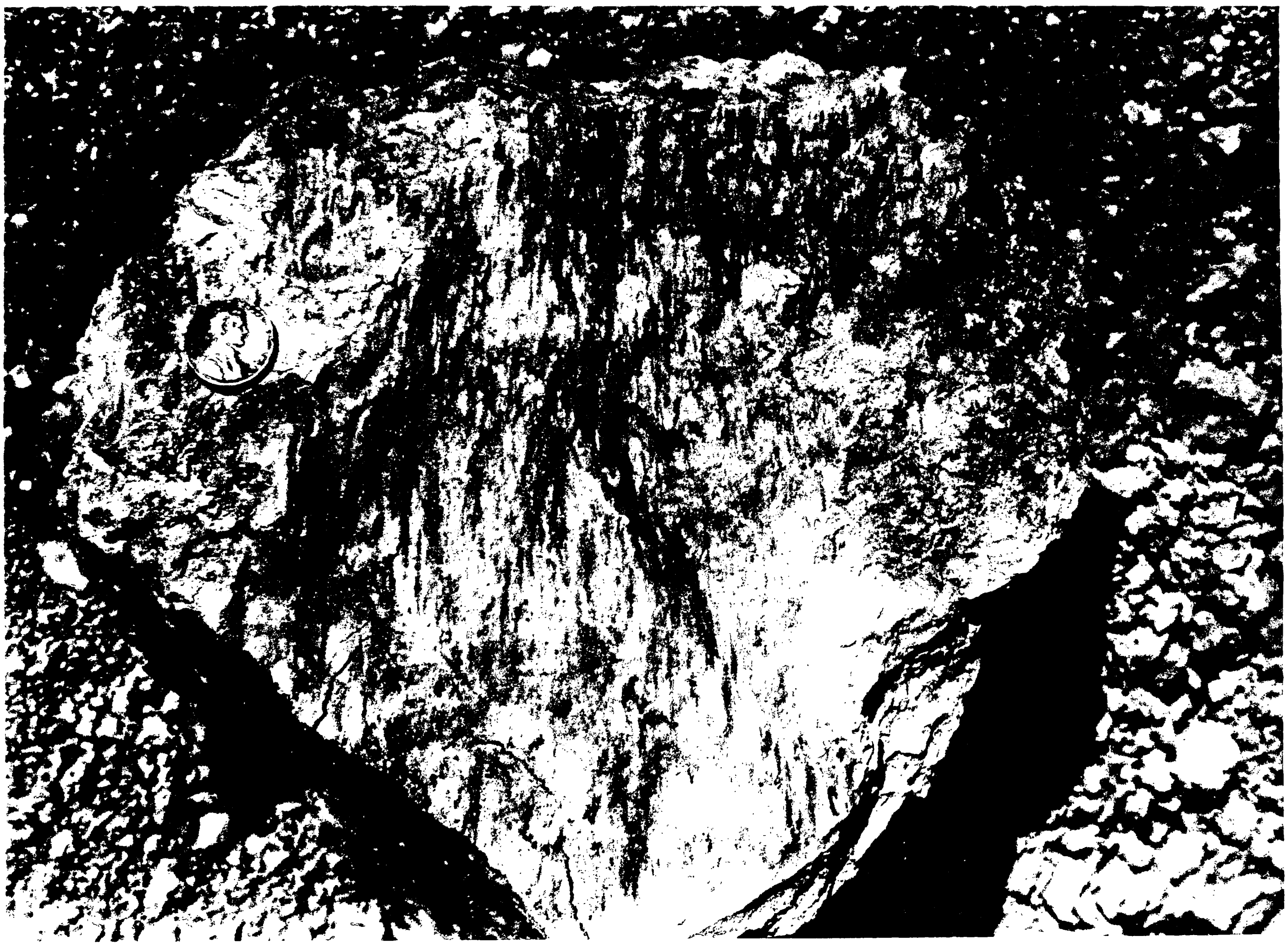


Figure 27. Slickensides on a blocky soil aggregate from a buried Vertisol, Fort Hancock Formation.

