QUATERNARY EVOLUTION OF PLAYA LAKES ON THE SOUTHERN HIGH PLAINS—A CASE STUDY FROM THE AMARILLO AREA

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ABSTRACT

Playa lakes are abundant, small (generally <0.5 km in area) ephemeral lakes that occur in shallow (<11 m deep) depressions on the surface of the Southern High Plains. This study, based on analysis of excavations and 63 hollow-stem auger cores taken from 10 lakes in the study area around the Pantex Plant northeast of Amarillo, Texas, resolves long-standing controversies regarding origin, evolution, and recharge behavior of playa lakes.

Origin of playa lakes has been debated for decades because the lakes are abundant but small, and the processes that form them obscure. Although the ephemerally ponded playa lakes are floored by clay soils, ground-water and unsaturated-zone investigations show that playa lakes serve as sites of focused recharge. Description of a spectrum of playa basins of various sizes and recharge behaviors defines the similar characteristics and variable features in playa basins and documents the long-term maintenance of the seasonally ephemeral lakes and their responses to past climatic changes. These observations can be used to constrain assumptions that will be made about subsurface stratigraphy and recharge from the playas at the Pantex Plant.

Playa lake basins contain 5 to 18 m of Quaternary lake sediments, including gray clays, oxidized red-brown clays, heterogeneous lacustrine delta deposits, fine lacustrine–eolian sand and silt beds and laminae, and admixed sand and clay. Lake sediments interfinger with calcic soils and red-brown loam of the Blackwater Draw Formation near the edges of the playas. As many as 12 calcic soil horizons are identified in the Blackwater Draw Formation in the upland. A sand unit underlies both playas and uplands at depths of 10 to 20 m.

All of the lake basins studied have had a long history, originating as topographic lows before or during the early phases of Blackwater Draw deposition. Stacked depositional cycles identified in lake sediments record repeated phases of (1) initial highstand, (2) ephemeral lake conditions, and (3) lake shrinkage and prolonged subaerial exposure. Although sedimentary structures show that during all phases the lakes were ephemeral, duration and frequency of flooding varied, thus changing relative amounts of sediment accumulation, deflation, and soil formation.

Evidence of preferential pathways controlling flow is abundant beneath playas, including shrink–swell cracks and roots in Randall clay soils and gleying, illuviated clay, leached carbonate, or mineralized fractures in older sediments. Sand interbeds within the lacustrine deposits may influence flow rates. Vertical fractures served as conduits for both oxidizing and reducing fluids in high-permeability, well-sorted sands, as well as in low-permeability sediments.

KEYWORDS: Ogallala recharge, playa lakes, Quaternary climate

INTRODUCTION

Geologic Setting

The Southern High Plains (fig. 1) have been an area of sediment accumulation through the late Tertiary and Quaternary. Fluvial sands and gravels of the Miocene–Pliocene Ogallala Formation (fig. 2) were deposited in valleys (Seni, 1980; Reeves, 1984), and eolian sands and silts were deposited in upland areas. The latter were deposited during the later phases of Ogallala deposition as well (Gustavson and Winkler, 1988; Gustavson, 1994). Fine-grained sediments were deposited in large lakes. The study area lies on the south margin of a major paleovalley (fig. 1), which coincides with an area of Permian halite dissolution (Gustavson and others, 1980) and increased rates of Ogallala sedimentation (Gustavson, 1994). Calcic soils accumulated during periods of landscape stability during Ogallala time, culminating in development of the widespread, thick calcrete known as the Caprock that marks the top of the Ogallala Formation. Finer grained eolian clayey silt and loam deposited after this prolonged episode of landscape stability are known as the Blackwater Draw Formation (Reeves, 1976) (fig. 2). This formation is composed of amalgamated silty clay loam and soils containing well-developed Bt and Bk horizons (Holliday, 1989). Sediment was transported as eolian dust and deposited in a grassland setting. Alternating intervals of soil-carbonate accumulation record

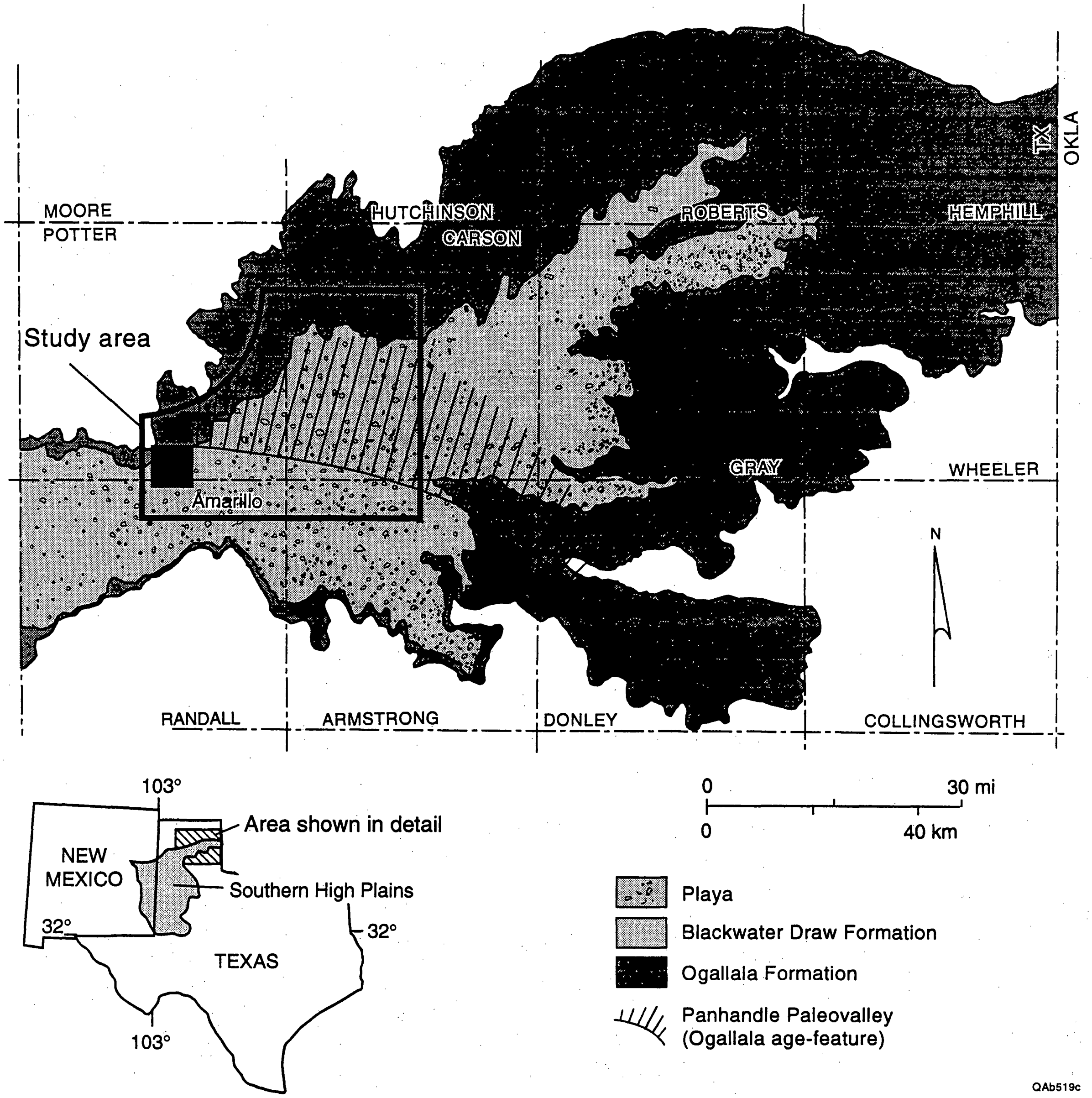

Figure 1. Location map of the Southern High Plains (SHP) and geologic setting of the study area, modified from Mullican and others (1994). Location of the Panhandle Paleovalley in the Ogallala Formation from Gustavson (1994).

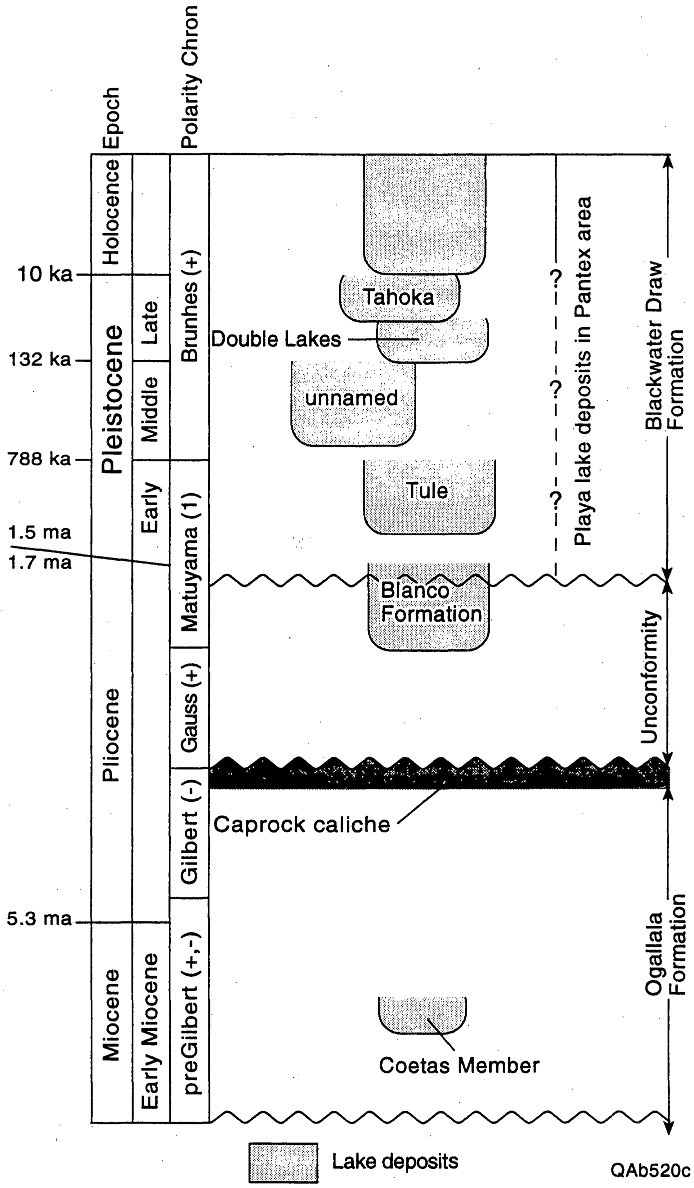

Figure 2. Quaternary stratigraphy of the Southern High Plains, simplified from Caran (1991), showing lake deposits documented in the literature.

episodes of slower deposition or erosion. The grain size of surficial deposits decreases toward the northeast, away from the presumed Pecos River source, supporting an eolian transport model (Seitlheko, 1975; Holliday, 1990). The study area in the northeast part of the Southern High Plains contains finer grained surficial sediments than do other parts of the Southern High Plains. The Blackwater Draw is relatively thick in the study area, averaging about 20 m, compared with 10 m in the type locality north of Lubbock (Holliday, 1989). This thickening may reflect either variation in the eolian depositional pattern or subsidence along the Panhandle Paleovalley regional salt dissolution trend (fig. 1).

The Ogallala aquifer, the High Plains' major ground-water supply, lies within the Ogallala Formation (Knowles and others, 1984). Recharge to the Ogallala aquifer from playa lakes has been documented by many studies, described in detail by Mullican and others (1994). Evidence that ponded water from playa lakes recharges the aquifer includes aquifer water-level responses to flooding (White and others, 1946), water-budget calculations (Havens, 1966; Reed, 1994), and chemical mass-balance and geochemical-tracer data (Wood and Osterkamp, 1987; Nativ, 1988; Mollhagen and others, 1993; Scanlon and others, 1994). Recharge from ponded water in playa lakes has been used to explain water level and water chemistry of a perched aquifer beneath the Pantex Plant, northeast of Amarillo (A. E. Fryar, personal communication, Bureau of Economic Geology, 1994; Mullican and others, 1994).

Purpose of Study

The geologic evolution of abundant, small, closed playa basins on the Southern High Plains is a subject of long-standing controversy (Gustavson and others, 1995). In addition, playa lakes play an important but poorly understood role in recharging the Ogallala aquifer. This report documents the stratigraphy beneath playa lakes and associated lake margin, playa basin, and upland settings. Genetic facies interpretation of the observed lithologies was undertaken to (1) better predict the nature of lateral, vertical, and interplaya stratigraphic variability and (2) extract information about the long-term geologic and paleoclimatic evolution of the area.

Cores of the sedimentary fills of seven playa basins near the Pantex Plant, northeast of Amarillo (fig. 3), were examined to identify (1) types of sediments beneath the floors of playa lakes, (2) relative permeabilities of these sediments, (3) geometries of playa lake clays and interbedded and interfingering facies, and (4) potential flow paths through the clays. This study focused on core data rather than exposures because (1) core recovery was excellent, whereas most exposures have been degraded; (2) cores penetrate to greater depths than most exposures; (3) playas cored are from the study area close to the Pantex Plant, and (4) core data can be integrated with hydrologic and geochemical test results. Playas outside the Pantex Plant were investigated in preference to those on the plant property because (1) basic data are needed about the typical heterogeneity of playa sediments, and borehole and trench data could be collected and analyzed faster and at lower cost in off-site areas where there was no history of contamination, and (2) baseline data taken from playas with minimal modification to the playa or to the recharge regime are needed, which could better be collected in off-site playas. During the next phase of study, cores from two playas historically used for ponding wastewater—playa 5 on the Texas Tech University farm adjacent to the Pantex Plant and Pantex Lake (separate from but under the management of the Pantex Plant) (fig. 3)—will be analyzed.

Playa basins were selected to examine a spectrum of geomorphologic characteristics (table 1) and flooding histories. Typical playa basins in the area, including those at the Pantex Plant, contain lakes that have areas of about 0.5 km^2 and typically have maximum basin-to-upland relief of about 11 m. The floor of the basin is occupied by a lake, and runoff is supplied from the surrounding upland by small centripetal drainages. A twin playa (two small lakes in one basin) was examined on the E. Vance property (fig. 3). The geometry of this playa provides information about the types of variation that might be expected in the double lakes at playa 4 at the Pantex Plant. Several playa basins having dimensions outside the range seen at the Pantex Plant were examined. The smallest lake examined, on the Bradshaw property (fig. 3), has no well-defined basin, and the lake is only 0.04 km^2 in area. The floor of the 13-km^2 largest

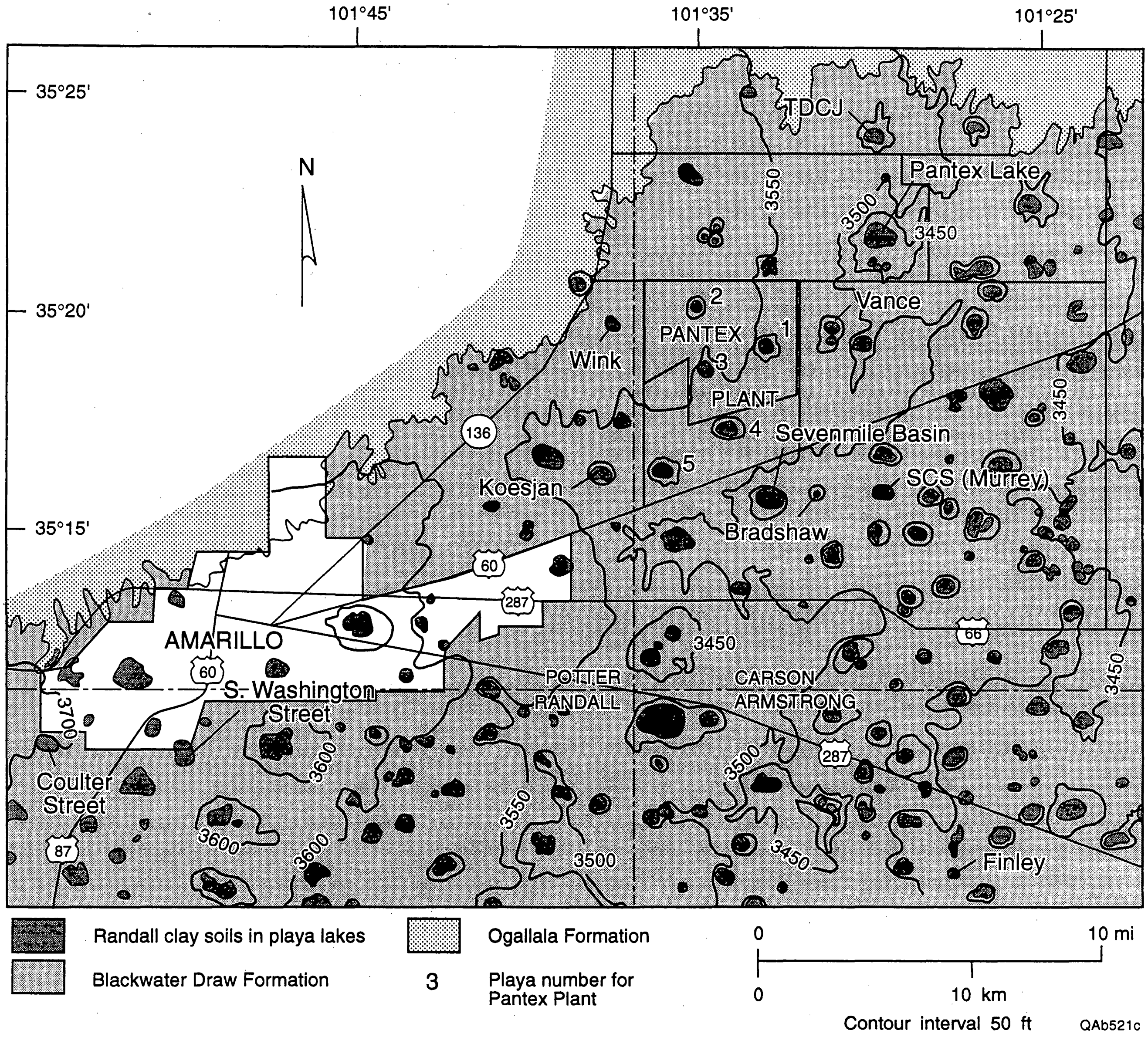

Figure 3. Location map of investigated playas and others mentioned in the text in the area of the Pantex Plant. Geology modified from Eifler (1969).

Table 1. Characteristics of playa basins examined during this study.

Playa name	**Playa size (km^2)**	**Drainage basin (km^2)**	**Depth of basin from upland (m)**	**Depth of basin to lowest closed contour (m)**	**Length of defined drainages (km)**	**Modification**
South Washington Street	0.39	4.5	6	2	0	Urban, highly modified
Coulter Street						
TDCJ (Texas Department of Criminal Justice)	0.53	11	11	3	4.9	Excavation, construction
Wink	0.29	8	11	8	4.6	Two tanks, two farms
Vance	0.45	5	11	2	10	Pipeline, small tanks
Sevenmile Basin	1.3	47	20	6	8.2	Ditches, farm to market road
Bradshaw	0.04	3	3	1	0	Minimal
Finley	0.19	4	5	2	0.9	Pipeline, two farms
Koesjan	0.43	7	12	6	2.3	

basin, Sevenmile Basin (fig. 3), contains several active playa lakes, the largest of which has an area of 1.3 km^2. This basin was selected to provide a comparison with Pantex Lake, which has received wastewater in the past.

Methods

Four methods have been used to examine the stratigraphy of sediments in playa lakes: (1) coring, (2) ground-penetrating radar transects (GPR), (3) trenching, and (4) analyzing exposures in large excavations. Basin sediments were examined by drilling hollow-stem auger cores in playas and corresponding interplaya areas in a variety of geomorphic settings near the Pantex Plant. During this phase of study, 53 cores totaling 1,059 m of section from 7 playa basins were collected by the Bureau of Economic Geology (table 2). Cores were drilled to auger refusal and are typically 20 to 30 m long. Playas examined (fig. 3) are (1) Sevenmile Basin, located south of U.S. 60 south of the Pantex Plant; (2) Wink playa basin west of the west gate of the Pantex Plant; (3) TDCJ playa (property leased from the city of Amarillo, Texas, by the Texas Department of Criminal Justice) north of Pantex Lake; (4) Koesjan playa west of Pantex playa 5; (5) Vance playa, east of the east gate of the Pantex Plant; and (6) Finley playa in Armstrong County.

The large Sevenmile Basin basin has a playa that did not flood during the study period. Wink, Koesjan, and TDCJ playas are average-size playa basins that have lakes that were flooded above the rim during the late summer of 1992, although lake levels dropped during the winter of 1993 and permitted coring of playa sediments. Vance playa is in a composite of two basins, and Finley playa is in a shallow basin; both have been mostly dry during the 1992–1994 study period.

Hollow-stem auger cores 10 cm in diameter were labeled, sampled at regular intervals for water-content, grain-size, and chloride analysis, and sealed in plastic lay-flat tubing in the field. Recovery was excellent, the only significant core loss occurring in intervals of unconsolidated loose sand and in unusually well cemented soil-carbonate horizons. Core was returned to the

Table 2. Hollow-stem auger cores collected for playa studies.

Playa and borehole number	Total depth (ft)	Facies
Finley 1	13.9	upland
Finley 1 b		upland
Finley 2	39.9	annulus
Finley 3	46.5	playa
Finley 3 b	17.5	playa
Sevenmile Basin 1	74.5	basin floor
Sevenmile Basin 2	88.7	playa
Sevenmile Basin 3	72.1	playa
Sevenmile Basin 4	33.9	annulus
Sevenmile Basin 5	34.6	playa
Sevenmile Basin 6	35.1	playa
Sevenmile Basin 7	62.6	upland
Sevenmile Basin 8	70.1	slope
Sevenmile Basin 9	55.3	slope
E. Vance 1	24.2	slope
E. Vance 2	83.6	playa
E. Vance 3	94.7	playa
E. Vance 4	58.2	annulus
E. Vance 5	49.6	between lakes
E. Vance 6	39.9	slope
E. Vance 9	24.5	annulus
E. Vance 10	50.4	upland
T. Bradshaw 2	71.7	slope
T. Bradshaw 3	72.2	playa
TDCJ 1	14.2	upland
TDCJ 2	29.7	annulus
TDCJ 3	80	annulus
TDCJ 4	86	annulus
TDCJ 5	60.9	slope
TDCJ 6	75	upland
TDCJ 7	73.3	slope
TDCJ 8	100.7	annulus
TDCJ 9	98	drainage
TDCJ 10	76.6	
TDCJ 12	87.7	playa
TDCJ 13	86.9	annulus
TDCJ 15	82.5	upland
TDCJ 16	30.8	playa
TDCJ 21	65.1	playa
TDCJ 28	70.2	playa center
TDCJ 35	84.8	annulus
TDCJ 36	96.4	delta
TDCJ T1-04	44.4	playa
Koesjan 4	103.3	annulus
Koesjan 02	43.8	slope
Wink 1	86.2	upland
Wink 3	56.8	slope/drainage
Wink 5	105.1	annulus
Wink 6	99.4	annulus
Wink 7	110.8	playa
Wink 8	115.9	playa
Wink 11	100.3	playa
Wink 12	95.5	playa

laboratory for detailed examination and description and then archived at the Core Research Center, Bureau of Economic Geology, The University of Texas at Austin. Detailed core descriptions are archived. The stratigraphic studies described in this report complement geochemical and hydrologic studies. Where possible, boreholes were located to provide stratigraphic information for geochemical and hydrologic studies.

A GPR survey was conducted to investigate the feasibility of this technique for noninvasively describing the shallow subsurface of playa basins. This study was sited at TDCJ playa basin (fig. 3). The GPR transect, 790 m long, extended from the upland in the southeast corner of the property, down the slope of the playa lake basin, to the east shore of the playa lake (fig. 4). The survey was conducted on October 16, 1991, by Envirometrics, Inc., of Houston, Texas, using a GSSI SIR System-10 (Envirometrics, 1991). Both 300- and 120-MHz antennas were used to investigate the best combination of resolution and depth penetration. Because GPR responds to contrasts in the permittivity (dielectric constant) and electrical conductivity of the upper few meters of sediment, it can image water-content variation or contrasts in soil mineralogy and texture (Annan and Cosway, 1992). Envirometrics (1991) estimated that whereas the 300-MHz antenna penetrates about 2 m, the 120-MHz antenna penetrates about 4 m.

Seven shallow trenches and pits into playa sediments were examined during this phase of the study. Two large benched trenches were excavated near the GPR line in TDCJ playa to evaluate the geologic significance of the images. One trench was excavated May 11, 1993, on the gentle slope of the playa lake basin (fig. 4). It was 14 m long, 3.6 m wide, and 2.5 m deep and lay a few meters west of TDCJ Borehole No. 5. Ponding tests 1 and 2 (Xiang and others, 1993) were conducted at the playa basin slope trench. The second trench was sited across the annulus or diffuse shoreline on the east side of the lake a short distance north of the GPR survey line. This trench, excavated June 2, 1993, was 24 m long, 2 m wide, and a maximum of 1.9 m deep. The playa had flooded during the previous summer but had drained and dried up during the late winter. At the time the trench was excavated, although summer rains had

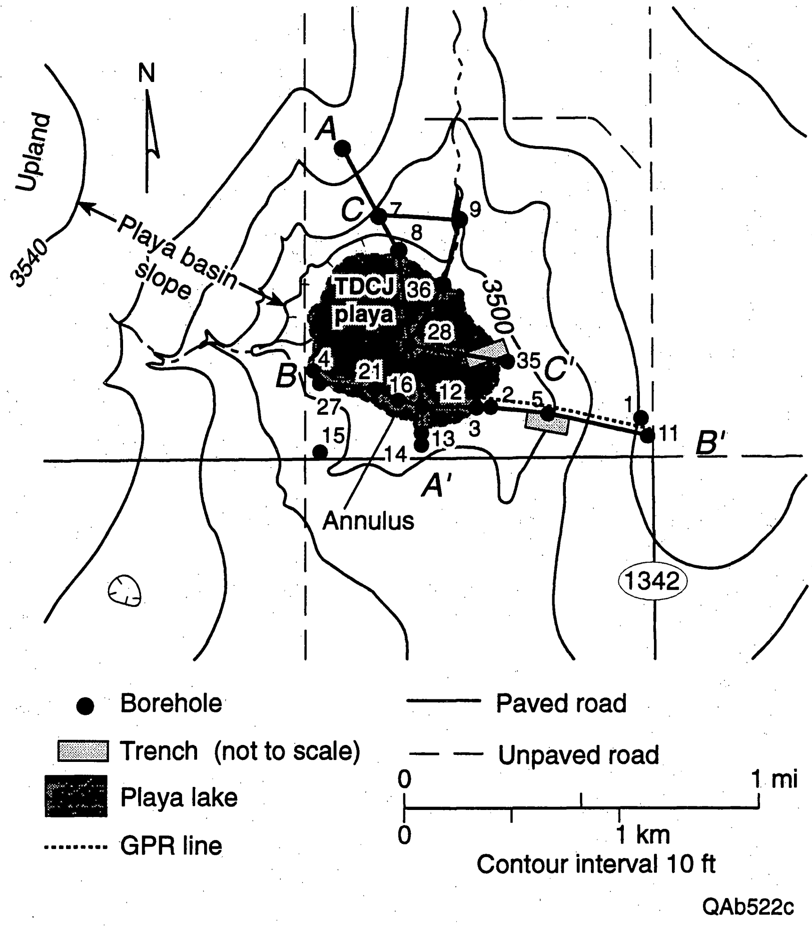

Figure 4. Detailed location map of TDCJ playa, along with the GPR survey line, trenches, and boreholes. Topography from Pomroy and Abel USGS 1:20,000 quadrangles. Cross section A–A′ shown in figure 27, B–B′ in figure 28, and C–C′ in figure 29.

started, only the center of the playa ponded water. The east end of the trench was placed at the 1992 high-water mark, and the trench extended across a zone of rapid vegetative change into the nearly flat floor of the playa. Ponding tests 3 and 4 (Xiang and others, 1993) were conducted at this trench. In addition, four pits excavated in TDCJ playa basin as part of the unsaturated-zone hydrologic studies were examined. Two pits were excavated close together in the upland, and two pits were excavated within the playa lake during December 1994 at distances of about 100 and 200 m from the east shore of the playa. A trench excavated by the Soil Conservation Service (SCS) into the center of a historically dry playa (Murrey playa, fig. 3) was examined in November 1994.

Playa sediments exposed in two excavations dug for drainage and floodwater control in Amarillo were examined during this phase of study: South Washington Street playa (Willow Lake) and Coulter Street playa (fig. 3). Photomosaics of the excavation walls were prepared from a series of photographs taken of South Washington Street playa by T. C. Gustavson, Bureau of Economic Geology, during 1984 when the excavation was new. Growth of vegetation and additional modifications of the excavation have obscured some of the relationships apparent on the photographs; however, most units could be identified in the field. Coulter Street playa is exposed in a new excavation that was photographed and examined in the field.

GEOMORPHIC SUBDIVISIONS OF PLAYA BASINS

Geomorphic components identified in the playa basins examined during this study include upland, playa basin slope, annulus, and playa lake (figs. 4 and 5). Upland areas that form the drainage divides between basins have little topographic relief and conform to the gentle southeastward slope of the Southern High Plains. The upland surfaces are characterized by Pullman or Estacado soils (Paleustoll) (fig. 6). Distinct lee dunes (Gustavson and others, 1995), throughgoing drainages, and large saline lakes, although significant features in other parts of the Southern High Plains, are not developed in the study area.

