GENETIC STRATIGRAPHY OF THE DOCKUM GROUP (TRIASSIC),

PALO DURO CANYON, PANHANDLE, TEXAS

APPROVED

J. H. McGowen

Alan J Scott

W. E. Galloway

Robert L. Folk

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by

STEVEN JOHN SENI, B.S.

THESIS

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Steven J. Seni

ABSTRACT

The Triassic Dockum Group is a complex assemblage of lacustrine, deltaic, and fluvial facies. Excellent exposures of these rocks were studied in and around Palo Duro State Park where the Prairie Dog Town Fork of the Red River and its tributaries have carved a network of steep-walled canyons. Three-dimensional exposures of the Dockum have permitted study of lateral as well as vertical facies relationships.

Three progradational genetic sequences were delineated within the study area. A genetic sequence consists in ascending order of: lacustrine mudstone, deltaic siltstone-sandstone-conglomerate, and fluvial sandstone-conglomerate.

The following three lines of evidence indicate that complex base-level changes, caused by fluctuations in lake area and depth, occurred during deposition of the Dockum Group. Within the first genetic sequence burrowed lacustrine mudstones are interbedded with caliche horizons. These caliche horizons contain discrete burrowed and pisolitic carbonate nodules that are composed of microspar calcite, sparry calcite, and minor dolomite. Silicified evaporite nodules occur at the base of this unit. The second genetic sequence comprises a progradational lacustrine delta system which was truncated by a valley-fill system which formed in response to diminished lake depth and area. The valley-fill system comprises a transgressive fluvial-deltaic-lacustrine sequence encased within an overall progradational sequence. The third genetic sequence is composed of classic "Gilbert-type" lacustrine deltas with prominent foreset beds indicating deposition in 8 to 15 m of water.

Ephemeral lakes characterized the first and second progradational sequences. Lacustrine fan deltas formed in water 1 to 10 m deep. The third progradational sequence was deposited in more continuously deep-water (10-20 m) lakes. A vertical sequence through Dockum Group rocks reveals a change from alternating humid and arid conditions of the first and second progradational sequences toward continuously humid conditions which prevailed during deposition of the third progradational sequence.

TABLE OF CONTENTS

LIST OF FIGURES

Figure | Page

INTRODUCTION

The Triassic Dockum Group is a complex assemblage of predominantly terrigenous clastic and minor chemical rocks, which accumulated in a shallow, continental interior basin. In the past the depositional environments have been broadly defined as continental (Cummings, 1889, 1891a,b; Drake, 1891; Gould, 1906, 1907; Adams, 1929; Green, 1954; Kiatta, 1960; Cazeau, 1960, 1962; Cramer, 1973; and Asquith and Cramer, 1975). Recently, lacustrine, deltaic, and fluival depositional systems have been recognized and described (McGowen, Granata, and Seni, 1975, 1977, 1978, in press; Boone, 1978a, 1978b, in preparation).

The main purpose of this study was to determine the genetic stratigraphy of the Triassic Dockum Group exposed within the Palo Duro Canyon area. Depositional systems and component depositional facies were identified. The mineralogy, texture, sedimentary structures, and spatial relationships of all Dockum sedimentary rock types were studied. Holocene and ancient depositional models were then used to interpret depositional systems and genetic sequences, and to explain the distribution of facies.

This study focused on a small area of Dockum outcrop, mainly within Palo Duro State Park, and is a part of a much larger regional study of the Dockum Group by the

Bureau of Economic Geology. The regional study is aimed toward understanding geologic factors that control occurrence and distribution of uranium in the Dockum. Genetic stratigraphy as expressed in sandstone body geometry and depositional systems, aids in understanding several factors which may control uranium distribution in the Dockum. Genetic stratigraphy is the main emphasis of this study.

Study Area and Methods

The eastern margin of the High Plains (Llano Estacado) Physiographic Province in the Texas Panhandle is coincident with the outcrop of the resistant Tertiary Ogallala Formation. The North-central Texas Rolling Plains, east of the Llano Estacado, is underlain by Triassic and Permian formations. The Triassic Dockum Group crops out along a narrow, north-south oriented belt below the High Plains "Caprock" escarpment. The Dockum outcrop belt marks the eastern margin of the preserved Dockum basin which extends beneath the High Plains to the west. Rocks of Quaternary, Tertiary, Triassic, and Permian age are exposed within valleys which have been cut into the High Plains escarpment. The study area is located within Palo Duro Canyon, one such valley in Randall and Armstrong Counties (Figure 1).

Most of the study area is within Palo Duro State

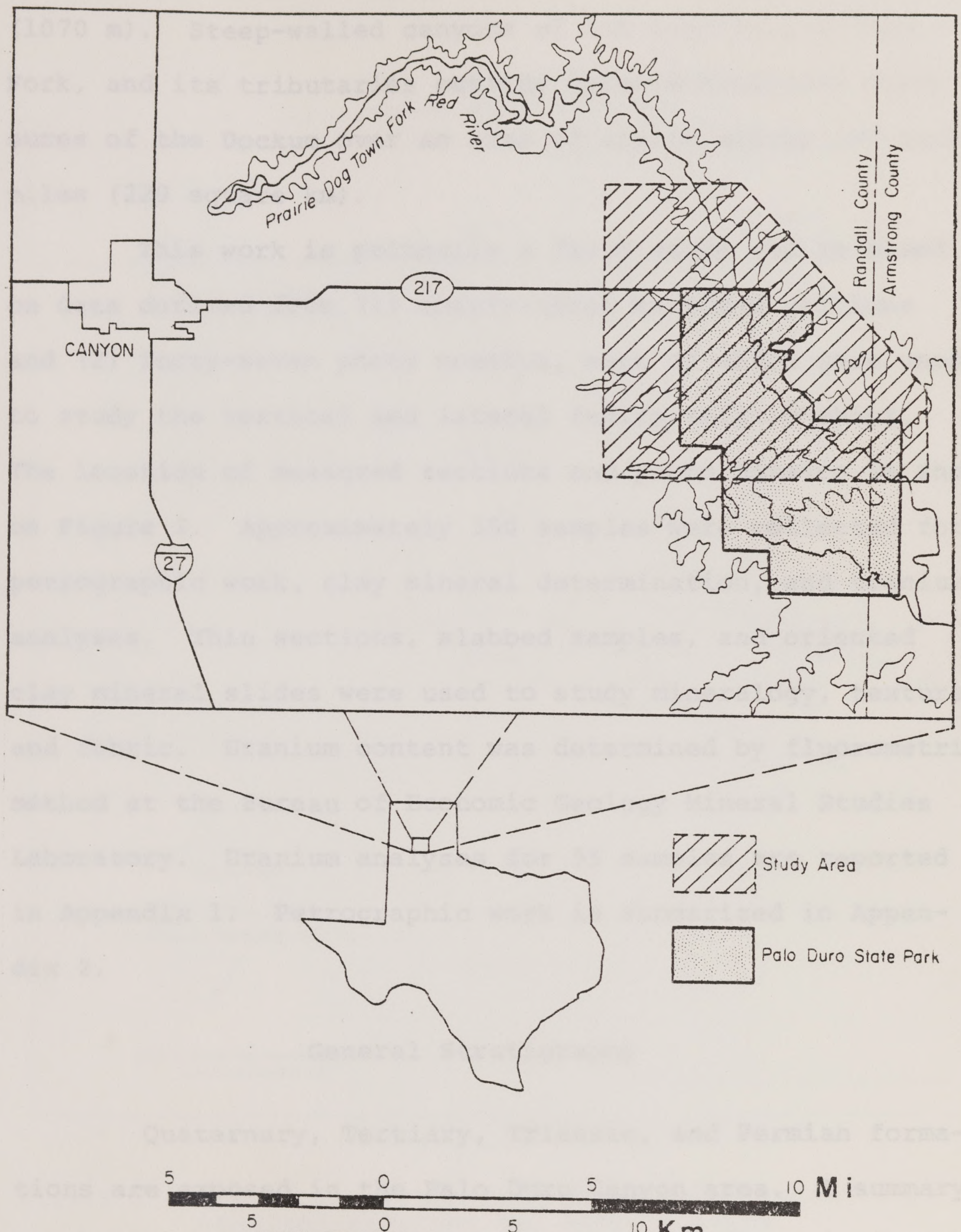


Figure 1. Map of the study area.

Park where elevations range from 2700 ft (820 m) to 3400 ft (1070 m). Steep-walled canyons of the Prairie Dog Town Fork, and its tributaries provide three-dimensional exposures of the Dockum over an area of approximately 100 square miles (220 square km).

This work is primarily a field study and is based on data derived from (1) thirty-three measured sections and (2) forty-seven photo mosaics, both of which were used to study the vertical and lateral facies relationships. The location of measured sections and photo mosaics is shown on Figure 2. Approximately 350 samples were collected for petrographic work, clay mineral determination, and uranium analyses. Thin sections, slabbed samples, and oriented clay mineral slides were used to study mineralogy, texture, and fabric. Uranium content was determined by fluorometric method at the Bureau of Economic Geology Mineral Studies Laboratory. Uranium analyses for 55 samples are reported in Appendix 1. Petrographic work is summarized in Appendix 2.

General Stratigraphy

Quaternary, Tertiary, Triassic, and Permian formations are exposed in the Palo Duro Canyon area. A summary of the characteristics of the exposed formations is shown in Figure 3. These units were mapped and described re-

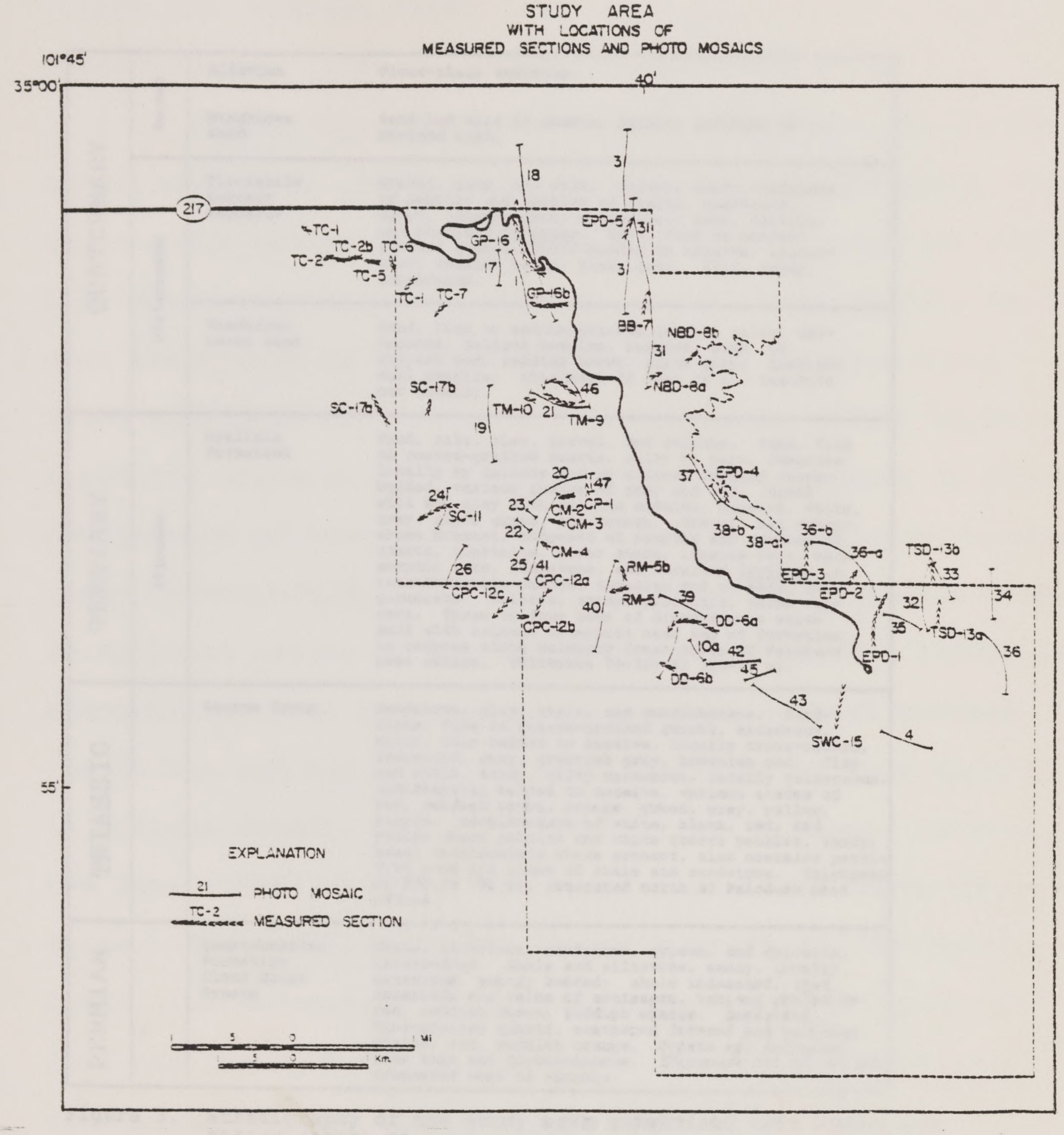


Figure 2. Map of the study area showing the location of measured sections and photo mosaics.

QUATERNARY	Recent	Alluvium	Flood-plain deposits.
		Windblown sand	Sand and silt in sheets, locally modified by surface wash.
	Pleistocene	Fluviatile terrace deposits	Gravel, sand, and silt. Gravel, sandy, composed of pebbles and cobbles of quartz, quartzite, chert, igneous rock, metamorphic rock, caliche, and abraided Gryphaea. Sand, fine to coarse-grained quartz, cross-bedded to massive, lenticular, reddish brown, pink, gray. Silt, sandy, lenticular.
		Windblown cover sand	Sand, fine to medium-grained quartz, silty, calcareous, caliche nodules, massive, pink to grayish red, reddish brown, olive gray; distinct soil profile; thickness 25 feet (8 m), feathers out locally.
TERTIARY	Pliocene	Ogallala Formation	Sand, silt, clay, gravel, and caliche. Sand, fine to coarse-grained quartz, silty in part, cemented locally by caliche and by silica, locally cross-bedded, various shades of gray and red. Minor silt and clay with caliche nodules, massive, white, gray, olive green, and maroon. Gravel, not everywhere present, composed of pebbles and commles of quartz, quartzite, minor chert, igneous rock, metamorphic rock, limestone, and abraided Gryphaea in intraformation channel deposits and in basal conglomerate. Caliche, sandy, pisolitic, forms caprock. Three to four beds of diatomaceous white marl with caliche interbeds near top of formation in canyons along Mulberry Creek north of Paloduro post office. Thickness 75-300 ft (23-90 m).
TRIASSIC		Dockum Group	Sandstone, clay, shale, and conglomerate. Sandstone, fine to coarse-grained quartz, micaceous, silty, thin bedded to massive, locally cross-bedded, indurated, gray, greenish gray, brownish red. Clay and shale, sandy, silty micaceous, locally calcareous, indistinctly bedded to massive, various shades of red, reddish brown, orange, green, grey, yellow, purple. Conglomerate of white, black, red, and yellow chert pebbles and white quartz pebbles, sandy; basal conglomerate where present, also contains petrified wood and slabs of shale and sandstone. Thickness of 300 ft (90 m), truncated north of Paloduro post office.
PERMIAN		Quartermaster Formation Cloud Chief Gypsum	Shale, siltstone, sandstone, gypsum, and dolomite, interbedded. Shale and siltstone, sandy, locally micaceous, evenly bedded; shale indurated, thin interbeds and veins of satinspar, various shades of red, reddish brown, reddish orange. Sandstone, fine-grained quartz, scattered frosted and polished grains, red, reddish orange. Gypsum and dolomite beds thin and discontinuous. Thickness 300 ft (90 m), truncated west of Memphis.

Figure 3. Stratigraphy of the study area summarized from Barnes and Eifler (1968) Plainview sheet.

gionally by Barnes and Eifler (1968) at a scale of 1:250,000. Hood (1978) mapped and described formations within the Fortress Cliff 7.5 minute Quadrangle (U.S. Geological Survey, 1956).

In the Palo Duro Canyon area, the Dockum is overlain unconformably by the Pliocene Ogallala Formation which forms the caprock escarpment. In Texas the Dockum overlies Permian formations (Sellards, Adkins, and Plummer, 1932), however the nature of the systematic contact is disputed. Gould (1906, 1907), Baker (1915), and Adams (1929) emphasized the presence of a sharp contact, discordance in dip, and absence of Lower and Middle Triassic fossils as evidence for an unconformity. In contrast, Case (1922) stressed the gradational nature of the contact. Boone (1978a, 1978b, in preparation) also reported a gradational contact between the Dockum and the Quartermaster Formation at Tule Canyon in Briscoe County. In a regional study, McGowen, Granata, and Seni (1975) observed both gradational and sharp contacts. They concluded that in updip areas of the Dockum basin, the underlying rocks were eroded, and a sharp contact was formed. Toward the basin center, sedimentation was continuous between the Quartermaster and the Dockum. In the northern part of the Dockum basin (Palo Duro Canyon-Canadian River Valley areas) Permian and Triassic rocks are separated by an unconformity (Drake, 1891; Gould, 1906, 1907).

The Dockum Group in the Palo Duro Canyon area was divided by Gould (1906, 1907) into a basal shaly Tecovas Formation and an upper sandy Trujillo Formation. Some workers (Kiatta, 1960) add the Chinle Formation as the uppermost shaly unit. Drake (1891) originally described three similar units in the Palo Duro Canyon area, but he did not formally name them. The formal stratigraphic units have local distribution and were not used in this study.

Within the Dockum, genetic sequences that are defined in terms of depositional systems and genetically linked facies cut across the boundaries of formal stratigraphic units. Because of this conflict, formal nomenclature was deleted in favor of delineation of depositional systems and genetic sequences.

Previous Investigations

Previous investigations of the Dockum Group fall into four main categories: (1) stratigraphic, (2) paleontologic, (3) sedimentologic, and (4) basin analysis-genetic stratigraphic. Studies of the Dockum have evolved from lithostratigraphic and paleontologic studies during the early twentieth century to present day basin analysis and genetic stratigraphic studies.

The first workers to study the Dockum were physical stratigraphers (Cummings, 1889, 1891a, b; Drake, 1891; Gould, 1906, 1907). Cummings (1889) identified Triassic rocks in west Texas as continental and assigned these to the Upper Triassic Dockum Beds. Drake (1891) subdivided these rocks into three units. Gould (1906, 1907) divided the Dockum into a lower shaly Tecovas Formation and an upper sandy Trujillo Formation. Adams (1929) used a basin analysis approach in the first regional study of the Dockum. He identified two formations south of the thirty-third parallel--a lower sandy Santa Rosa Formation and an upper shaly Chinle Formation.

Paleontologists accompanied the original stratigraphers. Cope (1893), Simpson (1895), and Case (1922, 1932, 1933) studied vertebrate and invertebrate remains and assigned a late Triassic age to the Dockum. Case (1922, p. 8) was an early proponent of a transitional boundary between the Triassic and Permian rocks in the area.