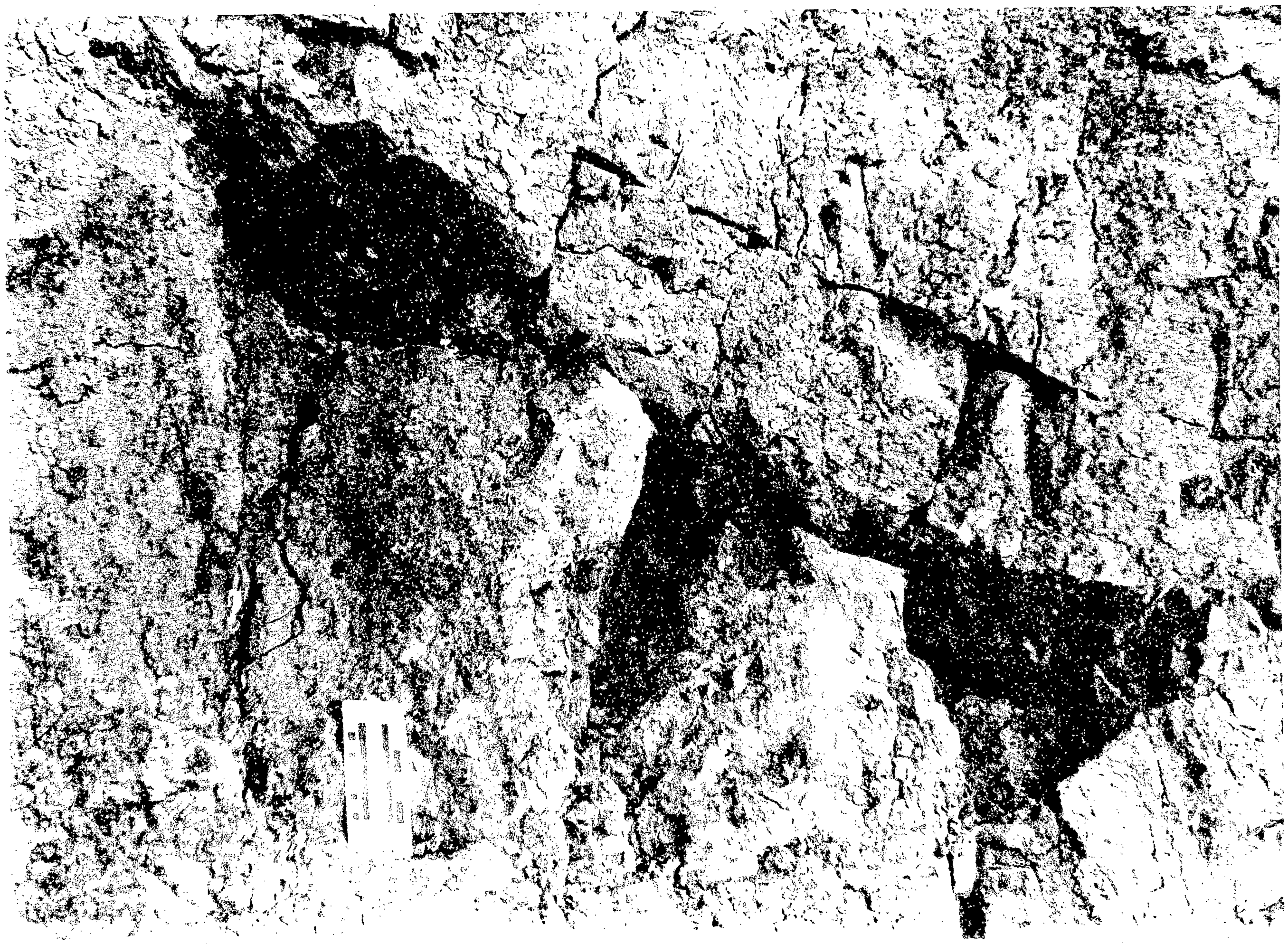