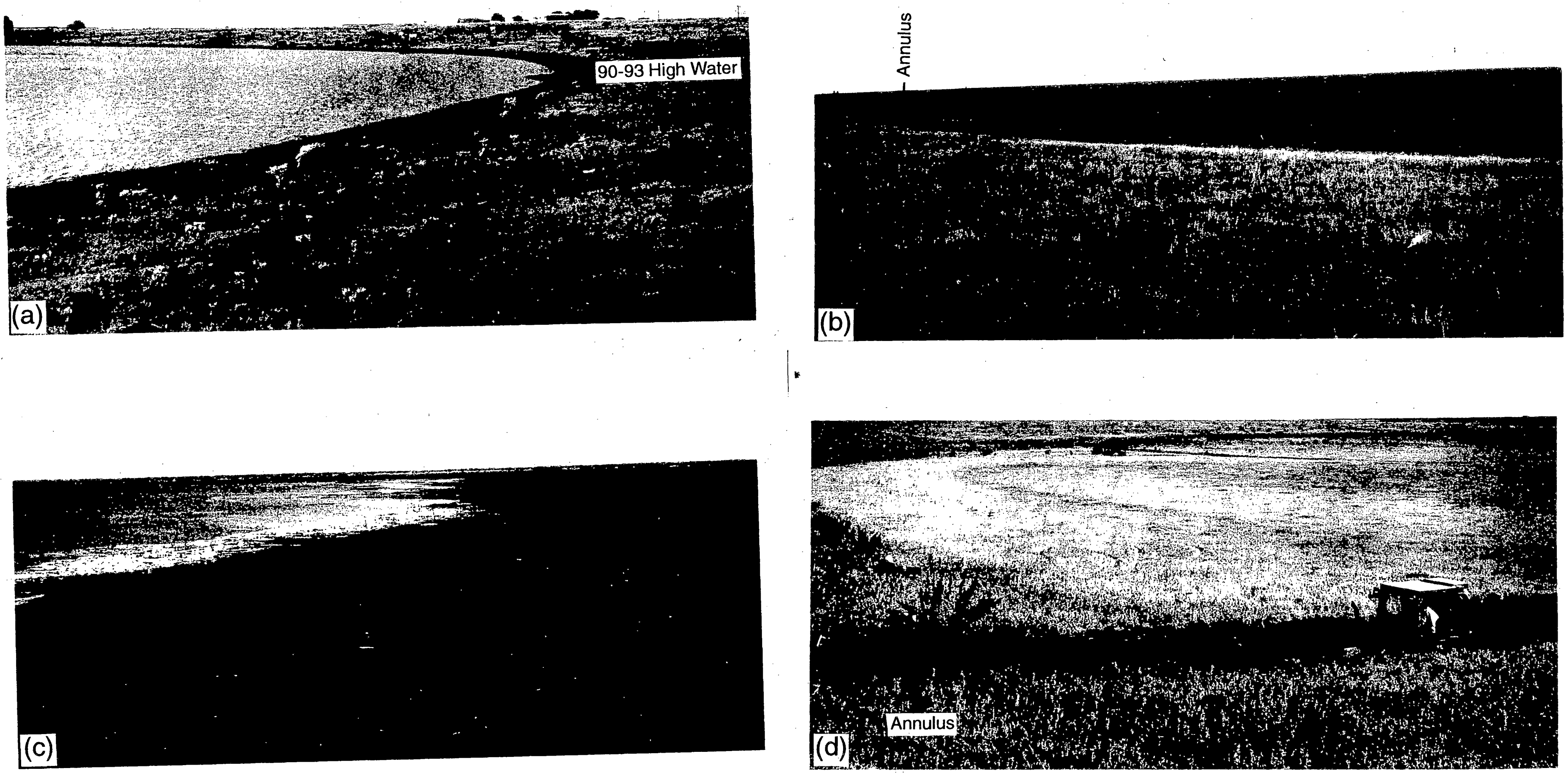

Figure 5. Photos of typical appearance of playa basins. (a) Wink playa lake, near maximum observed high-water level, August 1992. View toward south from near borehole 5, on the northwest corner of the lake. (b) North shoreline of Vance playa lake, which was not flooded during the investigation and has dense sedge and other grasses on the playa floor, February 1993. (c) Floor of TDCJ playa as it dried out after a long period of flooding, which killed vegetation, February 1993. (d) Eastern annulus of TDCJ playa during excavation of trench 2, June 1993. During the 4 months between photographs c and d, sedge, smartweed, and other plants have colonized the playa floor. By June, water again started ponding in the center of the lake as a result of summer rainfall but did not become deep or permanent enough to kill vegetation.

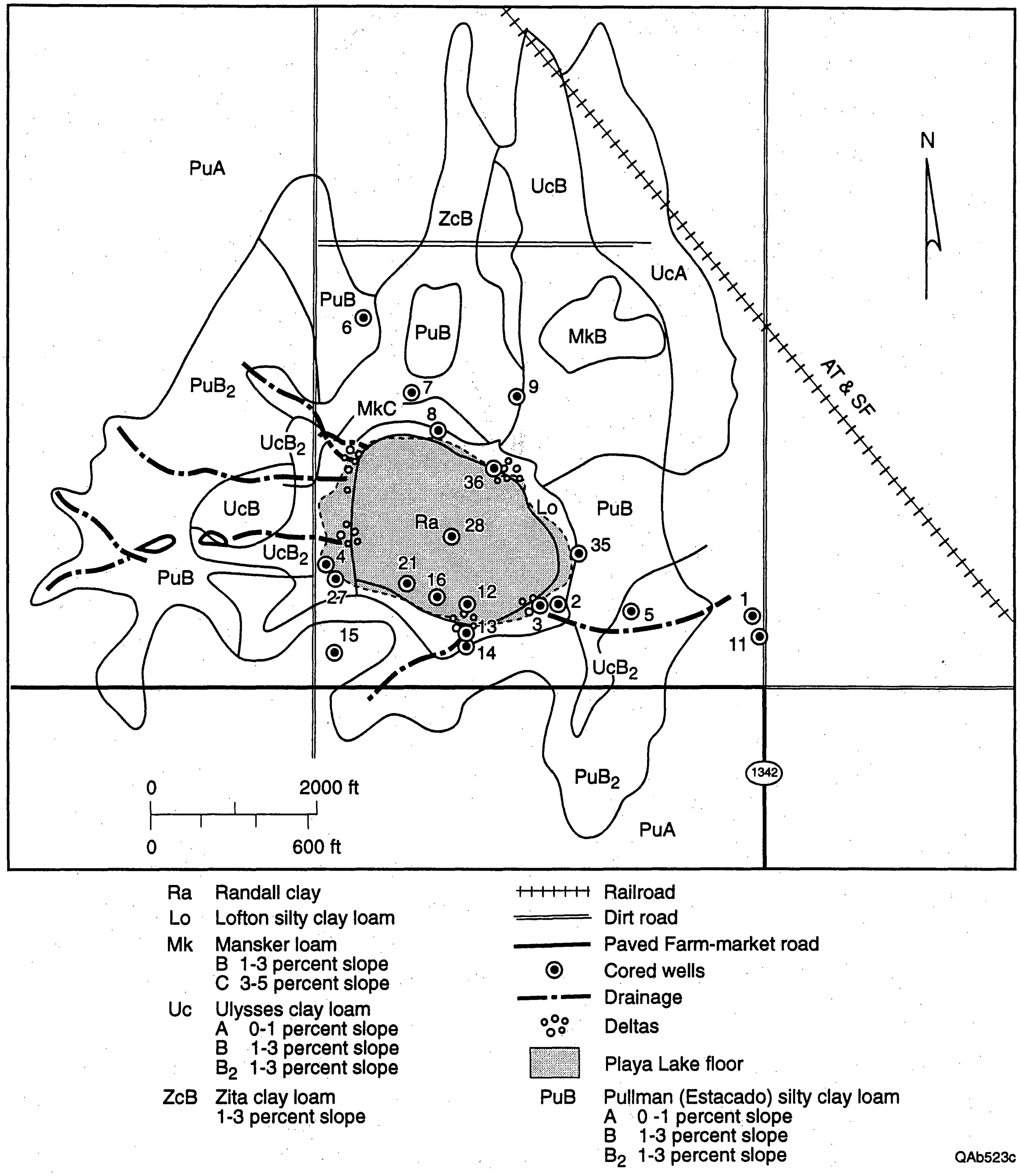

Figure 6. Soil map of TDCJ playa. Adapted from Jacquot (1959).

Playa basin slopes are characterized by a variety of soils, including Pullman, Zita, and Ulysses clay loams and Mansker loam (Jacquot, 1959; Jacquot and others, 1961). Small drainages, incised into the playa basin slope, drain centripetally into the playa. Drainages typically 0.5 m deep and as much as 2 m wide may pond water locally and have floors of either sand and chips of caliche or mud. The geometry and depth of modern drainages appear to have been modified by use as animal paths. Slopes of playa basins are generally steep on the northwest side of the playa lake and gentler on the south and east sides of the lake.

Large playa basins, including Sevenmile Basin and Pantex Lake in the study area, have different relationships between basin and lake than do average-size basins. Sevenmile Basin has a well-defined basin slope between the low-relief upland and the low-relief basin floor on three sides, the south side having a more gradual slope. The major playa lake occupies only the northwest corner of the basin floor. Another small playa is found in the northeast part of the basin floor. A detailed topographic survey across the south slope of the playa basin shows a bench 2 m above the basin floor (J. G. Paine, Bureau of Economic Geology, personal communication, 1995).

The annulus of most playas is marked by a break in slope that defines the normal high-water mark of the playa lake (fig. 5a, 5b, and 5d). In some playas, particularly Pantex Lake (fig. 3), the edge of the playa is marked by a wave-cut bench (fig. 7a). Pantex Lake ponded water during the period that it served as a discharge point for treated sewage, and this prolonged high water level may have allowed a wave-cut bench to develop more clearly than more intermittently flooded playas. Small erosional scarps occur on the northwest slope of TDCJ playa above the shoreline. Some of the sparse, coarse-grained material in the playa, including logs, bones, and caliche pebbles, are sometimes preferentially concentrated on the surface of the lake sediments along the northwest shore. The annulus is much less well defined on the south and east lake margins (fig. 5d). Zoning of hydrophilic vegetation, such as sedge and wheatgrass, and rapidly growing annuals, such as aster, through this area emphasizes the subtle changes in slope that mark the break between the nearly flat playa lake bed and the

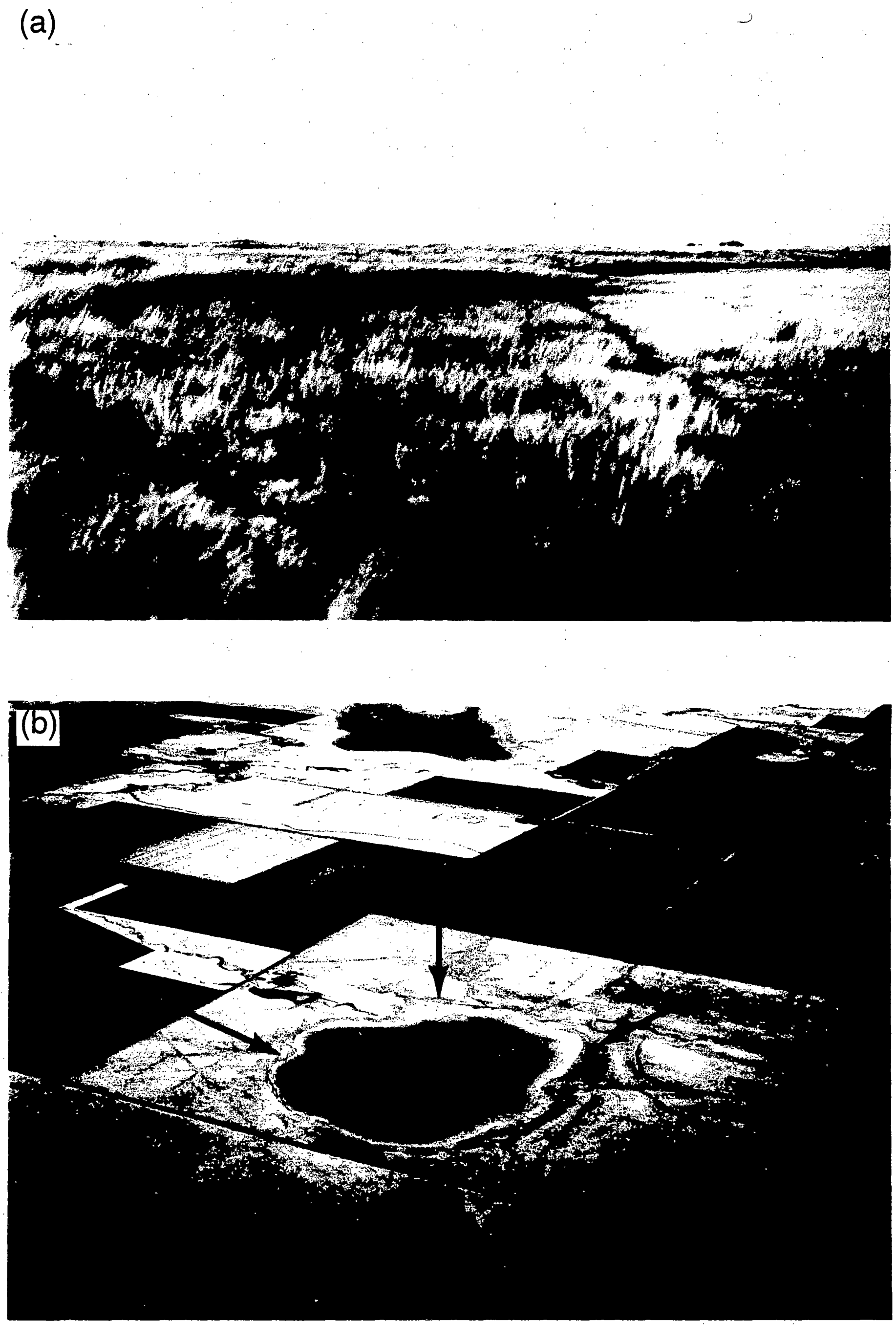

Figure 7. Photos of playa shoreline features. (a) Wave-cut bench on the north shore of Pantex Lake. (b) Deltas (arrows) have accumulated where drainages divulge onto the playa floor. The delta on the right has a valley fill and a progradational bulge, whereas the two on the left have a dominantly progradational morphology. Unnamed playa in Armstrong County.

gentle grassy slope of the basin. Vegetative zonation was used to define geomorphic subdivisions of the playa. The shoreline of many of the study playas has been disturbed by construction of stock tanks and earthen dams near one or more of the drainages discharging into the playa.

Low-relief deltas can be identified where drainages discharge onto the playa floor. Sediment supplied down the drainages has accumulated as wedges of fine-grained sediment (fig. 7b). Deltas appear both to infill small incised areas along drainages and to prograde as low-relief bulges of sediment out into the playa floor. Channels that extend drainages can be identified in the upper parts of some deltas. The lower parts of deltas are flooded at high-water level, but a topographically or vegetatively defined annulus is uncommon on the delta.

The nearly flat floors of playa lakes (fig. 5c) are characterized by dark Randall clay soils. A very gradual slope from the margins toward the center of the playa is evident in the vegetative zonation and wetness of the sediment. Microtopography, areas of water input from irrigation or other sources, and human modification influence the wetness and vegetative patterns visible on the playa floor.

SEDIMENTS WITHIN PLAYA BASINS

On the basis of examination of cores from seven playas and pits in three playas, a facies classification of playa basin and related sediments has been developed (fig. 8). Facies include (1) upland and basin slope accretionary eolian facies (clayey silt that has buried soil horizons typical of the type section Blackwater Draw Formation), (2) gray and red lacustrine clays, (3) lacustrine–eolian sand beds, (4) clays interbedded or admixed with sand laminae, (5) poorly sorted lacustrine delta deposits and (6) lower fine to medium sand.

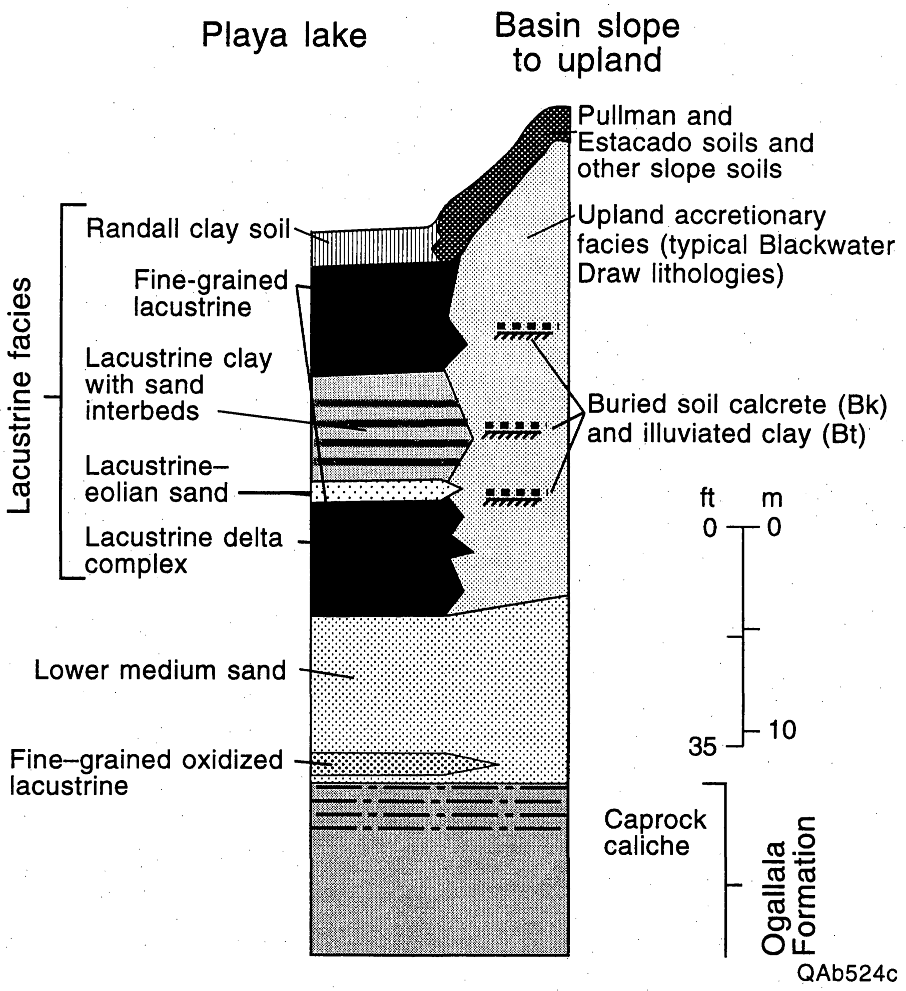

Figure 8. Generalized playa stratigraphic section showing major facies. Vertical scale is generalized.

Upland and Basin Slope Accretionary Eolian Facies

Upland and slope soils in the study area are classified as Pullman silty clay loam (Jacquot, 1959; Jacquot and others, 1961). Revised classification of the soils in the area has described them as the slightly more carbonate rich Estacado soil series (Fred Pringle, Soil Conservation Service, personal communication, 1994). Soils have 20-cm-thick A horizons characterized by abundant grass roots, 80-cm-thick red-brown (7.5YR 4/2) B horizons that have well-developed blocky peds, and at a depth of about 1 m, a well-developed stage III soil-carbonate horizon (pedogenic carbonate classification of Machette, 1985).

The typical upland facies of the Blackwater Draw Formation is characterized by red-brown (5YR 5/6) clayey silt having textures and soil structures very similar to those of the surface soils. Sediments have abundant root casts, well-developed soil peds, local distinct soil horizons (soil-carbonate and illuviated clay concentrations), and abundant pedogenic carbonate nodules (figs. 9a and 9b). Root casts are tubules that have elongate open pores 0.1 to 1 mm in diameter having smooth clay-coated walls (fig. 9b). They appear to form networks in three dimensions. Peds, the fundamental structural unit of soils, are present throughout the accretionary eolian facies, and they typically produce blocks 1 to 5 cm across (fig. 9b). Iron oxide, manganese, clay, and calcite mineralization are common on root tubules and ped surfaces. Soil carbonate forms discrete rounded masses, vertical accumulations that are probably rhyzoliths, and disseminated carbonate cement. Complex crosscutting relationships within soil carbonates document multiple episodes of calcite precipitation followed by dissolution (fig. 9c).

Horizontal bedding defined by variation in types and intensity of soil textures, particularly amount and distribution of soil carbonate, can be observed (fig. 9a). Concentration of carbonate to form Bk soil horizons is noted throughout the Blackwater Draw Formation. Vertical variation in clay content also appears to reflect soil processes, slightly higher clay content and deeper red colors observed above Bk horizons marking incipient Bt horizons. Intervals of silty clay loam have no horizonation, although abundant soil features such as peds, root tubules, and soil

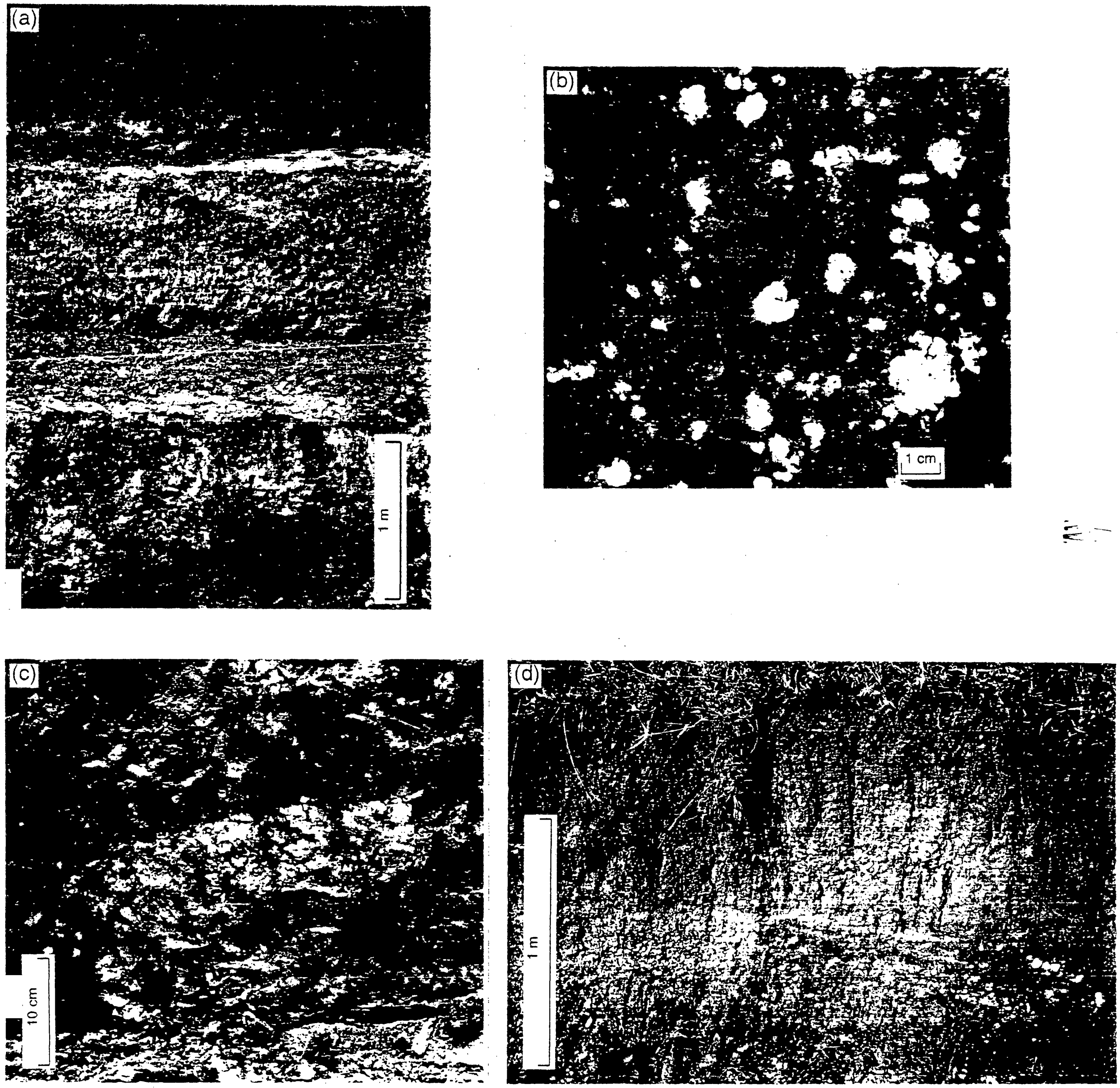

Figure 9. Photos of features typical of upland and basin slope eolian accretionary facies (Blackwater Draw silty clay loam). (a) Trench through typical slope eolian accretionary facies, TDCJ trench 1 (see location map, figure 4). (b) Detail of discrete nodules (type II soil carbonate) in accretionary facies, depth 1.5 m in TDCJ trench 1. (c) Lower type III Bk horizon at 2.5 m depth in TDCJ trench 1 has been locally corroded along roots, R, and in larger krotovina, K (prairie dog burrows). (d) Crossbedded channel deposit exposed along drainage in northwest corner of Pantex Lake.

carbonate alternate with well-formed soil horizons composed of a Bk with or without an overlying Bt (fig. 10). Few A horizons or sharp contacts are preserved, indicating that each soil has been welded onto older soil profiles.

Lenses of caliche pebble conglomerate and crossbedded red-brown muddy sand or silt (fig. 9d), moderately abundant within the upland and slope accretionary eolian facies, are interpreted as deposits that formed on the floor of small centripetal drainages. Lenses, typically a few decimeters thick, have overprinted soil textures that partly obscure the sedimentary structures.

GPR Character

The GPR survey illustrates that in the upland setting, the 120-MHz transect shows strong horizonation (fig. 11). The sharp break in character of the GPR image may correspond to the top of the uppermost buried carbonate horizon (40 percent carbonate) found at about 1 m depth in TDCJ Borehole No. 1 (fig. 10). Alternatively the break may correspond to a decrease in gravimetric water content from 0.11 to 0.08 g H_2O/gram soil at about the same depth (B. R. Scanlon, Bureau of Economic Geology, written communication, 1994). Layering in the lower part of the GPR image appears to correspond to zones of carbonate accumulation within buried soils of the Blackwater Draw Formation.

Sediments on the slope of the playa basin show similar strong horizonation (fig. 12). Changes in character and processing of the GPR images between sections of the survey make lateral tracing of soil horizons uncertain so that relationships between upland and slope soils are indeterminate. One section on the slope (line 1-E, 120-MHz antenna) imaged a feature resembling 5° dipping beds between markers 54 and 60 (fig. 12). This area is 270 m east of and about 3.5 m above the high-water level in the playa.

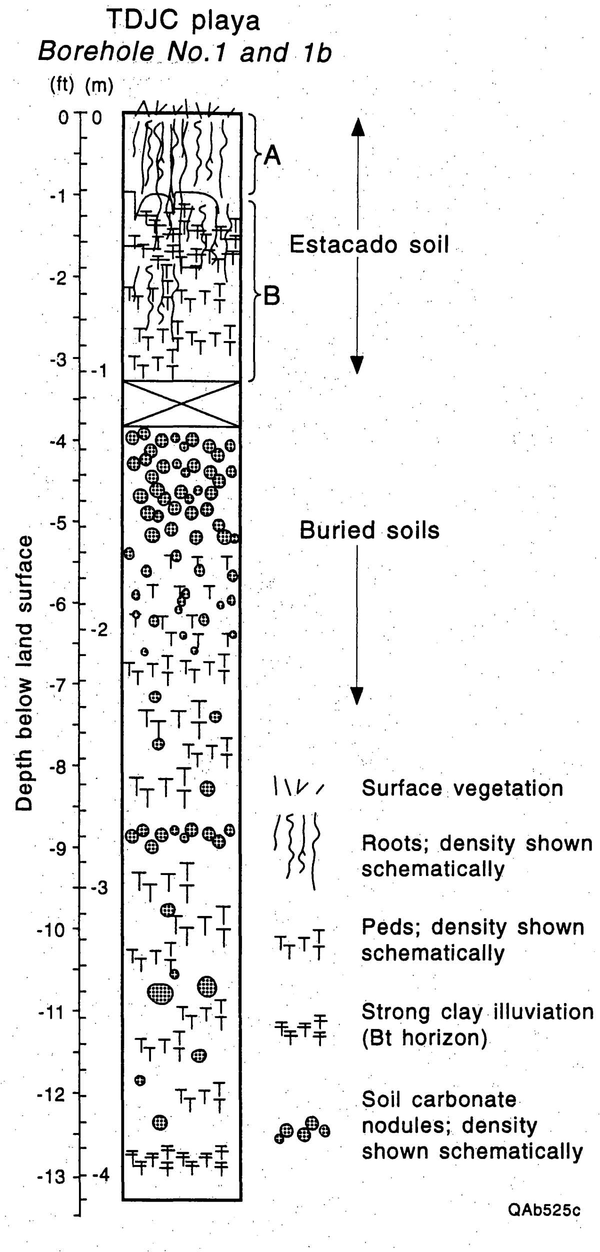

Figure 10. Lithologic log of hollow-stem auger core from TDCJ playa and Boreholes No. 1 and offset No. 1B.