> "On the borders of the Staked Plains as in other regions of the United States where the Triassic is exposed, there seems no possibility of determining the boundary between the Permo-Carboniferous beds and Triassic. The Red Beds are apparently continuous across the interval..."

Whereas interest in stratigraphic correlation has waned, important contirbutions continue in the field of paleontology (Daugherty, 1941; Schaeffer and Gregory, 1961; Gregory, 1962; Schaeffer, 1967; Ash, 1976; and

Elder, 1978, in preparation).

The fossil remains recovered from the Dockum Group by early workers consisted primarily of water worn and abraided fragments (Green, 1954). Simpson (1895) described six species of Unio all of which were abraided. Vertebrate remains have received the most attention from paleontologists (Cope, 1893; Case, 1922, 1932, 1933). The most abundant vertebrates are the amphibian Buettneria and the reptile suborder Phytosauria (Green, 1954). Recently, fish remains (Schaeffer and Gregory, 1961; Gregory, 1962; Schaeffer, 1967) and plant remains (Daugherty, 1941; Ash, 1976) have been described. According to Elder (1978, in preparation) although the terrestrial component of the fauna is important, most of the vertebrates were adapted for aquatic living.

Starting in the 1950's sedimentologic problems were addressed in a number of theses and short articles. Paleocurrent analyses by Green (1954), Cazeau (1960, 1962), Kiatta (1960), Cramer (1973), and Asquith and Cramer (1975) indicate southeastern or eastern sources for braided stream deposits in west Texas. Green (1954) identified some lacustrine mudstones. Petrographic and heavy mineral analyses by Kiatta (1960) and Cazeau (1962) indicate that Dockum source rocks were multicycle sedimentary rocks. Boone (1978a, 1978b, in preparation) studied the complete section of Dockum exposed in Tule Canyon, Briscoe County, Texas. He concluded that the vertical trend resulted from an overall transgressive, expanding lacustrine system.

McKee and others, (1959), utilized subsurface data in a basin analysis of the Triassic System in Texas, New Mexico, Oklahoma, Kansas, and Colorado. McGowen, Granata, and Seni (1975, 1977, 1978, in press) analyzed the regional genetic stratigraphy of the lower half of the Dockum. This study integrated a subsurface basin analysis approach with a regional depositional systems outcrop study. They concluded that: (1) the Dockum basin was filled by sediment supplied at various points around the basin margin, (2) climatic cycles altered base level by expansion and contraction of lacustrine systems, (3) deltaic and fluvial deposits filled shallow lakes, and (4) the west Texas outcrop belt is predominantly composed of deposits of fluvial depositional systems.

Other studies do not fit into the categories mentioned above. Baker (1915) initiated study of the region's ground water and included a study of the Dockum. Fink (1963) studied the ground water in the Triassic aquifers of the northern Southern High Plains. Hood (1978) mapped the surface geology of the Fortress Cliff Quadrangle in Randall County.

This brief summary of some previous works shows that the continental nature of the Dockum is unquestioned. Specific lacustrine, deltaic, and fluvial systems have been described only recently. Only the latest Dockum studies by McGowen, Granata, and Seni (1975, 1977, 1978, in press) and Boone (1978b, in preparation) have applied the modern concepts of depositional environments and genetic interpretations which are used in this investigation.

Economic Potential

The Dockum is currently a minor source of ground water for the Texas High Plains (Alexander, 1961; Fink, 1963; Cronin, 1964). Scattered uranium occurrences have been documented within the Dockum by various authors (Eargle, 1956; Finch, 1956, 1975; Hayes, 1956; Flawn, 1967; Southern Interstate Nuclear Board, 1969; Finch and Wright, 1975; McGowen, Granata, and Seni, 1975; Finch, Wright, and Davis, 1976; Nichols and others, 1976; Dickenson, Drake, and Reese, 1977; and Nichols, Kane, and Cale, 1977). Recently, both government and private uranium exploration efforts have intensified. The Bureau of Economic Geology is conducting a basinwide study of the uranium potential of the Dockum under the supervision of Dr. J. H. McGowen.

DEPOSITIONAL SYSTEMS

In the Palo Duro Canyon area, the Dockum Group is composed of: (1) lacustrine systems, (2) delta systems, and (3) fluvial systems. In the study area most of these systems produce progradational genetic sequences; only one transgressive valley-fill sequence was identified. There are three superposed genetic sequences. Each genetic sequence characteristically begins with lacustrine mudstone and ends with fluvial-deltaic sandstone-conglomerate. This reflects a minimum of three complete cycles beginning with lacustrine deposition and ending with fluvial-deltaic progradation.

Lacustrine system rocks are composed of two lithologies: (1) varicolored burrowed mudstones, and (2) calcareous zones. The burrowed lacustrine mudstones are the dominant lithology comprising 90-99 percent of the lacustrine section. Lacustrine mudstones represent deposition in lake center and lake margin environments unaffected by fluvial-deltaic deposition.

Calcareous zones comprise nodules composed of microspar calcite, sparry calcite, and minor dolomite which occur as caliche horizons that separate mudstone units. Caliche horizons formed in intermittently dry mudflats or possibly in a shallow subsurface diagenetic environment.

No vertical textural trends were identified. Characteristics of the lacustrine deposits are illustrated in Figure 4.

Delta system rocks are genetically related, texturally diverse depositional units that are grouped into 2 models (Figures 5 and 6).

Shallow-water lacustrine deltas overlie lacustrine mudstones and are capped by fluvial sandstone-conglomerate sheets deposited on delta platforms. Shallow-water lacustrine deltas are characterized by thin sequences of rocks deposited in delta front, distributary channel, and channel mouth bar environments. Abundant slump structures also characterize this sequence. These deltas prograded into water 1 to 10 m deep.

Deep-water lacustrine deltas are characterized by thick sequences of inclined delta front foresets. These inclined, wedge-shaped units are 8-15 m thick indicating that deposition occurred in a lake basin at least 8-15 m deep.

Fluvial system rocks are sandstone-conglomerate bodies that occur in two distinct geometries: (1) sheets, and (2) linear belts. Progradational deltaic sequences are capped by fluvial sandstone-conglomerate sheets that represent fluvial deposition on coarse-grained braided-stream delta platforms. The characteristics of fluvial system rocks associated with lacustrine deltas are illus-

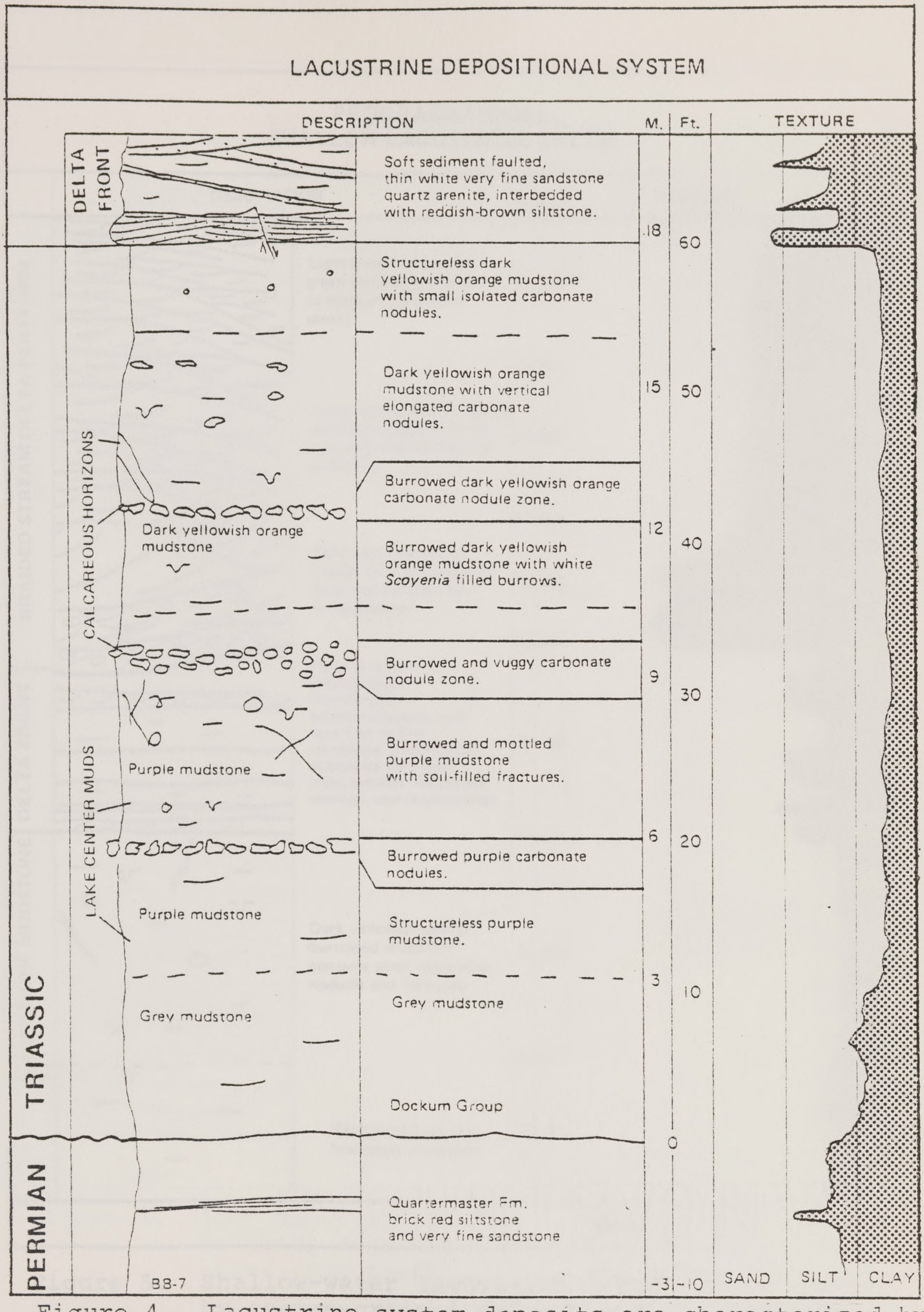


Figure 4. Lacustrine system deposits are characterized by fine-grained mudstones bearing Scoyenia and Teichichnus, and caliche horizons.

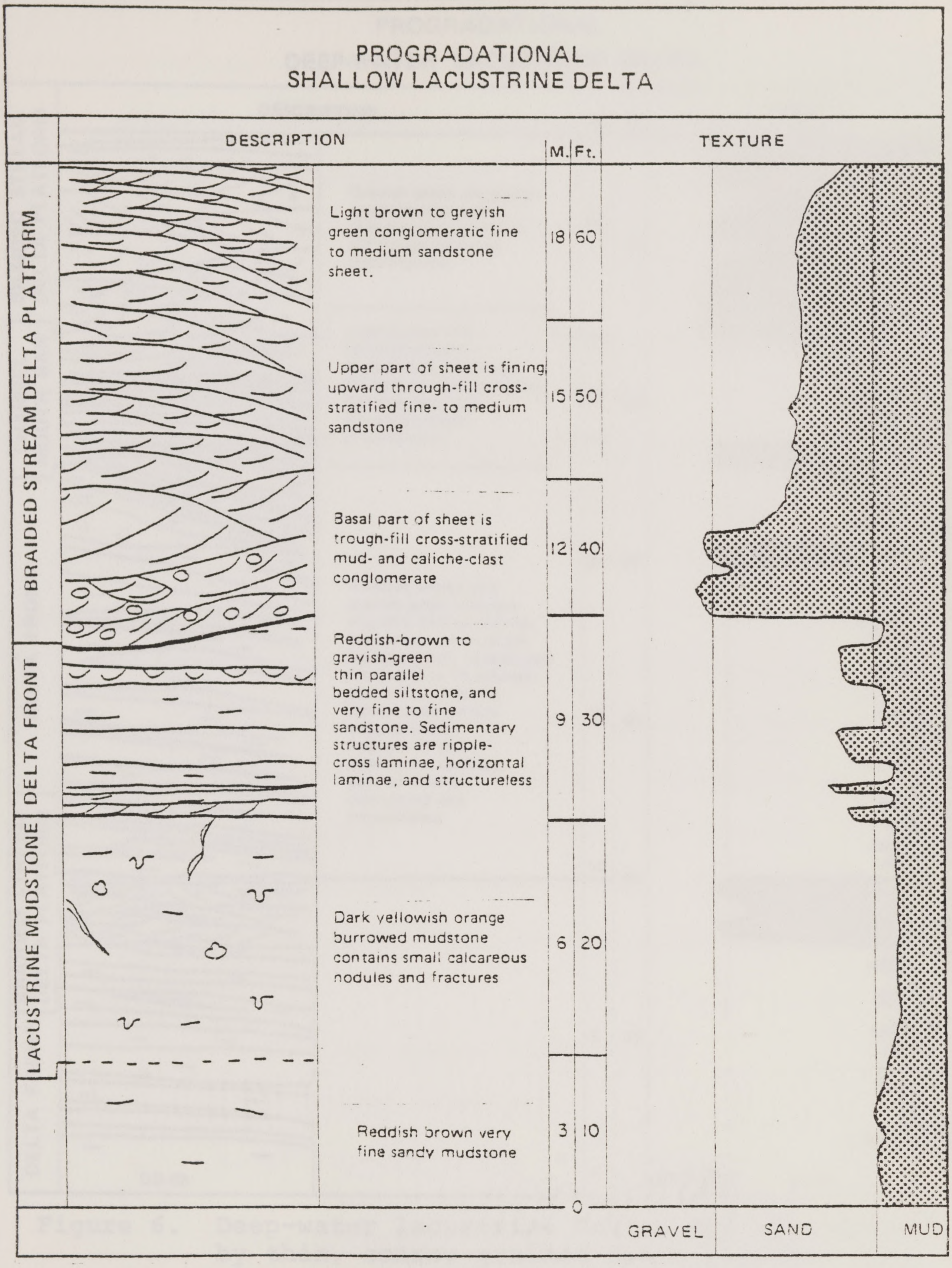


Figure 5. Shallow-water lacustrine deltas are characterized by coarse-grained delta platform sandstone-conglomerate sheets that overlie progradational coarsening-upward lacustrine and thin delta front sequences.

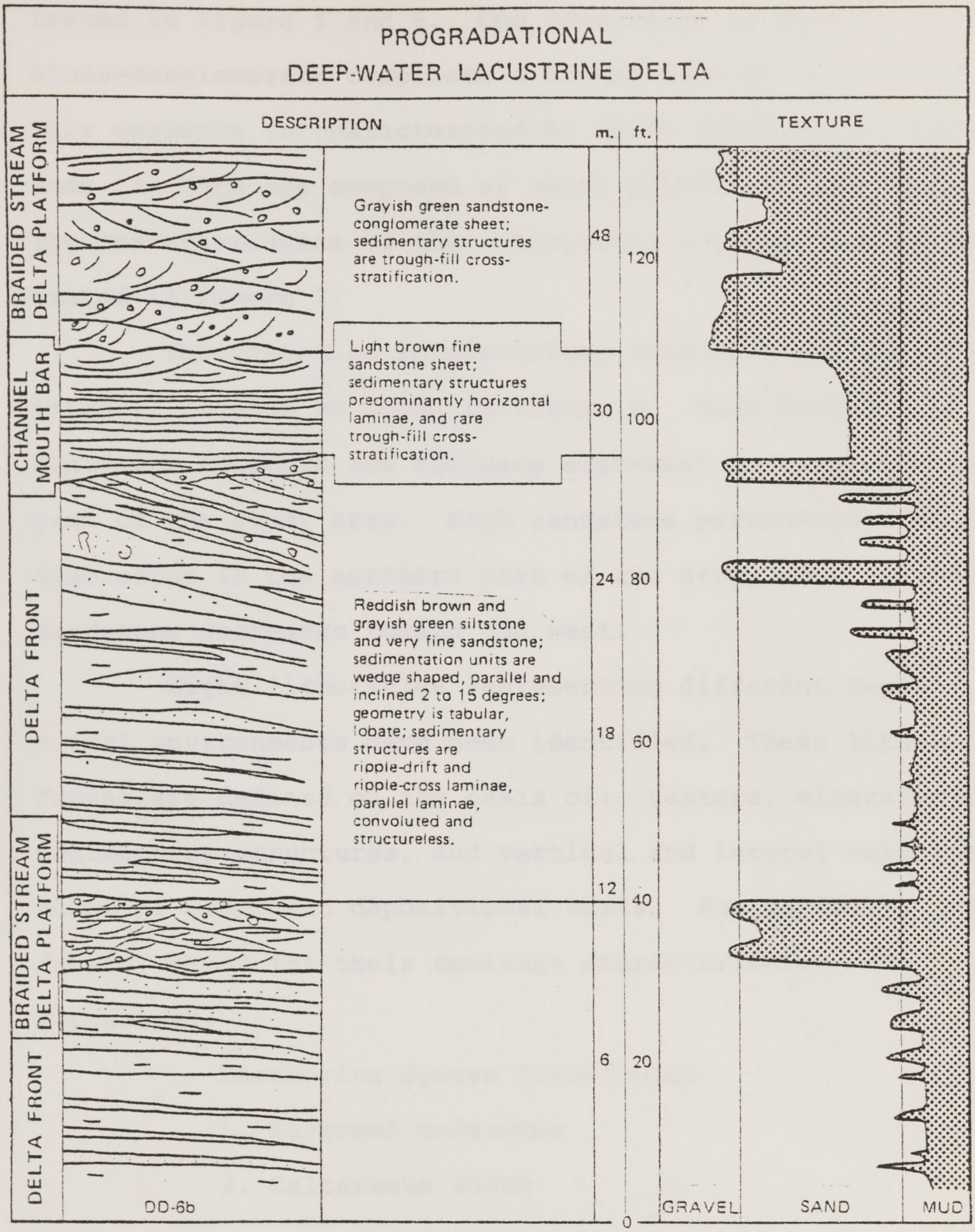


Figure 6. Deep-water lacustrine deltas are characterized by thin, coarse-grained delta platform sandstone-conglomerate sheets that overlie thick, progradational foreset inclined delta front deposits.

trated in Figure 5 and 6. One occurrence of fluvial sandstone-conglomerate comprises a linear belt of valley-fill. This sequence is characterized by thick channel-fill lenses, some of which are composed of chert pebble conglomerate. The characteristics of the valley-fill sequence are illustrated in Figure 7.

The variation in percentage sandstone for the total Triassic section is shown in Figure 8. High percentage sandstone contours are elongate east-west in the southern part of the study area. High sandstone percentage contours also occur in the northern part of the study area. Percent sandstone decreases toward the west.