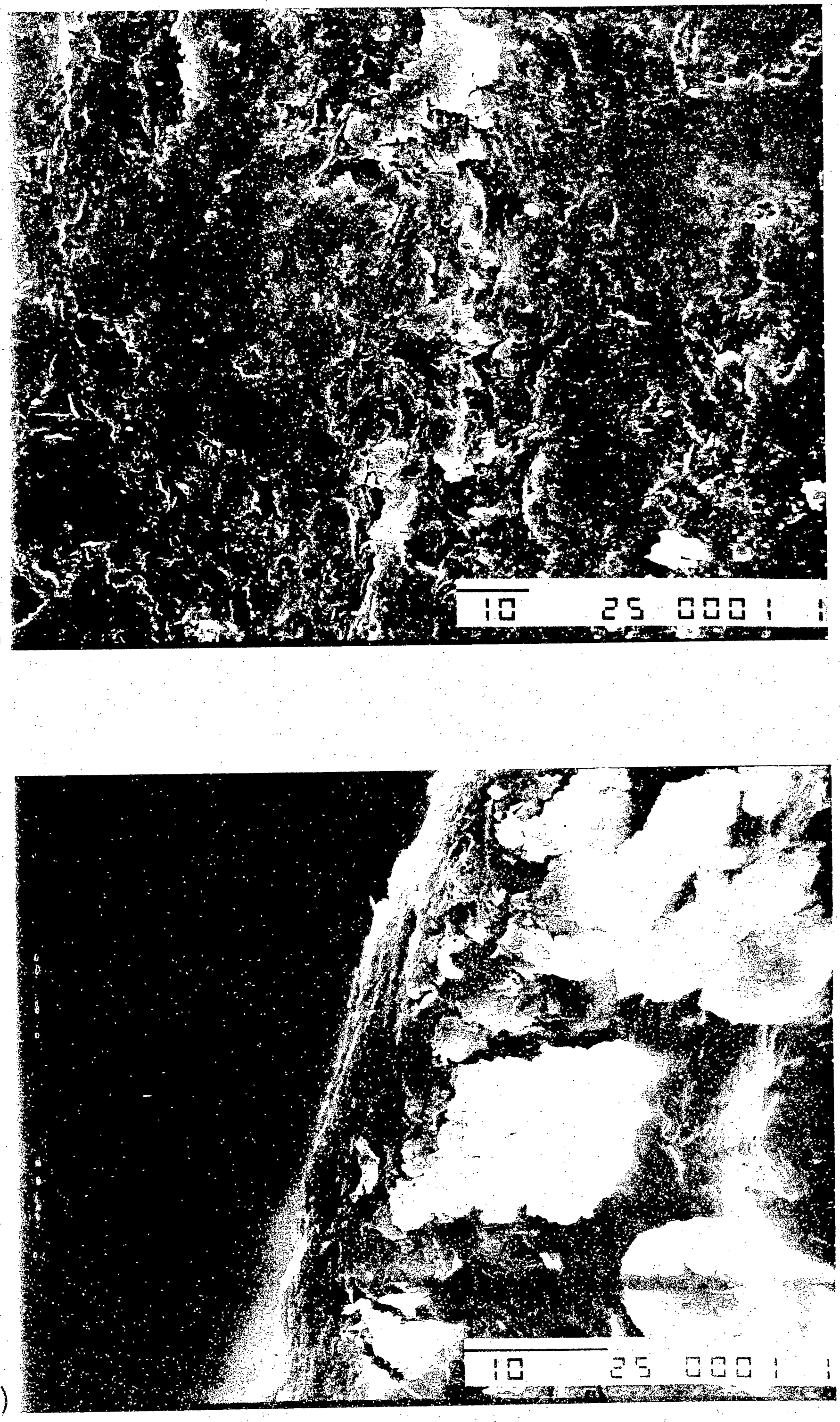