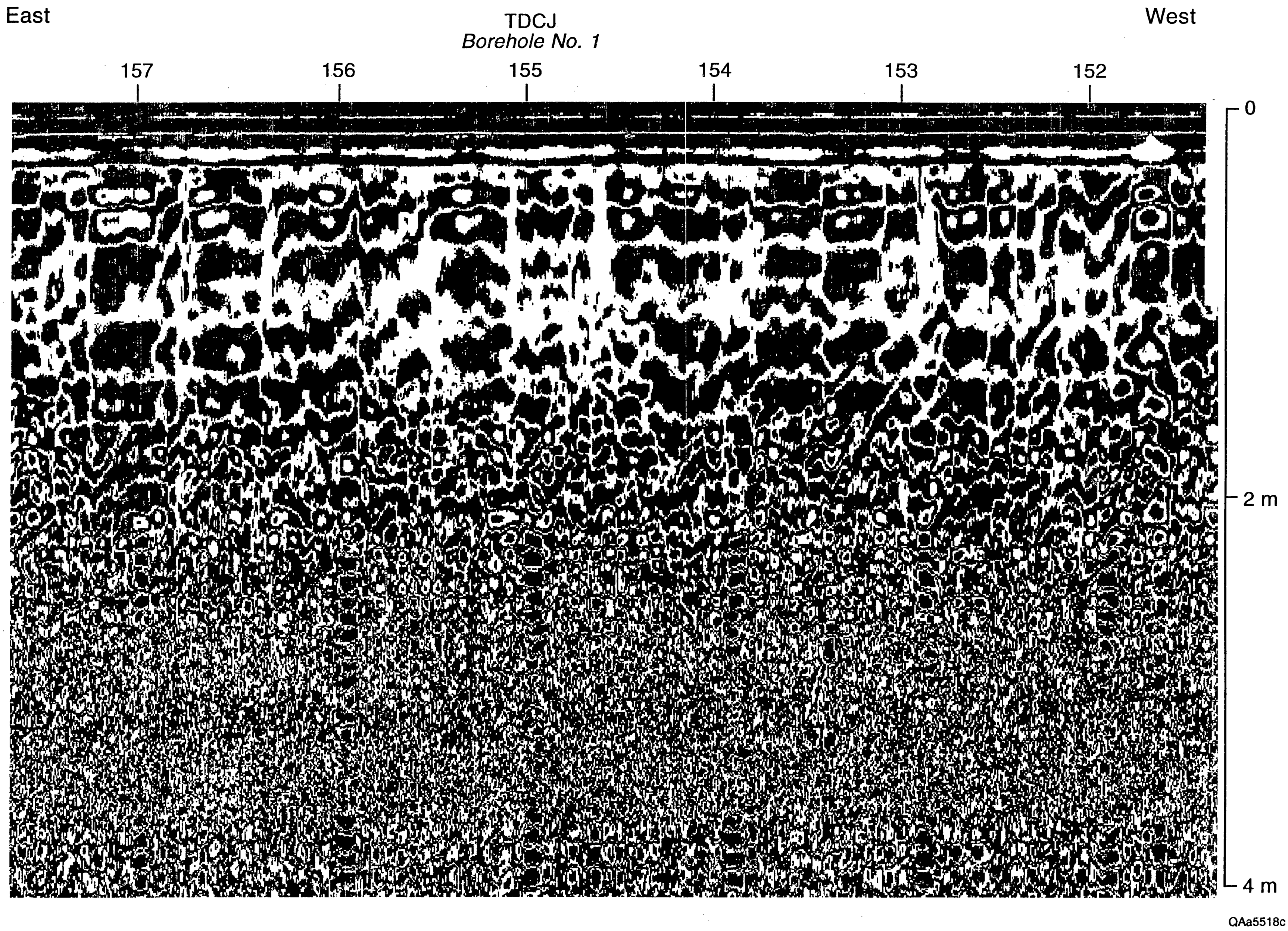

Figure 11. Segment of the GPR survey, in the upland east of TDCJ playa, 120 MHz, (segment A), depth approximately 4 m. Survey station numbers spaced at 5-m intervals provide horizontal scale. Location of survey shown in figure 4. Reproduced from Envirometrics (1991).

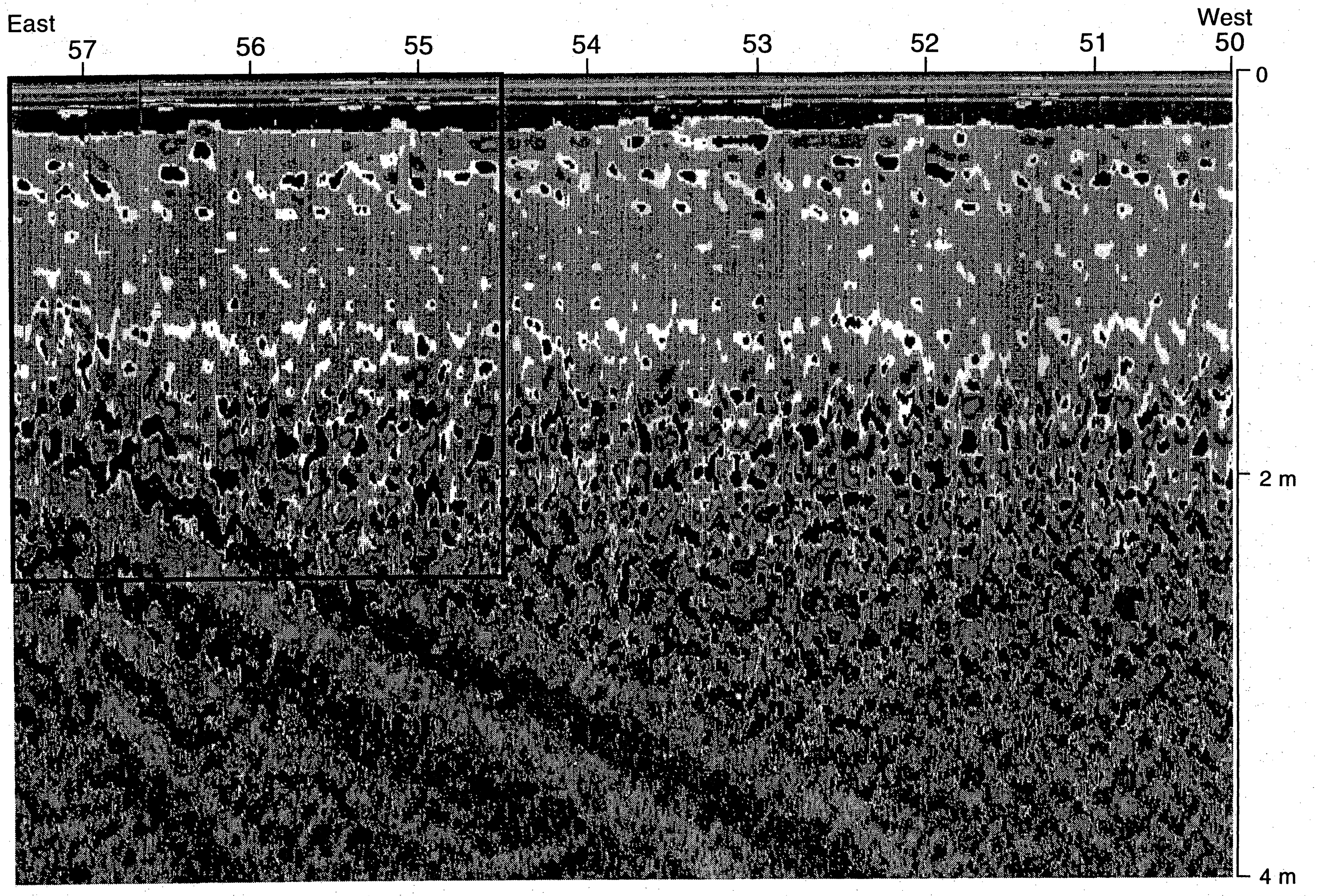

Figure 12. Segment of the GPR survey, on the east slope of TDCJ playa basin, 120 MHz, (segment E), depth approximately 4 m. Survey station numbers spaced at 5-m intervals provide horizontal scale. Note that vertical exaggeration of the image makes dipping features appear steeper. Box shows approximate area trenched. Location of survey shown in figure 4. Reproduced from Envirometrics (1991).

Trench Description

A trench was excavated in the area of the dipping feature in the GPR survey in an attempt to identify the geologic significance of the images. Red-brown silty clay and clayey silt of the basin slope facies of the Blackwater Draw Formation are exposed in the trench. Major stratigraphic units observed, in descending order, were (1) the modern Estacado soil profile that has a soil carbonate at the base, (2) a zone having evenly distributed soil-carbonate nodules that have incised tops and local weakly bedded channel deposits, and (3) a lower interval having two horizons of well-developed but discontinuous soil carbonate (fig. 13). Some of the irregularity in the distribution of soil carbonate is related to a complex of infilled prairie dog burrows. Local dissolution and reprecipitation of carbonate may also have occurred. The sharp break in the GPR image may correspond to the top of the uppermost soil carbonate. Soil moisture content decreased sharply below this horizon. The small channel seen in the trench is not evident on the GPR. No features corresponding to the 5° dipping structures imaged by the GPR survey were identified in the lower part of the trench. Other vertical anomalies on the GPR images were not trenched.

Genetic Facies Interpretation

Soils that developed on upland areas and basin slopes provide modern analogs to Quaternary eolian accretionary deposits. Modern Pullman and Estacado soils were developed in a grassland setting on upland and moderate slopes in a semiarid climate. The modern soil is assigned a minimum age of 30,000 yr on the basis of a radiocarbon date from beneath a lunette near Lubbock and the degree of carbonate accumulation (Holliday, 1989).

On the basis of grain-size distribution, regional trends in grain size, soil character, and thermoluminescence and radiocarbon dating, the Blackwater Draw Formation is interpreted as a deposit formed by accumulation of eolian dust in a grassland setting during the Pleistocene (Holliday, 1989). Alternating periods of aggradation and soil formation have been documented

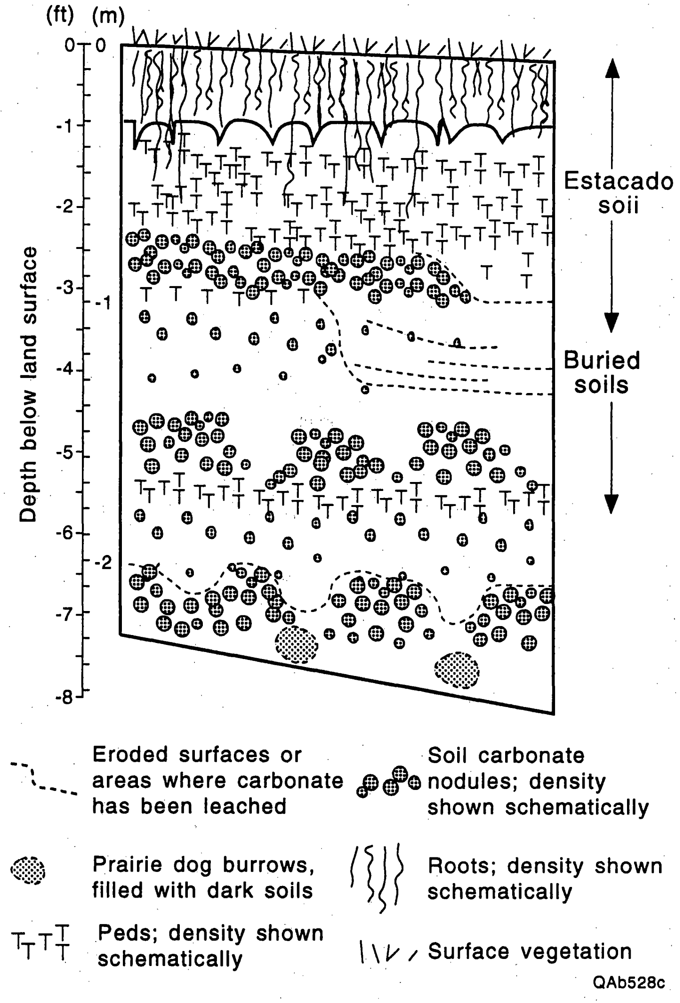

Figure 13. Segment of the trench in the slope setting on the east side of TDCJ playa basin, showing typical stratigraphy near station 56.

in the Blackwater Draw Formation at other locations across the Southern High Plains (Holliday, 1989). At the type section of the Blackwater Draw Formation north of Lubbock, four buried soils having well-developed Bk horizons alternate with silty clay loam that has less pedogenic carbonate. Holliday (1989) interpreted the silty clay loam as the product of episodes of eolian deposition; the soils having well-developed Bk horizons are evidence of episodes of landscape stability, and the absence of preserved A horizons and lateral variability in the thickness and number of soils are evidence of episodes of deflation.

Lacustrine Clays

Youngest Clays

The surface sediments of playa lakes have Randall clay soils developed on them. Randall clay soils are Vertisols developed in silty clay sediments, dark gray in color (10YR 3/1). Randall clay soils are fairly homogeneous vertically, having minimal compositional, textural, and color zonation to a depth of about 1 m. Clays, plastic when wet, shrink as they dry, forming cracks that are open to depths of about 1 m. Open cracks are commonly coated by white fungal growths. Woody roots of plants such as smartweed extend to depths of more than 1 m, and decayed roots are common. Carbonate is absent to sparse in Randall clay soils. In a few locations, especially near the margins of playas and the SCS trench in the middle of unusually dry Murrey playa, sparse nodules, granules, and pebbles of caliche are found in the upper meter of playa lake sediment. Some of this carbonate appears to be grains of carbonate that formed in upland soil profiles and were eroded and transported into the playa. Pebbles of soil carbonate have been observed on the sediment surface in high-energy parts of playa floors. For example, pebbles were collected along a fence line that crosses the delta on the northwest shoreline of Wink playa.

Texture and color of the upper few centimeters of Randall clay soils commonly have been affected by surficial processes. These include acquisition of darker colors, suggesting more abundant organic material, or a more brownish color, suggesting partial oxidation of organic material. The water content of this upper interval changes frequently. Clay becomes plastic when wet (fig. 14a), and broken chips of clay are produced when the interval has been dry for many months (fig. 14c). Formation of fine grains, possibly fecal pellets, from wet mud aggregates, has been observed in shallow, ponded settings on the playa floor (fig. 14b). A layer of silt a few millimeters thick has been observed accumulating on the dry surface of the playa during the late winter (fig. 14c). Silty layers are commonly not preserved in the near-surface playa sediments, either because they are deflated as the sediments dry or because they are mixed into the sediment by plant, animal, or soil processes.

At depths of about 1 m below the surface of playas in the study area, changes in texture and color of the sediment can be observed. In the center of most playas, the modern Randall clay soil profile has developed on top of older, nearly identical soil profiles. At depths of 1 to 1.4 m, the base of the youngest soil profile is marked by decreasing abundance of modern roots, slightly increasing stiffness of the clay, larger and better developed slickensided vertic soil structures, and slightly lighter gray colors.

Toward the margins of playas, the gradational change found at about 1 m below the surface is between youngest dark, silty Randall clay and underlying redder (7.5YR 4/4) and commonly slightly siltier sediments (figs. 15a and 16). The top of the gradational change is marked by blebs of red sediments within dark, silty clay. The amount of red material increases downward until, at depths of about 2 m below the surface, the red material appears to be the host that has been discolored by dark stains along a network of fractures (figs. 15a and 16). The red sediments contain variable amounts of carbonate.

Older, Gray Clays

Gray clay (2.5YR 9/2 to 10YR 3/2) is massive or mottled silty clay, fairly plastic near the surface, that becomes stiffer at depth. Textures generally resemble those of the youngest clays that have Randall clay soils developed on them (fig. 16) but that are more variable, reflecting a

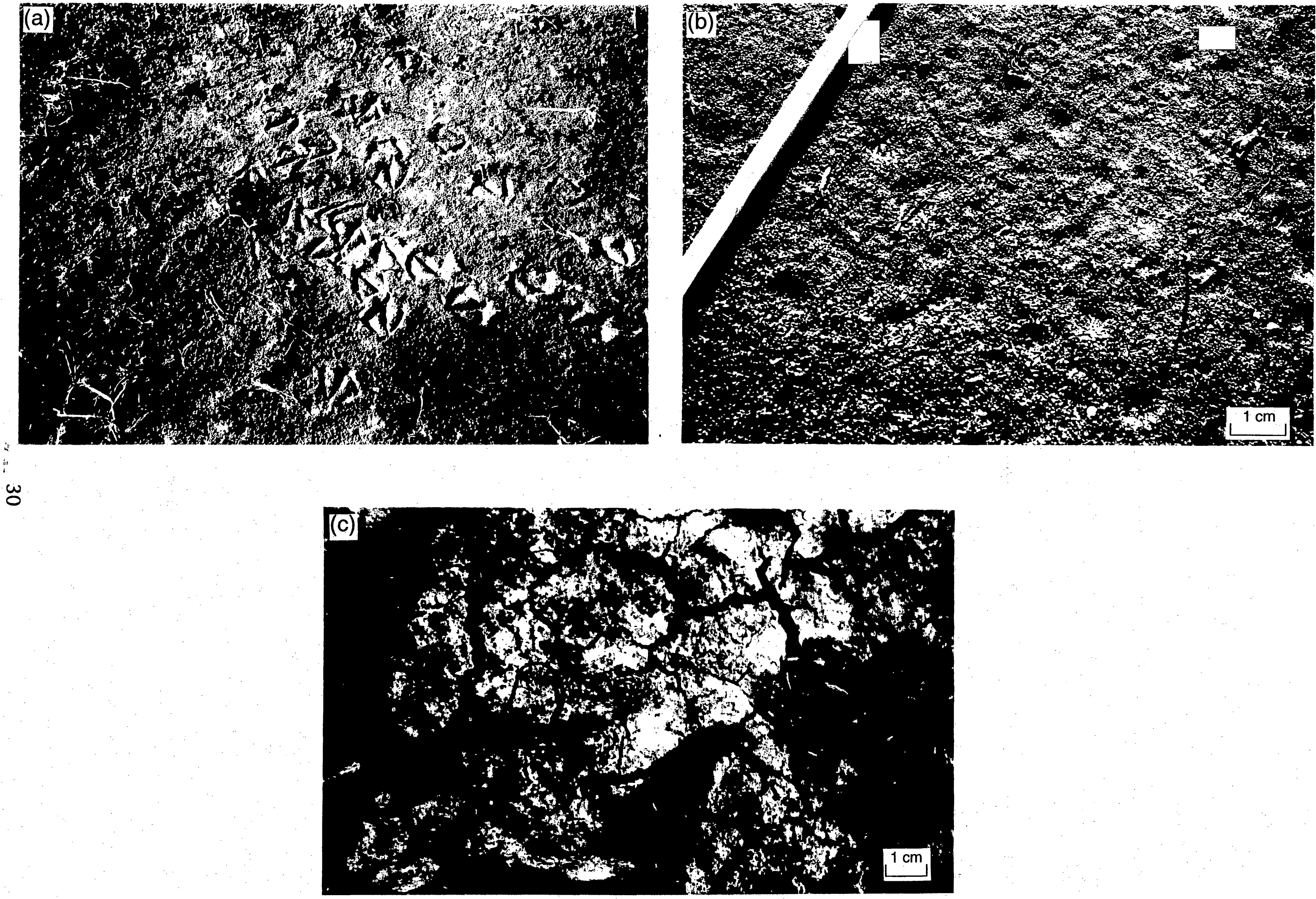

Figure 14. Photos of representative sedimentary structures in surface lake clay. (a) Soft, plastic mud on the lake floor a few days after withdrawal of the lake from this part of the lake floor. February 1993, TDCJ playa. Vegetation has been killed or become dormant because of prolonged ponding, but roots remain. Small desiccation cracks are visible in the sediment as well as bird tracks and invertebrate burrows. (b) Pelleted clay sediment on the dry surface of the playa in an area that has been dry for a longer period. Pelleting by invertebrate activity or fragmentation by freeze–thaw may break the sediment surface. (c) Desiccated clay surface of TDCJ playa after several months of drying (end of May 1993) has accumulated a layer of silt.

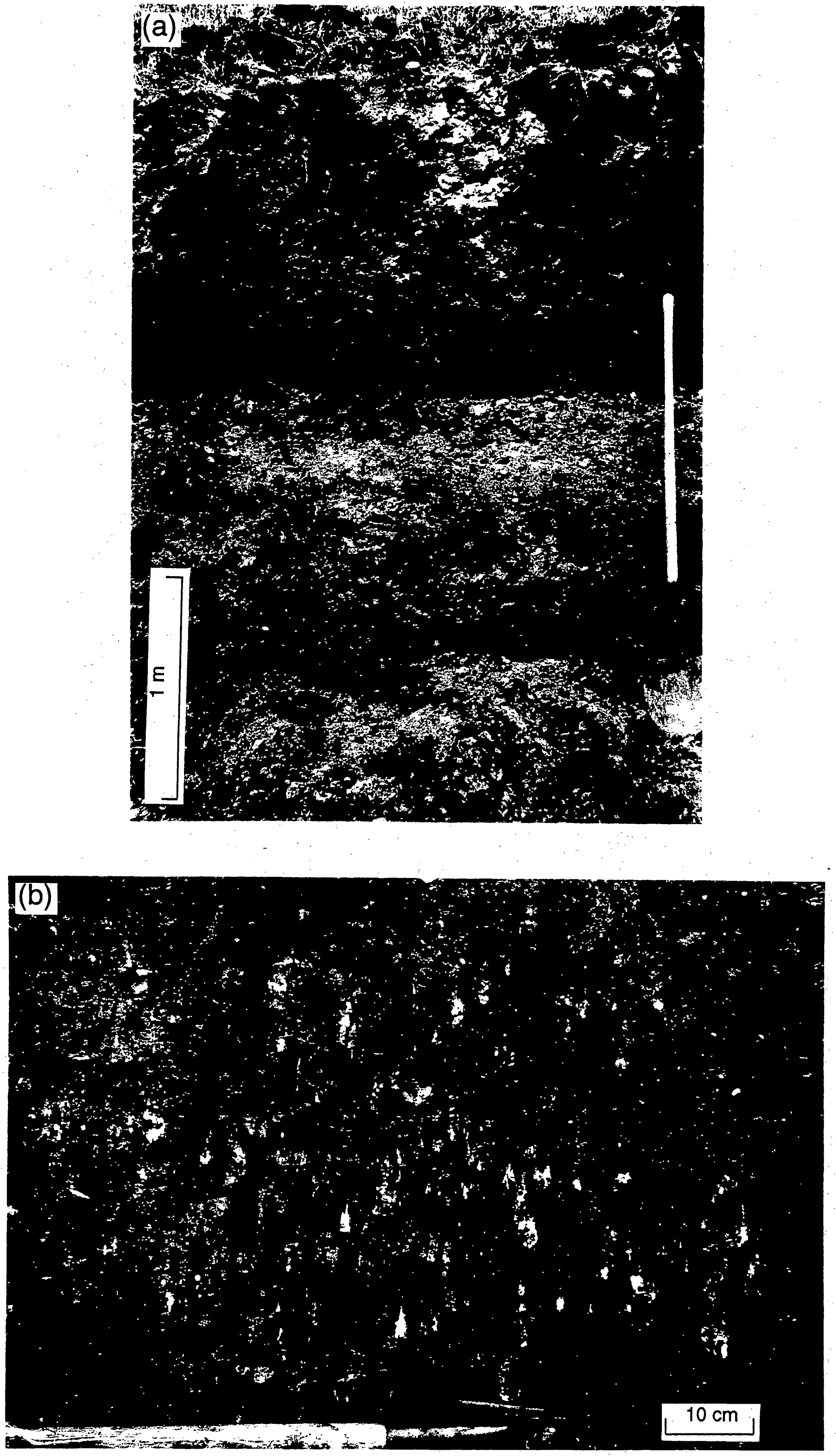

Figure 15. Photos of characteristics of lacustrine sediments in trenches. (a) Side of TDCJ trench 2, showing 1 m of dark silty clay having Randall clay soil developed in it overlying redder silty clay containing minor carbonate. (b) Horizontal exposure on the floor of the SCS trench (Murrey playa), showing dark stain and translocated material that extend from the upper dark unit into the underlying red unit. Soil carbonate is more abundant in this playa than in others.

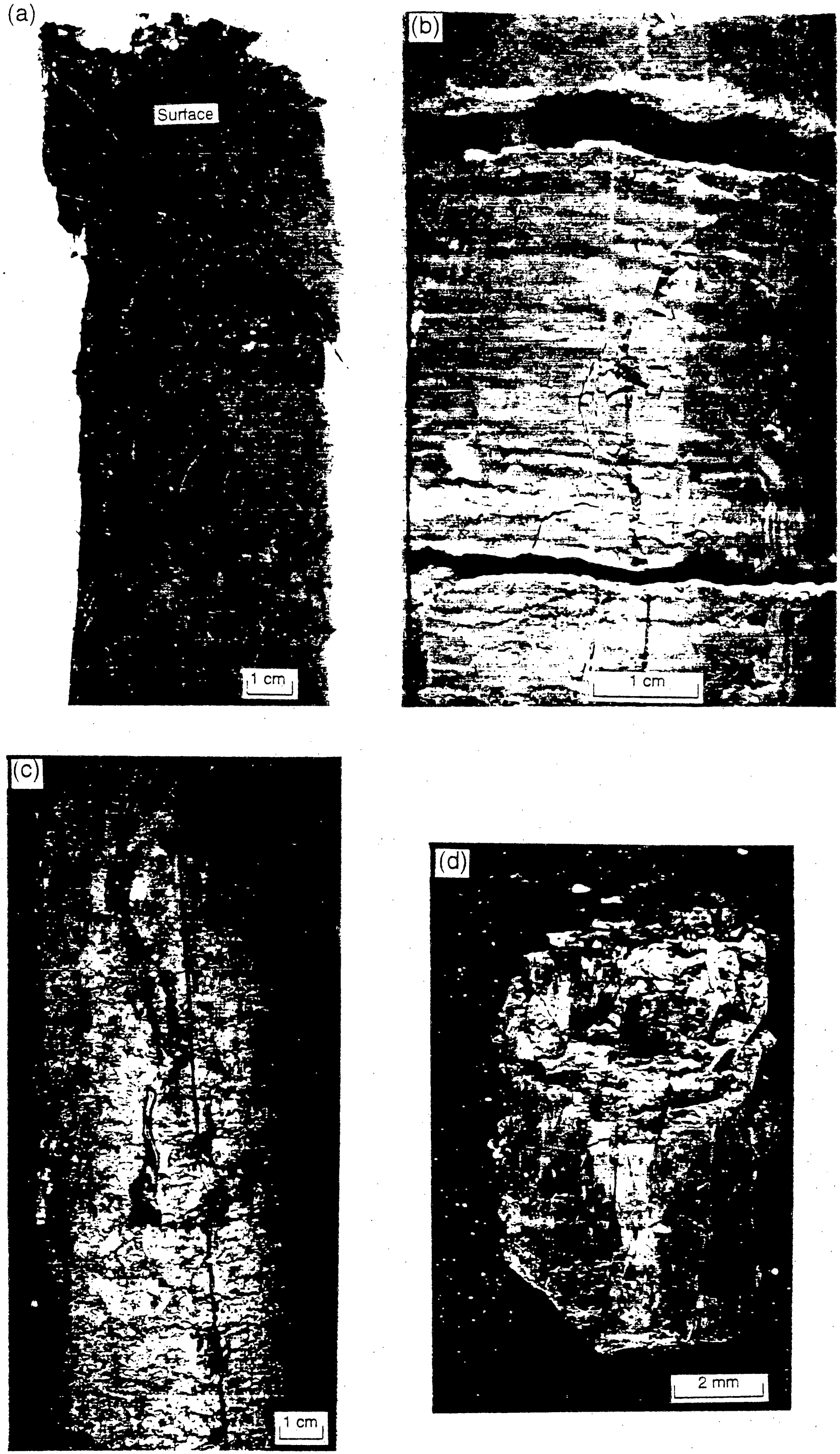

Figure 16. Photos of fine-grained lacustrine facies. (a) Typical surface lake sediment that has Randall clay soil developed on it. Bradshaw playa, borehole 2, top of core at surface. (b) Laminated lake clays, Sevenmile Basin, Borehole No. 5, 3.8 m. (c) Dark material translocated downward into the underlying lighter gray clay along soil structures and roots, Sevenmile Basin, Borehole No. 6, depth 1.16 m. (d) Older, gray clay, typically fractured, and fractures stained by manganese and iron oxides and hydroxides. Sevenmile Basin Borehole No. 2, 5.8 m.

more complex depositional and shallow burial history. Some of the older, gray clays have preserved sedimentary structures and textures, including fine lamination within clays (fig. 16b), bedding where clays are interbedded with sand and silt, and rare, small pelecypod valves within the clay. Destruction of depositional layering by biogenic and soil processes is more common, and soil slickensides, infilled or stained cracks, root tubules, and mixed clay and silt or sand layering, producing a churned appearance are typical of older clay beds (fig. 16c). Most gray clay beds are stiff and have been fractured, and the fracture surfaces have been mineralized by black iron or manganese oxides or hydroxides (fig. 16d). Round nodules of manganese oxide 1 mm to 1 cm in diameter are abundant in lake clays in some areas.