Eight lithofacies representing different depositional environments have been identified. These lithofacies are defined on the basis of: texture, mineralogy, sedimentary structures, and vertical and lateral relationships of component depositional units. The following lithofacies, named for their dominant characteristics, are recognized:

Lacustrine System Lithofacies

1. Burrowed mudstones
2. Calcareous zones

Delta System Lithofacies

3. Parallel bedded, horizontal, sheet siltstone-sandstone-conglomerate

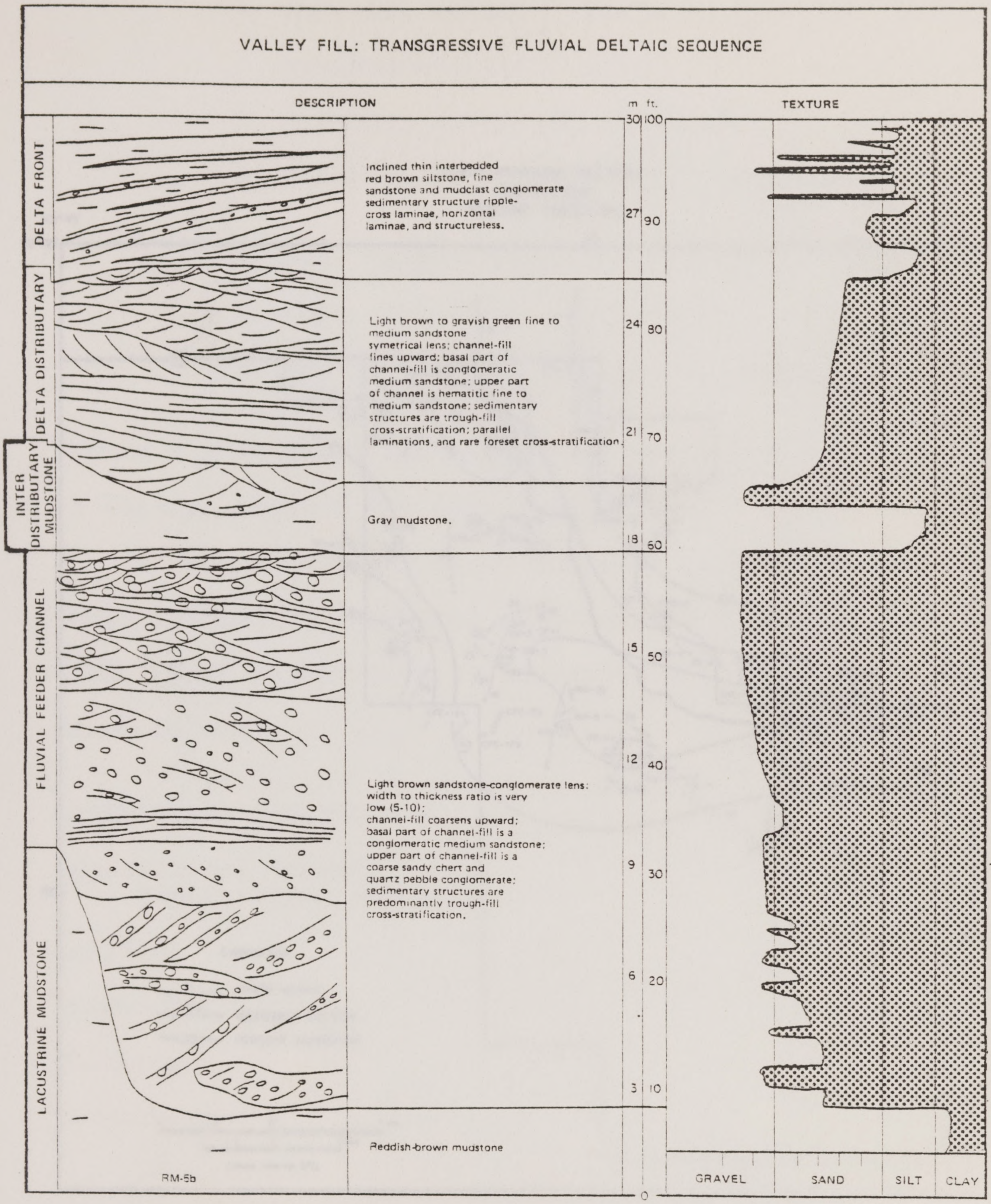


Figure 7. Valley-fill system comprises a transgressive fluvial-deltaic-lacustrine system that is composed of a basal fluvial chert pebble conglomerate, overlain by delta distributary, and delta front deposits that are capped by lacustrine mudstones.

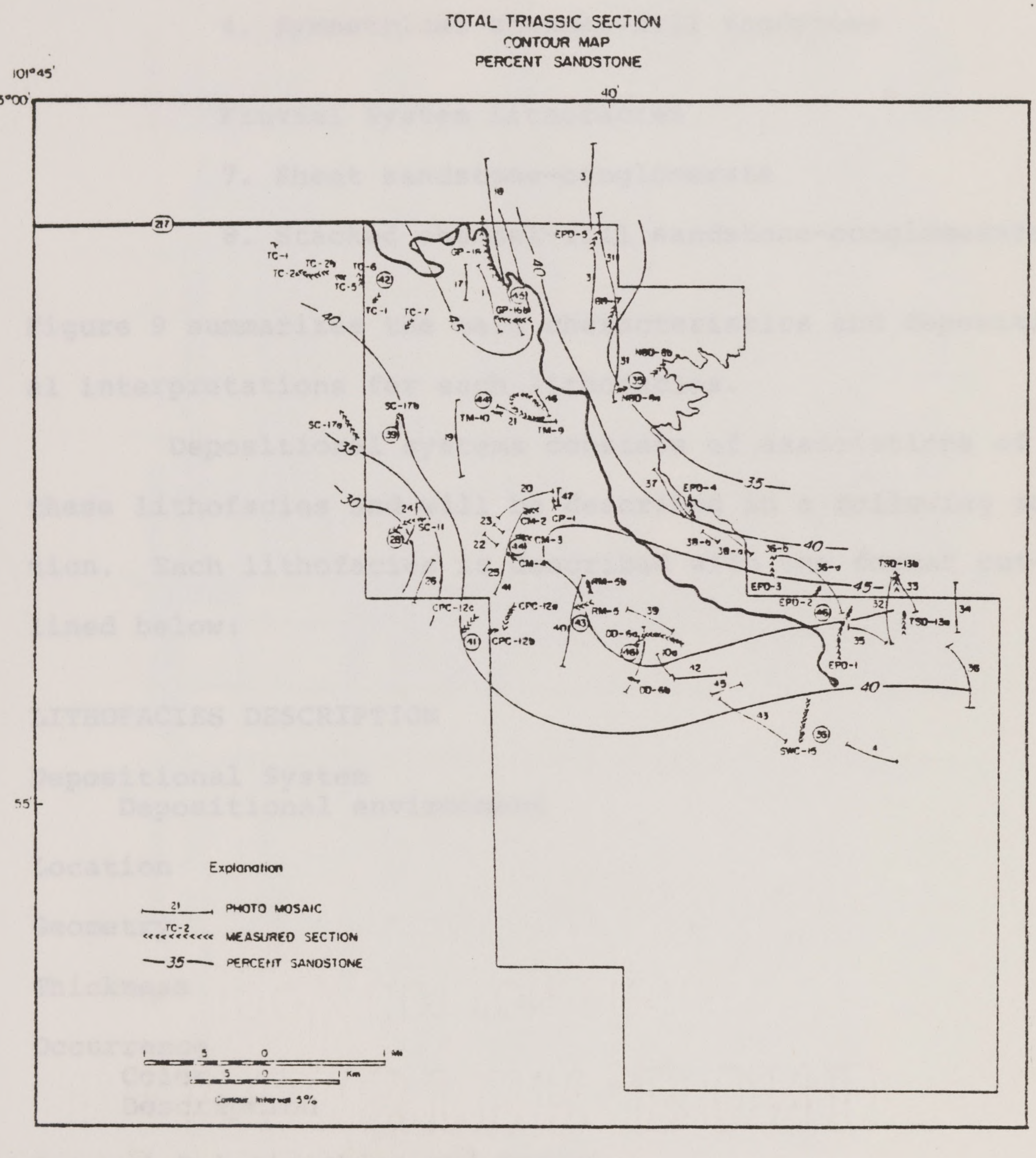


Figure 8. Map of the study area showing the variation in percentage sandstone.

4. Parallel bedded, inclined, lobate siltstone-sandstone-conglomerate
5. Mudclast siltstone-sandstone
6. Symmetrical channel-fill sandstone

Fluvial System Lithofacies

7. Sheet sandstone-conglomerate
8. Stacked channel-fill sandstone-conglomerate

Figure 9 summarizes the main characteristics and depositional interpretations for each lithofacies.

Depositional systems consists of associations of these lithofacies and will be described in a following section. Each lithofacies is described with the format outlined below:

LITHOFACIES DESCRIPTION

Depositional System
    Depositional environment

Location

Geometry

Thickness

Occurrence
    Color
    Description

Lateral Relationships and Trends

Sedimentary Structures
    Type of structures
    Vertical and lateral trends of structures

LITHOFACIES	ENVIRONMENT	TEXTURAL TREND (Gravel / Sand / Mud)	STRUCTURES	THICKNESS
Lacustrine (1) Burrowed Mudstone	Lake center, lake margin.		Burrowed sandy mudstone, desiccated and brecciated, popcorn weathering surface.	Total 20-50 m, genetic units 1-10 m.
(2) Calcareous Zones	Lake margin mudflat.		Calcareous zones are discrete pisolitic and burrowed nodules; clay and quartz sand normally in microspar calcite matrix; sparry calcite, dolomite and opal also present.	Total less than 1 to 3 m, individual zones 0.1 to 1 m.
Deltaic (3) Parallel bedded, horizontal, sheet, siltstone-sand-stone-conglomer-ate.	Lacustrine-fan delta front, shallow water 1 to 5 m deep.		Parallel laminae, ripple drift, contorted laminae, and soft sediment slumps and faults; trough-fill cross-stratification is rare.	Total 5-15 m, individual units 1-7 m.
(4) Parallel bedded, inclined, lobate, siltstone-sand-stone-conglom-erate.	Lacustrine delta front foresets, deep water 5 to greater than 15 m deep.		Ripple-cross laminae, ripple-drift, parallel laminae; trough-fill cross-stratification and soft-sediment faults and slumps are rare, sedimentation units are inclined and wedge shaped.	Total 15-35 m, genetic units 5-15 m.
(5) Mudclast siltstone-sandstone.	Interdeltaic mudflat, embayment.		Ripple-drift is the primary sedimentary structure, contorted laminae is common.	Total less than 1 to 10 m, genetic units 0.05 to 0.4 m.
(6) Symmetrical channel-fill sandstone.	Distributary channel.		Trough-fill cross-stratification, texture fines upward, ripple-cross laminae and parallel laminae at top.	Lenses are 2 to 13 m thick.
Fluvial (7) Sheet sandstone-conglomerate	Fan delta-delta platform.		Trough-fill cross-stratification is the most abundant sedimentary structure, ripple-cross laminae and parallel laminae at top, accre-tionary grain and curved bed set boundaries are common.	Total 10-30 m, individual sheets 2-20 m.
(8) Stacked channel-fill sandstone-conglomerate	Fluvial valley-fill.		Multiple channel-fill scours, trough-fill cross-stratification occurs at base of channels, cross-strata fines upward, parallel laminae occurs at top.	Total 20-45 m, individual chan-nel-fills 7-20 m.

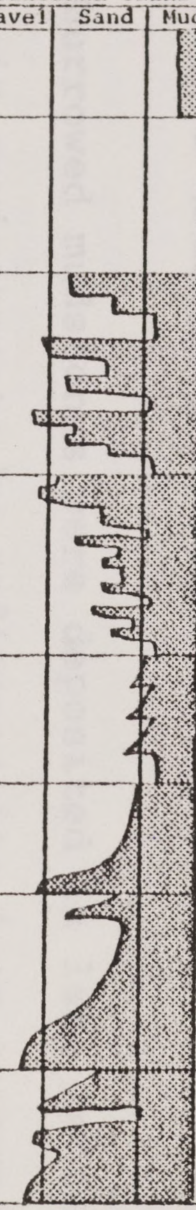


Figure 9. Summary of the main characteristics of Triassic Dockum Group lithofacies.

Grain Size
Grain size trends

Mineralogy

Petrographic Name (when applicable)

Lacustrine System Lithofacies

Lithofacies 1 (burrowed mudstones) and Lithofacies 2 (calcareous zones) were deposited in a lacustrine system. Although Lithofacies 3, 4, 5, and 6 also were deposited in a lacustrine system they are dominated by fluvial or deltaic depositional processes. Characteristics of the lacustrine deposits are illustrated in Figure 4.

Lithofacies 1 (burrowed mudstones)

Burrowed mudstones were deposited in lake center and lake margin environments by sedimentation from suspension. The fine grain size of the rocks indicates low-energy conditions at the site of deposition. Ubiquitous and thorough burrowing destroyed stratification which would indicate more specific depositional processes (Figures 10 and 11).

Although not described previously in the study area, Scoyenia burrows (Häntzchel, 1962) have modified all dark yellowish orange, reddish brown, reddish purple, and purple mudstones present in the lower 30 m to the Dockum. These burrows are mud-filled cylinders 2 to 15 mm in diameter, and less than 50 mm long. Cross-sections through

LACUSTRINE LITHOFACIES DESCRIPTION

Lithofacies 1. Burrowed mudstone

Depositional System: Lacustrine; lake center, lake margin environment.

Location: Present everywhere in the study are in the lowest 70 m; less common in the upper 70 m.

Geometry: Horizontal, massive, blanket to broadly lens shaped; fills lows and depressions; thins toward the west and north.

Thickness: Total thickness 20 to 50 m; genetic packages less than 1 to 7 m thick.

Occurrence: Burrowed mudstones are reddish brown, reddish purple, purple, and dark yellowish orange; from 4 to 7 genetic mudstone packages occur in the study area; most mudstone packages are capped by calcareous zones.

Lateral Relationships and Trends: Burrowed mudstones are interbedded with Lithofacies 2 and are separated by sharp upper and lower contacts; burrowed mudstones are overlain by Lithofacies 3 and 4, and separated by a gradational contact; Lithofacies 7 commonly underlies burrowed mudstones and is separated by sharp contacts; Lithofacies 3 rarely underlies burrowed mudstones; Lithofacies 3, 4, and 6 are laterally equivalent.

Sedimentary Structures: Primary sedimentary structures are not preserved due to burrowing; Scoyenia burrows are abundant, diameter 2-15 mm, length less than 50 mm; mottled and structureless fabric is common; dessication fractures 1 to 100 mm wide commonly filled with brecciated mudstone and calcite.

Grain Size and Grain Size Trends: Silty to fine sandy mudstone.

Mineralogy: Clay minerals are smectite and illite; silt and sand sized quartz is common; gypsum occurs as 2 to 20 mm wide horizontal and inclined seams; hematite and ferrugenous nodules are common; opal-filled fractures .1 to 3 mm and opal spherules

.1 to 2 mm occur within mudstones associated with calcareous zones.

Petrographic Name: Slightly fine sandy burrowed illite-smectite mudstone.

Lithofacies 2. Calcareous zone

Depositional System: Lacustrine; intermittently dry mud-flat or shallow subsurface diagenetic environment.

Location: Present everywhere in the study area in the lowest 70 m; absent in the upper 70 m.

Geometry: Horizontal thin blankets; random isolated nodules; small scale vertical to high angle fractures.

Thickness: Total thickness .5 to 3 m; individual zones .1 to 1 m.

Occurrence: Calcareous zones are reddish brown, reddish purple, purple, pink, and dark yellowish orange; the color is related to the color of the underlying mudstone; from 2 to 5 horizons are composed of individual carbonate nodules; nodules also occur randomly isolated within mudstones, or as vertical or high angle fracture fills; calcareous zones apparently replace Lithofacies 1 mudstone; the lowest burrowed mudstone lithofacies of genetic sequence 1 has from 2 to 5 calcareous horizons; burrowed mudstones of genetic sequence 2 contain randomly isolated carbonate nodules; high angle fracture-fills are common in genetic sequence 1 and 2.

Lateral Relationships and Trends: Overlain and underlain by Lithofacies 1; sharp contact between carbonate nodules and mudstone.

Sedimentary Structures: Three types of replacement structures occur:

1. Scoyenia burrows on outer nodule edge;
2. pisolitic nodules expand, and replace mudstones;
3. high angle fractures are structureless.

Grain Size and Grain Size Trends: Most nodules are entirely calcite microspar, crystals are from 5 to 15μ; central areas of nodules may have inward pointing coarsely crystalline calcite spar, crystals are from 15μ to 10 mm.

Mineralogy: Microspar is abundant; sparry calcite dolomite, and opal are common; quartz-replaced and chert-replaced (?) evaporites are rare; central parts of carbonate and quartz nodules may be filled with barite, calcite spar, manganite, and dolomite.

Petrographic Name: Not appropriate for replacement textures.

burrow fills reveal arcuate back-fill structure or spreite (Figure 12); this trace fossil is known as Teichichnus. The outer wall of whole (loose) burrows has a ropy surface texture possibly produced by the packing of elongate pellets into the burrow wall. Häntzchel (1962) states that Scoyenia is characteristic of red bed sequences and that polycheate worms may have produced the trace.

The presence of these burrows indicates that bottom waters were oxygenated and that the lake system was not a highly stratified system as postulated for the lacustrine environment in which the Eocene Green River Formation accumulated (Bradley, 1964; Eugster and Bradley, 1969; Picard and High, 1968).

Lithofacies 2 (Calcareous Zones)

Calcareous zones are interbedded repeatedly with burrowed lacustrine mudstones. These horizontal zones are composed of discrete carbonate nodules. High angle and vertical carbonate fractures in mudstone also are common.

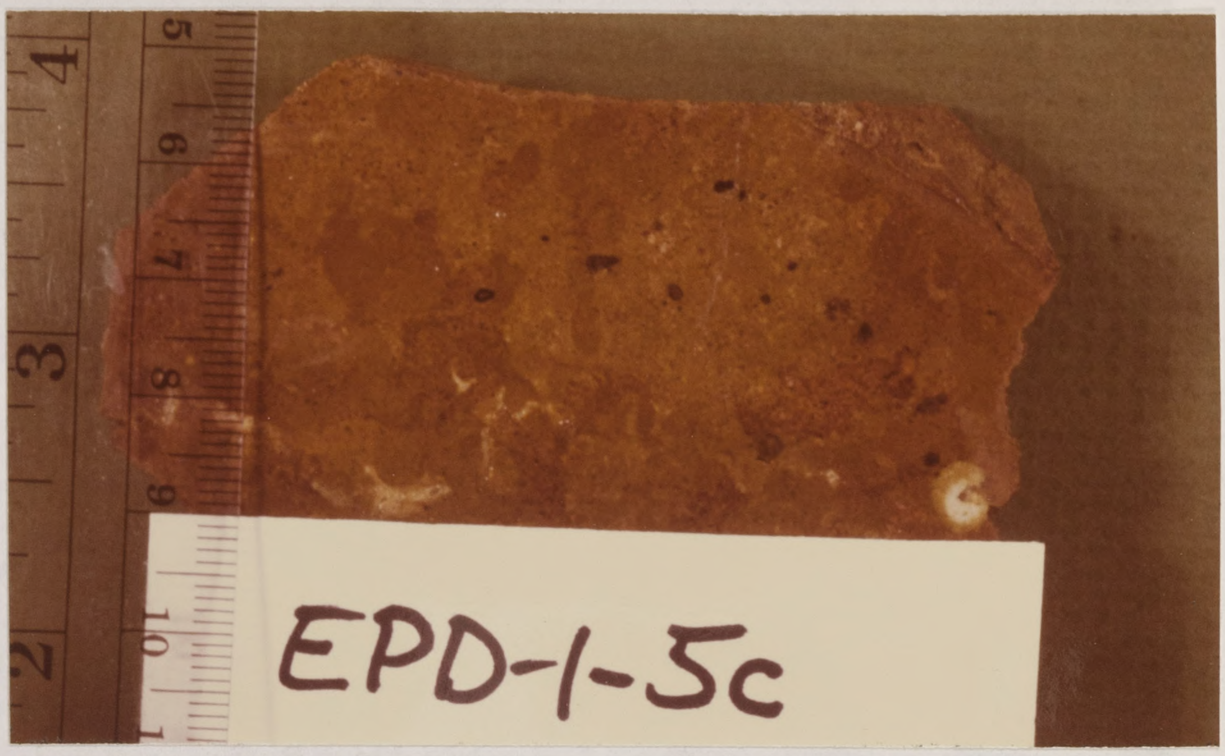


Figure 10. Dark yellowish orange burrowed mudstone.