Figure 28. Large wedge-shaped soil aggregate bounded by slightly concave-up fracture surfaces with slickensides. Fractures are in a buried Vertisol developed in the Fort Hancock Formation. Scale is 10 cm (4 inches) long.



(a)

(b)

Figure 29. Scanning electron microscope image of the edge (a) and surface (b) of slickensides developed on a fragment of soil aggregate from a buried Vertisol, Fort Hancock Formation.

Table 1. Fort Hancock Formation lithologies and interpreted depositional environments.

Lithofacies	Sedimentary characteristics	Depositional environments
I. Gravel	Mostly flat-bedded, clast-supported, partly imbricated, locally $CaCO_3$-cemented pebble- to boulder-sized gravel. Locally nonstratified matrix-supported pebble- to boulder-sized gravel. Crops out adjacent to mountain fronts and overlies Cretaceous bedrock.	Proximal alluvial fan (McGowen and Groat, 1971; Bull, 1972; Heward, 1978)
II. Sand, sandy mud, or sandy silt and gravel	Clast-supported, partly imbricated pebble- to cobble-sized gravel interbedded with crossbedded to horizontally laminated sand and sandy mud. Common pedogenic $CaCO_3$ nodules and filaments.	Medial alluvial fan
III. Sand, sandy mud, and sandy silt	Common horizontal laminations and ripple and climbing ripple cross-laminations. Rare $CaCO_3$ nodules and filaments. Rare gravel-sized clasts. Lower contacts commonly upward-coarsening from underlying lacustrine clay. Upper contacts typically sharp.	Distal alluvial fan /fan delta
IV. Clay and sand clay	Smectite-rich clay and sandy clay contain many calcic paleovertisols. Sedimentary structures commonly destroyed by pedoturbation. Rare, locally preserved, mud-cracked, thin horizontal laminated clay or sandy clay.	Ephemeral lake
V. Clay, mud, sandy mud, and gypsum	Massive to thin horizontally laminated smectite-rich clay, mud, and sandy mud. Rare desiccation cracks. Gypsum interbedded with clay laminae or as beds of intergrowths of crystals with mud or clay matrix or as isolated crystals.	Saline playa

Table 2. Soil characteristics of modern Vertisols and paleovertisols of the Fort Hancock and Camp Rice Formations, Hueco Bolson.

Vertisol characteristics	Paleovertisol characteristics (Soil Survey Staff, 1975)
1. Develop most commonly in smectite-rich clay.	1. Developed in smectite-rich lake clay.
2. Develop gilgai (surface microtopography).*	2. Gilgai not recognized.
3. Develop deep, wide desiccation cracks (≥1 cm wide at a depth of 50 cm) at some time of year.*	3. Common desiccation cracks to depths of 1 m. Cracks filled with fine sand or clay soil aggregates.
4. Develop mulch or nut zone at surface of small angular (popcornlike) soil aggregates.*	4. Mulch zones commonly preserved as angular clay aggregates separated by thin cracks filled with fine sand. Mulch zones mark former exposed surfaces.
5. Slickensides on ped faces close enough to intersect at some depth between 25 cm and 1 m.*	5. Common blocky, angular peds (joint blocks) bounded by fractures with slickensides.
6. Large wedge-shaped structural soil aggregates, bounded by surfaces with slickensides. Long axes dip between 10° and 60°.*	6. Common wedge-shaped structural soil aggregates bounded by fractures with slickensides. Long axes dip between 10° and 60°.
7. High bulk density and slow hydraulic conductivity.	7. Density not determined. Hydraulic conductivity is low (Scanlon and others, 1990).

* Vertisol characteristics 2 through 6 result from soil expansion and contraction caused by wetting and desiccation.

Table 3. Camp Rice Formation lithofacies and interpreted depositional environments

Lithofacies characteristics	Sedimentary	Depositional environments
1. Sand and gravel	Flat-bedded to ripple to trough cross-stratified sand and gravel. Gravel limited to lithoclasts and pedogenic $CaCO_3$ nodules of Fort Hancock Formation. Low channel depth-to-width ratios. Channel fills commonly fine upward.	Braided stream (tributary to Rio Grande)
2. Sand and exotic gravel	Flat-bedded to ripple to trough cross-stratified sand and gravel. Gravel contains abundant igneous and metamorphic clasts derived from outside of the Hueco Bolson.	Braided stream (Rio Grande)
3. Sand	Well-sorted planar crossbedded medium sand. A single 1-m- to 1.5-m-thick bed rests unconformably on Fort Hancock sediments.	Eolian dune
4. Coarse silt and very fine sand	Clayey to muddy, fine to very fine sand. No preserved primary sedimentary structures. Few to common $CaCO_3$ nodules and filaments. Blocky to prismatic fractures. Rare to common $CaCO_3$-filled root tubules. Buried illuvial B soil horizons.	Eolian loess
5. Clay, sandy clay, and gypsum	Smectite-rich clay and sandy clay with calcic paleovertisols. Rare horizontally laminated sand silt. Rare coarsely crystalline gypsum. Sedimentary structures destroyed by pedoturbation.	Ephemeral lake