A variety of types of color modification of gray clay beds is apparent. Gray colors vary from as dark as the surface soils to light gray (10YR 7/2), probably reflecting variable preservation of organic material. Clay adjacent to many root tubules and soil structures is stained red or yellow, producing mottled gray and red clay. In addition, some fractures appear to have been filled by siltier red material derived from overlying beds. The gray clay beds that directly underlie Randall clay soils typically have dark (organic) discoloration and dark sediment infilling fractures (figs. 16c and 17a). Many gray clay beds contain carbonate. Two end members are identified: (1) carbonate filaments (fig. 17b) and diffuse nodules and (2) compact blebs and fracture fillings (fig. 17c). Preserved fine structures in carbonate filaments and diffuse nodules indicate that carbonate precipitation was the last event. The smooth and truncated-looking shapes of compact blebs and fracture fillings suggest partial dissolution of soil carbonate.

Older, Reddish Clays

Although reddish clays resemble older, gray clays in texture, appearance, and occurrence, they are colored red-brown (5YR 4/4 to 5YR 5/6). Red clays, either massive (fig. 17d) or bedded, are typically firm, containing fracture surfaces pigmented by iron and manganese oxides and hydroxides. The colors in clays may indicate either postdepositional oxidation or conditions of less effective reduction in the lake environment.

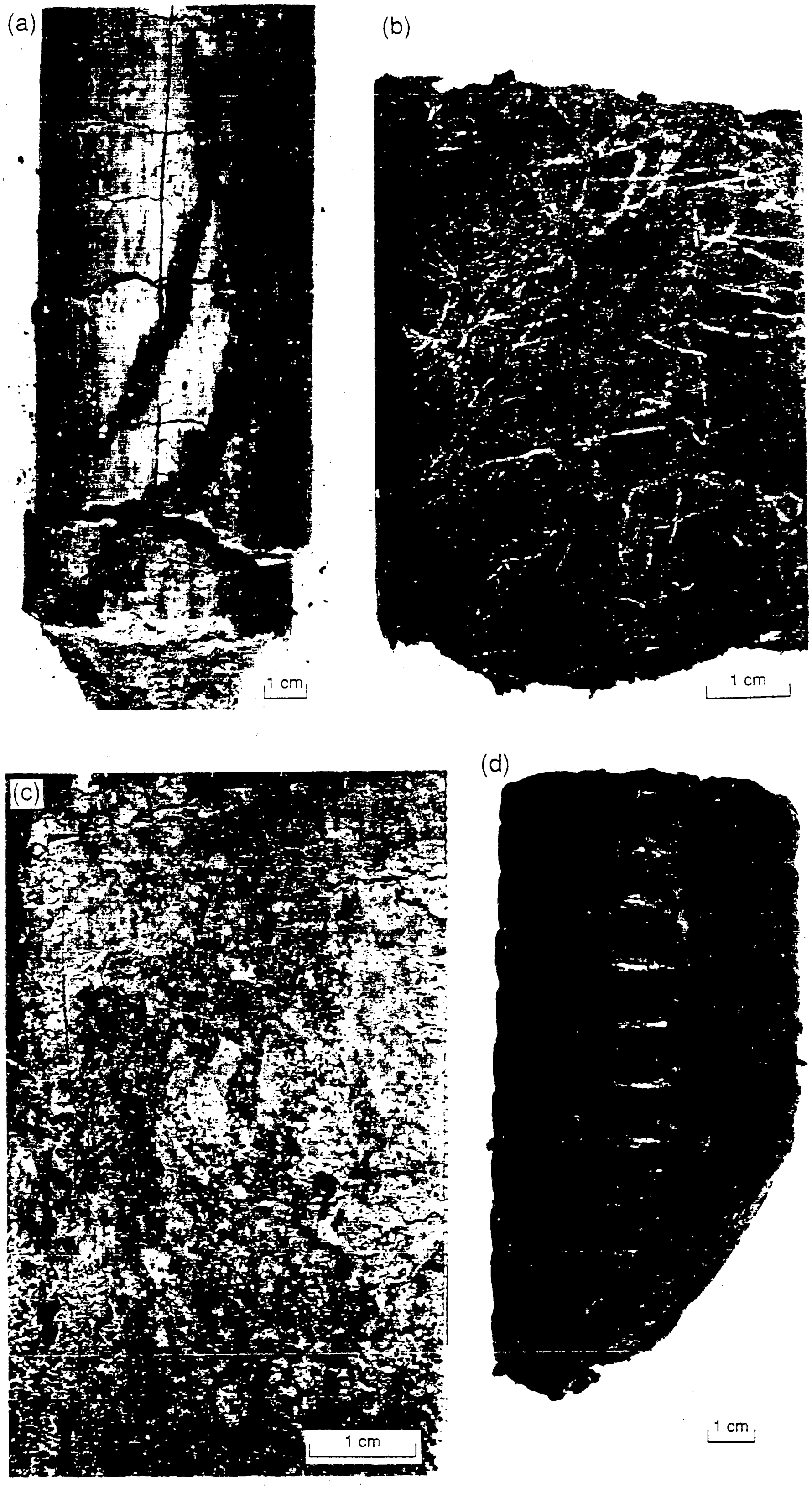

Figure 17. Photos of fine-grained oxidized and gray lacustrine facies. (a) Dark clay filling fractures in older light gray, slightly calcareous clay. Sevenmile Basin, Borehole No. 9, 2.4 m. (b) Calcareous filaments along a fracture in gray clay having red mottles. Vance playa, Borehole No. 2, 3.2 m. (c) Mottled red clay introduced into gray clay. Rounded calcite blebs suggest that an episode of carbonate dissolution followed precipitation. Wink playa, Borehole No. 8, 7.55 m. (d) Slickensided fracture in massive red lake clay that has abundant manganese oxide stains. Vance playa, Borehole No. 2, 9.6 m.

GPR Character

The west end of the GPR survey (section F) imaged the lower slope of the playa basin to the lake shore (fig. 18). The thickness of the upper layer on the GPR image increases gradually toward the playa lake shore at the west end of the transect. Comparing the lakeward end of figure 18 with the core from TDCJ Borehole No. 3 (fig. 19) shows that the well-defined layer in the GPR image may be the base of the Randall clay soil at 1.4 m. Lower layers may correspond to coarser grained and slightly more calcareous slope soils beneath the lake clays. The upper layer at the shore of the playa lake thins by about 15 percent away from the shoreline, and it appears to be gradational into the Estacado soils on the slope of the playa basin. The character of the GPR image changes abruptly between sections E and F on the 120-MHz survey. It does not change correspondingly on the 300-MHz survey, indicating that the change may be an artifact of data collection or processing. No change that might correspond to increased water content at or near the playa lake shore was identified in either survey.

Trench Description

A trench through the annulus on the east edge of TDCJ playa was sited north of the line of the GPR survey (fig. 20) where the annulus was well defined. A series of sections measured on the trench wall show that the surficial Randall clay soil thins and gradually changes from the lake floor to the high-water line (fig. 20). The drier soil had better developed peds and more roots and contained more silt toward the upper part of the annulus. The base of the Randall clay soil was marked by a gradational color change 0.6 m below the surface. Dark materials appear to have been translocated downward along elongate features, imparting a darker color to the sediment. These dark-stained areas may be the natural equivalent to planar features in the Randall clay soil that were dyed blue in ponding experiments (Xiang and others, 1993). These planar features may be areas of preferential flow, where pigments carried by downward-moving water accumulate. Similar features were found in the SCS trench (fig. 15b). The GPR survey was

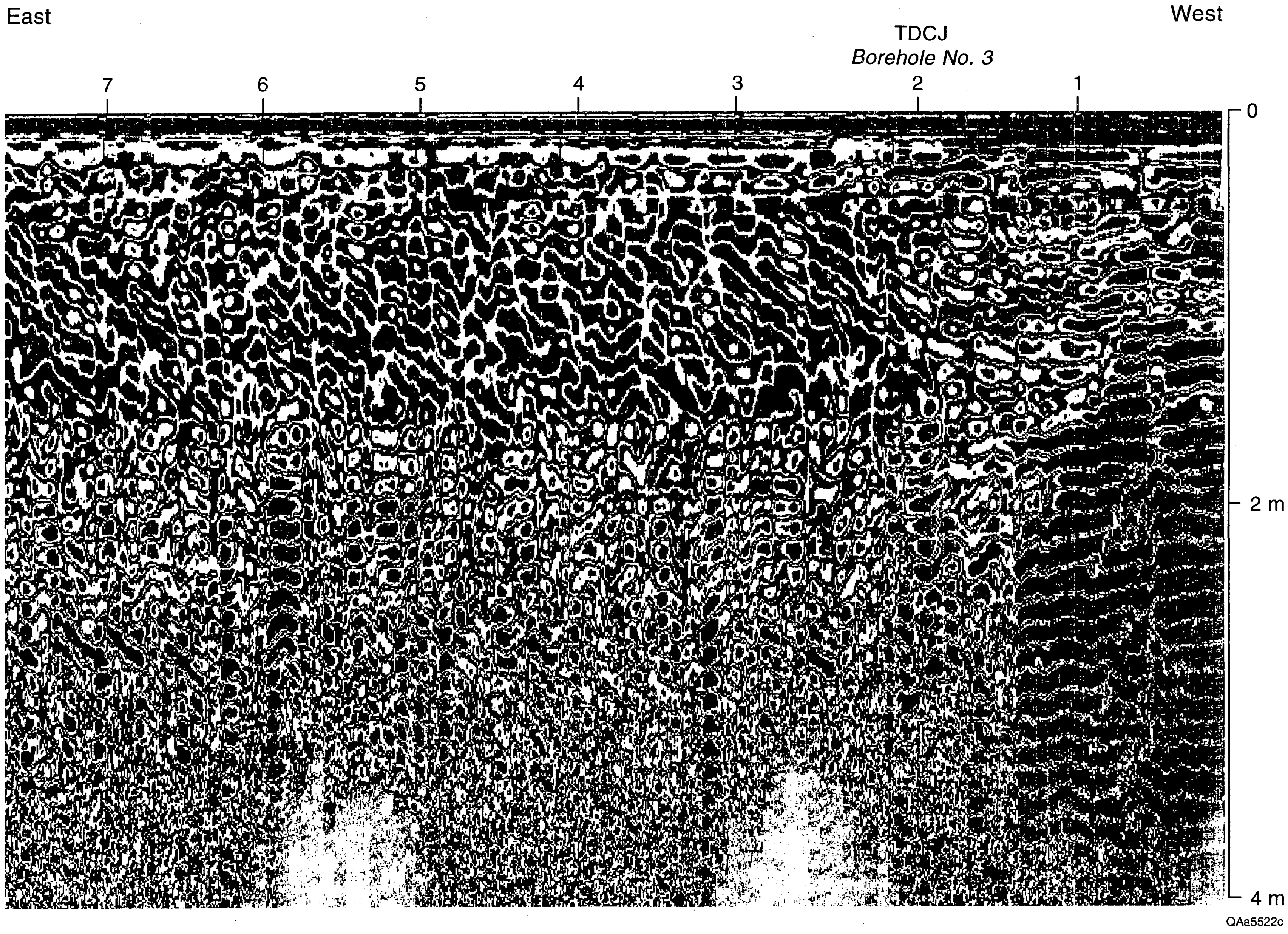

Figure 18. Segment of the GPR survey, 120 MHz, depth approximately 4 m. Survey station numbers at 5-m spacing provide horizontal scale. Location of survey shown in figure 4. Reproduced from Envirometrics (1991).

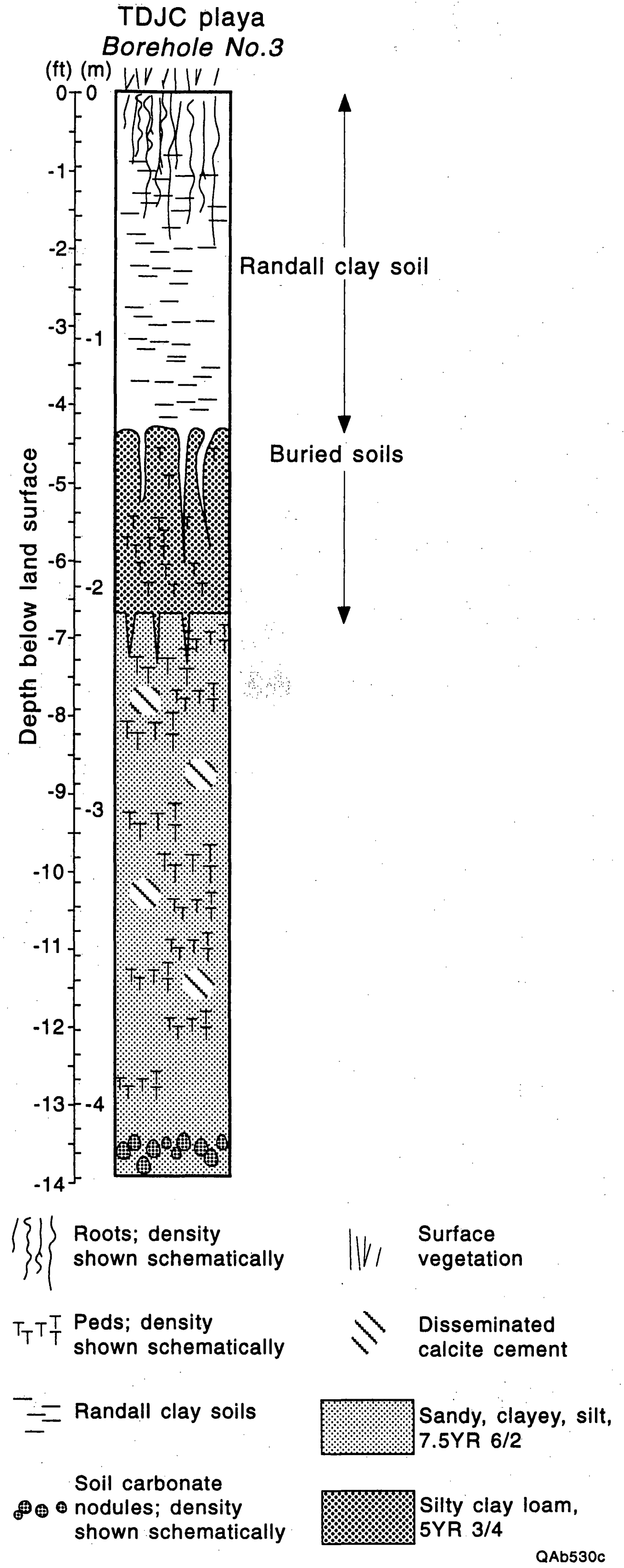

Figure 19. Lithologic log of hollow-stem auger core from TDCJ Borehole No. 3.

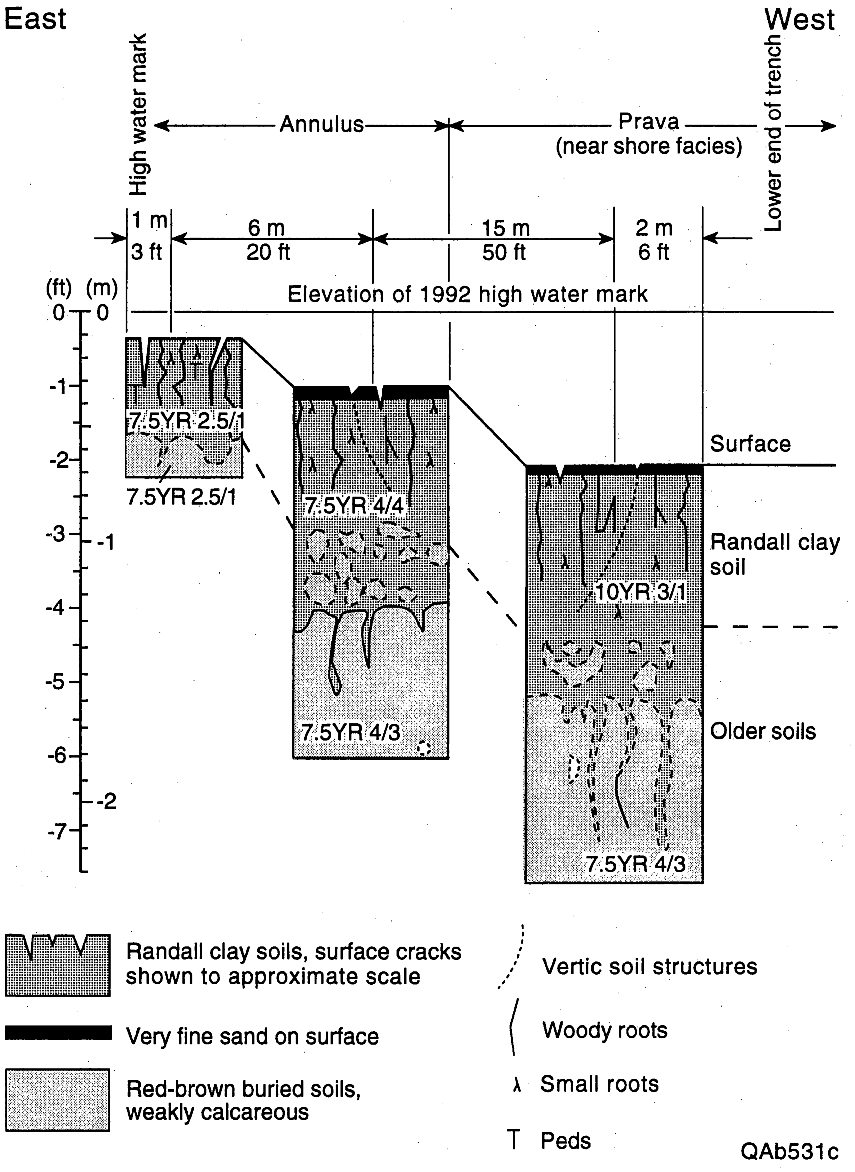

Figure 20. Segment of trench 2 in the annulus setting at TDCJ playa, showing typical stratigraphy from the high-water mark down into the playa.

run at the margin of a small delta at the mouth of the two drainages entering the playa from the southeast. Infilling of a broad, wide valley by Randall clay and delta sediments may explain the greater thickness of clay in this area. In neither trench nor GPR image on the east edge of the playa was a sharp or erosional base to the upper bed of lake sediments observed. The lake soils and sediment appear to thin and grade laterally into the slope soils, increasing in silt and decreasing in water content. Slope soils are better horizonated than Randall clay soils, high organic material appearing in the A horizon only and increasing amounts of carbonate in the B horizon. A gradational trend toward more silt, lower water content and better horizonation was observed in the trench along a transect from lake to upper annulus.

Genetic Facies Interpretation

Surface sediments; older, gray clay; and older, red clay are all interpreted as lacustrine deposits that formed in ephemeral lakes similar to modern playa lakes. Evidence leading to this conclusion includes texture, sedimentary and pedogenic structures, and spatial distribution of these deposits. The dominantly clay texture demonstrates that much of the sediment was deposited from suspended load in ponded water. Erosion of upland loam by storm runoff would supply subequal amounts of sand, silt, and clay that could be moved down small drainages (Simpkins and others, 1982). When mixed load encounters the lake, bed load is deposited on deltas, and fines are transported out into the lake. Preserved fine lamination and rare bivalves in clays demonstrate lacustrine deposition. High organic content, dark colors, and gleying of sediments beneath the surface are additional evidence of ponding and diminished oxidation. Data on spatial distribution of clays corroborating lacustrine deposition are discussed in each lake description.

All modern and most older clays have intensely developed soil structures. Sedimentary bedding is disrupted and homogenized by pedogenic and biologic churning. Roots, peds, and slickensided vertic structures are evidence of soil formation. Silt admixed with clay may partly reflect incorporation of surface silt layers into the soils during dry periods. Precipitation of carbonate nodules and filaments and partial or complete oxidation of gray clays to red suggest more intense or prolonged soil formation than is occurring currently in playa lakes. Precipitation and preservation of pedogenic carbonate and formation of oxidized colors indicate an environment where less ponding occurred. Preservation of bedding in some red clays suggests that they may have been deposited with minimal soil formation but in environments that had less strongly reducing or less organic-rich depositional environments—on the lake margins, for example. This relationship is further described in the section on South Washington Street playa, p. 48.

Lacustrine–Eolian Sand Beds

Well-sorted sand and silt layers, found in most cores sited in the playa lakes and playa annulus, are closely associated with lacustrine clays. Colors are commonly pale yellow (10YR 7/2) or red (7.5YR 4/4). Most sand beds are a few millimeters to a few centimeters thick, although the thickest sand unit, in TDCJ Borehole No. 12 core on the south side of the playa, is 4 m thick. Each bed is well sorted, very fine sand being the most common grain size. Fine and medium sand and silt beds are less common. Although sedimentary structures are difficult to see because of the good sorting and lack of cementation, both upward-fining and upward-coarsening grain-size distributions have been seen. Millimeter-scale lamination is common (fig. 21a), defined by interbedding (1) of sand and clay and (2) within sand beds. Centimeter-thick lamination and sand–clay interbedding (fig. 21b) and massive or laminated decimeter- to meter-thick sand beds (fig. 21c) are also found. Root tubules in sand beds indicate incipient soil formation. Muddy sand units containing evidence of intense soil formation are also commonly seen overlying or laterally equivalent to bedded sand units (fig. 21d).

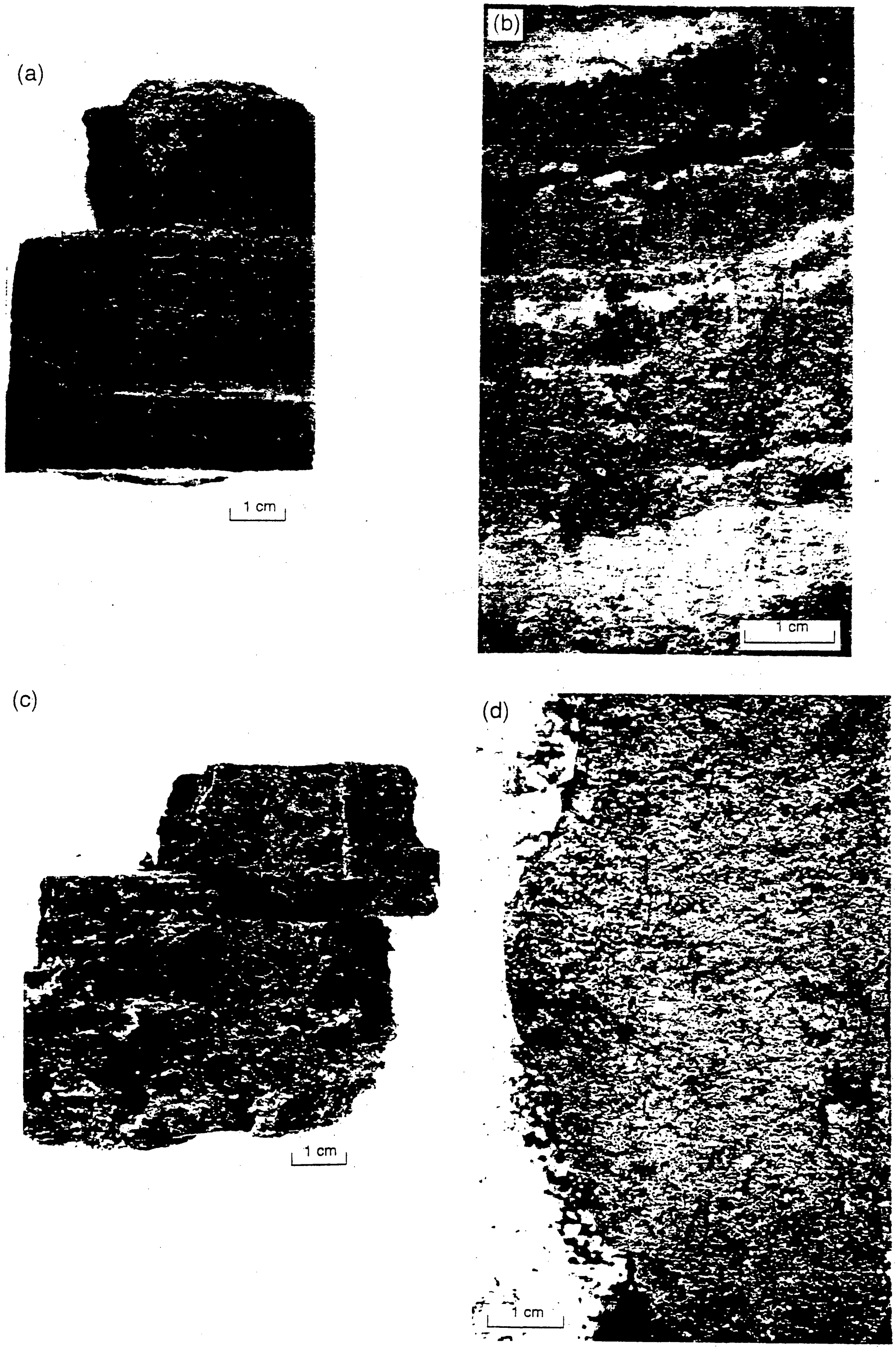

Figure 21. Photos of features typical of the lacustrine–eolian sand facies. (a) Millimeter- to centimeter-thick interlamination of very fine sand and dark clay. Wink playa, Borehole No. 12, 6.4 m. (b) Interlaminated very fine sand and clay, slightly disrupted by cracking and shrink–swell. Sevenmile Basin, Borehole No. 8, 1.5 m. (c) Thick interval of laminated fine sand beneath south shoreline. TDCJ playa, Borehole No. 13, 6.3 m. (d) Sand and clay admixed by pedogenic processes. Sevenmile Basin, Borehole No. 1, 7.3 m.

Genetic Facies Interpretation

Sand and silt beds within lake sediments are interpreted as the product of episodic migration of sand sheets across the playa. Silt layers that accumulate on the dry playa during the winter are present-day examples of this type of sedimentation. Thin lamination, very good sorting, upward-coarsening laminae, and lateral continuity of beds are characteristic of this type of deposition. Many sand and silt layers are only a few millimeters thick, suggesting that they formed when eolian sand adhered to the top of the damp clay while overlying dry sand was deflated and removed from the basin (Kocurek and Nielson, 1986). Preservation of thicker sand beds (fig. 21c) may indicate that sand that was transported across the dry lake by eolian processes was trapped and prevented from deflating by lake-level rise. Many sand beds appear not to have been rippled, scoured, or resorted by water, suggesting that bottom wave energy under flooded conditions may have been insufficient to rework eolian sand. Laminated clay beds interbedded with sand document deposition from the lake. Preservation of discrete sand beds depends on the intensity of pedogenic modification of lacustrine sediments. Where pedogenesis or bioturbation has been intense, sand and clays have been mixed (fig. 21d). Where lacustrin–eolian sand beds are thick enough to be drafted separately, they are so designated on cross sections. Intervals having finely interbedded or partly admixed sand and clays are described as clays that have interbedded or admixed sand laminae. Lacustrine–eolian sand beds were not trenched or imaged on GPR.

Lacustrine Delta Deposits

Laterally and vertically heterogeneous deposits of interbedded sand, silt, clay, and caliche pebbles that interfinger with lacustrine sediments are interpreted as parts of delta complexes formed where draws discharged into playa lakes. Delta deposits vary highly from core to core. Sediments in delta deposits exhibit variable red-brown and gray colors, indicating differences in the oxidation state of iron oxides associated with clays. Most delta deposits are thin lenses less than .5 m thick (fig. 22a).

In contrast, a sequence of stacked delta deposits at the mouth of the major drainage into the north side of TDCJ playa is more than 3 m thick (fig. 22b). Preservation of bedding indicates minimal soil formation during delta deposition; root tubules and other soil textures increase toward the top of the deposit, making delta deposits gradational with the overlying Blackwater Draw slope facies. Delta deposits generally contain only thin, discontinuous sand and silt beds, the bulk of the deposit being composed of mud and sandy mud. Granules and pebbles of reworked soil carbonate are abundant. Sorting, lamination or crossbedding, and distinct abraded margins distinguish these grains from soil carbonate precipitated in situ. Manganese oxide nodules are abundant within some delta deposits, although whether manganese nodules grew in situ or were also transported is unclear.

The thick section of lake sediments imaged at the end of the TDCJ GPR survey (fig. 18) is near the mouth of several drainages, a geographic position where delta sediments might be expected, but no distinctive deltaic features were imaged or seen in the nearby TDCJ 3 core (fig. 18).