Figure 11. Lacustrine mudstone with <u>Scoyenia</u> and small caliche nodule exposed at TM-6 below a currently active spring.

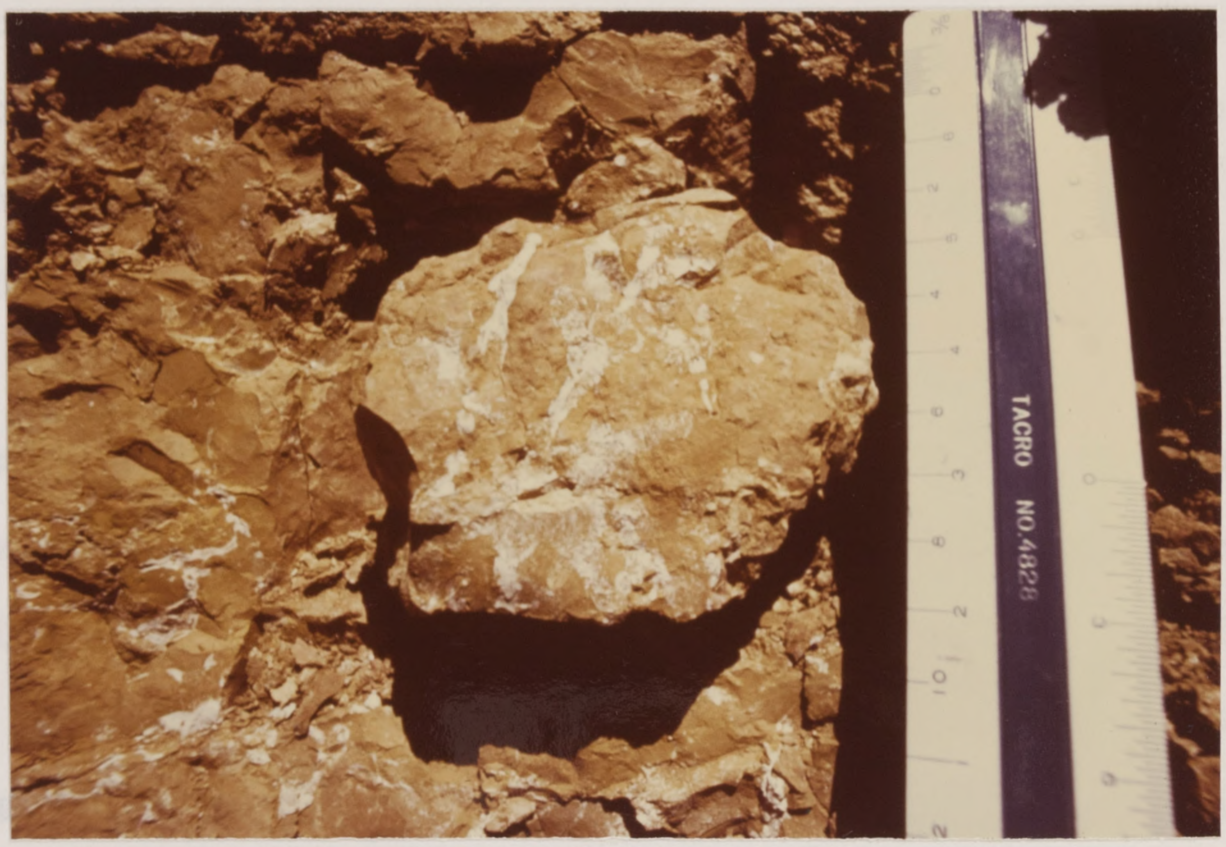


Figure 12. Arcuate back-fill burrow structures (*Teichichnus*) in dark yellowish orange mudstone.

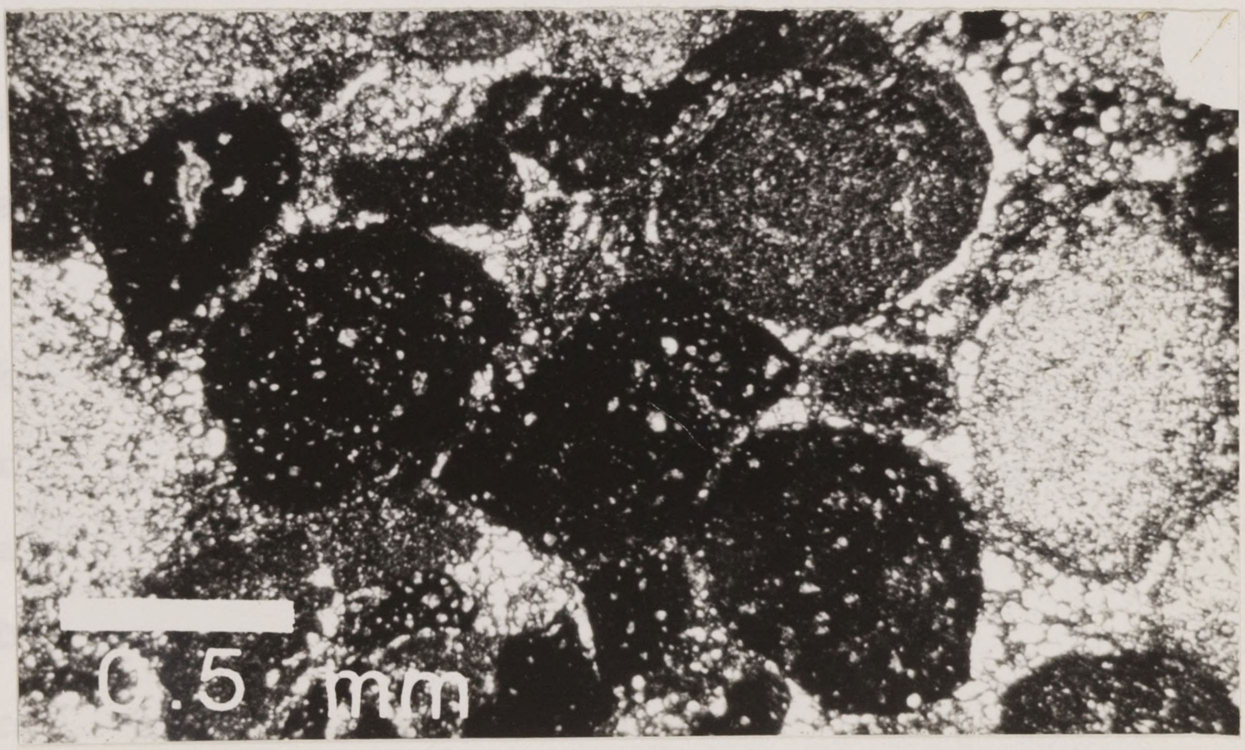


Figure 13. Very well rounded caliche carbonate rock fragments are stained red with alizarine red S. Darker grains in center are mudstone grains. Scale is 0.5 mm.

Calcareous zones are interpreted as paleocaliches. Surface fabrics and microtextures indicate that calcareous zones replaced borrowed mudstones. Characteristics of caliche and caliche nodules have been described by Brown (1956), Dunham (1969), and especially Nagtegaal (1969). Nagtegaal (1969) compared recent caliche to paleocaliches in Quaternary, Triassic, and Permian rocks exposed in eastern Spain. According to Nagtegaal (1969), Triassic and Permian mudstones contained isolated caliche nodules and incompletely developed caliche profiles. The caliche is predominantly fine-grained calcite (5-30μ). Corroded silicate grains float in calcite. Also, late stage dolomitization and alternation of calcite and ferric oxides were described. The microtextures and mineralogy of paleocaliches described by Nagtegaal are very similar to paleocaliches in the study area.

Two lines of evidence indicate that calichification of Dockum mudstones may be continuing today: (1) nodules vary from hollow to sparry calcite filled, and (2) the association of small nodules with currently-active springs below Dockum sandstone bodies. Evidence that the calichification processes also occurred extensively during Dockum deposition is conclusive. Petrographic analysis indicates that carbonate rock fragments are the most abundant rock fragment in Dockum Group sandstones and conglomerates in the study area (Figure 13). Thirty percent of Dockum rocks are litharenites (classification by Folk, Andrews, and Lewis, 1970); 80 percent of these are calclithites. Many carbonate rock fragments are miniature replicas of larger carbonate septarian concretions with internal fill of sparry calcite surrounded by microspar (Figure 14).

Isolated ferruginous and black psilomelane nodules, analogous to calcareous nodules, are also present in Dockum mudstones.

Similar nodules were observed by Bernard and others (1970) in Texas coastal zone soil zones. One Dockum sedimentation unit comprises reworked ferruginous and black psilomelane nodules (Figure 15), indicating that nodules also were present during Dockum deposition.

The outer surface of an estimated 60 percent of the carbonate nodules have a borrowed fabric exactly similar to the Scoyenia and Teichichnus burrowed mudstones (Figure 16). Slabs and thin sections of calcareous nodules reveal that whereas the outer surface perfectly mimics the mudstone fabric, microtextures of the nodules interior indicate a replacement origin (Figure 17). The nodules outer surface is consistently composed of microspar calcite, which is an indicator of fresh water diagenesis (Folk, 1974a). Interiors of nodules are brecciated microspar fragments in a sparry calcite matrix.

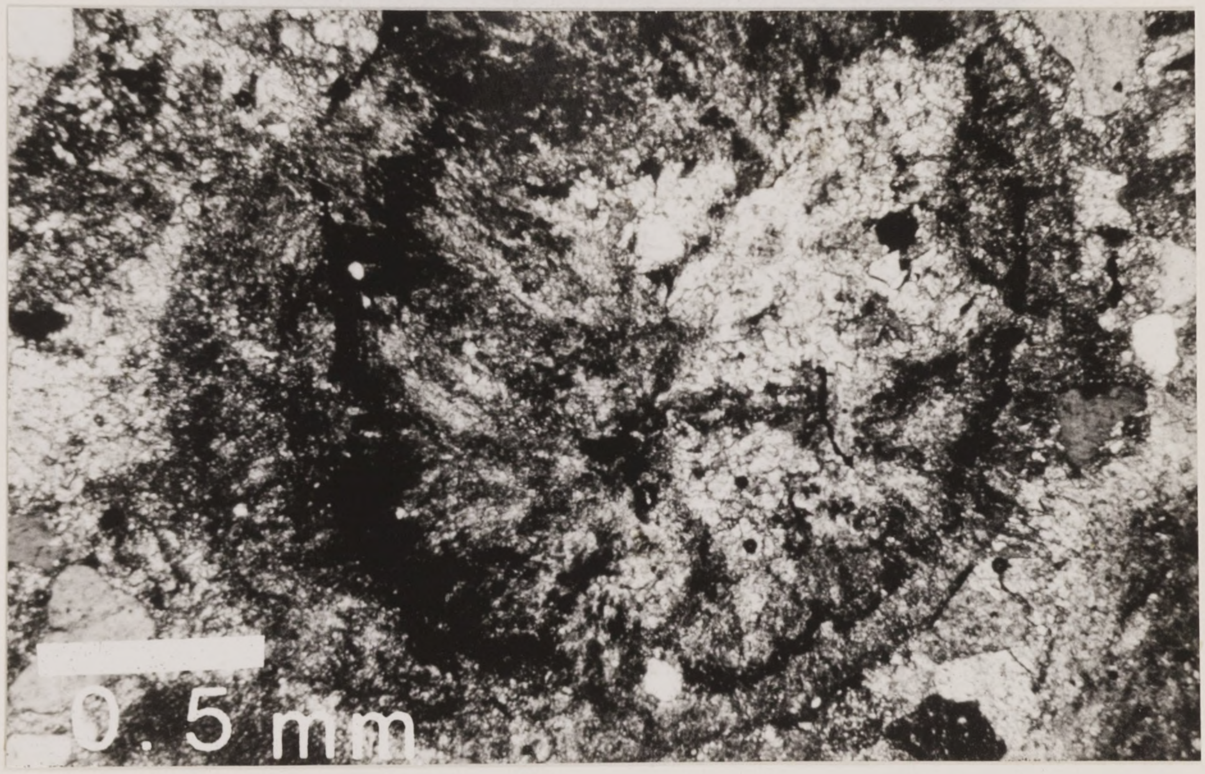


Figure 14. Thin section of carbonate rock fragment with sparry calcite filled fractures which become thinner toward the exterior of the grain. Crossed nichols.

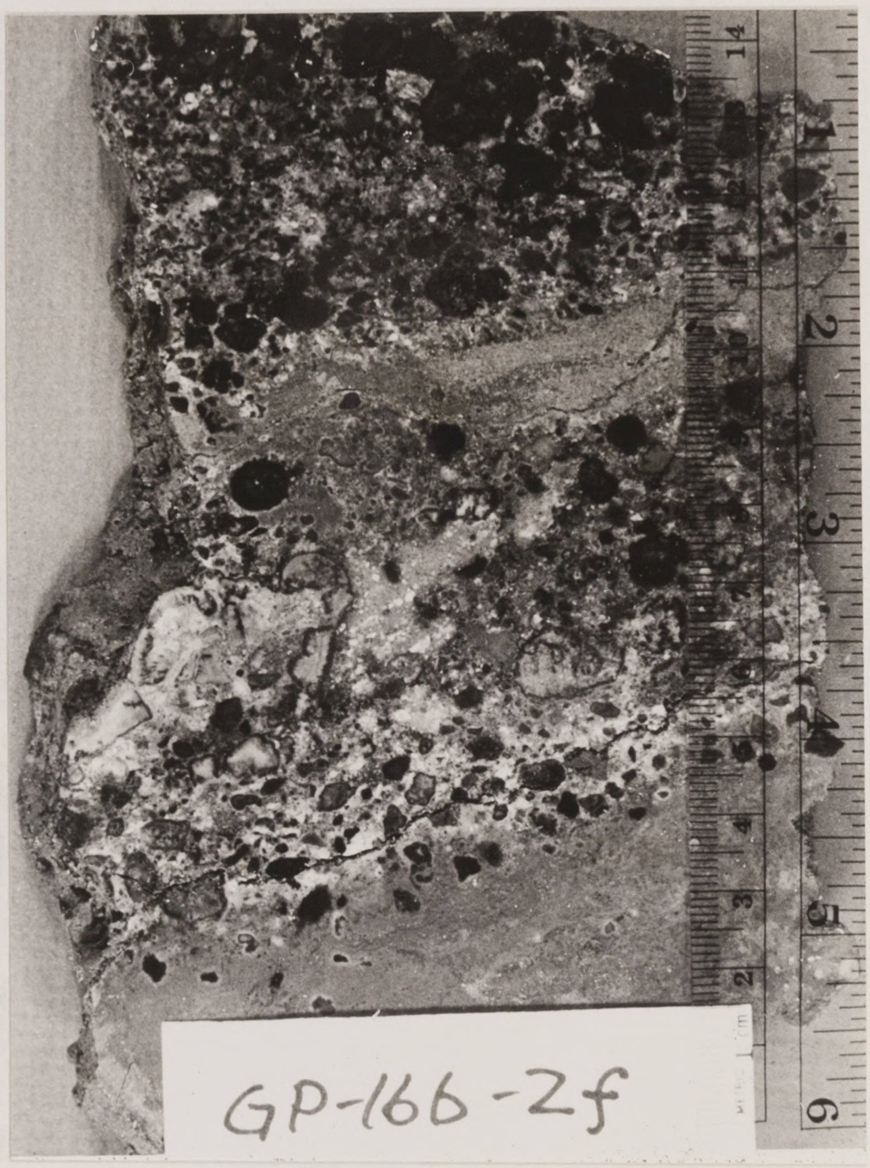


Figure 15. Sedimentation unit composed of black ferruginous and psilomelane nodules.

Figure 16. Caliche nodule with outer surface composed of Scoyenia and Teichichnus surrounded by burrowed lacustrine mudstone.

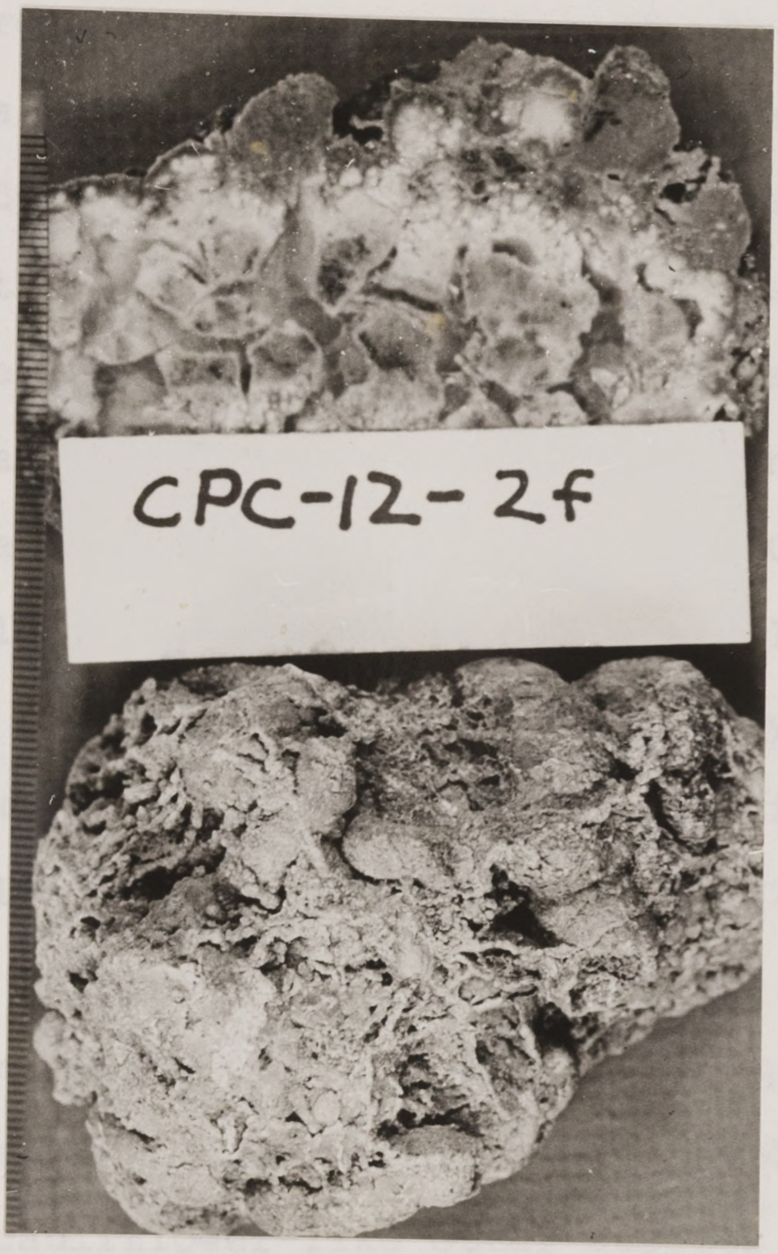


Figure 17. Interior and exterior of caliche nodule with Scoyenia and Teichichnus. Septarian fractures of nodule interior are filled with sparry calcite.

An estimated 40 percent of the calcareous nodules have pisolitic surface texture (Figure 18). A thin section of the outer edge of a pisolitic nodule shows that clayey microspar contains floating quartz silt displaced by nodule growth (Figure 19). A thin section of the interior of the nodules reveals pure microspar and fracture-fills of sparry calcite and dolomite. Dolomite is common in pisolitic nodules where it fills fractures and alternates with sparry calcite. The alternation of dolomite and sparry calcite with microspar indicates that precipitation took place within waters characterized by fluctuating Mg/Ca ratios or salinity (Folk, 1974a, and Folk and Land, 1975).

Less common nodule types are rusty maroon-colored, burrowed, hematitic mudstone that is brecciated with opal fracture-fills and opal spherules (Figure 20). At one location (Figure 2, CPC-12), within 3 m of the Dockum Group-Quartermaster Formation contact, quartz-replaced and chert-replaced(?) evaporite nodules were observed. Quartz nodules have a cauliflower-like outer surface and internally consists of quartzine grading into megaquartz (Figure 21). Folk and Pittman (1971) recognized quartzine as a common quartz type in evaporite replacement. Anhydrite inclusions and lath-shaped holes occur within the quartzine. The nodules are also characterized by a range of silicification textures (spherules, euhedral quartz, pseudocubic quartz,

Figure 18. Pisolitic caliche nodule. Slab on right is stained with alizarine red S.

Figure 19. Exterior margin of pisolitic nodules with dark area that contains abundant ferric oxide, clay minerals, and quartz silt in microspar matrix. Toward interior (left) is dolomite and sparry calcite filled fracture.

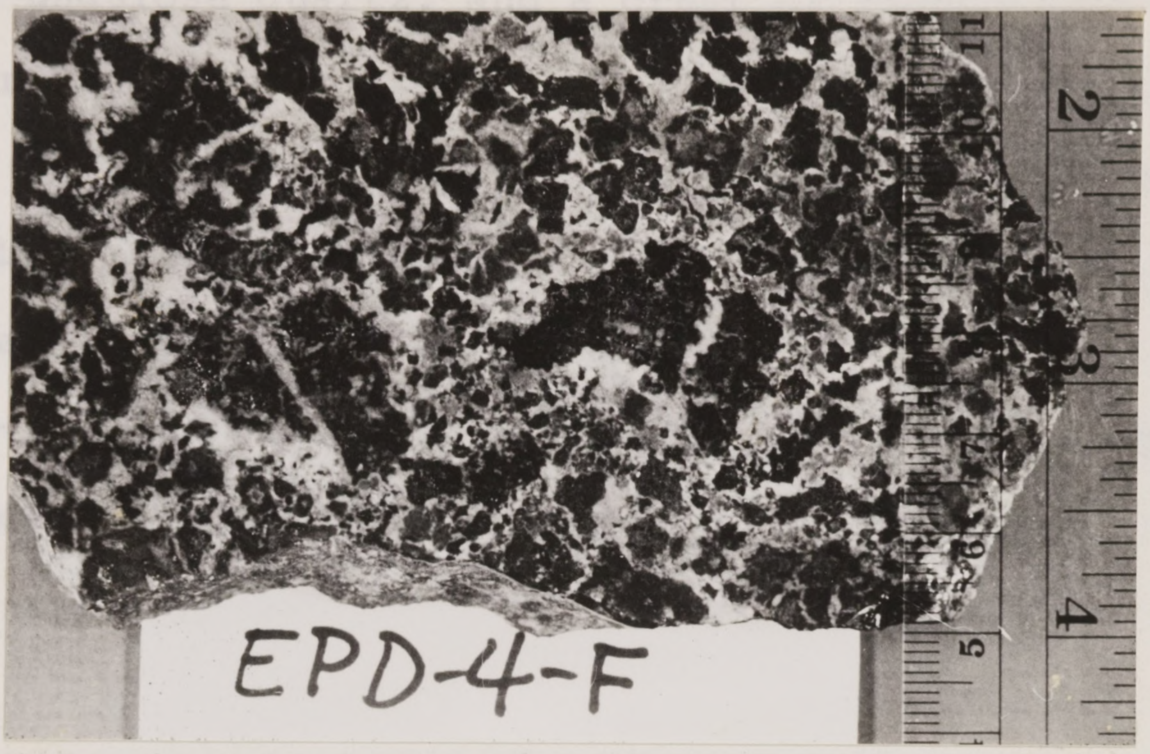


Figure 20. Slab of dark maroon hematitic mudstone brecciated with opal filled fractures.

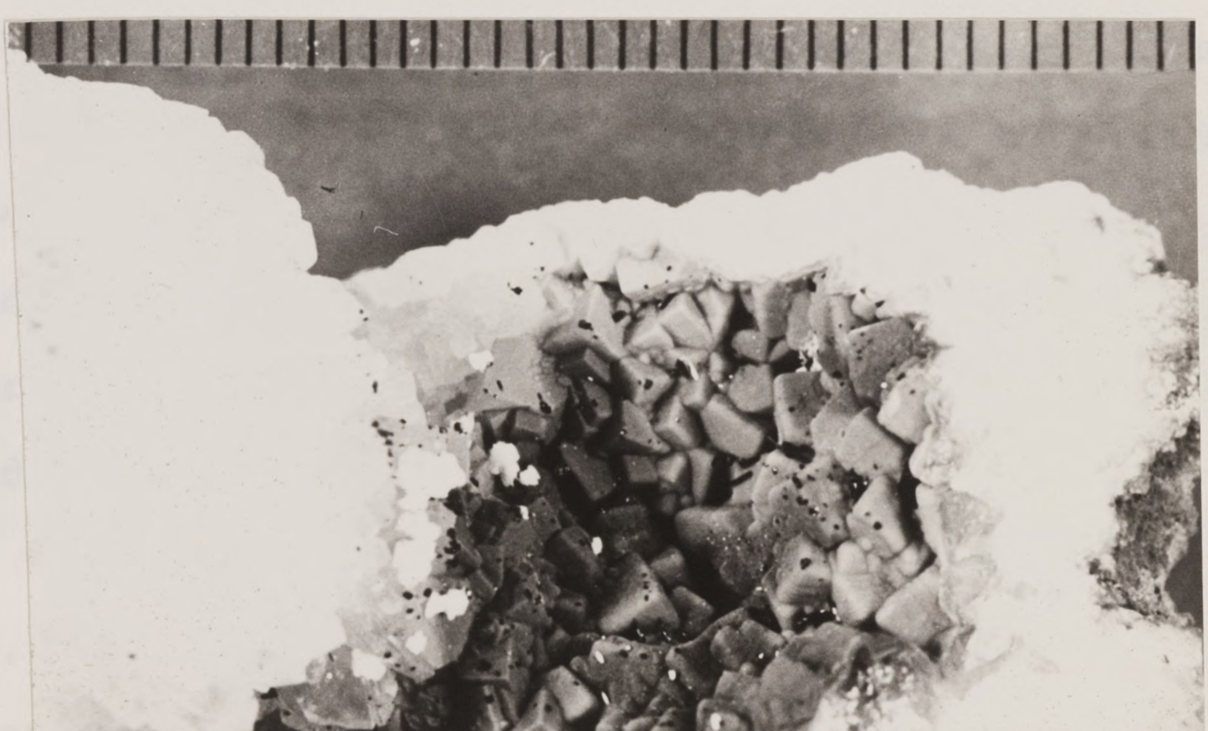


Figure 21. Quartz nodule with pseudocubic terminations coated with gray chalcedony. Black specks on chalcedony are manganite. Scale marks are 1 mm.

strained undulose quartz, and a crust of length fast fibrous quartz) which are found in silicified evaporites from numerous localities (Milliken, 1977). Chert nodules present in the same area, have a fractured outer surface, alternating bands of length fast and slow chalcedony, and silt- and sand-sized quartz. These chert nodules may be magadiite replacements (McGowen, 1976, personal communication).

Summary

Varicolored burrowed mudstones within the lower 30 m of the Dockum at Palo Curo Canyon accumulated in lake center and lake margin environments. The widespread distribution of Scoyenia and Teichichnus indicates that lake bottom waters were oxygenated. Calcareous zones, which may be paleocaliches, are interbedded with burrowed lacustrine mudstones. This interbedding indicates an alternation of arid and humid climatic conditions. Ephemeral Lake Eyre may represent a modern analogue of this environment (Bonython and Mason, 1953).

The presence of a complex suite of diagenetic calcareous, siliceous, and ferruginous nodules, and the alternation of carbonate minerals indicate that the nodules formed from water with fluctuating chemistry. The paleocaliches may have formed in a variety of lake environments during arid cycles, probably in exposed mudflats and in the shallow subsurface by precipitation in the vadose zone (the unsaturated zone above the water table). Alternately, some calcareous zones may represent diagenesis of a calcareous lake bottom ooze during times of lake area reduction.

Delta System Lithofacies

Lithofacies 3 (parallel bedded, horizontal, sheet siltstone-sandstone-conglomerate), Lithofacies 4 (parallel bedded, inclined, lobate siltstone-sandstone-conglomerate), Lithofacies 5 (mudclast siltstone-sandstone), and Lithofacies 6 (symmetrical channel-fill sandstone) were deposited within lacustrine delta systems. Each lithofacies was deposited in a specific deltaic environment. Characteristics of the deltaic deposits are illustrated in Figure 5 and 6.

DELTAIC LITHOFACIES DESCRIPTION

Lithofacies 3. Parallel-bedded, horizontal, sheet siltstone-sandstone-conglomerate.

Depositional System: Deltaic; delta front environment.

Location: Present everywhere in the study area in the lower 80 m.

Geometry: Horizontal, thin sheets composed of many thin sedimentation units.

Thickness: Total thickness 5 to 15 m; individual genetic units 1 to 7 m.

Occurrence: Lithofacies 3 is reddish brown or light grayish green; Lithofacies 3 occurs in 2 or 3 packages 1 to 7 m thick; individual sedimentation units are parallel beds 2 cm to 2 m thick; in most sequences the bedding thickens upward, however a few sequences exhibit an upward thinning of sedimentation units.

Lateral Relationships and Trends: Lithofacies 3 consistently occurs below Lithofacies 7, and is separated by a sharp contact; to the west and south Lithofacies 3 is laterally equivalent to Lithofacies 7; Lithofacies 1 underlies Lithofacies 3 and is separated by gradational contacts.

Sedimentary Structures: Sedimentary structures are diverse; primary sedimentary structures, in decreasing abundance, are horizontal laminae, ripple-cross laminae, and ripple-drift laminae; small scale trough-fill cross-stratification occurs in coarser units; soft-sediment deformation, faults, and roll structures are common; major slump features are present.

Grain Size and Grain Size Trends: Grain size is variable; individual sedimentation units are clayey siltstone, silty very fine to fine sandstone, conglomeratic sandstone, and pebble to cobble conglomerate; siltstone and very fine to fine sandstone are most abundant; coarsening upward sequences occur within individual sedimentation units and within sequences of sedimentation units.

Mineralogy: Conglomeratic units are composed of intrabasinal mudclasts and caliche clasts, clasts are very well rounded and commonly well sorted; silts and very fine to fine sands are quartzarenites and subsedarenites.

Petrographic Name: Granule conglomerate: calcitic immature mudclast-bearing caliche calclithite. Very fine sandstone: calcitic mature very well sorted caliche clast-bearing subsedarenite to quartzarenite.

Lithofacies 4. Parallel-bedded, inclined, lobate siltstone-sandstone-conglomerate.

Depositional System: Deltaic; delta front environment, delta foresets.

Location: Present everywhere in the upper 50 to 70 m; best exposures in the western part of the study area.

Geometry: Tabular, lobate bodies are composed of many thin inclined wedge-shaped sedimentation units.

Thickness: Total thickness 15 to 35 m; 3 genetic units are 5 to 15 m thick; some units thicken toward the west.

Occurrence: Lithofacies 4 is reddish brown, reddish purple, or light grayish green. Lithofacies 4 occurs in 3 genetic units in the upper 50 to 70 m in the western part of the study area; parallel inclined sedimentation units are .05 to 2 m thick; inclination angles vary from 2 to 15 degrees and decrease along a sedimentation unit from the top to the toe of the unit; thickness of individual units decreases towards the toe.

Lateral Relationship and Trends: Lithofacies 4 occurs below and west of Lithofacies 7, and is separated by sharp to gradational contacts; Lithofacies 4 overlies finer grained and near horizontal bedded units of Lithofacies 3 or rarely Lithofacies 1; the contacts are gradational.

Sedimentary Structures: Structures are similar to those in Lithofacies 3; ripple-cross laminae and ripple-drift are more abundant, parallel laminae less common; trough-fill cross-stratification is common in coarser units, and scale of structures decrease along a sedimentation unit toward the toe; small scale soft-sediment deformation is common.

Grain Size and Grain Size Trends: Grain size variations are similar to Lithofacies 3; siltstone is most abundant, increasing toward the west; thin very fine sandstone units 0.005 to 0.5 m are interbedded with ripple-cross laminated and ripple-drift siltstone; grain size along a sedimentation unit generally increases from toe to top of unit, grain size along a unit rarely decreases toward top of unit.

Mineralogy: Mineralogy is similar to Lithofacies 3; conglomerate units well rounded, poorly to well sorted mudclast and caliche sedarenites; silts and very fine to fine sandstones are quartzarenites and subsedarenites.

Petrographic Name: Granule conglomerate: calcitic immature mudclast-bearing caliche calclithite. Very fine sandstone: calcitic mature very well sorted caliche clast-bearing subsedarenite to quartzarenite.

Lithofacies 5. Mudclast siltstone-sandstone.

Depositional System: Deltaic; interdelta mudflat or embayment.

Location: A single exposure at EPD-4.

Geometry: Linear belt elongate in direction of sediment transport.

Thickness: Less than 1 to 10 m.

Occurrence: The color of Lithofacies 5 is dark reddish brown; lithofacies occurs in the eastern part of the study area at one location; sedimentation units are 0.05 to 0.4 m thick, they are horizontal and parallel bedded; the entire sequence coarsens upward but individual sedimentation units fine upward.

Lateral Relationships and Trends: Lithofacies 5 occurs between and is equivalent to laterally extensive sheets of Lithofacies 7; Lithofacies 3 underlies Lithofacies 5 and is separated by a gradational contact; Lithofacies 6 overlies Lithofacies 5 and separated by sharp basal scours.

Sedimentary Structures: Ripple-drift is the primary sedimentary structure; contorted laminae are common in the finer grained lower units; lower units also may be structureless; individual sedimentation units fine upward.

Grain Size and Grain Size Trends: The lower 5 m is convoluted very fine sandy siltstone; the upper 5 m is silty very fine sandstone.

Mineralogy: Silt and very fine to fine sand sized grains are predominantly reddish brown mudclasts, well rounded and well sorted.

Petrographic Name: Silty very fine to fine sandstone: immature well sorted mudclast bearing sedarenite.

Lithofacies 6. Symmetrical channel-fill sandstone.

Depositional System: Deltaic; distributary channel.

Location: Present throughout the study area.

Geometry: A symmetrical lens with a convex-down lower surface; three-dimensional geometry is a shoestring; width to thickness ratio ranges from 10:1 to 30:1.

Thickness: Lenses are from 2 to 13 m thick, and decrease in thickness to the west; total thickness at any one location is variable.

Occurrence: The color of Lithofacies 6 varies from light reddish brown and light brown, grayish green to white; commonly reddish brown on the 0.5 to 5 cm thick weathering surface; symmetrical lenses are thickest in the eastern part of the study area, lenses thin and become more abundant toward the west; lower contacts are convex-down and sharp; upper contacts are variable, and may be straight, convex up or down; upper contacts are normally sharp; gradational upper contacts are rare.

Lateral Relationships and Trends: Symmetrical lenses overlie Lithofacies 3, 4, 5, and 7; Lithofacies 1 and 7 overlie the symmetrical lenses; to the west Lithofacies 1, 3, and 4 are laterally equivalent; to the east Lithofacies 7 is laterally equivalent to Lithofacies 6.

Sedimentary Structures: Trough-fill cross-stratification is the most abundant sedimentary structure; within individual channel-fills trough-fill cross-strata vary in thickness from 0.5 to 2 m; sedimentary structures decrease in size upwards; foreset cross-strata are rare; ripple-cross laminae and ripple-drift are common at the top of channel-fill bodies.

Grain Size and Grain Size Trends: Grain size within individual lenses fines upward; granule and pebble channel lags are common; very fine to medium sandstone is present, with very fine to fine sandstone most abundant.

Mineralogy: Granule to pebble clasts are predominantly intrabasinal mudclast and caliche; extrabasinal chert granules are rare; quartz is the most abundant sand sized material, caliche clasts are common.

Petrographic Name: Slightly granular very fine to medium sandstone: calcitic submature to mature moderately well sorted subsedarenite to sedarenite.

Lithofacies 3 (parallel bedded, horizontal, sheet siltstone-sandstone-conglomerate)

Lithofacies 3 accumulated along the margins of shallow lakes in delta front environments where fluvial braided streams prograded into standing water. This lithofacies is developed in two horizons. The lowest occurrence is at the base of a white sandstone sheet 12-45 m above the Dockum Group-Quartermaster Formation contact. The upper occurrence is along the eastern part of the Palo Duro State Park, below and west of a continuous sandstone sheet that is said to record the base of the Trujillo Formation (Hood, 1978) (Figure 22).

Criteria which identify Lithofacies 3 as a product of delta front environments include: (1) lateral lithofacies assemblage and tract; (2) lithofacies distribution and geometry; and (3) vertical sequences, sedimentary structures, and textures.