Genetic Facies Interpretation

Modern deltas, which form where drainages divulge onto the flat, intermittently ponded playa floor, are composed of broad muddy areas slightly higher than the playa floor. Deltas commonly grade onto the playa floor and into the grassy playa basin slope without distinct edges. The muddy sediments on the modern deltas appear to be mostly top soil eroded off upland fields. Core through the distal part of a modern delta on the northeast edge of Wink playa intersected 0.4 m of laminated sets and crossbedded 4- to 12-cm-thick beds composed of brown (7.5YR 3/2) clay chips and minor carbonate granules at the base and clay drapes at the top (fig. 22c). This delta overlies 20 cm of lake clay. Channels 5 to 30 cm deep are commonly cut into the upper parts of deltas, and on modern deltas these are floored by coarse material,

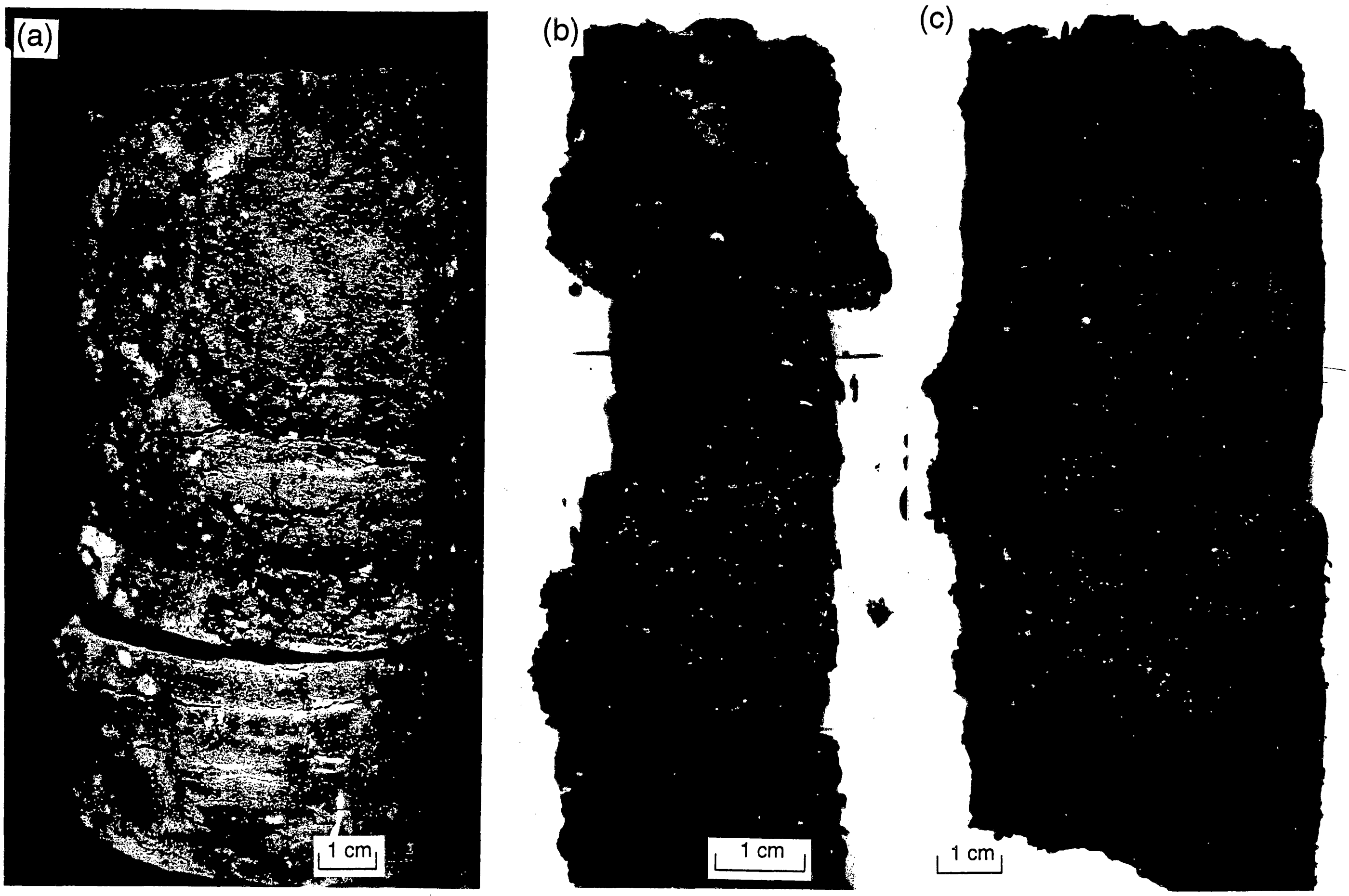

Figure 22. Photos of delta deposits. (a) Thin, ripple-cross-laminated red silt containing clay drapes from beneath the eastern annulus is interpreted as rapidly deposited delta sediments. TDCJ playa, Borehole No. 4, 10.6 m. (b) Thick delta sequence composed of carbonate granules; dark brown sand, silt, and clay are from the mouth of the major drainage. TDCJ playa, Borehole No. 36, 5.4 m. (c) Modern delta deposit composed of upward-fining beds of carbonate granules, sand, and clay. Wink playa, Borehole No. 6, 0.2 m.

mostly debris from human activities, and thin clay drapes. Some deltas are strongly progradational, producing a bulge in the otherwise circular to oval lake shoreline. Other deltas have partly infilled small valleys, and an inlet remains where the channel intersects the lake. Deltas commonly have complex microtopography, suggesting that the erosion and deposition that occurred at different lake levels may have been overprinted.

Formation of deltas in older playa basins was probably similar to that in modern playas. Deltas form where fluid velocity decreases as water from drainages divulges onto the ponded playa floor. Thin delta deposits that have preserved bedding demonstrate rapid deposition that minimized soil formation before abandonment of the delta as a result of lake-level changes. The size and sediment in modern deltas have probably been strongly influenced by human activities, abundant fine material being eroded from plowed fields and coarse material being supplied by debris.

Lower Fine to Medium Sand

Description

A thick unit of moderately well sorted, poorly consolidated fine to medium sand has been encountered in the lower part (~15 m below lake level) of the Blackwater Draw section beneath upland and playas in all boreholes that penetrated deep enough. This unit is generally red-brown (5YR 4/4), having locally bleached or reduced olive colors (5YR 7/2). Vertical fractures marked by discoloration are common in the lower Blackwater Draw sands. Fractures in red sands are characteristically light colored (fig. 23a), and those within light sand beds are typically stained red, indicating that they have transmitted oxidizing or reducing fluids from overlying layers. Carbonate contents of the lower Blackwater Draw sands are generally low and laterally variable, more carbonate lying beneath uplands than beneath playas. In many playa basins one or more thin, typically red lake-clay beds occur within the lower sand. Most lower

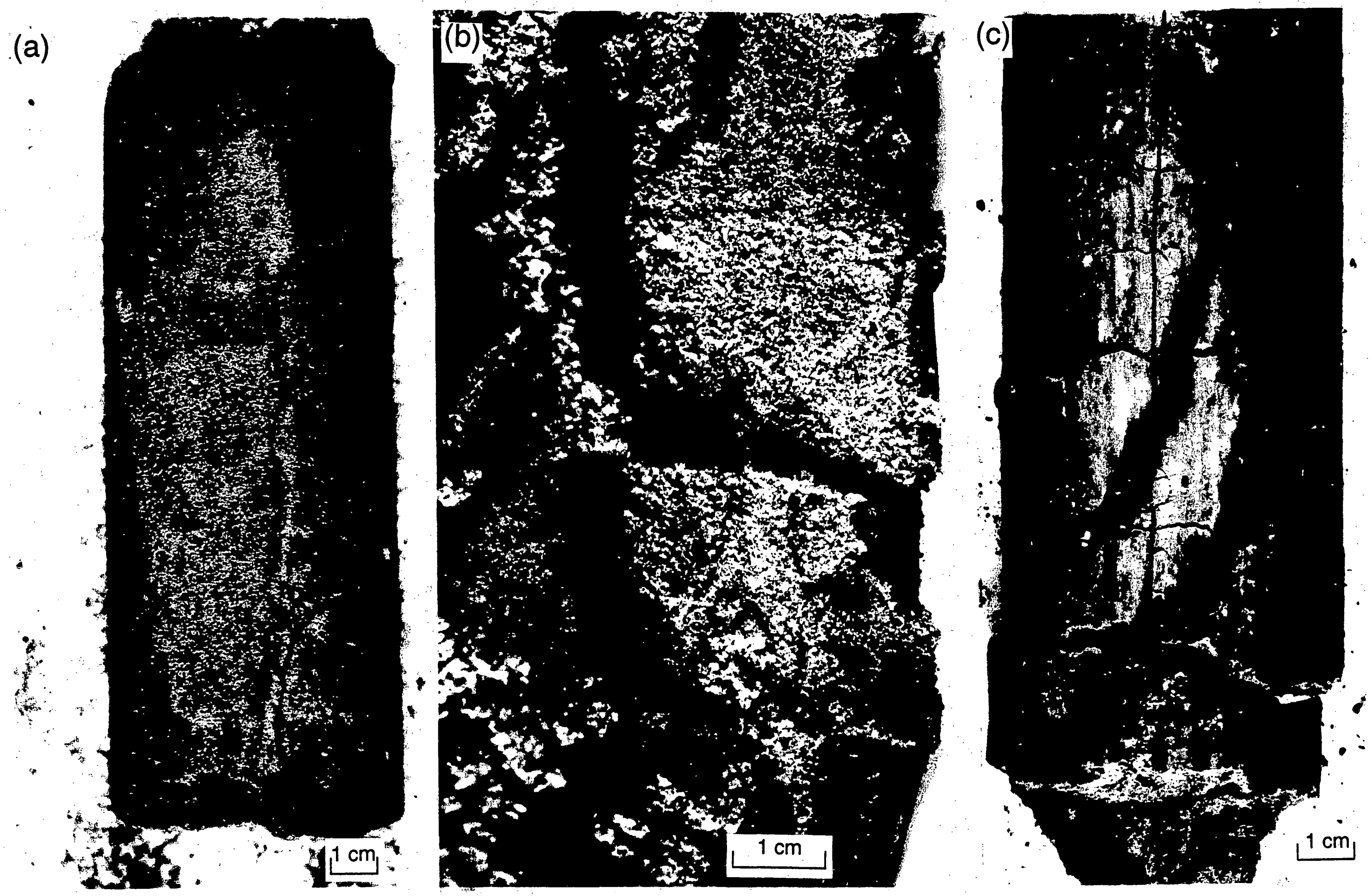

Figure 23. Photos of the lower fine to medium sand. (a) Typical pink massive sand, gleyed along a vertical fracture. Sevenmile Basin, Borehole No. 1, 16.8 m. (b) Laminated fine to medium sand from beneath the playa lake. Wink playa, Borehole No. 6, 18.4 m.

sand is massive and poorly cemented. Beneath the playa and associated with thin clay units, the lower sand is locally laminated.

The upper contact of fine to medium sand, somewhat gradational, has overlying finer grained units. Variable amounts of sand are incorporated in the red-brown silty clay loam of the Blackwater Draw upland and basin slope accretionary eolian facies, and the amount of sand decreases over several meters marking the top of the lower sand unit. In some places in the upland, a pedogenic carbonate is found in or just below the upper occurrence of abundant sand. Some of the gradational character may also be a product of downward translocation of clay beneath finer Blackwater Draw soil profiles. Beneath the lake, the contact is gradational because large amounts of clay have been translocated into the sand, and, along with reducing water, produce a gray to tan muddy sand, locally stained by limonite. The base of the fine to medium sand was cored only in four boreholes near Wink playa. Here the base of the sand, a coarser medium sand, overlies a prominent pedogenic carbonate at the top of a tan (7.5YR 5/6) silt.

Correlation Problems

The relative age of the lower fine to medium sand is not well constrained by stratigraphic evidence. In core from the upland at the Pantex Plant (BEG PTX 2 and BEG PTX 3), the base of the Blackwater Draw Formation, selected on regional criteria, is at the top of a prominent pedogenic carbonate, the Caprock caliche, found at a depth of 23 m (Gustavson, 1994). This carbonate is overlain by red-brown silty clay loam that has abundant pedogenic carbonate of the Blackwater Draw Formation, of which the lower few meters is sandier than the rest of the unit and underlain by red-brown fine to medium sand. The correct temporal relationship between upland sections and those near playa basins is unclear because near playa basins a single most prominent pedogenic carbonate was not cored—either because borehole depth was insufficient or because the Caprock carbonate is inconsistently present as a prominent feature near playa basins. One possible correlation would be to match grain-size change at the Caprock with grain-size change at the top of the sand unit in the playa basins, making the sand part of the Ogallala Formation. This correlation produces a thinner Quaternary section in playa basins. Alternatively, assuming that auger refusal occurred at the Caprock carbonate or correlating some of the more prominent pedogenic carbonates in the lower part of the sand unit with the Caprock would put the base of the Ogallala below the lowest lake beds and make the Quaternary section thicker in the playa basins.

GEOMETRY OF PLAYA BASIN SEDIMENTS

Two exposures in excavations into parts of playas were examined to define the geometric relationships among playa facies. Core data from 51 boreholes were used to prepare cross sections of each of six playas, using relationships seen in the excavations to assist in interpreting correlations. Each of these playa sequences is described herein. Two cores from Koesjan playa basin are not shown in cross section.

South Washington Street Playa

South Washington Street playa (Willow Lake) is a storm-water storage structure excavated into the northwest corner of a former playa. The structure was photographed when new (1984) by T. C. Gustavson. Since that time, the sides of the structure have been modified by vegetation, erosion, and maintenance activities, substantially obscuring the features visible in photographs; however, many beds could be identified and their composition and fabric described during the 1994 field season.

The playa was initially a moderate-size playa in a fairly shallow basin (table 1). The area has now been extensively modified by urbanization. This playa is near the south city limits of Amarillo, 20 km southwest of most of the study area playas.

Units seen on the east side of the excavation (fig. 24), which is toward the center of the original lake, are (from bottom to top) (1) Caprock pedogenic carbonate, (2) leached Blackwater

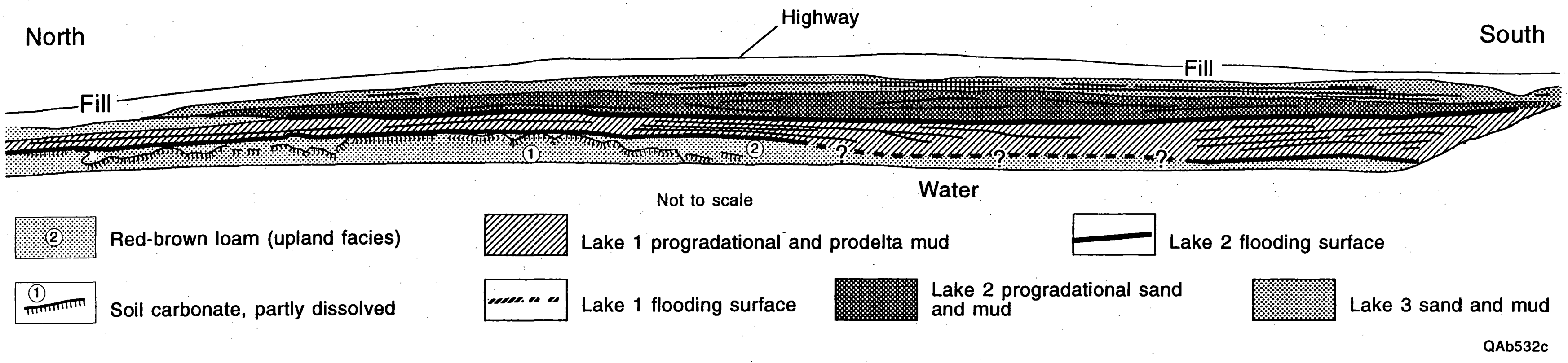

Figure 24. Mosaic of east side of flood control structure at South Washington Street playa, Amarillo.

Draw silty clay loam, (3) blocky red silty lacustrine clay, (4) lacustrine–eolian sand and silt, (5) dark brown lake clays, (6) tan lacustrine–eolian silt interbedded with red-brown lake clays, and (7) dark gray lake clays that have Randall clay soils developed on them. The top of the exposure has been extensively modified by road construction and fill.

The Caprock pedogenic carbonate, locally dense and pisolitic, occurs 6 to 8 m below land surface. Underlying units are not exposed above water level, and no fine to medium sand analogous to the lower sand in the Pantex area is found; however, this unit is thought to be the Caprock caliche at the Ogallala–Blackwater Draw Formation boundary because it exhibits stage IV to stage VI carbonate formation (classification of Machette, 1985), diagnostic of a long period of landscape stability identified regionally at their contact (Gustavson and Winkler, 1988). The Caprock pedogenic carbonate is well exposed toward the north end of the excavation, and is less well developed (and at a lower elevation) toward the center of the original playa. Part of the lateral change in carbonate distribution can be attributed to partial dissolution of carbonate, which is especially apparent in color photographs of the island, which was formerly visible in the center of the excavation. Because underlying units are not exposed, whether the top of the Caprock is at a lower elevation because the top has been dissolved or whether the bottom of the Caprock also dips toward the center of the original playa is unclear.

Overlying the Caprock is a unit of variable thickness composed of mottled light red and dark red silty clay loam having pedogenic features. This unit is interpreted as Blackwater Draw accretionary eolian facies, from which most of the nodular carbonate has been leached, producing mottles. The top of this unit dips toward the original playa center (fig. 24).

Blocky, red, silty lacustrine clay partly infills the depression. Accretionary beds demonstrate infilling from the basin edges, the presumed sediment source area. The red lacustrine clay extends beyond the edges of the modern Randall clay. This geometry is especially visible on the north end of the west wall of the excavation (fig. 25), where it extends outside the modern playa, and one of the lower red clay beds can be traced for about 15 m beyond (to the north of) the color change marking the northern extent of the Randall

Figure 25. Photomosaic of west side of flood-control excavation at South Washington Street playa, Amarillo. Photographs by T. C. Gustavson.

clay. In this area, the strata equivalents of the lacustrine red clay are bedded but appear white and mottled, suggesting that they contain pedogenic carbonate. The present lakeward extent of the visible carbonate matches the limit of the overlying Randall clay.

Overlying the red lacustrine clay are several beds of laminated light gray, very fine sand and silt of the lacustrine–eolian facies. This unit is of limited lateral extent, being identified only toward the center of the original playa. Sand and silt appear to fill irregularities in the top of the red clay. On the west wall of the excavation, the irregular top of the red clay is filled by another laminated clay unit, and no sand could be identified in the exposure.

The upper part of the sand and silt are interbedded with and overlain by very dark brown lake clays in the center of the playa. Toward the margins the upper part of this bed is lighter colored and redder. On color photographs this color change can be seen to be gradational.

Tan lacustrine–eolian silt overlies the dark brown to red clays. This unit is of variable thickness, the thickest silt appearing on the east exposure in channels or sags in the overlying units. This lacustrine–eolian silt is interbedded with red-brown lake clays. Internal bedding in thick parts suggests deposition as sheets rather than prograding wedges. Small lenses of red clay just south of the lake margin on the west exposure might be small clay-rich deltas or other shoreline complexities.

Dark gray lake clays are interpreted as the most recent lake sediments on which Randall clay soils have developed. At the lake margin of the west exposure, a thin bed of gray clay indicates an episode of transgression of the lake across nodular carbonate-bearing Blackwater Draw slope facies (fig. 25). Overlying lighter and redder facies may indicate progradation of upland facies in this area. Farther north along the exposure, inclined bedding might indicate incision through a small delta near the mouth of a former drainage.

Coulter Street Playa

A shallow (1.5 m exposed above ponded water) storm-water-retention pond has been recently excavated in the northeast corner of a small playa, which shows the relationships of playa facies in the annulus. This playa is in southwestern Amarillo, 33 km southwest of most study area playas.

In a fresh outcrop, red clay, gray clay, and sand lacustrine units can be seen to thin, merge, become truncated, or lap up on the Blackwater Draw facies (fig. 26). Red, silty clay loam having typically well developed pedogenic textures, although partly leached of carbonate (unit 1, fig. 26), crops out toward the edge of the playa. Overlying this is a wedge of gray clay (unit 2, fig. 26), similar to surface clay sediments having Randall soils developed on them, that pinches out toward the edge of the playa. Overlying this is a bed of lacustrine–eolian sand (unit 3, fig. 26). This bed, composed of pink, well-sorted fine to very fine, massive to bedded sand, dips toward the center of the original playa. It can be traced across the upper part of the Blackwater Draw facies toward the margin of the playa. Overlying the sand is another wedge of lacustrine clay (unit 4, fig. 26). This dominantly red clay has been intensely altered. Fractures and enlarged (10-cm-diameter) pipes are developed in this clay and filled by multiple generations of green and gray clay. Pipes exposed along the lower sides of the excavation are abundant—circular to elongate in horizontal cross section. The red clay also contains carbonate nodules that appear to have been smoothed by an episode of leaching after deposition. On the east side of the excavation, the top of the red clay is irregular, suggesting that some erosion of the clay could have occurred before deposition of the overlying bed. Another silt and sand bed overlying the red clay (unit 5, fig. 26) merges with the older sand bed toward the playa margin. This sand, as much as 20 cm thick, is distributed irregularly over the complex surface of the red clay. Overlying the sand is dark gray Randall clay (unit 6, fig. 26). This fairly homogeneous unit, showing little lateral or vertical change, can be traced to the end of the exposure toward the playa margin. The surface has been disrupted by berm construction at the edges of the excavation.

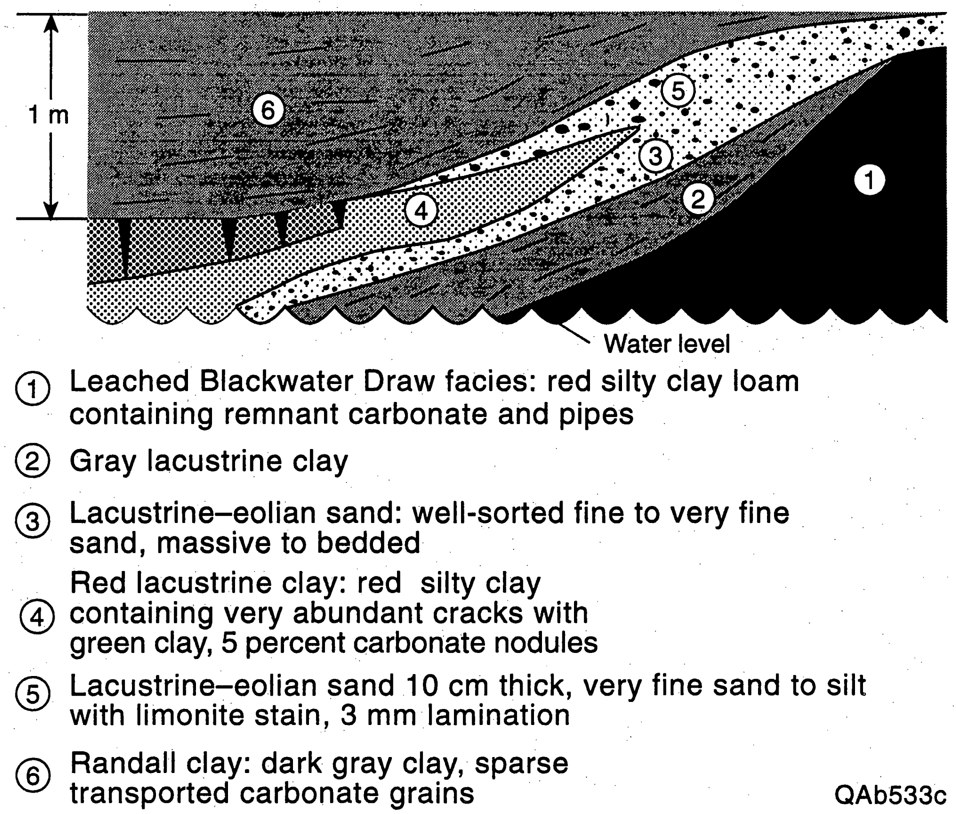

Figure 26. Cross section showing geometry of sediments exposed on north side of flood-control excavation near Coulter Street, south Amarillo.

TDCJ Playa Basin

TDCJ is an average-size playa (table 1) at the north edge of the study area. It was selected for detailed study because not only has it been minimally disturbed, it is a representative playa and basin and is publicly owned, facilitating repeated access.

A north-south transect across the playa basin (fig. 27) shows the overall geometry of the playa. An east-west transect (fig. 28) shows complexly interfingering shoreline deposits in the south part of the playa lake and in the annulus. Figure 29 shows a transect revealing sediments along the axis of a minor drainage on the north side of the lake.

The lower sand is found throughout the playa basin. Although multiple pedogenic carbonates are found in the sand beneath the upland and annulus, no distinctive stage IV carbonate Caprock was penetrated. The best-formed carbonate was encountered at the bottom of TDCJ Borehole Nos. 4 and 12 (fig. 28). In cores taken in the lake (Borehole Nos. 21 and 28), carbonate is found only in a few small nodules in the sand. The upper 5 m of the sand in the playa center core (Borehole No. 28) had less intense red-brown color (7.5YR 4/6) than did the typical sand (5YR 5/6), and it had reduced gray sand defining vertical fractures and gray clay infilling some fractures. The decreased carbonate, reduced colors, and translocated clay all suggest preferential flushing of the sand beneath the playa. The top of the lower sand generally mimics the surface topography of the playa basin, the highest areas being on the north side of the playa and the lowest beneath the playa floor (fig. 27).

TDCJ playa basin sediments record several episodes when the playa lake was more extensive to the south and east than it is at present and several episodes when the playa lake was smaller or confined to the north part of the basin and when red-brown silty clay of the upland facies of the Blackwater Draw accumulated in the area occupied by the present playa lake. These relationships are significant because they demonstrate the temporal equivalence of lacustrine and upland sedimentation. The oldest lake unit is found at least 300 m east and 100 m south of the present annulus. In the lake center, the oldest lake unit is yellow-gray clay

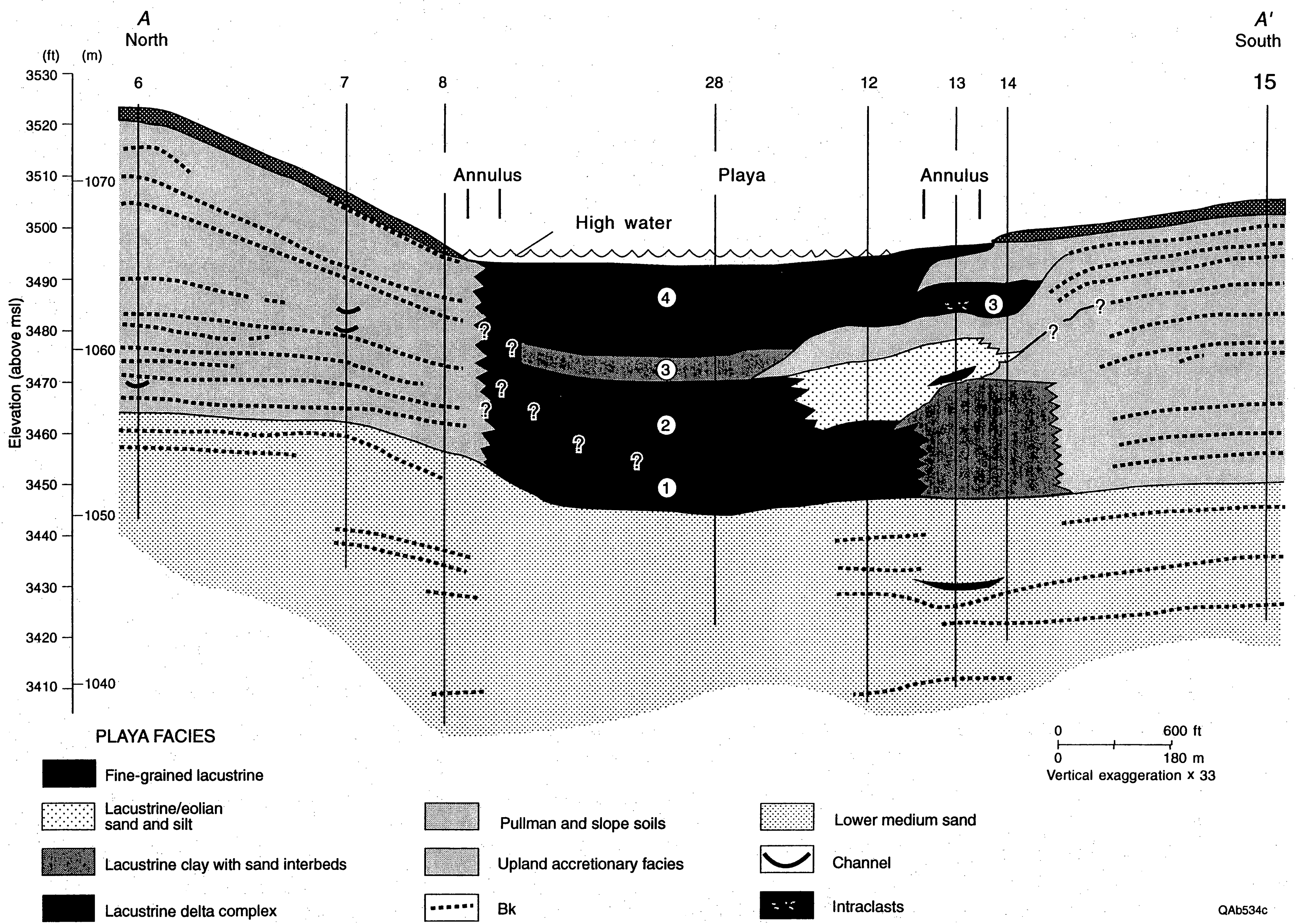

Figure 27. North-south cross section A–A′ of TDCJ playa. Line of section shown in figure 4.