Lithofacies 3 is transitionally underlain by burrowed lacustrine mudstones of Lithofacies 1. Overlying Lithofacies 3, and separated by a sharp contact are Litho-

Figure 22. Upward coarsening delta front deposit along the eastern part of Palo Duro State Park. Staff is 1.8 m (6 ft).

facies 6 and 7 (Figure 23). To the west Lithofacies 3 is laterally equivalent to Lithofacies 7 (Figures 24 and 25). This normally upward-coarsening vertical sequence is a genetic package that is characteristic of fluvial-deltaic progradation (Fisher and others, 1969; Fisher and Brown, 1972). Lithofacies 3 comprises thin horizontal sheets that are made up of many thin sedimentation units. According to Fisher and others (1969) this is characteristic of high constructive lobate deltas which prograde into shallow water and overlie thin muds.

A vertical sequence of sedimentary structures and textures within Lithofacies 3 is complex and characterized by a variety of sedimentary structures, textures, and abundant soft-sediment deformation. Soft-sediment deformation is the most diagnostic feature of Lithofacies 3. Both small-and large-scale deformation structures were observed. Small-scale deformation structures include faulted ripple-cross laminae and roll structures (Figures 26 and 27). The lower stratigraphic segments of Lithofacies 3 are characterized by large-scale slumps which have been observed over 25 square km (Figures 28 and 29). Slumping ensued when a caliche clast conglomerate accumulated rapidly upon a water-saturated silt and sand sequence. Rapid loading caused the silt and sand underlying the conglomerate to move downslope. The overturned nose of the conglomerate

Figure 23. Delta front deposits overlain by and separated by a sharp contact from overlying channel sandstone-conglomerate at TM-6.

Figure 24. Fining upward delta front deposits exposed at DD-6b. Staff is 1.8 m (6 ft).

Figure 25. Delta front deposits exposed at PDSP-43.

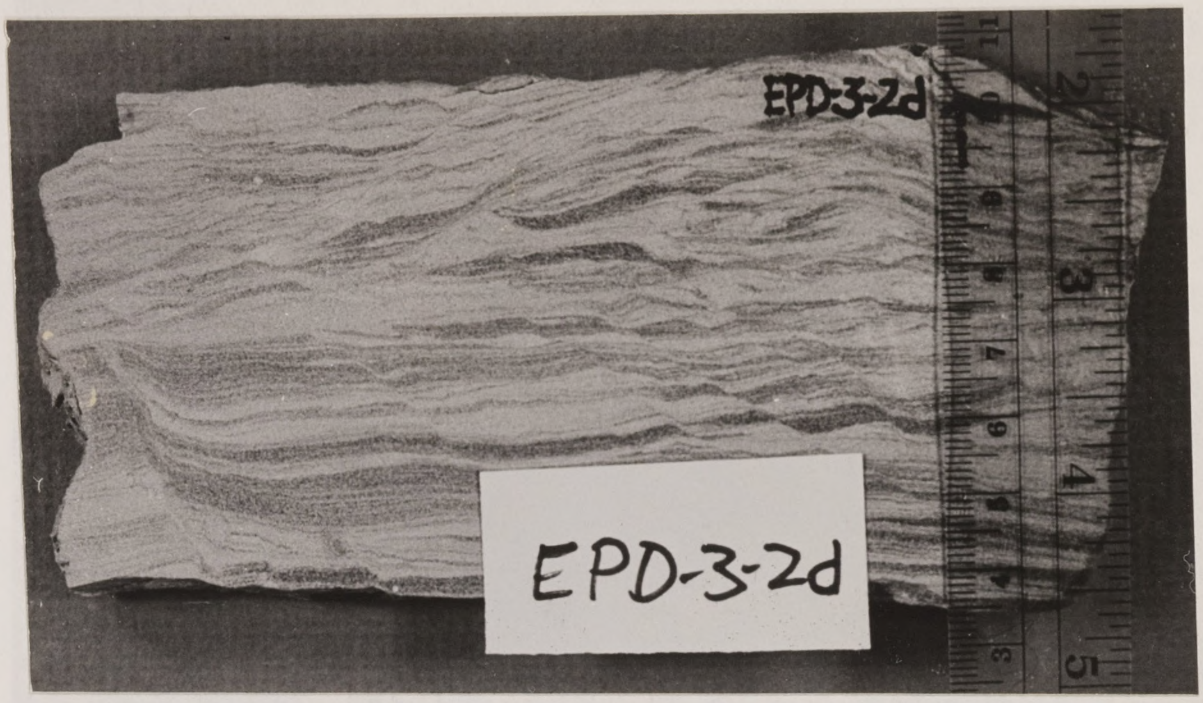


Figure 26. Delta front siltstone and very fine sandstone with soft-sediment faults.

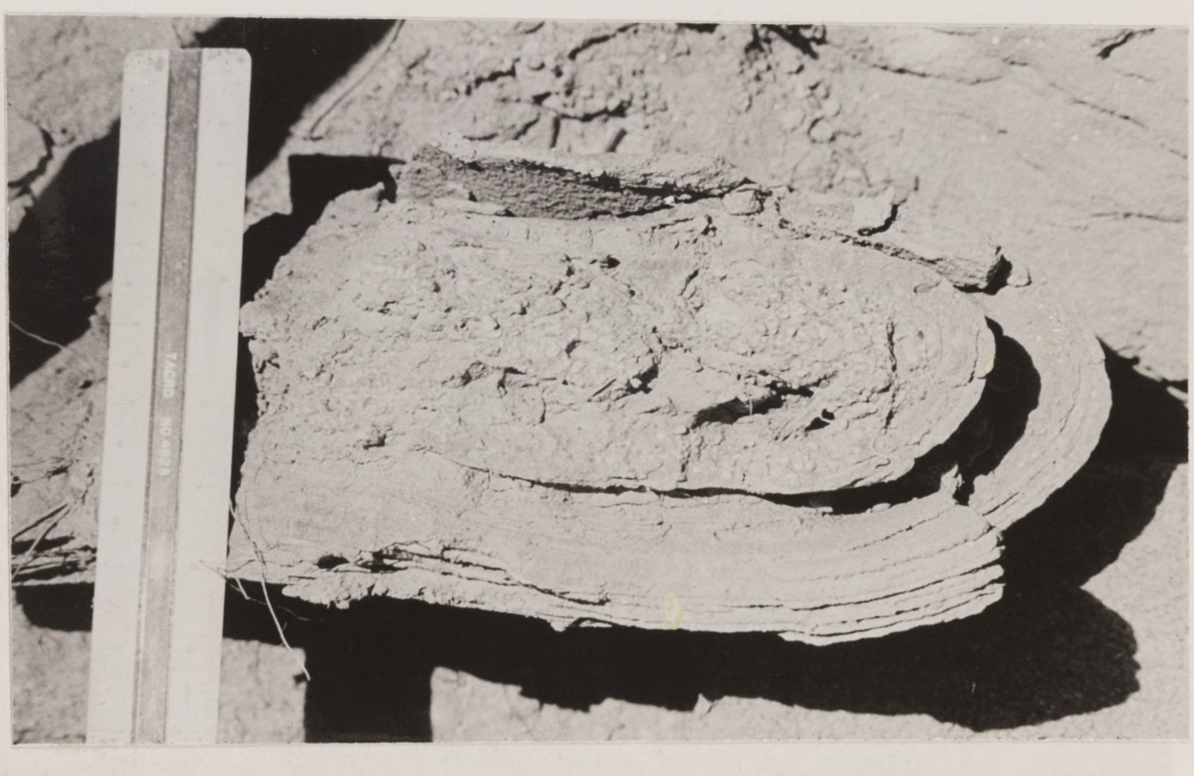


Figure 27. Delta front parallel laminated, very fine sandstone exposed at TM-6 is contorted by soft-sediment slump.

Figure 28. Delta front deposits exposed at SC-17a are disturbed by slumping. Slumped section is 2 m (6 ft) thick.

Figure 29. Normal faults in sandstone bed overlying slumped section exposed at BB-7.

was observed (Figure 30) at the southern end of the disturbance (DD-6). Sixty-seven measurements of the orientation of soft-sediment faults and joints are shown in Figure 31. These data indicate that extension was in a north-south direction. Born (1972) described a modern and late Quaternary lacustrine delta in west-central Nevada that has very similar lithofacies, geometry, and soft-sediment slump structures.

Lithofacies 4 (parallel bedded, inclined, lobate siltstone-sandstone-conglomerate)

Lithofacies 4 is exposed in the upper 75 m of the Dockum in the Palo Duro Canyon area (Figures 32 and 33). This lithofacies is very similar to Lithofacies 3 in geometry, lateral lithofacies assemblage, and vertical sequence of sedimentary structures and textures. It is differentiated from Lithofacies 3 by two major characteristics: (1) Lithofacies 4 is much thicker (genetic packages are from 8 to 15 m thick), and (2) the sedimentation units of Lithofacies 4 are inclined from 2 to 15 degrees. The inclined sedimentation units are parallel bedded and wedge-shaped, thickening at the top, and thinning toward the toe. Grain size, within a sedimentation unit, increases from the toe to the top, as does the scale of sedimentary structures. These continuous foreset beds indicate that dep-

Figure 30. Overturned nose of conglomerate sheet which overlies slumped section is visible at right. Relatively undisturbed siltstone and very fine sandstone are adjacent to and underlie conglomerate sheet. Visible length of staff is 1.5 m (5 ft). Section is exposed at DD-6a.

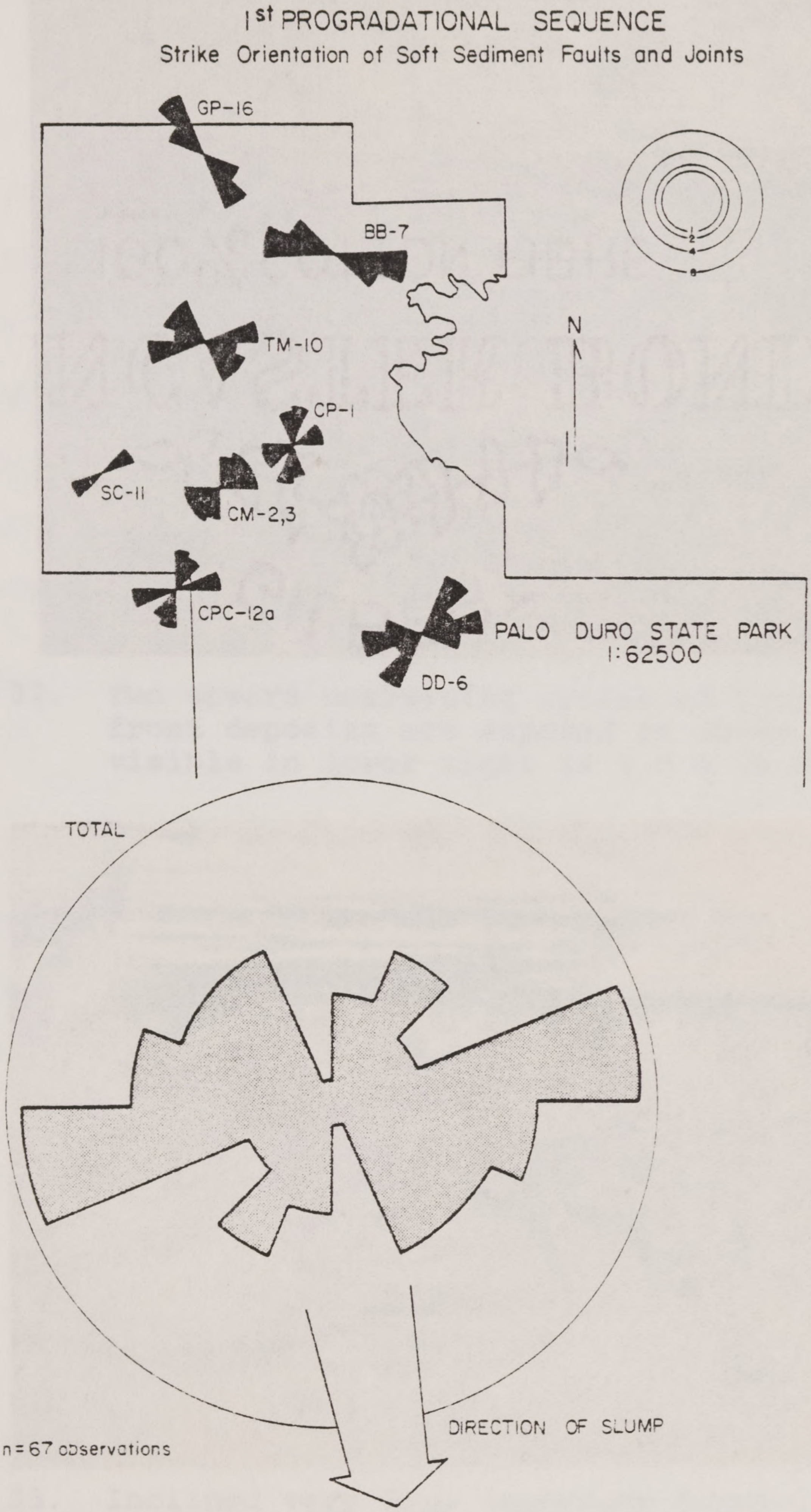


Figure 31. Soft-sediment fault and joint orientation.

Figure 32. Two upward coarsening cycles of inclined delta front deposits are exposed at DD-6b. Staff visible in lower right is 1.8 m (6 ft).

Figure 33. Inclined very fine sandstone foresets 7 to 8 m (24 to 27 ft) thick are encased in reddish brown siltstone at TC-1. Apparent dip angle is 10 to 15 degrees.

position occurred in at least 8 to 15 m of water.

The main criteria used to interpret a delta front environment of deposition for Lithofacies 3 also apply to Lithofacies 4. Increased thickness and development of fore-sets indicate that Lithofacies 4 represents deeper water lacustrine delta front deposits than does Lithofacies 3. Jopling (1958) produced, in a flume, micro-deltas which had similar geometry and sedimentary structures. Lithofacies 4 has clear affinities to the classical "Gilbert-type" deltas first described by Gilbert (1890).

Lithofacies 5 (mudclast siltstone-sandstone)

This lithofacies is exposed only in one location (EPD-4) between two laterally extensive sheets of Lithofacies 3 and 7. Lithofacies 5 is apparently a linear belt elongate in the direction of sediment transport. Primary sedimentary structures are ripple-drift within a sequence of silt to fine sand sized mudclasts. Lithofacies and facies geometry suggest deposition in a low interdeltaic embayment. Mineralogy of Lithofacies 5 and characteristics of laterally associated lithofacies suggest that the depositional environment may have been a low-energy embayment or mudflat. Progradation of lacustrine deltas may have produced a sheltered embayment which would have received sediment during delta flooding, delta foundering, or by longshore transport.

Lithofacies 6 (symmetrical channel-fill sandstone)

Symmetrical channel-fill sandstone bodies (Figure 34) were deposited in straight channels throughout the Dockum section in the Palo Duro Canyon area. Symmetrical sandstone lenses overlie and are laterally equivalent to lacustrine mudstone, delta front siltstone-sandstone-conglomerate, and delta platform sandstone-conglomerate (Lithofacies 7). The laterally associated lithofacies, and the geometry and symmetry, indicate that the straight channels were delta distributary channels. Brown and others (1973) proposed two depositional models for straight distributary channels. Brown's model for the high-constructive lobate delta may be applied to Dockum channel-fill sandstones.

Summary

Deltaic lithofacies are extensively developed throughout the Dockum at Palo Duro Canyon. Lacustrine mudstones are overlain by delta lithofacies deposited in delta front, distributary channel, and interdeltaic environments. Shallow water lacustrine deltas are characterized by near horizontal delta front deposits of Lithofacies 3. A modern and ancient analogue at Pyramid Lake in west-central Nevada

Figure 34. Symmetrically-filled sandstone body at SC-17b is 1 to 4 m (3 to 12 ft) thick. Staff in center is 1.8 m (6 ft).

was studied by Born (1972). Deeper water lacustrine deltas are characterized by inclined sedimentation units of Lithofacies 4 that were formed during deltaic progradation. Prominent foreset units of Lithofacies 4 indicate deposition in water at least 8 to 15 m deep. Deltaic processes within the Dockum lacustrine basin were characterized by the interaction of sediment-laden streams with a standing body of water.

Bates (1953) developed a theory of delta formation based on contrasting densities of water in the basin and that of associated rivers. He described the interaction of sediment laden streams entering a standing water body in terms of axial or plane jet flow. According to Bates (1953) when the density of the inflow and basin waters were equal, mixing occurred in three-dimensions (axial jet), and bed load is rapidly deposited (Figure 35). Bates only considered that density was a function of salinity or temperature. Several important factors not considered by Bates are: (1) sediment load (suspension load: bed load ratio), (2) caliber and composition of bed load, and (3) water depth. "Gilbert-type" delta foresets are commonly cited as indicators of fresh water deposition. However, sediment volume, sediment caliber, and water depth are equally important with water density as factors which affect delta formation.

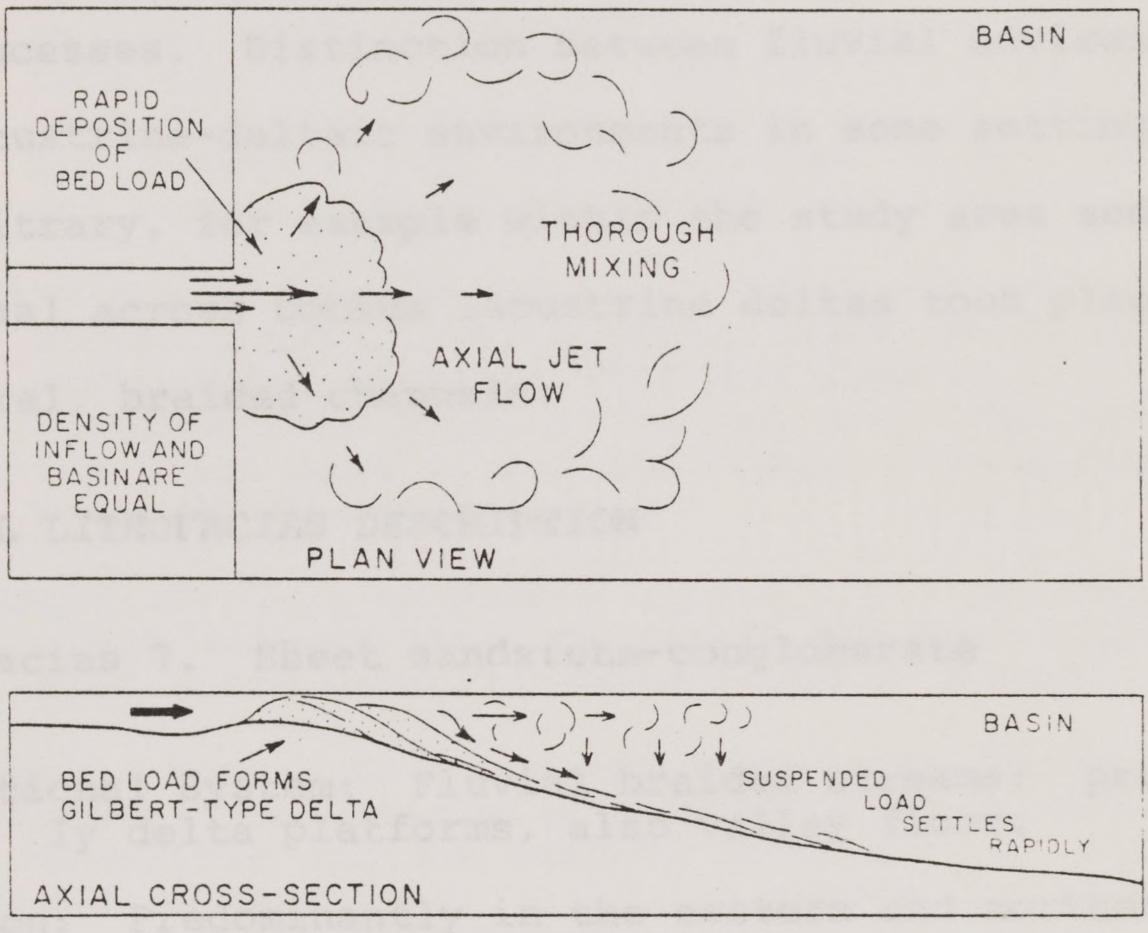


Figure 35. Rapid deposition occurs when inflow and basin waters are equally dense (Fisher and others, 1969, after Bates, 1953).