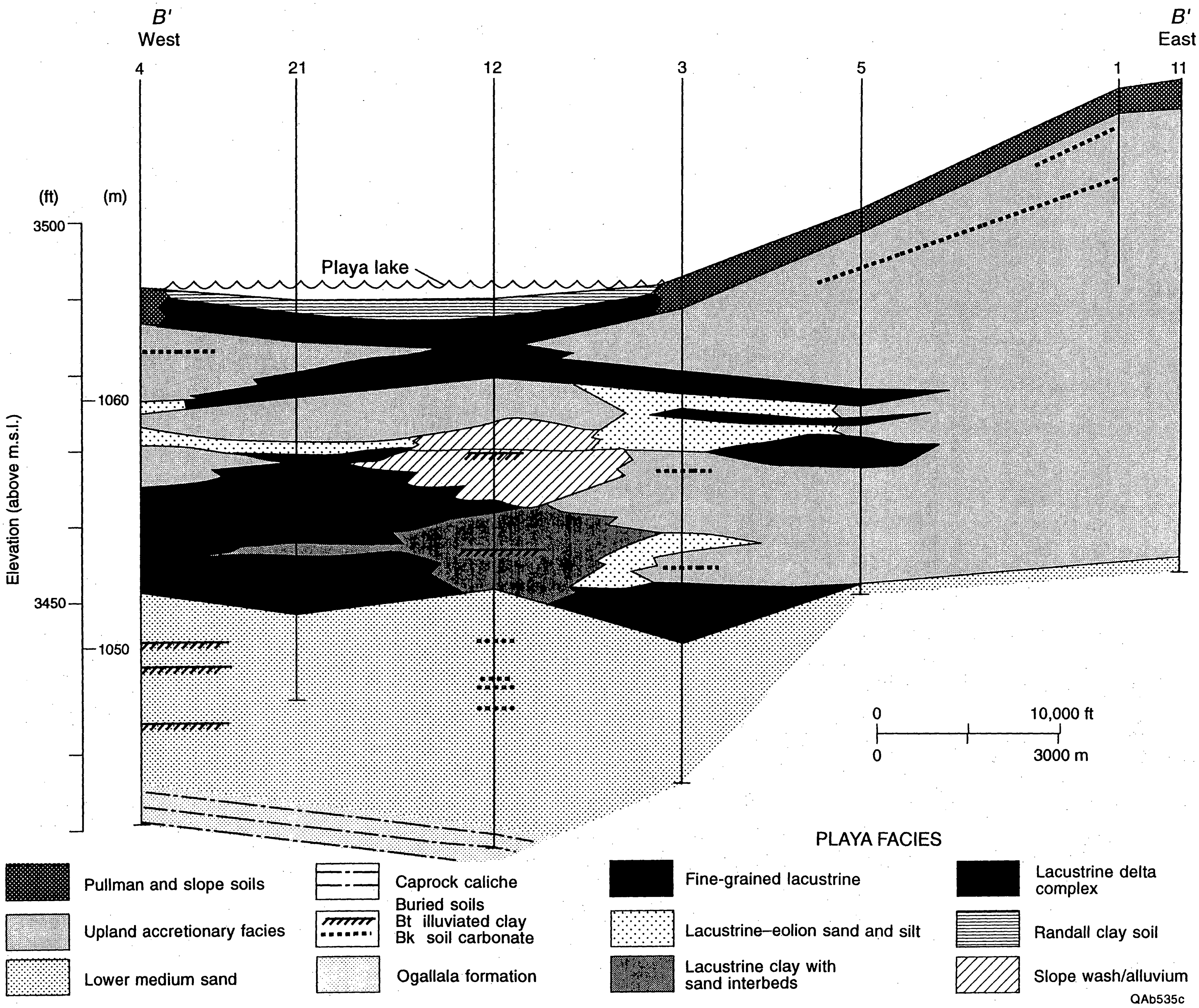

Figure 28. West-east cross section B–B′ of the southern annulus of TDCJ playa. Line of section shown in figure 4.

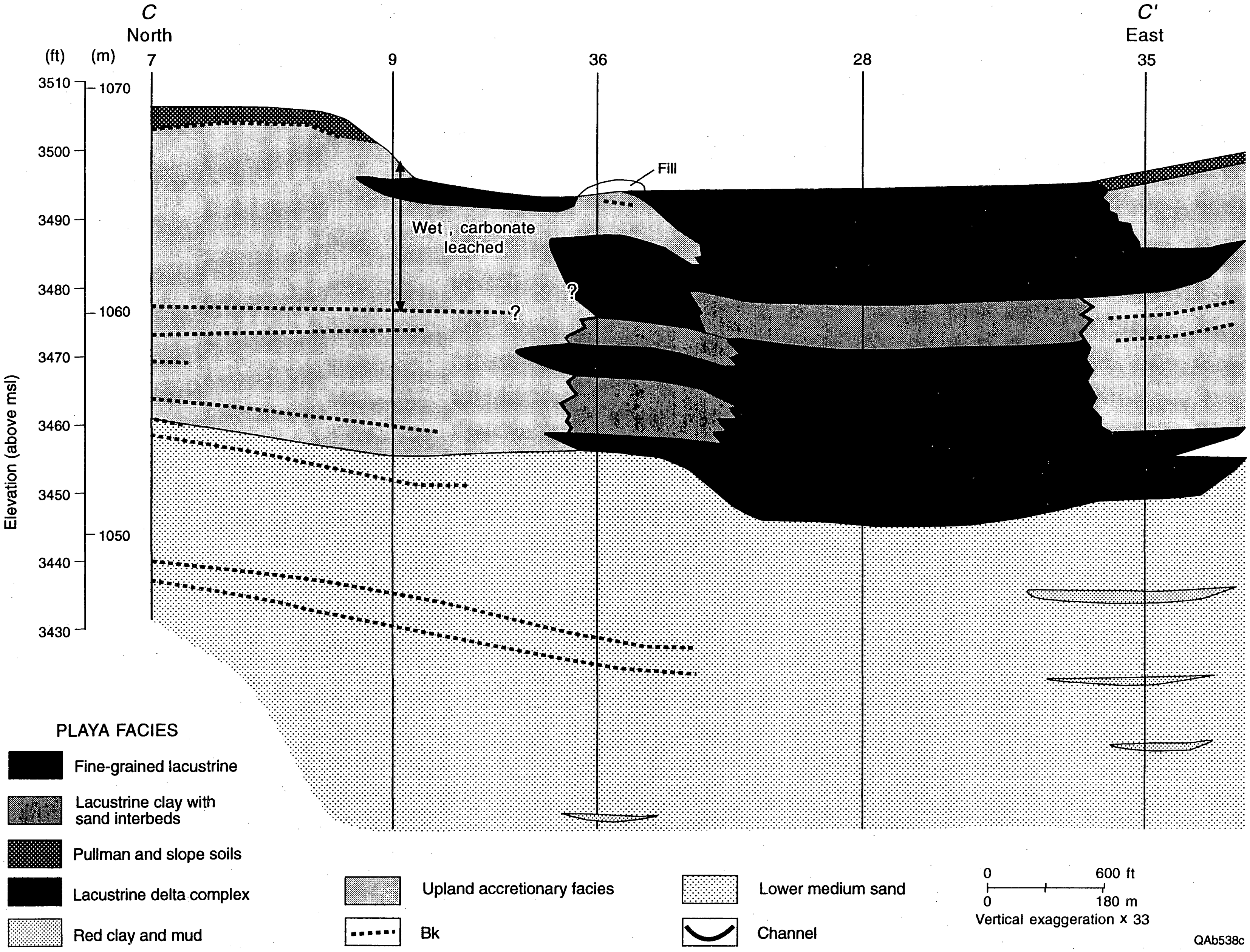

Figure 29. North-south cross section C–C′ of TDCJ playa, showing relationships along the major drainage. Line of section shown in figure 4.

that has manganese oxide coats. Well-formed peds, minor carbonate, red fillings between peds, and local bleached areas are evidence of complex postdepositional alteration. Beneath the annulus the unit is more diverse, containing more sand, more carbonate, and a redder color (fig. 28).

Partly overlying the lower lake unit is a wedge of typical Blackwater Draw slope accretionary facies. This thick unit extends farthest into the playa in the southeast corner of the playa (fig. 28), where it contains abundant pedogenic carbonate and one distinct Bk horizon. This unit was either not deposited or not preserved in the center of the lake (fig. 27).

In the center of the lake, a change in clay color and ped development is interpreted as the base of the second lake unit. In TDCJ Borehole No. 28 core, the second lake unit is brown (7.5YR 3/1) clay containing small peds. The top of the unit has a minor amount of carbonate. Beneath the southern annulus, this unit contains a complex of lacustrine deltas, thick beds of lacustrine–eolian sands, and lake clays (fig. 28). Lateral correlations demonstrate the small-scale complexity and variability through time of facies along the lake shore.

Another wedge of Blackwater Draw eolian accretionary facies overlies the second lake unit. This unit extends at least 100 m into the lake from the south shore (fig. 27) and displaces all the shoreline facies lakeward along that shore (fig. 28).

The third lake unit contains a lacustrine–eolian sand at its base within the lake (fig. 28). This unit is distinctive because the clays that interbedded with the sand are very dark brown and they have only incipient soil textures. Thin sand interbeds are also well preserved, containing fine mud cracking. Upward through this unit the amount of sand diminishes, the clays become a more normal dark gray color (7.5YR 3/3), and the abundance of slickensided peds increases. Beneath the annulus, this lake unit contains a complex of deltas, lake clays, and nearshore deposits. Carbonate appears to be mostly sparse detrital grains. One lake-clay bed in the TDCJ Borehole No. 13 core contains clasts of poorly cemented Blackwater Draw accretionary eolian facies, suggesting deposition in the lake at the foot of a small cliff. This topography would have resembled the wave-cut benches seen at the shoreline of Pantex Lake. This lake sequence can be identified about 30 m south of the modern lake shore.

The top of the third lake sequence is marked by a small wedge of Blackwater Draw accretionary eolian facies (fig. 27). Although pedogenic carbonate nodules, cements, and filaments are found in the wedge, no well-developed Bk horizons were found in the annulus. Within the lake, no Blackwater Draw accretionary eolian facies are found, and the boundary between lake units is placed at a subtle decrease in the abundance of fractures and a minor change in color.

The fourth lake sequence is composed of clays that have Randall soils developed on them and active deltas. No shoreline sand accumulations were identified at the surface or in the shallow subsurface, suggesting that no modern analog for the shoreline sand exists in this area.

Dating

The carbon in clays from two samples from Borehole No. 28 (lake center) was dated using C^{14} techniques on organic material in lake clays. The results of this analysis are reported in table 3. The ages should be considered minimum ages of sediment deposition because younger organic material may have been flushed downward into the clays.

Wink Playa

Wink playa basin, directly west of the Pantex Plant, is a well-defined basin that has a slightly smaller than average playa (table 1 and fig. 30). Four well-developed drainages enter the playa from the northwest, northeast, and southeast (fig. 30). Boreholes were drilled along a transect from the northwest lake margin, into the elongate part of the playa associated with the drainages to the southeast, in the drainage, and into the minimally disrupted grassy upland south of the playa.

Table 3. Radiocarbon analysis of soil samples from TDCJ playa.

Location	**Depth (ft)**	**Percent modern carbon**	**δC^{13} (‰)**	**Age (yr)**	**Error**
TDCJ Borehole No. 28	4.9	71.482± 0.1315	−22.3	2,700	50
TDCJ Borehole No. 28	16.1	21.006±.25 1	−18.6	12,530	270

Analyses: Salvatore Valastro, Radiocarbon Laboratory, The University of Texas at Austin.

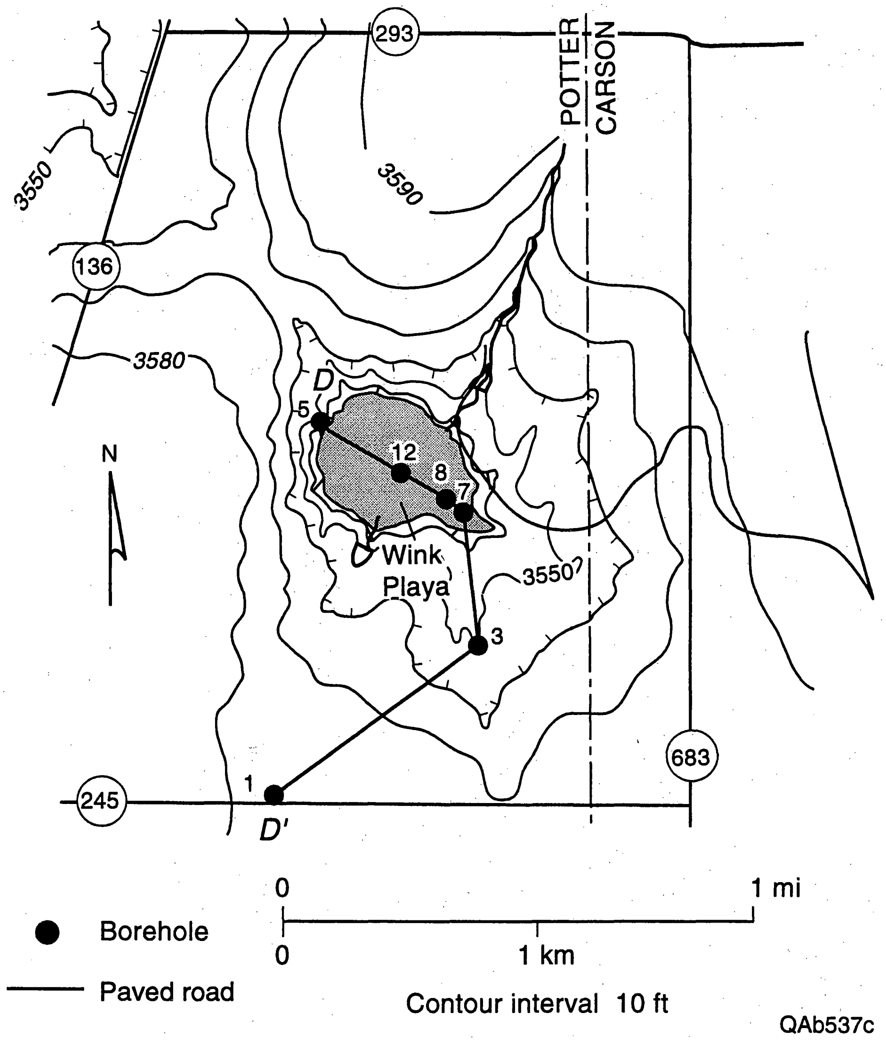

Figure 30. Wink playa basin topographic map, showing well locations. Location of playa basin shown in figure 3. Cross section D–D′ shown in figure 31.

Most boreholes in Wink playa basin penetrated the lower fine to medium sand and an underlying tan (7.5YR 6/4) silt at depths of 22 to 26.5 m below the surface (fig. 31). In most cores, the grain-size change from silt into sand occurs abruptly, directly above a laminated, hard pedogenic carbonate. Beneath the playa, the carbonate is thinner than beneath the uplands, and the carbonate is completely missing in playa-center Wink Borehole No. 12. The grain-size change and well-developed soil carbonate are interpreted as possible correlatives to the Caprock and top of the Ogallala Formation in nonplaya areas.

The lower sand unit occurs beneath both the playa basin and upland. Beneath the upland and playa basin slope, it contains four pedogenic carbonates. Beneath the playa, the lower sand is thicker, containing little or no carbonate. Multiple red or brown lake-clay units occur in the lower sand beneath the playa. The lowest clay units are thin beds that lie directly on the pedogenic carbonate of the underlying Ogallala silt. Fine sand and clay interlaminations are preserved in some of these clay beds. The elevation of the lower sand is lowest in the borehole in which it is thickest, Wink Borehole No. 8, which is in the southeast part of the lake, not the modern center of the lake. The lower few lake-clay units could be correlated to show some postdepositional dip toward the lake center (fig. 31), having a maximum of 7.6 m of differential subsidence of the thickest section relative to the northwest margin. Younger lake clays can be correlated to suggest no postdepositional tilting.

Overlying the lower sand in upland and basin slope areas is the accretionary silty clay loam of the Blackwater Draw Formation. It contains five Bk horizons that appear to be traceable from the upland into the basin, paralleling the present slope of the basin. Several small channel deposits were cored in the Wink Borehole No. 1, which was drilled in a flat upland area remote from any modern drainage, indicating that minor features of the landscape have changed during the accumulation of the Blackwater Draw Formation.

Overlying the lower sand in the playa basin is a sequence of red and gray lacustrine clays and lacustrine–eolian sands. Although core control in the annulus is inadequate to define the complete sequence of lake enlargement and shrinkage observed in TDCJ playa, the lake and

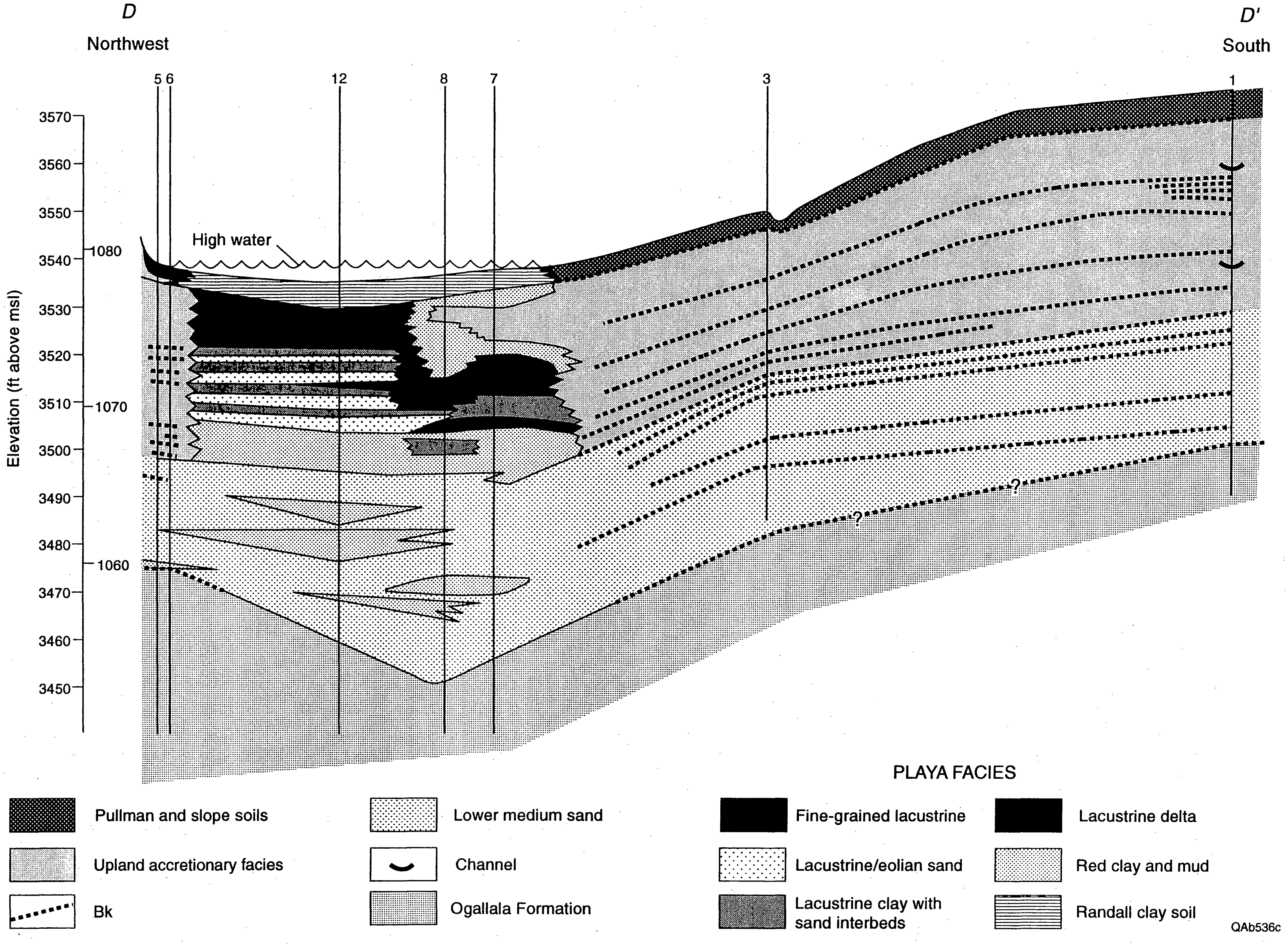

Figure 31. North-south cross section D–D′ of Wink playa basin. Line of section shown in figure 30.

lake marginal sediments encountered suggest a similar evolution. The oldest lake-clay sequence is oxidized (2.5YR 5/3) and intensely cracked by some sand-filled cracks, and it probably extends over the area of the present lake. The oldest clay is thickest and occurs in the structurally lowest position in the southeast corner of the lake (fig. 31), suggesting that at the time of formation of the oldest lake, this may have been the deepest part of the basin. Blebs of calcite appear to have formed as pedogenic calcite that was later mostly dissolved. The underlying sand exhibits complex crosscutting textures and fracture fills, demonstrating that multiple episodes of reducing-water influx have occurred, followed by conditions during which sand and clay were oxidized.

Overlying the oldest clay is a sequence of lacustrine–eolian sand and silt interbedded with lake clay. This sequence, 5 m thick in the center of Wink playa, has more sand and more silt than do comparable intervals in other lakes. Although lamination and mud-cracked clay beds are well preserved through much of the interval, several intervals display churned fabrics, suggesting episodes of more intense soil formation.

Toward the southeast, only the lowest part of the sand interval is present. Laterally equivalent to the sand is a thick interval of silty clay having abundant deep soil cracks, abundant manganese oxide or hydroxide nodules, complexly overprinting colors, and a complex carbonate-dissolution–precipitation history. This sequence is interpreted as nearshore deposits documenting several episodes of lake enlargement and deposition of red or gray clays followed by lake shrinkage, resulting in soil development, soil-carbonate precipitation, and oxidation and illuviation of clay. One interval of progradation of Blackwater Draw slope and upland facies into the lake is recorded in the cored sediments, which have produced a tongue of Blackwater Draw loam having abundant pedogenic carbonate in the southeast corner of the lake. A preceding Blackwater Draw progradational episode might be inferred from the sequence of overprints in the lake core. The core control is inadequate to constrain the relationships uniquely between the wedges of upland facies and the lake center. In the lake center, an interval of fractured gray clay overlying the sequence of interbedded sand and clay may correlate with the upper interval of Blackwater Draw progradation.

The top of the lake sequence in both the center of the lake and the southeast corner is deposition of lacustrine clays on which the Randall clay soils are developed. In the lake center, because they appear to have gradational contacts with the preceding sediments, the youngest lake sediments are distinguished only by the more fractured appearance of the older clays. The Randall clay soil profile is developed mostly in the younger clays, the base of the soil profile marked by darker, downward-translocated organic material along soil structures. In the southeast part of the lake, the youngest lake transgressed the Blackwater Draw deposits, resulting in gleying and staining soil structures and fractures in the Blackwater Draw. On the northwest margin of the lake, the edge of the youngest lake sequence was cored just within the modern lake at a depth of 1 m. Overlying a few centimeters of lake sediment are delta sediments composed of upward-fining sets of dark clay chips. The lower parts of two cores from the northwestern annulus contain only Blackwater Draw slope facies, indicating that the modern lake extends farther to the northwest than any preceding lake.

Vance Playa

Vance playa basin has two interconnected playa lakes within one playa basin east of the east edge of the Pantex Plant. The shallow basin, having only 2 m of relief on the highest closed contour, lies on a gradual slope to the east in the upland (fig. 32). The lake floors at approximately the same elevation have not been observed when flooded. The floor is heavily vegetated by grasses, suggesting that flooding has not been frequent or prolonged. A peninsula of upland partly separates the lakes. The north and west margins of the lake basin are steep, the south margin gentle, and relief minimal to the east. Boreholes were selected to sample the sediments along a transect from the upland on the north, through the center of the north lake, across the low peninsula separating the lakes, through the south lake, and into the lower basin slope on the south.

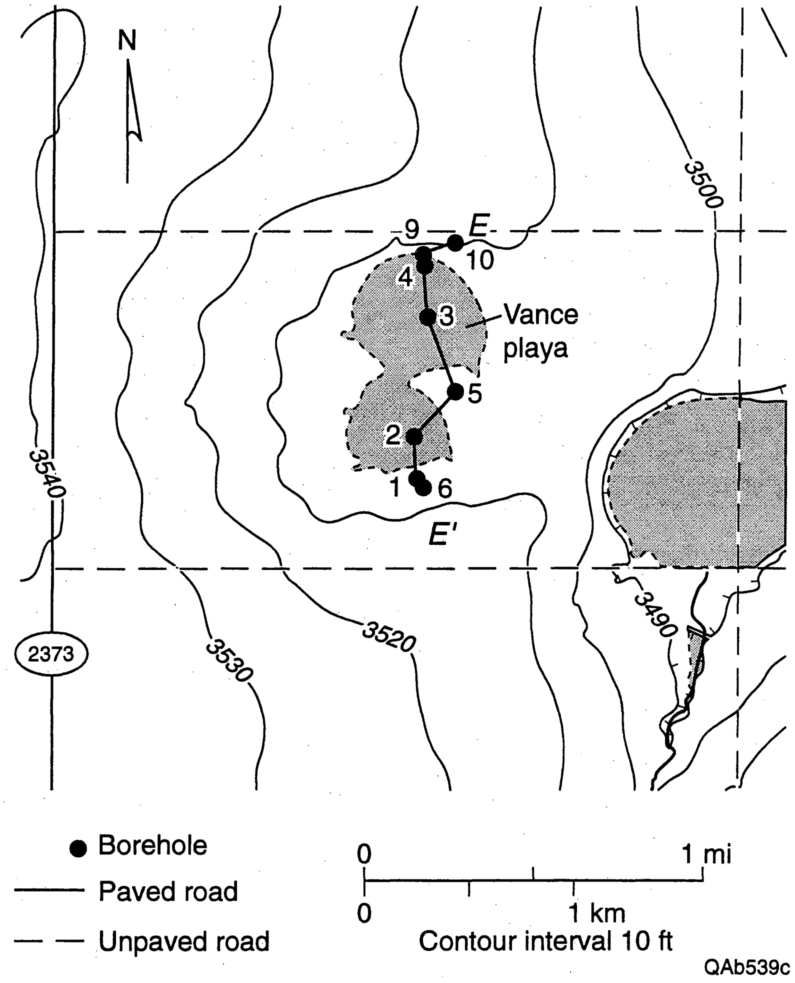

Figure 32. Vance playa basin topographic map, showing well locations. Location of playa basin shown in figure 3. Cross section E–E′ shown in figure 33.

The oldest sediment cored in Vance playa basin was the lower fine to medium sand (fig. 33). Several Bk horizons in the lower part of the sand appear to be correlatable across the basin. In the upper part of the sand, two thin clay beds and associated bedded lake marginal sand are found beneath the north lake. Soil carbonate horizons found beneath the upland and south lake are noncontinuous across the north lake. Relief on the Bk horizons and on the top of the sand mimics the modern, subdued topography of the basin, lake centers being slightly lower than uplands.

In the uplands, the lower sand is overlain by Blackwater Draw facies, typically containing six traceable Bk horizons. Several small channel deposits were identified. On the north shore of the lake, in Borehole No. 4, several amalgamated thick Bk horizons occur at the contact between the lower sand and the Blackwater Draw facies. The thickest carbonate, 4.5 m thick, is hard and platy at the top. Farther from the lake, in Borehole No. 10, the thickness of this carbonate decreases, to resemble the other Bk horizons.

The lake sequences are slightly different beneath each lake. The sediments cored beneath the peninsula separating the lakes show relationships between the lake and shoreline. Initial lake sediments are admixed sand and clay, with evidence of intense pedogenic reworking. In the south lake, lake sediments overlie a Bk horizon, which appears to have been reworked by the lake. Beneath the peninsula, a well-sorted lacustrine–eolian silt bed records the initial increase in lake level. After this initial high lake level, lake-margin to upland sediments were deposited on the peninsula, including red sandy clay, interpreted as lake edge, overlain by accretionary eolian facies of the Blackwater Draw. Correlations suggest that red clay and lacustrine–eolian sand deposition and churning by soil formation continued in the lakes during the time that accretionary eolian facies were deposited on the peninsula (fig. 33). Remnant soil carbonate is abundant beneath the south lake and present beneath the north lake. Soil carbonate is not in discrete horizons nor can a soil profile be identified, suggesting that carbonate accumulated episodically in soils that developed across the playa.