Fluvial System Lithofacies

Lithofacies 7 (sheet sandstone-conglomerate) and Lithofacies 8 (stacked channel-fill sandstone-conglomerate) were deposited in fluvial-delta plain environments by fluvial processes. Distinction between fluvial environments and lacustrine-deltaic environments in some settings may be arbitrary, for example within the study area sediment dispersal across Dockum lacustrine deltas took place within ephemeral, braided channels.

FLUVIAL LITHOFACIES DESCRIPTION

Lithofacies 7. Sheet sandstone-conglomerate

Depositional System: Fluvial braided streams; predominantly delta platforms, also valley floor.

Location: Predominantly in the eastern and northern part of the study area.

Geometry: Tabular to sheet-like very elongate lenses; width to thickness ratios vary from 125:1 to 300+:1.

Thickness: Total thickness 10 to 30 m; individual sheet 2 to 20 m thick.

Occurrence: The color of Lithofacies 7 is commonly reddish brown on a 0.5 to 5 cm thick weathering surface; true color ranges from light reddish brown and light brown, grayish green to white; 5 to 7 separate sheets occur in the eastern part of the study area, they thin and pinch out to the west, one sheet thins to the south.

Lateral Relationships and Trends: Sandstone-conglomerate sheets overlie Lithofacies 3 and 4, generally with sharp basal contacts; Lithofacies 6 overlies and is interbedded with sandstone-conglomerate sheets; Lithofacies 6 is laterally equivalent west and south of sandstone-conglomerate sheets; in the southern and northern parts of the study area sandstone-conglomerate sheets are truncated by Lithofacies 8.

Sedimentary Structures: Trough-fill cross-stratification is the most abundant sedimentary structure; within individual sheets cross-laminae vary in size from 0.1 to 2 m; cross laminae decrease in size upwards; ripple-cross laminae and parallel laminae are common at the top of sheets; accretionary grain and curved bed set boundaries are common.

Grain Size and Grain Size Trends: Grain size within individual sheets fines upward; basal parts of sandstone-conglomerate sheets are granule to pebble conglomerate, upper parts are very fine sandstone; the grain size within individual sheets fines in a westerly direction.

Mineralogy: Granule to pebble clasts are intrabasinal mudclast and caliche; quartz is the most abundant sand sized material and caliche is common.

Petrographic Name: Coarse sandy granule to pebble conglomerate: calcitic slightly dolomitic submature hematitic caliche bearing calclithite. Fine to medium sandstone: calcitic mature fresh feldspar bearing sublitharenite.

Lithofacies 8. Stacked channel-fill sandstone-conglomerate

Depositional System: Valley fill; transgressive sequence of fluvial-deltaic-lacustrine deposits.

Location: There are 2 belts that occur in the northern and southern sectors of the eastern part of the study area; Lithofacies 8 stratigraphically occupies the central 50 m of the section.

Geometry: Linear belts are oriented east-west and elongate in the direction of sediment transport; individual channel-fill bodies have width to thickness ratio ranges from 5:1 to 30:1.

Thickness: Total thickness ranges from 20 to 45 m; individual channel-fills vary from 7 to 20 m thick.

Occurrence: The color of Lithofacies 8 sandstone-conglomerate bodies is commonly reddish brown on a 0.5 to 5 cm thick weathering surface; true color ranges from light to dark reddish brown, light grayish green, to white; the southern belt of Lithofacies 8 is thickest in the east where 3 to 5 channel-fill sandstone-conglomerate bodies are confined to an east-west oriented trough; the northern belt is more complex, 4 to 6 complex channel-fill units are exposed; the lower contact is sharp, erosional; the upper contact is normally gradational.

Lateral Relationships and Trends: The southern belt of Lithofacies 8 is thickest in the east where 3 to 5 channel-fill sandstone-conglomerate bodies are vertically stacked and confined to an east-west valley; the southern belt thins toward the west; vertically and to the west channel-fill bodies become smaller and finer grained; to the west Lithofacies 7 is laterally equivalent to the lowest stacked channel-fill sandstone-conglomerate bodies; in an upward direction channel-fill bodies become parallel bedded sandstone sheets; to the south channel-fill sandstone bodies are laterally equivalent to parallel bedded sheet sandstones; Lithofacies 3 and 4 occur at the top of Lithofacies 8.

Sedimentary Structures: Trough-fill cross-stratification is the most abundant structure in the channel-fill bodies; parallel-bedded, horizontal and inclined laminated siltstone-sandstone-conglomerate overlie stacked channel fill.

Grain Size and Grain Size Trends: Overall grain size trend fines upward; most channel-fill bodies fine upward; one channel fill is coarsening-upward granule to pebble conglomerate.

Mineralogy: Granule to pebble clasts are predominantly extrabasinal chert pebble conglomerates; very fine to coarse quartz sand is abundant; medium sand to granule caliche clasts are common.

Petrographic Name: Coarse sandy granular pebble conglomerate: calcitic and hematitic submature chertarenite; fine to medium sandstone: calcitic and hematitic mature caliche bearing subsedarenite.

Lithofacies 7 (sheet sandstone-conglomerate)

This lithofacies occurs in three horizons throughout the study area. The lowest occurrence is a white sandstone sheet 15-45 m above the Dockum Group-Quartermaster Formation contact (Figure 36). The middle Lithofacies 7 horizon consists of three or four individual sheets and crops out along the eastern part of Palo Duro State Park (Figure 37). This horizon of widespread sandstone-conglomerate deposition was described by Hood (1978) as the base of the Trujillo Formation. The uppermost occurrence is composed of two vertically superposed sheets within 25 m of the unconformity between the Dockum Group and Ogallala Formation.

Lithofacies 7 occurs as a sheet-like sandstone-conglomerate lens with a width to thickness ratio varying from 125:1 to 300+:1 (Figure 38). The distal margins thin to a feather edge, and interfinger with Lithofacies 3, 4, 5, and 6. Lithofacies 7 overlies and is separated by sharp contacts from Lithofacies 3 and 4 which represent delta front environments. Symmetrically-filled delta distributary channels overlie Lithofacies 7 and are laterally equivalent. Delta distributary channel-fill sandstone bodies that overlie fluvial sheet sandstone-conglomerate suggest initiation of lacustrine expansion and the replacement of proximal facies (fluvial Lithofacies 7) with more

Figure 36. White sandstone sheet capping Capitol Peak overlies thin bedded and slumped delta front siltstone and sandstone.

Figure 37. Fining-upward delta platform sheet overlies parallel-bedded coarsening upward delta front deposits at EPD-2. Staff at lower right is 1.8 m (6 ft).

Figure 38. Capitol Peak Mesa is capped by coarse-grained, delta platform sandstone-conglomerate sheet less than 1 to 13 m thick. Sandstone-conglomerate sheet overlies thin-bedded, white delta front siltstone, and burrowed, reddish-brown lacustrine mudstone. View is west.

distal facies (deltaic Lithofacies 6). Lithofacies 1 overlies Lithofacies 7, but is not genetically related. The texture of Lithofacies 7 fines upward, and trough-fill cross-stratification is the predominant sedimentary structure.

Laterally extensive (multilateral) sheet geometry, texture, and structure suggest that Lithofacies 7 was deposited in ephemeral braided channels. The abundance of trough-fill cross-stratification indicates that sediment deposited in laterally extensive sheets moved downstream predominantly as dune bedforms (Figures 39 and 40). Vertical profiles of Lithofacies 7 show similarities with both Donjek and Platte type braided stream depositional profiles described by Miall (1977).

The braided stream depositional environments have been reviewed by Miall (1977). Doeglas (1962), Ore (1964, 1965), Smith (1970), and Rust (1972) have described stratification types in modern braided stream deposits. Braided streams are component facies within alluvial fan (Bull, 1963; Gole and Chitale, 1966; McGowen and Groat, 1971), fan delta (McGowen, 1970; McGowen and Scott, 1974), and braided outwash fan (Boothroyd, 1972; Boothroyd and Ashley, 1975) depositional systems.

The interpretation that braided stream deposits are present in the study area are based on external sandstone body geometry and internal stratification. The external

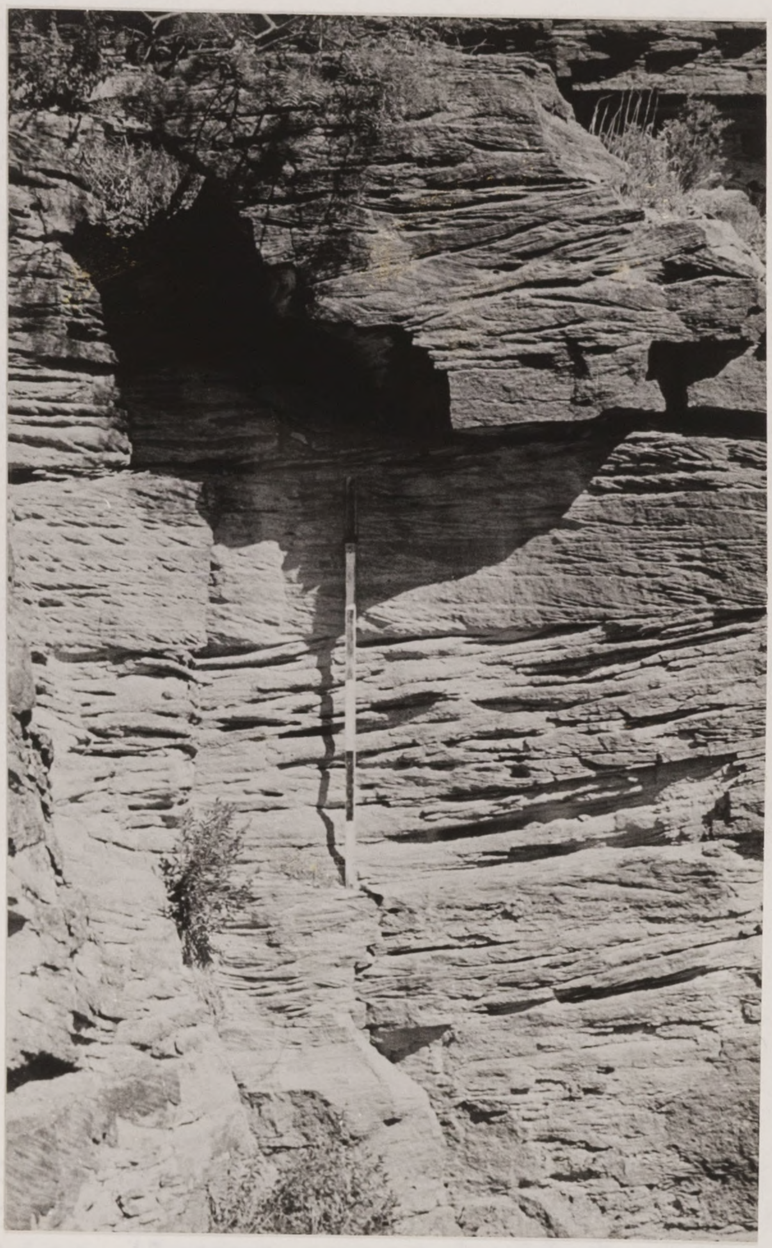


Figure 39. Trough-fill cross-stratification in fan delta platform facies is exposed on Timber Mesa. Staff is 1.8 m (6 ft).

Figure 40. Trough-fill cross-stratification (upper two cross-bedded units) and foreset cross-stratification (lower cross-bedded unit) occurs within a lenticular sandstone body at EPD-4. Dune form 0.3 m (1.0 ft) high and reactivation surface is preserved in lowermost foreset cross-stratified unit. Alternately the lower cross-bedded unit may represent lateral migration (to left) of a transverse bar.

geometry of braided stream channels are characterized by width to thickness ratios which exceed 40 to 1 (Schumm, 1972). In the study area, width to thickness ratios of sandstone bodies vary from 125 to 1 to 350+ to 1. Although no stratification type is uniquely characteristic of braided stream deposits, trough-fill cross-stratification is present in modern braided streams described by Doeglas (1962) and Rust (1972). In the study area, lacustrine and deltaic facies are laterally equivalent to braided stream deposits. The braided stream deposits are interpreted as sand-rich delta platforms composed of shallow braided stream channels. Some sand-rich delta platforms, which represent proximal delta facies, are overlain by more distal delta facies represented by small distributary channel-fill lenses. This vertical sequence occurs during lacustrine expansion which causes delta foundering.

Lithofacies 6 and 7 are the uppermost deposits of genetic sequences that begin with lacustrine mudstones and delta front siltstone-sandstone-conglomerate, and mark the top of a coarsening-upward progradational deltaic cycle. In the Palo Duro Canyon area, most Dockum delta platforms are composed of coarse-grained sandstone-conglomerate sheets. This differentiates these Dockum deltas from oceanic deltas with fine-grained delta plains. A modern analogue of these deposits is the on delta (delta platform) sediments of Pyramid Lake, Nevada that are described by Born (1972). Those subaerial sediments are largely composed of sand and gravel and were deposited in a valley floor covered by a complex network of channels and alluvial islands.

Lithofacies 8 (stacked channel-fill sandstone-conglomerate)

Lithofacies 8 is a very complex assemblage of sediment types and depositional units that is characterized by vertically stacked channel-fill sandstone-conglomerate bodies and deltaic units. This lithofacies is interpreted to represent a valley-fill sequence of transgressive-fluvial-deltaic-lacustrine deposits that postdate a period of incision and valley cutting. Characteristics of the transgressive sequence are shown in Figure 7.

Lithofacies 8 occurs as two linear belts in the northern and southern sectors of the eastern part of the study area. These belts stratigraphically occupy the central 50 m of the Dockum in the study area. Asymmetrical and symmetrical channel-fill sandstone-conglomerate units occupy the base of the lithofacies. At the easternmost exposure of the southern belt (Figure 2, TSD-13, PDSP 32, 33, and 35) three to five channel-fill sandstone-conglomerate bodies attain a maximum combined thickness of 34 m (Figures 41 and 42). Vertically and to the west channel-

Figure 41. Mosaic of valley-fill sandstone-conglomerate exposed at Tub Springs Draw (TSD-13b) where approximately 34 m (110 ft) of sandstone-conglomerate is exposed. Stadia rod is 4.3 m (14 ft) long.

Figure 42. Valley-fill chert pebble conglomerate is overlain by distributary channel sandstone at RM-5b. Approximately 25 m (80 ft) is exposed.

Figure 43. Distributary channel sandstone lenses exposed 300 m (1000 ft) west of valley-fill conglomerate at RM-5b. View is north.

fills become similar to Lithofacies 6. Channel-fill becomes thinner, more narrow, and finer grained than comparable sequences exposed at the base of the lithofacies (Figure 43). Lithofacies 8 thins toward the west where a sandstone-conglomerate sheet (Lithofacies 7), 2 to 13 m thick, is laterally equivalent to the lowest stacked channel-fill sandstone-conglomerate bodies (Figure 44). The uppermost part of Lithofacies 8 contains Lithofacies 3 and 4 rocks (Figure 45).

The sequence is interpreted to represent a valley-fill sequence of transgressive fluvial-deltaic-lacustrine deposits. Lacustrine mudstones that underlie the valley-fill sequence contain calcareous zones which indicate arid conditions. Arid conditions caused a decrease in lake area, a lowering of base level, and valley incision. Streams which carved the valley also constructed a small lacustrine delta-fan delta at the margin of the lake. A wet cycle caused lake area expansion which flooded the valley. A transgressive deltaic sequence formed within the drowned valley, was overlain by lacustrine mudstones. Fisk (1944) documented a similar history of Mississippi River Valley aggradation during the Quaternary. Wilkinson and Byrne (1977) reported a similar transgressive deltaic sequence in Lavaca Bay (Texas) was deposited during the past 10,000 years of rising sea level. Gilbert (1885, 1890), Butzer

Figure 44. Capitol Peak Mesa is capped by a delta platform sandstone-conglomerate sheet which formed down dip and west of the valley-fill sequence. Delta platform covers 1-3 square km, and is a coarsening-upward sequence of burrowed, lacustrine mudstones, thin bedded, white delta front siltstone, and coarse-grained delta platform sandstone-conglomerate. View is west.

Figure 45. Inclined, parallel bedded delta front deposits overlie delta distributary channel-fill bodies exposed at RM-5b.

(1971), and Born (1972) document base level fluctuations in the lacustrine environment and describe delta modification by fluvial incision.

Summary

Braided fluvial depositional processes occur on delta platform and valley floor environments. In the study area braided stream delta platform deposits are sandstone-conglomerate sheets which cap progradational genetic sequences of lacustrine mudstones and deltaic siltstone-sandstone-conglomerate. These sequences are upward coarsening and occur in three horizons throughout the study area. One transgressive valley-fill sequence was identified. Braided stream fluvial deposits occupy the valley floor. The valley-fill sequence comprises in ascending order fluvial sandstone-conglomerate, deltaic siltstone-sandstone-conglomerate, and lacustrine mudstone. The valley, that was scoured during an arid cycle low stand of the lake, was filled during a wet cycle lacustrine expansion.

GENETIC SEQUENCES

Three progradational sequences comprise the Dockum Group in Palo Duro Canyon area and are composed of genetically related lacustrine, deltaic and fluvial rocks. Three main vertical, coarsening upward, genetic sequences consist in ascending order of: lacustrine mudstone, deltaic siltstone-sandstone-conglomerate, and fluvial sandstone-conglomerate. This association of component lithofacies and depositional environments is not coincidental. The interpretation that these environments are genetically related is derived from application of Walther's Law which states that a vertical sequence of genetically related rocks must have been produced in laterally equivalent environments. In the Dockum rocks lateral equivalence of vertically superposed lithofacies can be verified because of the three-dimensional exposure.

Base level fluctuations complicate interpretations of depositional history. Gilbert (1890) first recognized and described the effect of fluctuating lake level on associated deltas. He described a series of successively younger and stratigraphically lower deltas that were formed by partial destruction of older and stratigraphically higher deltas. Dockum Group rocks in the study area record at least one period during which base level was lowered, and sediment was reworked from older subaerially exposed deltas and deposited in stratigraphically lower, younger deltas down dip.