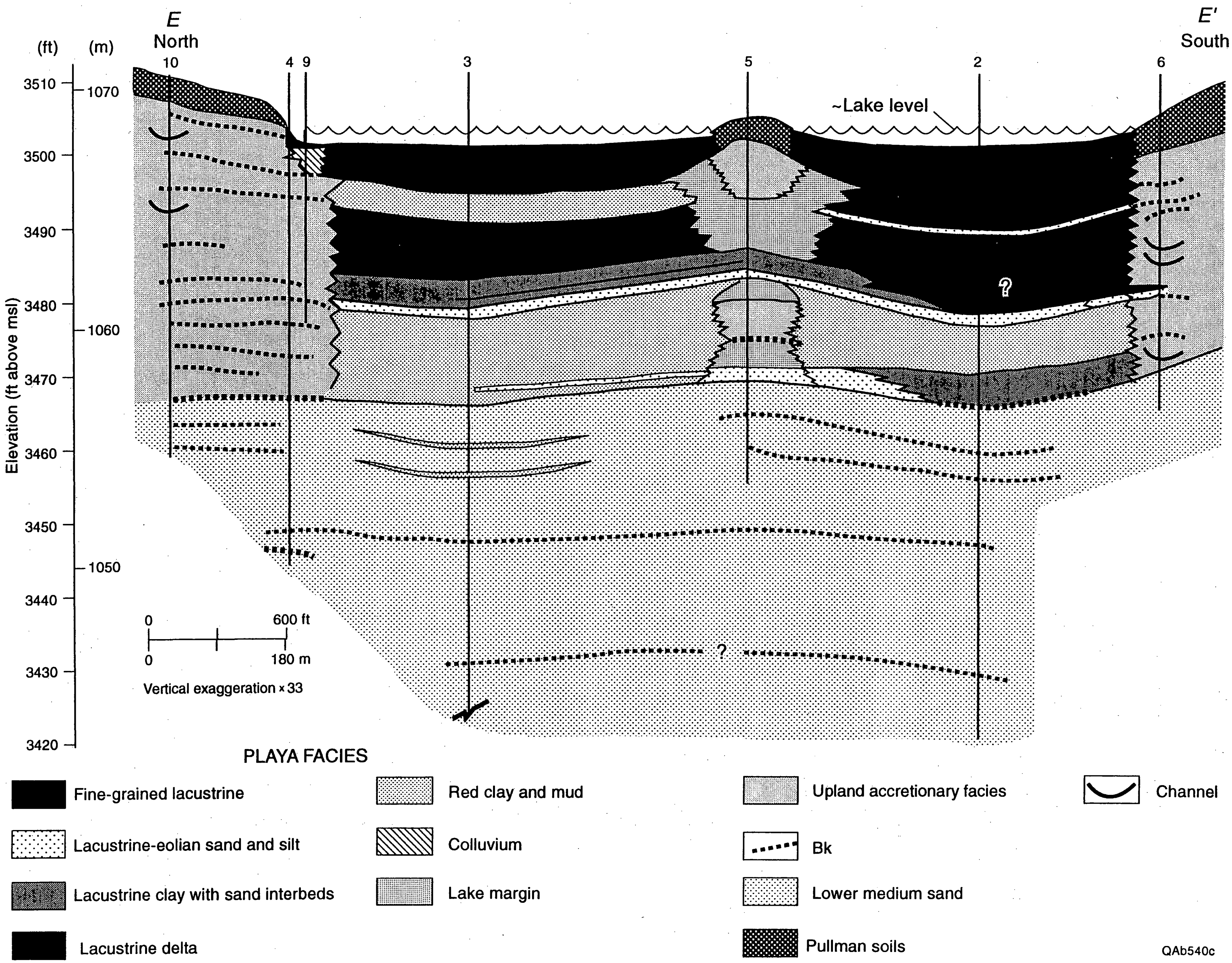

Figure 33. North-south cross section E–E′ of Vance playa basin. Line of section shown in figure 32.

The next episode of lake enlargement is marked by interbedded sand and clay in the lakes and across the peninsula. This lake expansion is also recorded by a few preserved beds of interbedded red clay and sand on the south shore of the lake. Beneath the south lake, sand infilled 1.4-m-deep cracks into the underlying clay. Beneath the north basin, red clays were reduced to green colors along fractures. The sand and clay unit is thickest and has the least pedogenic disruption beneath the north lake. In the lakes, the lacustrine–eolian sand grades upward into gray lake clays. In the north lake these clays have been strongly oxidized to form red clays; in the south lake only fractures are oxidized. The peninsula and lake shore accumulated red silty clays and accretionary eolian facies.

The next episode of lake rise is represented by a few thin sand beds beneath the lake, although they do not appear to influence sediment accumulation as far up on the peninsula as the borehole location. Above this sand bed, dark gray clay accumulated. Organic material and roots are abundant beneath the north lake. The south lake contains some carbonate filaments in the lower part. Several thin silt beds mark the base of the episode of accumulation of modern lake sediments, on which the Randall clay soil is developed. Sand in sediments beneath the peninsula contains abundant fine manganese nodules. The fine grain size, good sorting, and atypical occurrence in slope facies suggest that the fine manganese nodules may have been deflated from the lake floor.

Sevenmile Basin

The large Sevenmile Basin has an average-size modern playa in the northwest corner. The Sevenmile Basin cross-section transect extends from the south margin of the basin onto the floor of the playa, then turns eastward to characterize the lateral heterogeneity within playa sediments (fig. 34). A seismic reflection line collected across Sevenmile Basin shows 110 m of relief on Permian and Triassic bedrock and decreasing relief on overlying Ogallala reflectors, demonstrating long-term and deep-seated origins of the basin, possibly related to slow subsidence caused by dissolution of underlying salt (Paine, 1994).

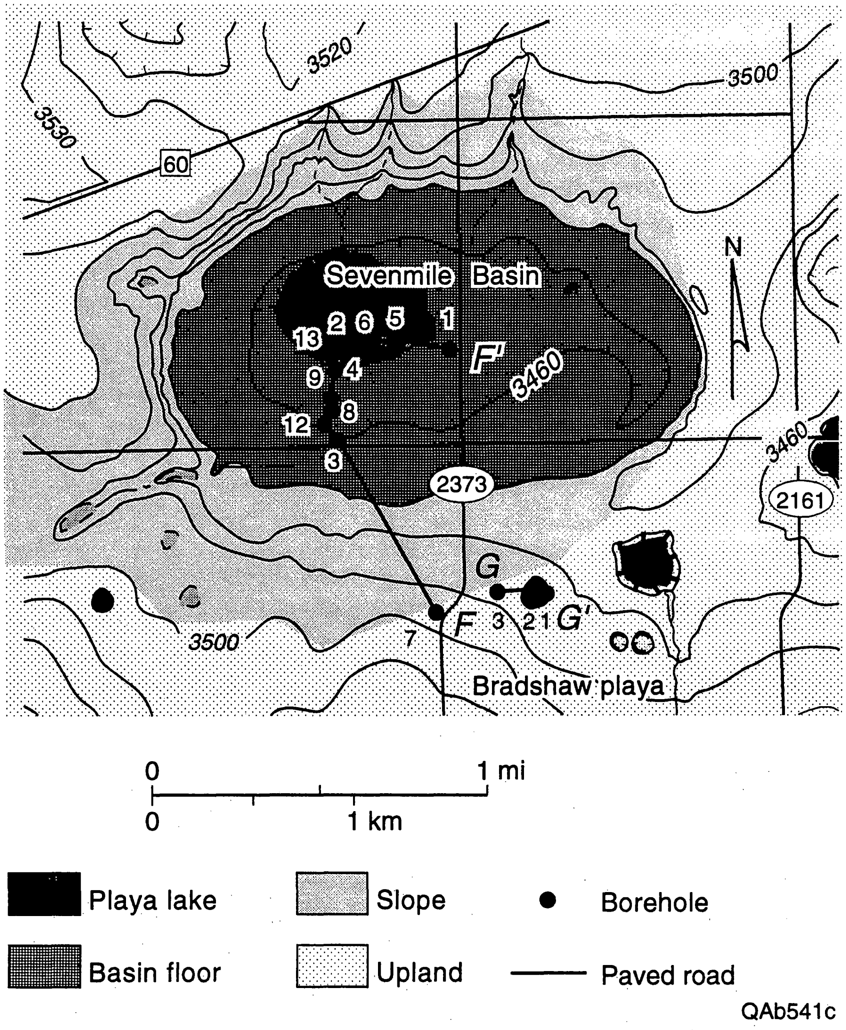

Figure 34. Sevenmile Basin topographic map of well locations. Location of playa basin shown in figure 3. Cross section F–F′ and G–G′ shown in figures 35 and 36, respectively.

Although the fine sand unit was penetrated by boreholes drilled to auger refusal, no Caprock was encountered (fig. 35). Soil carbonate is moderately abundant in the lower sand both in the upland and beneath the basin. Red clay beds within the lower sand were encountered by two boreholes in the basin. Whereas correlation of one of these beds as shown in figure 35 would indicate subsidence of the basin center relative to the basin margin, other interpretations not requiring subsidence are possible. Laminated sands and caliche pebble conglomerates occur in the upper part of the lower sand beneath the playa. Minimal soil formation suggests rapid deposition; facies are characteristic of lake margin (or, possibly, draw) depositional environments.

Sevenmile Basin lacustrine sediments, 20 m thick beneath the modern playa, are composed of complexly interbedded clays and sands (fig. 35). Two thick lacustrine depositional units were identified. The lower unit has interbedded sand and clay containing abundant slickensided fractures; sand–clay admixtures; and mottled, bleached, or red staining, all suggesting repeated or prolonged episodes of pedogenesis or postdepositional alteration. The upper unit has generally dark colors in lacustrine clays and variable low to moderate pedogenic overprint. Sevenmile Basin fill, unlike that observed in TDCJ playa basin, does not show interbedding between upland and playa lake sediments at the scale at which the cores were spaced. Instead, the lake facies appear to have occupied an increasingly larger area through time. Stratigraphic complexity within the lake section demonstrates high-frequency changes in lake level and lake size through time.

The Sevenmile Basin lacustrine sediments were cored on the slopes of the playa basin, 1.5 to 3 m above modern lake levels, indicating that the lake has formerly or episodically been much larger, filling most of the large depression that forms Sevenmile Basin (fig. 35). A facies of poorly sorted, poorly bedded sand having minimal pedogenesis interpreted as an alluvial or slope-wash unit is found at the contact between the lake sediments and the Blackwater Draw silty clay loam. The poorly sorted, coarse-grained alluvial sediments above lake level may affect the hydrologic behavior of the playa basin in that these sediments could potentially have

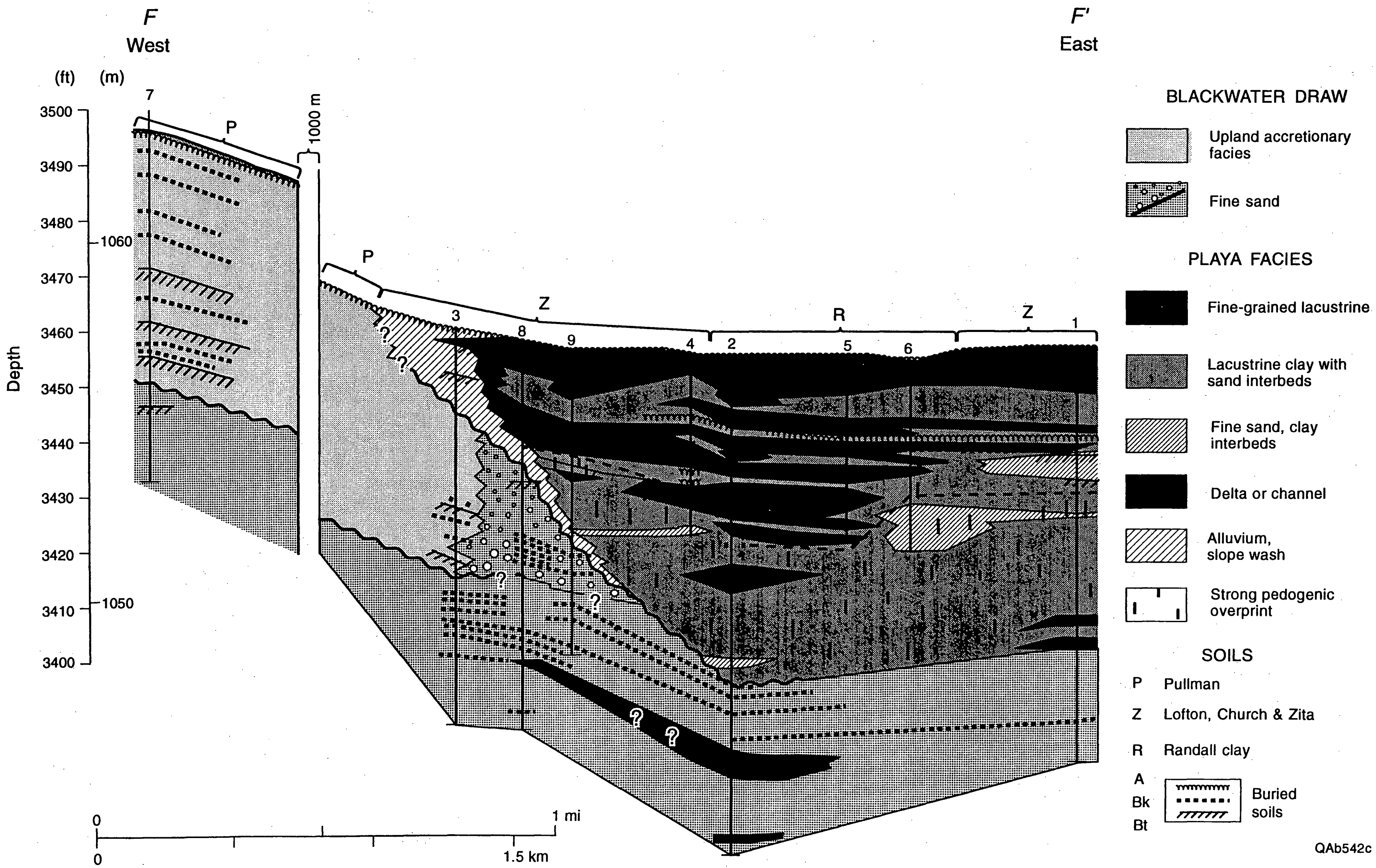

Figure 35. West-east cross section F–F′ of Sevenmile Basin. Randall clay soil (R) marks the floor of the modern playa lake. The floor of the entire basin has accumulated lake sediments in the past. Line of section shown in figure 34.

captured some surface flow from upland areas before it reached the playa lake. Sevenmile Basin lacustrine sediments interfinger with alluvial or slope-wash sediments on the south margin, containing small-scale sediment-filled faults. These faults are interpreted as evidence of down-slope creep, demonstrating that the topography resembled the present topography during basin infilling. Delta sediments are found interbedded with lake sediments beneath the modern playa. Because the coarse-grained material of the delta is deposited at the lake shore, this delta shows that the lake intermittently shrank to a size smaller than that of the present lake. However, the decrease in lake size was relatively brief, compared with that at TDCJ playa basin, because no wedge of Blackwater Draw upland eolian silty clay loam accumulated.

Lacustrine sediments in Sevenmile Basin show a systematic vertical evolution. The lower half of the lacustrine section contains lake sediments that have a strong pedogenic overprint, indicating prolonged exposure and soil development alternating with flooding of the playa. Most of the upper half contains abundant sand partings and interbeds. Pedogenic overprint is minor. Dark, organic-rich clay horizons are interpreted as possibly preserved soil A horizons. During deposition of the upper unit, dunes or eolian sand sheets migrated across the playa lake floor when the lake was dry, depositing abundant sand beds and laminae. The dry episodes, however, were not prolonged enough during which to develop strong soil textures. The upper 1 to 2 m of lacustrine clay sediment contains no sand beds and has minimal soil textures, although deep, clay-filled healed cracks are observed in the clay. This systematic variation of textures may indicate an evolution of the playa lakes from a period when they were originally flooded for relatively short or infrequent episodes (strongly ephemeral conditions) to the present when they are relatively frequently flooded or flooded for long periods (moderately ephemeral conditions).

Pedogenic carbonate composes several percent of some lake sediments. In areas not beneath the present playa but on the floor of the basin (for example, in Borehole No. 1) carbonate occurs as nodules in the older, more pedogenically altered sediments and as films and coats on ped surfaces in the younger, less altered sediments. Lake clays in this core appear to be much drier than similar clays beneath playas, ranging from dry and crumbly to dry and hard. Somewhat moist layers were encountered at depths between 0.5 and 1 m and at about 5 m. Carbonate content, minimal near the surface, increases abruptly beneath the modern Lofton and Church soils at a depth of 1.5 m (fig. 35). Beneath the playa lake, carbonate nodules in the lower pedogenically altered clays are somewhat less abundant and appear more corroded than those from Sevenmile Basin Borehole No. 1. In the overlying, less altered clay, carbonate content is lower and appears to be mostly disseminated through the clays. Carbonate is minimal in the Randall clay soils at depths of less than 1 m.

Bradshaw Playa

Bradshaw playa, a small lake lacking a basin, is found in the upland south of Sevenmile Basin (fig. 34). This lake was cored to provide information about the subsurface of the smallest end member of the spectrum of playas. Because the center of the playa was not dry during the drilling period, the south slope and lake margin were cored.

The lower sand was cored beneath the playa and slope (fig. 36). Although carbonate beds are slightly better developed beneath the slope than beneath the playa, carbonate is still abundant beneath the playa. A thick carbonate was cored at the contact between the sand and the overlying Blackwater Draw. This carbonate is flat lying.

Five Bk horizons were identified in the Blackwater Draw Formation on the slope. The lower Bk horizon is flat lying, the next three dip toward the lake center, and the upper one is truncated by the lake.

Lake sediments near the lake margin are 4.8 m thick. The lowest bed is red silty clay lake shore facies, overlain by a thin wedge of upland facies. The next lake sequence (base 4 m below the modern lake) has sand admixed with silt and gray clay at its base. The gray clay is intensely fractured, containing roots and fungus coats on peds. The upper 2 m of gray clay, less cracked than the underlying unit, has about 1 m of Randall clay soil profile developed on it.

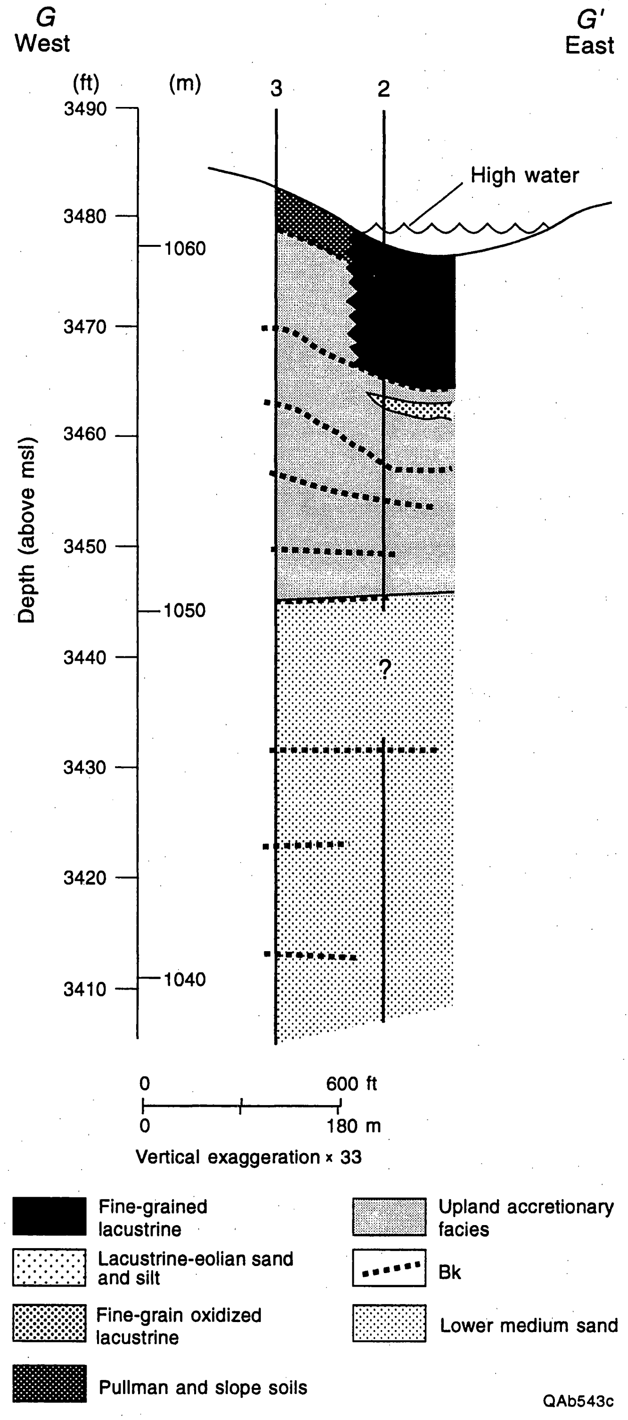

Figure 36. West-east cross section G–G′ of Bradshaw playa. Line of section shown in figure 34.

Dip on the Bk horizons and the analogy between facies seen in this lake and those seen in larger lakes suggest that the lake section might be thicker in the center of this small lake.

Finley Playa

Finley playa is an example of a small, shallow playa basin from Armstrong County southeast of the Pantex area (fig. 37). Although it was selected in order for workers to experiment with various types of drilling and initial sampling procedures, it is included in this study because it provides information about regional variability of playa basin stratigraphy. It was sampled along an east-west transect from upland to playa center.

The playa fill has more sand beds in the playa center than do other playa sections (fig. 38), and the lacustrine section is thinner than any except that of Bradshaw. Core density is insufficient to demonstrate the nature of the contact between lacustrine units and upland Blackwater Draw facies.

SCS (Murrey) Playa

A trench excavated by the Soil Conservation Service (SCS) in a playa southeast of the Pantex Plant was examined. This playa is notable because ranchers report that in their experience, this playa has not flooded (Fred Pringle, Soil Conservation Service, personal communication, 1994). The playa center has a dense cover of grasses and weeds and well-developed hummocky gilgai topography. Soils exposed by the trench are clay rich and gray, suggesting that on a geologic time scale, ponding has occurred in this playa, resulting in preferential deposition of clay suspended load from standing water and in gleying and preservation of organic carbon. The trench near the center of the playa encountered abundant soil carbonate in gray clayey soils at a depth of about 50 cm below the surface. This shallow a carbonate accumulation has not been found in other playa trenches or boreholes examined in our studies. Carbonate in soils might be related to decreased flushing because of low frequency

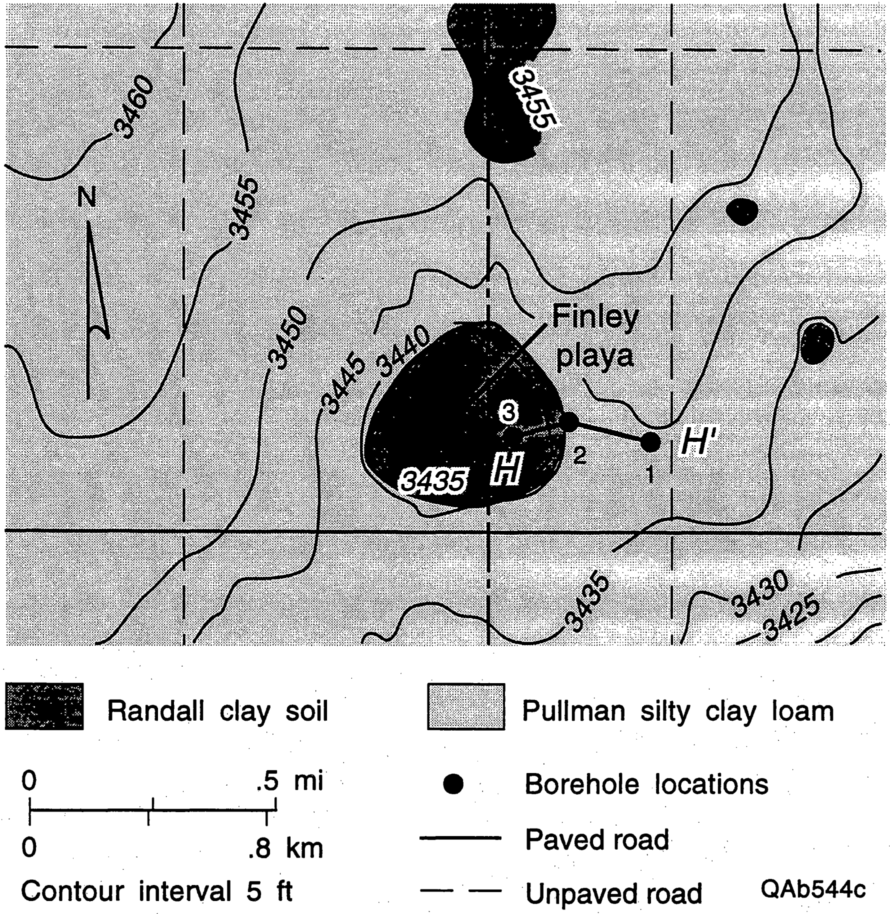

Figure 37. Finley playa basin topography and soils map. Location of playa basin shown in figure 3. Cross section H–H′ shown in figure 38.

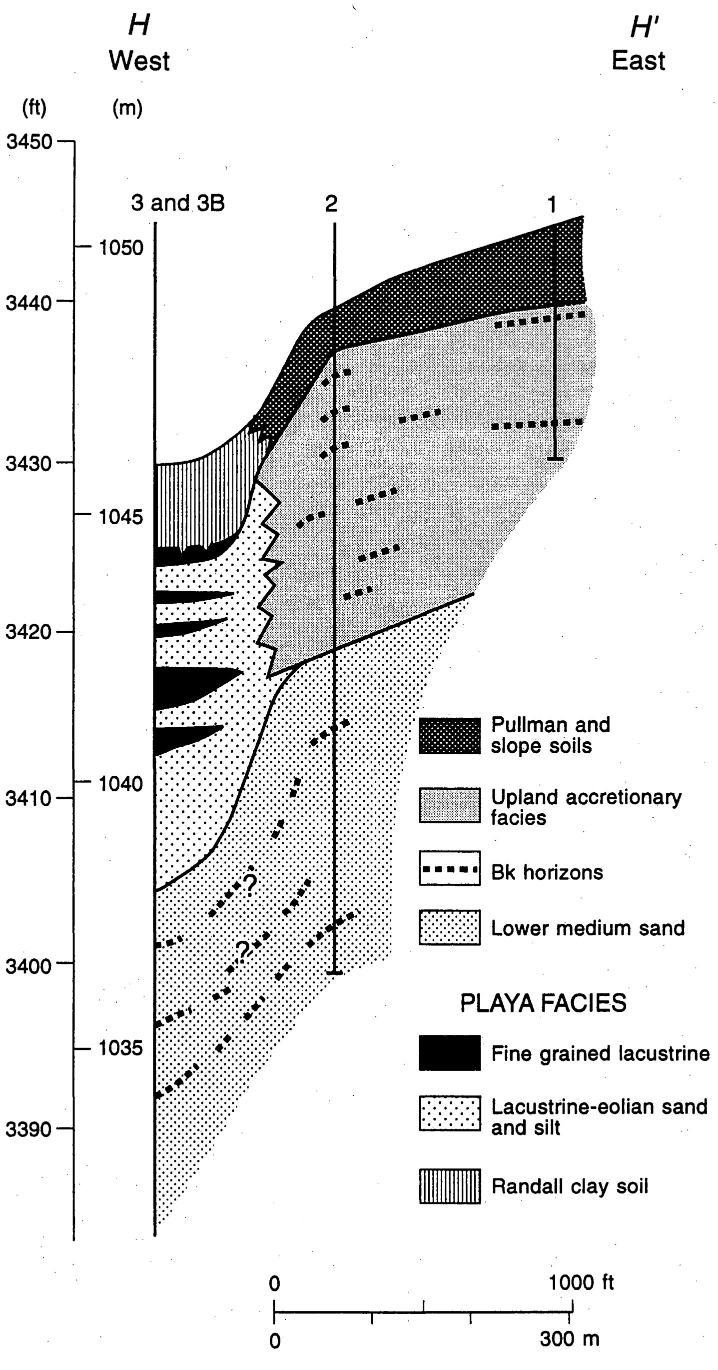

Figure 38. West-east cross section H–H′ across Finley playa basin. Line of section shown in figure 37.

of ponding. At a depth of about 1 m in the trench, red-brown silty clay soils were encountered. This facies is commonly encountered in annulus and lake margin sites in other playas; only at this site was it observed in the center of the playa. If this red-brown facies exists at depth throughout the playa, then before development of the modern playa, a prolonged episode occurred during which the playa was even less frequently ponded than at present, preventing organic accumulation and gleying. A ponding test was attempted at a site about 300 m from the west edge of this playa. Available water was insufficient to create a pond on the deeply and extensively cracked dry clays of the playa.

DISCUSSION

Facies Relationships in Playa Basins

Comparison of cross sections of the playa basins examined during this study shows (1) similar features observed in all basins, (2) significant variability among basins, and (3) significant variability within each basin. Features that are seen beneath all or most of the playa basins studied probably also occur beneath playas at the Pantex Plant. The variability among and within playas can be used to infer heterogeneity in the subsurface stratigraphy beneath playas at the plant.

Features observed in all basins include (1) a thick sequence of lake clays beneath the modern playa and Randall clay soils; (2) sand interbedded with clays at depths of 1.5 to 6 m beneath the playa lake; (3) complex interbedding of clay, sand, and loam near the shoreline (annulus) of the lake, demonstrating variation in lake size during accumulation; (4) a regional sand bed at depths of 6 to 18 m below the surface; and (5) paleotopography evident on subsurface stratigraphic horizons, indicating that the present playa basin topography is partly inherited from older landforms.

Features that vary somewhat among playa basins are (1) thickness of the lake sequence, (2) percent sand interbedded and admixed with lake clays and muds, (3) abundance and geometry of lake-clay units in the lower sand, (4) amounts of leaching or nondeposition of soil carbonates beneath the playas, and (5) amount of paleotopography, which is about as variable as the present topography of playa basins.

In addition, all the playa basins vary significantly in stratigraphy, depending on where they are sampled. This information can be used to avoid overgeneralizing where borehole data are sparse. The annulus is the most highly variable, exhibiting lateral facies variability over short distances both from the shoreline toward the lake and around the lake margin. The south and east parts of the annulus at TDCJ playa contain thick sections of well-sorted sand at depths of 6 m that may be significant high-permeability layers. This facies was not sampled in other playas possibly because borehole spacing was inadequate for characterizing the annulus. The steep northwest shore of playas appears more erosional than the south shore. The modern lake shore has incised into the upland so that in the northwest annulus, below the Randall clay soils, boreholes intercept upland facies. Borehole spacing is inadequate for determining relationships between older lake sediments and upland facies on the northwest side of the lake.

Delta deposits are found at the mouths of drainages. Some parts of deltas have sandy and silty intervals of high permeability; others are mud rich. Beneath the center of lakes, lake sediments vary laterally in amount of interbedded sand and in total thickness. The amount and type of soil carbonate vary within each lake. Carbonates show evidence of (1) leaching during episodes when high water level followed low and (2) precipitation within originally low carbonate lake sediments when desiccation followed high water levels.

Distribution of Permeability in Playa Basins

One of the goals in examining playa sediments was to seek resolution of the discrepancy between (1) observed low permeability and ability to pond that are typical of Randall clay soils and (2) hydrologic observation that playa lakes focus recharge to the Ogallala aquifer. Before this study, several concepts on facilitating recharge through playas had been suggested:

(1) annular flow; (2) intermittent rapid flow through the dry, cracked playa floor; and (3) preferential flow through the clay.

The concept of annular flow suggests that most recharge would occur at high water levels in the playa lake, when water is ponded at or over the annulus. If the annulus lacks a clay layer at the surface, recharge could proceed rapidly through coarser grained soils. Annular recharge was proposed by a number of workers (White and others, 1946; Cronin, 1964; Havens, 1966; Wood and Osterkamp, 1984) to account for rapid water-level declines at high water levels (Reddell, 1994).

In this study of the subsurface of playa sediments, additional details about the annulus are documented (fig. 39). No highly permeable strata are encountered at the surface in the annulus. Clayey sediments extend to the high water level in the playas, and surface sediments on the slope are silty clay loams. Surface sediments high in the annulus are slightly thinner, siltier, and drier than their equivalents in the playa. In the TDCJ annulus trench, the surface sediments high in the annulus are more cracked, and they contain more roots than do the wetter sediments toward the playa. Slight increases in carbonate content of the soil toward the upper annulus suggest that surface sediment is not as well flushed in the annulus as on the playa floor.

Underlying the surface sediments in the annulus is a wedge of Blackwater Draw slope facies, which was observed all the way around the lake, generally at depths of 1 m or less. The Blackwater Draw slope facies contains minor amounts of carbonate, reflecting upland soil-forming processes. Although this carbonate has not been flushed, organic material has been translocated downward into the slope facies along cracks, documenting downward flux of fluids. The silty clay loam of the Blackwater Draw slope facies beneath the annulus may have somewhat higher hydraulic conductivities than the silty clay of the playa floor because of its texture or its soil microstructure. However, silty clay loam generally shows as much or more gleying and discoloration by organic material beneath the clay sediments within the playa than does the same facies beneath the annulus.

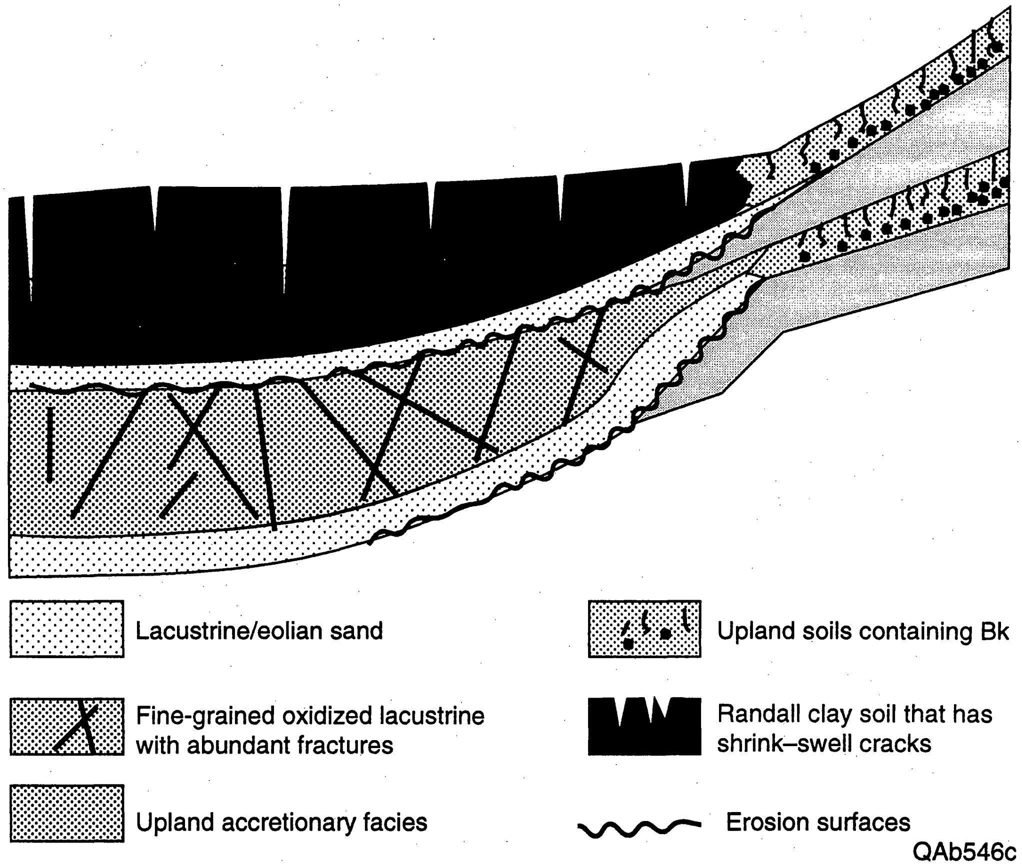

Figure 39. Schematic cross section of facies relationships at the playa margin beneath the annulus, showing interrelationships among sediments deposited at various lake levels and emphasizing distribution of potential preferential pathways in playa sediments.

Neither surface soils nor immediately underlying Blackwater Draw facies beneath the annulus therefore contain diagenetic evidence of higher downward flow of water through the annulus than through the playa floor. More complete removal of carbonate and more abundant evidence of downward translocated organic material beneath the floor of the playa suggest that more transport has occurred where ponding is prolonged. Downward fluid flow might be localized along texturally controlled or facies-controlled zones of high permeability. One such area might be where drainages have (1) eroded surface sediments, (2) complicated subsurface stratigraphy, and (3) increased potential for ponding. Two boreholes drilled into the major drainage on the north side of TDCJ playa suggest that this may be the case (fig. 29). The deltaic and interbedded sediments encountered in Borehole No. 36, near the present lake shore, were not particularly sandy, although they were damp, and carbonate appears to have been leached from Blackwater Draw facies for 15 m beneath the deltaic sediments to a total depth of 21 m. Borehole No. 9, 2,800 m up the drainage, moister than typical upland cores, has decreased carbonate in Blackwater Draw facies to a depth of 6 m. Decreased carbonate content from typical Blackwater Draw slope facies suggests that long-term recharge and leaching may be driven by ponded water in the drainage channel.

High-permeability sand units are encountered in the annulus in the marginal, older lake facies, at depths of about 6 m in TDCJ playa. These sands show abundant evidence of alteration by oxidizing as well as reducing fluids and translocation of clay; however, the timing of these diagenetic events is unconstrained. Overprinting during deposition of the overlying sediments may have created some or all of the observed alteration. In contrast, these sands could be modified by any modern recharging fluids that flowed through them.

A model of intermittent flow through the dry floor involved the large cracks that develop during desiccation of the shrink–swell clays on the playa floor as conduits, which enhance permeability. During initial flooding, these cracks transmit fluids rapidly. As the clays swell and the cracks shut, permeability decreases, decreasing the rate of flow. Initially high flow rates followed by decreased rates have been measured by means of large, small, and double-ring infiltrometers on the playa floor (Koenig, 1990; Truby, 1990; Zartman and others, 1994).

Open cracks are abundant in the near-surface clays. Cracks several tens of centimeters deep and several centimeters wide formed on the floor of TDCJ playa within 1.5 yr from when it dried out after being flooded for a prolonged period. Cracks of similar depth were observed in historically dry Murrey playa. Because the study period has not included prolonged drought, maximum crack development has probably not been observed. However, textures in cores and trenches suggest that at depths greater than about 1 m, dominant shrink–swell mechanisms produce abundant slickensided fractures. Apertures on slickensided fractures are small even where sediment was stiff because of low water, such as in Murrey playa. Rates and processes by which slickensided fractures transmit fluids have not been observed, but inspection suggests that because the fractures are abundant and well formed, they could be effective in transmitting fluid. Slickensided clays form a layer between the surface cracked zone and underlying sand beds in all playas studied. Clays appearing driest were cored in the Sevenmile Basin Borehole No. 1, which was sited on the floor of the basin but not within the playa. These clays were dry but soft and crumbly, and their hydrodynamic properties have not been documented.

Flow through the lake-clay soils occurs at rates higher than is typical in clay even after several days' ponding (Koenig, 1990; Truby, 1990) or when the soil was moist and cracks were shut before ponding (Xiang and others, 1993). Ponding tests using blue-dyed water were conducted in TDCJ playa. The ponds were then drained and trenches cut to expose the dyed areas. The distribution of dye showed that soil structures and roots transmit fluids even when soils are moist (cracks are shut), so that water penetrates to more than a 1-m depth within a few hours. Although planar soil structures were dyed blue, they were not planes of weakness under tension, as demonstrated by workers' attempts to peel the soils off in order to expose the blue surfaces. The planar surfaces were weak under shear, probably because of higher water content along the surfaces. When the trench dried out over the following months, the typically wide, deep desiccation cracks opened along the blue-dyed surfaces. No sand filling or other macroscopic textural contrasts are apparent, and the microfabrics that control cracking have not yet been documented. Transmissivity of wet clays is difficult to test because soil structures in plastic clays are easily damaged, resulting in decreased transmissivity. Additional work is needed to explain the behavior of these abundant and potentially dynamic structures.

Evidence of preferential flow abounds in playa sediments. In the surface lake clays that have Randall soils developed on them, the shrink–swell cracks and root tubules that have been observed transmitting water in short-term ponding tests are stained by dark organic material, showing that long-term translocation of organic material has occurred. These features are observed throughout the playa and in every playa sequence examined. Originally oxidized soils beneath modern and paleolake sediments are gleyed, clay illuviated, and carbonate leached, demonstrating long-term downward flow, especially along cracks and other soil structures. Although the staining and gleying probably occurred at the time the older lake sediments were accumulating, some of the older soil structures may still transmit fluids at depth. Older, stiffer, gray and red lake sediments contain numerous iron- and manganese-oxide- or hydroxide-stained fractures. Reduction adjacent to some sand beds suggests that the sands may have served as conduits. Vertical fractures served as conduits for both oxidizing and reducing fluids in permeable, well-sorted sands, as well as in low-permeability sediments. These features document that fractures dominate the entire playa section, not just the surface environment.

Effects of modern recharge have yet to be separated from diagenetic alterations produced during preceding cycles of high lake level. Many textures seem to be most easily related to the environment that produced the overlying sedimentary facies, not the modern surface environments. For example, oxidation and calcite related to former upland progradation and more ephemeral lakes are preserved as is gleying beneath older lake units. The modern episode of relatively large lakes and relatively prolonged ponding has neither pervasively reduced older sediments nor removed all previously accumulated carbonate. Either modern surface waters are at chemical equilibrium with the host sediment at shallow depths and are therefore failing to alter deeper sediments, or flow is occurring along some flow paths and bypassing the bulk of the older sediment.

Playa Basin Evolution Model

Before this study, investigators thought that small playa lakes might have formed fairly recently. In the playa basin classification of Reeves (1990), the small, round playas such as most of those in this study are interpreted as "young type I" basins on the basis of their geomorphic characteristics. Sevenmile Basin is the only playa studied that fits Reeves' criteria for "mature type II basins," and no "old, type III basins" or saline lakes are found near the study area. Playa sediments have been described as thin, surficial accumulations, and radiocarbon dating of organic material in the many sediments yields ages of less than 17,000 yr, maximum ages reaching 30,200 yr (Holliday and others, in preparation). This is only a fraction of the time of Blackwater Draw accumulation, which appears to span much of the Quaternary (Holliday, 1989; Patterson and Larson, 1990). In the Lubbock area, lunettes (small dunes fringing the playa that presumably deflated from the playa basin) overlie soils dated at 30,000 yr (Holliday, 1989). These soils have been correlated with other surface soils, suggesting that the modern land surface and Pullman and Estacado soils predate excavation of playa basins. As a corollary, playa basins are thought to have been excavated into an originally flat-lying Blackwater Draw host material (Reeves, 1990). Places where playa basins have truncated soils and Caprock caliche on top of the Ogallala (T. C. Gustavson, Bureau of Economic Geology, personal communication, 1995) appear to support an erosional model.

In contrast to these evolutionary or erosional models, detailed examination of the stratigraphy beneath seven playas in the Pantex area shows that all playa basins in this area have had a long evolution. In all but the case of small Bradshaw playa, the basin originated as a topographic depression that ponded water before, as well as during, Blackwater Draw deposition. Modern clay sediments that have Randall soils developed on them are underlain by one or more generations of lake clays. Several relationships demonstrate the long, multistage evolution of Pantex area playas:

(1) Topography on older surfaces.

The sandy facies of the lower part of the section is identified in all cores that penetrate to sufficient depth. Because this sand lies both beneath playa lakes and uplands, it may play a role in the movement of water downward from the playas. Its thickness varies from 10 to 13 m in the playa basins. The top of the sand facies rises in elevation from beneath the playa to interplaya areas, suggesting that playa basin topography is at least partly inherited from older topography. In most playa basins, the lower Blackwater Draw sand is at least 3 to 5 m higher outside the playa basin than beneath the playa floor. In Sevenmile Basin, the top of the sand facies is more than 15 m higher in upland areas south of the basin than it is on the basin floor.

Seismic data (Paine, 1994) show that many playa basins have had a long history, during which the geometry of the basin was maintained as sediment accumulated. Seismic sections through many basins in the Pantex area show depressions and sediment thickening into the basin within the Ogallala. The Sevenmile Basin depression shows the longest history, dip toward the basin center being observed on Permian and Triassic units as well as a sagging and thickening of strata at the base- and mid-Ogallala horizons.

(2) Facies changes from the upland into the basin in older sediments.

These changes demonstrate that the basin was a depression throughout Blackwater Draw accumulation. Lower sands beneath the playa floors locally contain thin red clay beds, which are interpreted as older lake deposits. Clay beds have not been cored beneath uplands. Carbonates, which are abundant beneath upland are fewer, thinner, or missing beneath the playa. Locally, bedding is preserved within the sand, indicating rapid deposition and minimal soil formation. Lake clays, flushed carbonate, and intermittent rapid sediment accumulation all suggest that during deposition of this lower unit playa basin topography was already developed, favoring ponding in playa areas.

During deposition of the overlying finer grained Blackwater Draw Formation, greater differentiation in sediment type developed between playa and upland. More clay accumulated in the depressions, prolonging and promoting ponding in the playa. Associated with ponding was accumulation of organic matter in the playa and continued flushing of carbonates from playa soils while carbonate accumulation and strong oxidation continued in the upland.

Deltaic deposits document the former break between slope and ponded water. Although they are most abundant beneath the annulus, these deposits also occur beneath and outside the modern playa, documenting migration of the shoreline. Local evidence of small-scale relief at the playa shoreline is recognized. Blocks of red Blackwater Draw sediment have been incorporated in gray lake clays at a former margin of TDCJ playa. Preservation of poorly consolidated blocks of upland sediment in older lake sediments suggests slumping from an adjacent lake shore bank. Sediment-filled clastic dikes in the subsurface of the lower slope bench at Sevenmile Basin suggest down-slope creep during sediment accumulation.

The sediments beneath the modern slopes of playa basins also suggest that the playa basins existed during Blackwater Draw accumulation. Deposits from small channels similar to modern centripetal drainages document erosion and deposition. Multiple soils in slope facies are similar in number, spacing, and degree of carbonate development to those in the upland, and they document alternating slow and less slow accumulation of eolian sediment in a grassland setting similar to modern playa basin slope environments. Correlation of paleosols parallel to the modern surface and to the surface of the lower sand is possible in most cross sections (for example, figs. 27 and 31).

(3) Interfingering upland and lake facies.

These facies document that present lakes evolved as part of the landscape during accumulation of the Blackwater Draw Formation. During at least three episodes, Blackwater Draw slope facies prograded part of the way across lake basins, depositing wedges of red-brown eolian sediment. Moderate to intense soil development, including types II or III soil-carbonate accumulations and correlation with slope and upland facies, demonstrate that these wedges are part of Blackwater Draw accumulation, not younger, discordant, reworked units. Interfingering relationships are best developed on the south and east sides of playa basins and are well displayed in TDCJ (figs. 27 and 28) and Wink (fig. 31) cross sections. Steeper and more erosional relationships on the north shores prevent these interfingering relationships from developing or from being preserved. Correlations of lake sediments suggest that subtle breaks in the character of lake sediment may be equivalent to wedges of Blackwater Draw. Breaks in character might correspond to episodes of slow sediment accumulation or net sediment erosion in the lakes. However, maintenance or reestablishment of ephemeral lakes on top of older lakes has minimized lithologic contrasts and possibly obscured the record of events at these boundaries.

Interfingering relationships demonstrate that the playa lake and playa basin have not grown or evolved along a unidirectional pathway from young to mature. Rather, these relationships show that playa basins and playa lakes in the Pantex area have generally been maintained by a long-term dynamic equilibrium. The first lake sediments deposited during the beginning of typical, fine-grained Blackwater Draw sedimentation were slightly larger, or extended farther to the south, than modern lakes. The episode following resulted in shrinkage of the lake and progradation of Blackwater Draw slope facies across the former lake. Cyclic return to enlargement of the lake caused erosion of wave-cut benches at the shoreline and deposition of thick sections of lake sediment.

(4) Soils and paleosoils parallel to present basin geometry.

Land-surface parallel structures on the slope of the playa basin imaged on the GPR survey indicate that the basin has not been cut into an originally flat landscape. Instead, aggradation of the land surface has occurred in approximate equilibrium, sediments accumulating in upland, slope, and playa environments at approximately equal rates. The older soil horizons in the playa basin slope appear to parallel the land surface and the modern soils rather than being truncated. The gentle slope of the playa basin therefore existed during previous episodes of sediment accumulation and soil formation.

Cyclic Deposition of Playa Sediments

As opposed to unidirectional growth and evolution of playa basins, the sediments beneath the playas in the Pantex area record a long history of basin maintenance as a result of cyclic episodes of rapid and slow deposition. Lake sediments record about four cyclic depositional episodes, each composed of (1) initial highstand, followed by (2) a long episode of ephemeral lake sediment accumulation, and finally (3) lake shrinkage and prolonged exposure. Sedimentary structures show that during all three phases the lake was ephemeral, as are modern playa lakes of the area, but that the length and frequency of flooding and desiccation varied, thus varying the ratio of sediment accumulation, deflation, and soil formation.

Sediments deposited during initial highstand are composed of interbedded very fine sand and organic-rich laminated mud. Tracing this unit laterally up the margins of the lake basins demonstrates deposition during high lake levels (see fig. 33). During this episode, sands blown across the dry lake bed became trapped and could not deflate when the lake flooded. Mud deposited from suspended load in the flooded lake was derived from erosion of wave-cut benches and steepened basin margins in response to high lake levels. Although episodic lake desiccation formed mudcracks and allowed additional eolian sand deposition, exposure episodes were relatively short or infrequent, and churning as a result of vertic soil formation, oxidation of organic material, and deflation were minimized.

Sediment aggradation or decreased frequency and duration of flooding created conditions similar to those under which modern lake sediments accumulate. Thin layers of eolian silt deposited across modern dry lake beds are mixed with suspended load clays during repeated episodes of wetting and drying of expansive clays. This situation is interpreted as the mechanism by which the typical massive, structureless, silty clay playa lake sediment was homogenized. Gilgai and slickensided fractures are additional evidence of wetting and drying of expansive clays. Organic material has been partly oxidized and partly translocated down soil structures and roots, and interbedded upland facies are gleyed. Slow aggradation, along with extensive pedogenic reworking, produced most of the lake sediments preserved.

Episodes when lakes were smaller are recorded by progradation of Blackwater Draw red-brown eolian loam (containing moderately developed calcic soils) across lake sediments. Because these eolian loams form on grassland slopes of playa basins during all phases of deposition, they record a decrease in the size of the playa lake and partial infilling of the basin by wedges of upland facies. In most lakes, wedges of Blackwater Draw are not found in the center of the lake, suggesting that lake environments were maintained in the center of the basin. Murrey playa is an exception because red-brown facies were trenched in the center of the playa. Correlation between the upland and lake sections suggests that little or no lake sediment accumulated at the time Blackwater Draw wedges were accumulating. Subtle breaks in the lake section are shown by reddening of originally gray clays and formation of weak calcic horizons within lake clays. One model for sedimentation at this time would be that decreased rainfall caused playas to flood less frequently. Slope wash might have decreased because storm intensity or frequency decreased, and eolian deflation from the floor of the playa might have increased, causing minimal sediment aggradation on the playa floor. Alternatively, the episode of Blackwater Draw progradation into the playa might have concluded with an episode of eolian erosion that deflated any accumulated lake sediments.

Cyclic sedimentation proposed by this model is driven by changes in climate that control frequency and duration of playa flooding. The net effect of cyclic sedimentation is that the area and depth of the playa lake increased at the expense of the basin slope during wetter episodes, and thick sections of lake sediments accumulated (fig. 40). During initial phases of lake expansion, sands were trapped during frequent flooding events. Soil formation was minimized at this time because of frequent high water and rapid sediment accumulation. Erosion from the slopes may have been enhanced as a result of wave-cut-bench formation and consequent oversteepened slope profiles. As the lake infilled with sediment, soil formation increased because of more frequent exposure, and bedding was destroyed, incorporating silt

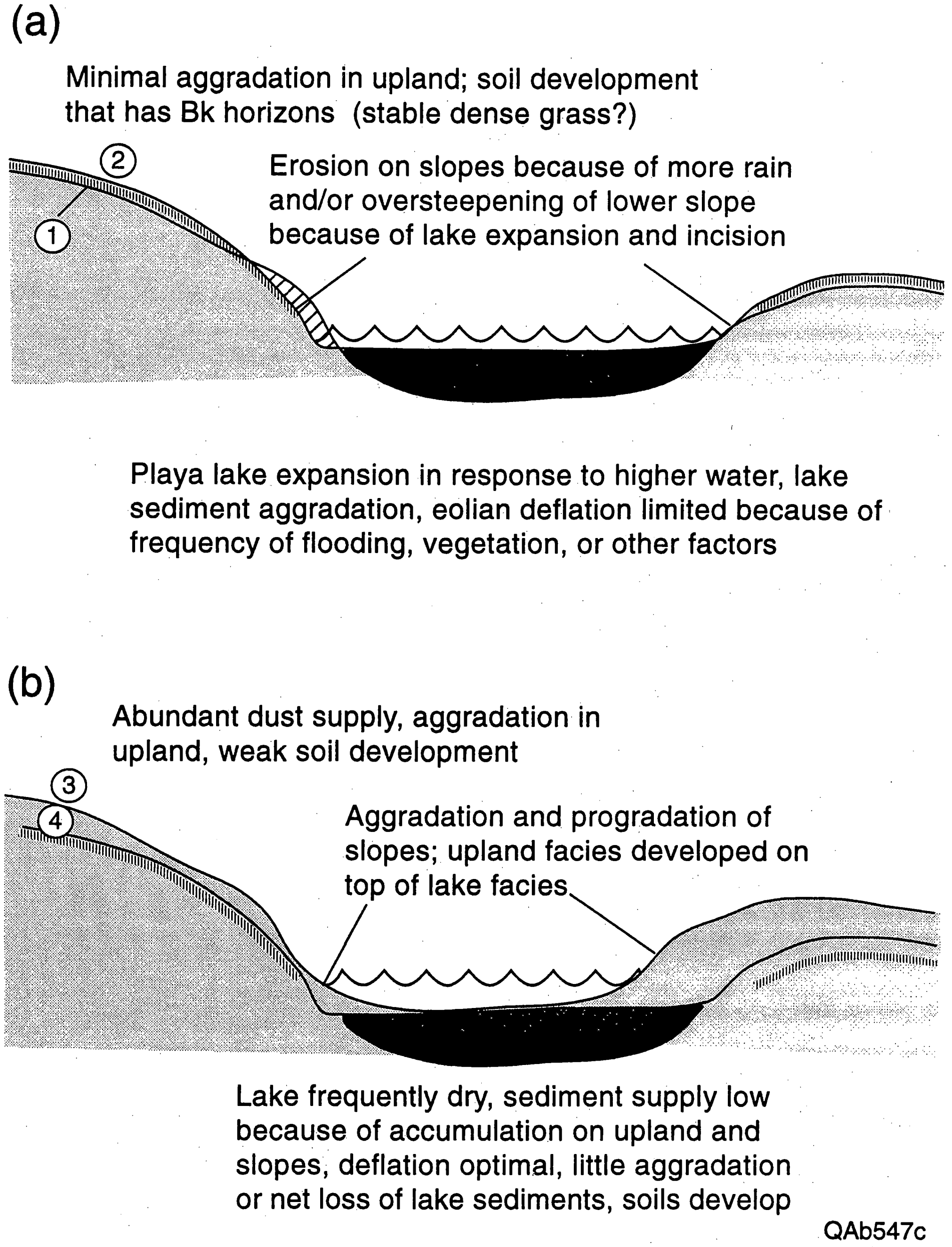

Figure 40. Conceptual model of the evolution of playa basins, showing alternating episodes of lake expansion and lake shrinkage. (a) Lake expansion results in erosion of the shoreline because wave-cut benches form and the slope oversteepens. This erosion supplies the sediment that accumulates in the playa. (b) During drier episodes, shrinkage of the lake allows deposition of Blackwater Draw eolian grassland facies out across the former lake sediments. Little or no lake sediments accumulate, and older lake sediments are partly oxidized and may accumulate some soil carbonate.

into the lake clays. During drier episodes, lake size decreased, and upland sediments began infilling the basin. However, deflation from the floor of the frequently dry lake maintained the depression. The next wet episode modified and partly reworked the wedges of Blackwater Draw, returning the profile to an earlier geometry.

Episodes of lake growth and shrinkage and deflation of playa lakes in the Pantex area parallel the evolution of larger saline lakes, such as Double Lakes (Vincent, 1991). This saline lake, originating toward the end of Ogallala deposition, records multiple episodes of lake accumulation and deflation. Although the ground-water regime in the saline lakes may be significantly different from that of playas, as evidenced by spring deposits and accumulation of solutes, some of the same climatic controls on sedimentation may be present.

Origin of Playa Basins

Although the evolutionary history proposed by this study moves the ultimate origin of the playa basins back in time, it does not demonstrate an origin of the basins. The dynamic equilibrium model of playa evolution explains the processes by which the basin is maintained as a depression. Playa basins might originate by a variety of processes (as reviewed by Gustavson and others, 1995). Localized salt dissolution is probably required by the deep structure observed on seismic sections beneath Seven Mile Basin (Paine, 1994). Other basins originated within the Ogallala, and might be related to Ogallala depositional patterns or to salt dissolution during Ogallala deposition (J. G. Paine, Bureau of Economic Geology, personal communication, 1994). Depressions that originate at the top of the Ogallala associated with the lower sand might be blowouts in areas where the Caprock was not developed. Whatever the origin of the depression, once it has formed, cyclic sedimentary processes tend to maintain it.

Limits of Study

Because playas in the Pantex area may not be typical of the entire Southern High Plains, results obtained from them cannot be extrapolated with confidence to other playas. The Blackwater Draw Formation, which hosts the playa sediments, is unusually thick in the Pantex area, typically more than 25 m, as compared with 10 m at the type section north of Lubbock and less toward the margins of the High Plains (Holliday, 1989). Grain size of the surface sediments is fine in the north part of the Southern High Plains and becomes coarser toward the Pecos and Canadian Rivers, the presumed sources (Seitlheko, 1975). Randall clay and related soils are mapped on floors of playas throughout the Southern High Plains; however, the similarity of these soils in terms of thickness, mineralogy, and grain size have not been tested and may also vary depending on proximity of sediment sources. The thick sections (as much as 20 m) of clay soils beneath playas in the Pantex area may not be typical of playas in other parts of the High Plains.

CONCLUSIONS

Playa basins in the Pantex area accumulated heterogeneous sediments through much of the Pleistocene and Holocene. Vertical heterogeneities resulting from changes in sediment supply, lake expansion and contraction, delta progradation, and variation in the intensity of soil development document climatic fluctuations. Lateral heterogeneities reflect the asymmetry of playa basins, localized sediment input, and variation in the amounts and types of sediment reworking. The playa basins studied developed during the early or middle part of Blackwater Draw sedimentation. Since that time, playa lake sedimentation and upland eolian accumulation have been in dynamic equilibrium so that upland–basin geometry has been maintained.

Complex patterns of clay oxidation and reduction and calcite precipitation and dissolution document the interaction between ground water and playa sediments. Recharge to the perched and Ogallala aquifers may be influenced by areas of increased permeability, such as mineralized fractures or eolian sand layers within lacustrine clays, lacustrine delta facies, or upland silty loam facies interfingering with lacustrine clays. Hydrologic testing is required to determine the extent to which these features serve as preferential pathways for recharge of surface waters.

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