In the study area three genetic sequences are vertically superposed. Laterally extensive progradational fluvial-deltaic sedimentation filled this part of the lacustrine basin three times. Each genetic sequence is a record of progradation and partial filling of a portion of the lake basin exposed in the Palo Duro Canyon area. One genetic sequence also records a transgression. Each genetic sequence will be discussed in ascending order in terms of lithofacies, environments, and depositional systems. Data on the genetic sequences are derived from contour maps, fence diagrams, cross-sections, paleocurrent analysis, and petrographic study.

First Progradational Sequence

The first progradational sequence occurs at the base of the Dockum Group. In outcrop this sequence is characterized by thick varicolored mudstones that are situated near the Dockum Group-Quartermaster Formation contact. The first progradational sequence consists of three units which are, in ascending order: (1) a lower unit composed of Lithofacies 2, 3, and 4; (2) a middle unit composed of Lithofacies 1 and 2; and (3) an upper unit composed of

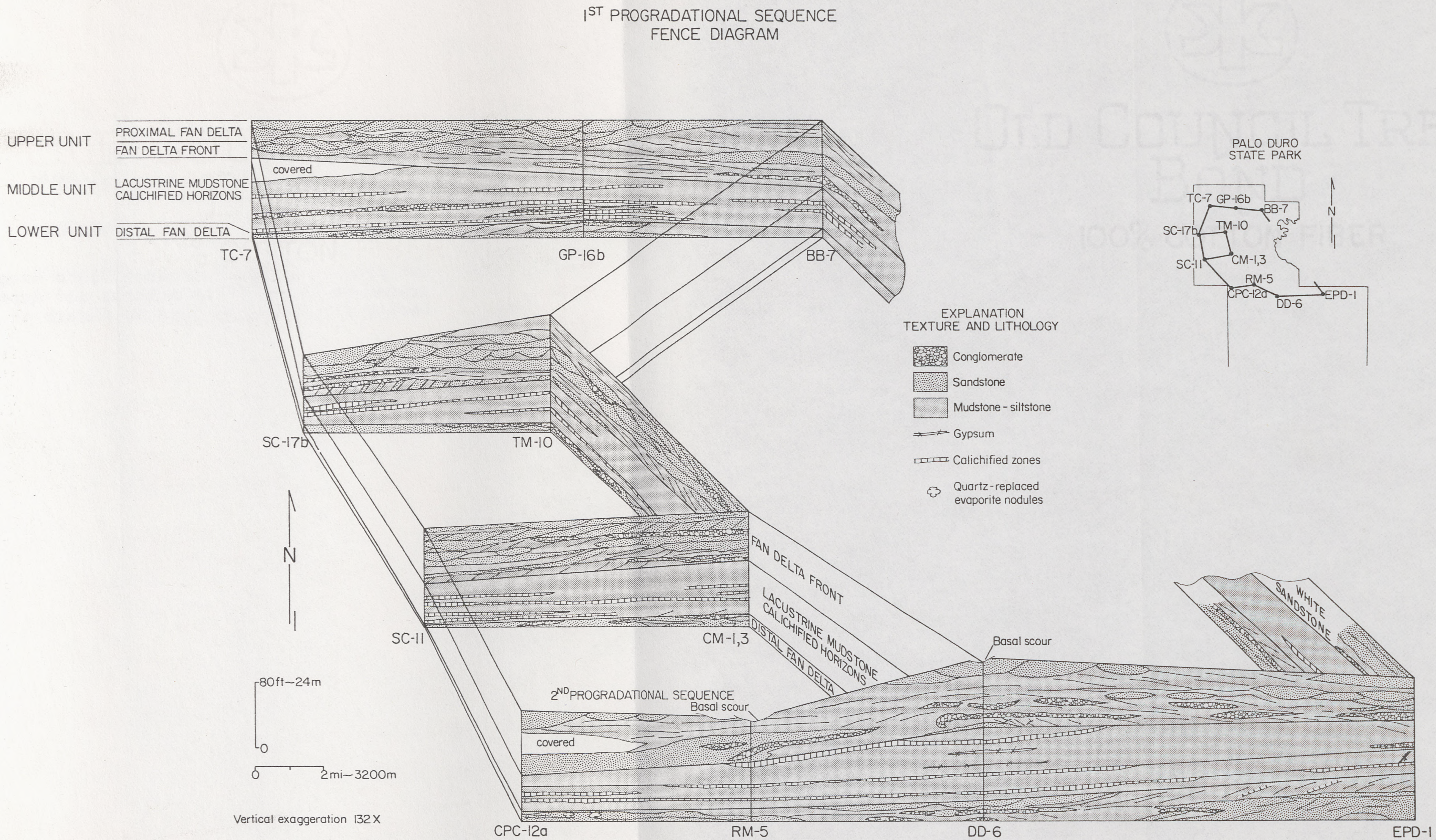
Lithofacies 3, 6, and 7. The lateral and vertical trends in thickness, texture, lithology, and sedimentary structures are illustrated in Figure 46 and 47.

LOWER UNIT

The lower unit of the first progradational sequence overlies the unconformity separating the Dockum Group and Quartermaster Formation. The lower unit is a thin set of westward-thinning, and westward-dipping delta front deposits (Figure 48), which represents initial Dockum sedimentation in the study area. The variation of sandstone percentage in the lower unit over the study area (Figure 49) indicates that the lower unit becomes finer in a westerly direction. There is an anomalous area in the northeast sector of the study area where sand did not accumulate. Within this area there are gray mudstones which contain abundant macerated and unoxidized plant debris. Sandstone-free areas are interpreted to be interdeltaic mudstones that are laterally equivalent to delta front sandstone-conglomerate.

Lateral and vertical trends of the lower unit are shown in Figures 46 and 47. Two areas in the northern and south-central sectors where the lower unit is thickest, also exhibit high percentage sandstone, and are interpreted to be areas of maximum sediment input. Sediment, supplied

Figure 46. 1st progradational sequence fence diagram illustrates texture, lithology, and depositional facies. Figure 47 covers the same area, and illustrates sedimentary structures. The 1st progradational sequence overlies the unconformity separating the Permian Quartermaster Formation and the Triassic Dockum Group. Three units represent in ascending order: lower unit --distal lacustrine fan delta and soil zone; middle unit--lacustrine mudstone and caliche horizons; and upper unit--proximal lacustrine fan delta (delta front, distributary channel, and delta platform environments). The lower unit is a delta front and soil zone sequence that dips and thins toward the west. Quartz-replaced and chert-replaced (?) evaporite nodules occur in this unit. Minor amounts of euhedral and bipyramidal quartz silt is present. The middle unit is composed of two to five varicolored, burrowed lacustrine mudstones. These mudstone layers were deposited in lake center and lake margin environments and contain abundant Scoyenia and Teichichnus. Caliche horizons consist of discontinuous caliche nodules that replace burrowed mudstones. Caliche nodules contain predominantly microspar calcite, sparry calcite, and minor dolomite. The upper unit is a white very fine sandstone sheet that is thickest in the north and east and thins toward the south. A slump occurred in delta front silt and very fine sand of the upper unit as result of rapid loading by deposition of a conglomeratic unit. The slump covered at least 25 sq km, and movement was southerly. The southerly thinning of sandstone bodies, and the decrease in percentage sandstone toward the south indicate southerly progradation of fan delta lobes in the upper unit of the first progradational sequence.



1ST PROGRADATIONAL SEQUENCE
FENCE DIAGRAM
UPPER UNIT
PROXIMAL FAN DELTA
FAN DELTA FRONT
MIDDLE UNIT
LACUSTRINE MUDSTONE
CALICHIFIED HORIZONS
LOWER UNIT
DISTAL FAN DELTA
covered
TC-7
GP-16b
BB-7
SC-17b
TM-10
SC-11
CM-1,3
CPC-12a
RM-5
DD-6
EPD-1
N
FAN DELTA FRONT
LACUSTRINE MUDSTONE
CALICHIFIED HORIZONS
DISTAL FAN DELTA
Basal scour
WHITE SANDSTONE
2ND PROGRADATIONAL SEQUENCE
Basal scour
covered
80ft~24m
0
0
2mi~3200m
Vertical exaggeration 132X
EXPLANATION
TEXTURE AND LITHOLOGY
Conglomerate
Sandstone
Mudstone - siltstone
Gypsum
Calichified zones
Quartz-replaced evaporite nodules
PALO DURO
STATE PARK
TC-7 GP-16b
BB-7
SC-17b
TM-10
SC-11
CM-1,3
RM-5
CPC-12a
DD-6
EPD-1
N

Figure 46

Figure 47. 1st progradational sequence fence diagram illustrates sedimentary structures and depositional facies for the same area as Figure 46.

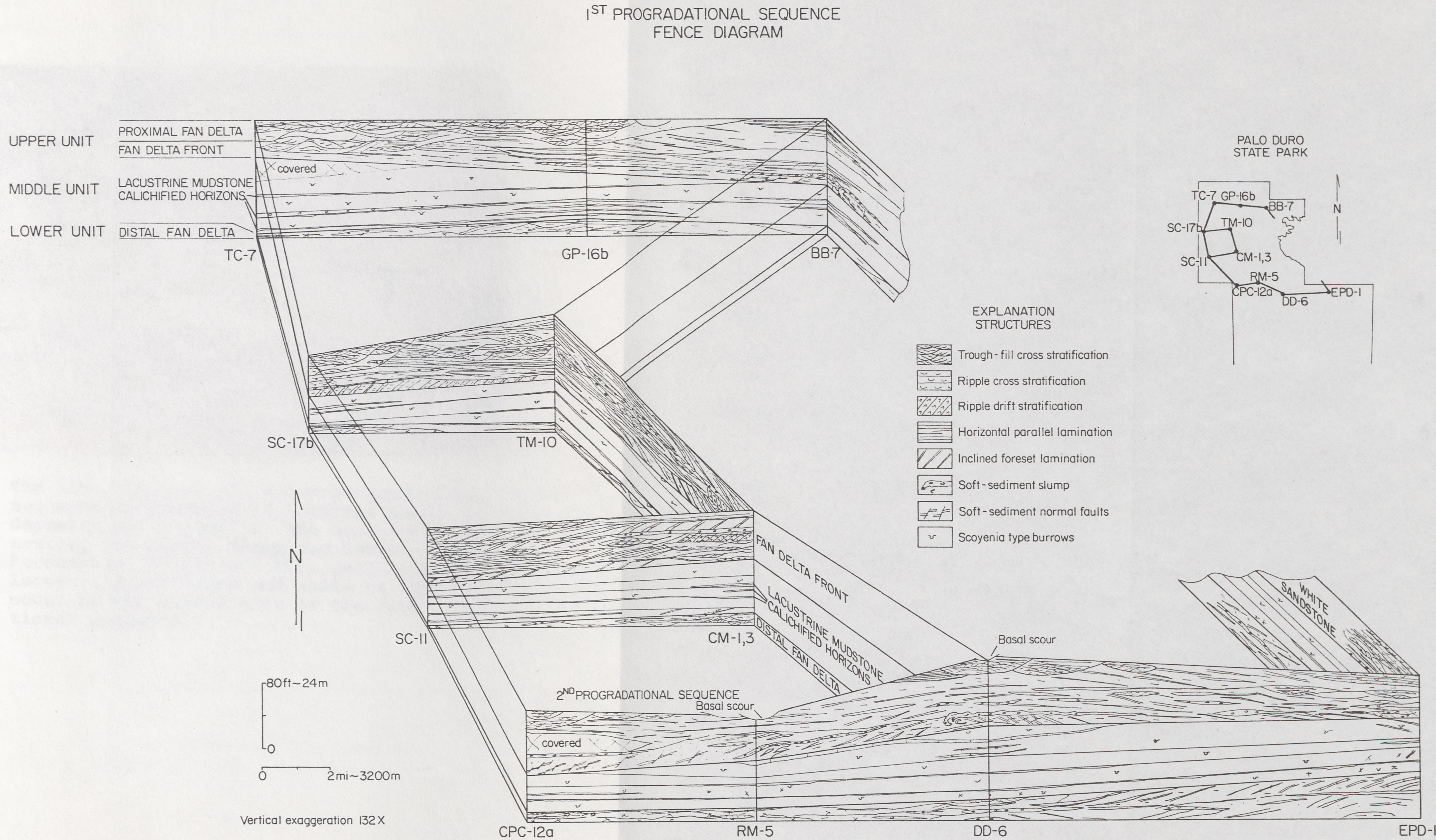

1ST PROGRADATIONAL SEQUENCE
FENCE DIAGRAM
UPPER UNIT
PROXIMAL FAN DELTA
FAN DELTA FRONT
MIDDLE UNIT
LACUSTRINE MUDSTONE
CALICHIFIED HORIZONS
LOWER UNIT
DISTAL FAN DELTA
covered
TC-7
GP-16b
BB-7
SC-17b
TM-10
SC-11
CM-1,3
FAN DELTA FRONT
LACUSTRINE MUDSTONE
CALICHIFIED HORIZONS
DISTAL FAN DELTA
Basal scour
WHITE SANDSTONE
2ND PROGRADATIONAL SEQUENCE
Basal scour
covered
CPC-12a
RM-5
DD-6
EPD-1
N
80ft~24m
0
0
2mi~3200m
Vertical exaggeration 132X
PALO DURO
STATE PARK
TC-7 GP-16b
BB-7
SC-17b
TM-10
CM-1,3
SC-11
RM-5
CPC-12a
DD-6
EPD-1
N
EXPLANATION
STRUCTURES
Trough-fill cross stratification
Ripple cross stratification
Ripple drift stratification
Horizontal parallel lamination
Inclined foreset lamination
Soft-sediment slump
Soft-sediment normal faults
Scoyenia type burrows

Figure 47

Figure 48. The lower unit of the first progradational sequence is composed of inclined delta front deposits which overlie the unconformity separating the Dockum Group and Quartermaster Formation. Purple and dark yellowish-orange lacustrine mudstones and white caliche horizons occur in the middle unit of the first progradational sequence.

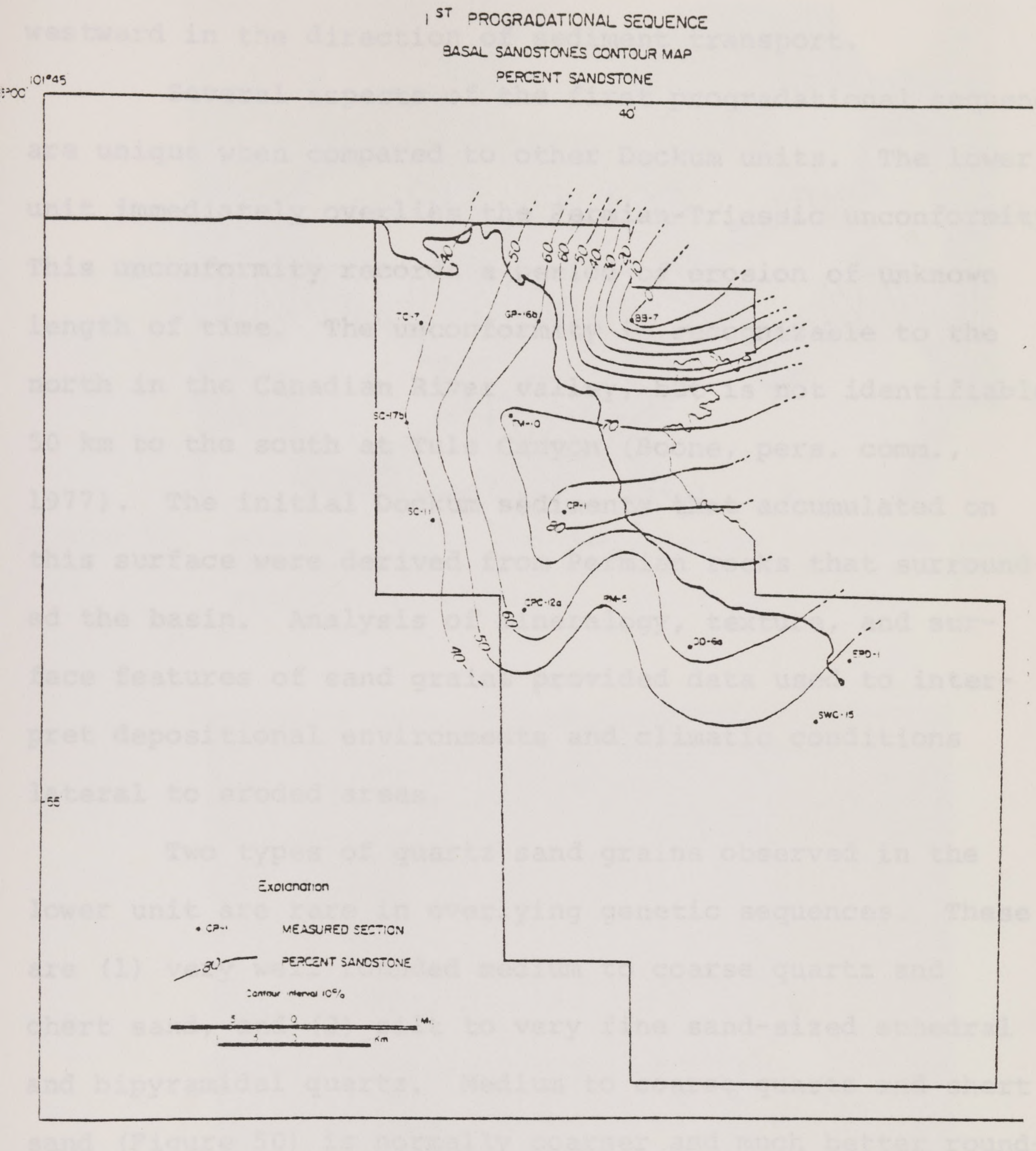


Figure 49. Percentage sandstone in the lower unit of the first progradational sequence.

from north and south-east sources, becomes finer-grained westward in the direction of sediment transport.

Several aspects of the first progradational sequence are unique when compared to other Dockum units. The lower unit immediately overlies the Permian-Triassic unconformity. This unconformity records a period of erosion of unknown length of time. The unconformity is recognizable to the north in the Canadian River valley, but is not identifiable 50 km to the south at Tule Canyon (Boone, pers. comm., 1977). The initial Dockum sediments that accumulated on this surface were derived from Permian rocks that surrounded the basin. Analysis of mineralogy, texture, and surface features of sand grains provided data used to interpret depositional environments and climatic conditions lateral to eroded areas.

Two types of quartz sand grains observed in the lower unit are rare in overlying genetic sequences. These are (1) very well rounded medium to coarse quartz and chert sand, and (2) silt to very fine sand-sized euhedral and bipyramidal quartz. Medium to coarse quartz and chert sand (Figure 50) is normally coarser and much better rounded than sand in overlying units. Much of the quartz sand is strongly undulose and some quartz sand contains anhydrite inclusions. This contrasts with very fine to fine common quartz sand abundant throughout the overlying Dockum.

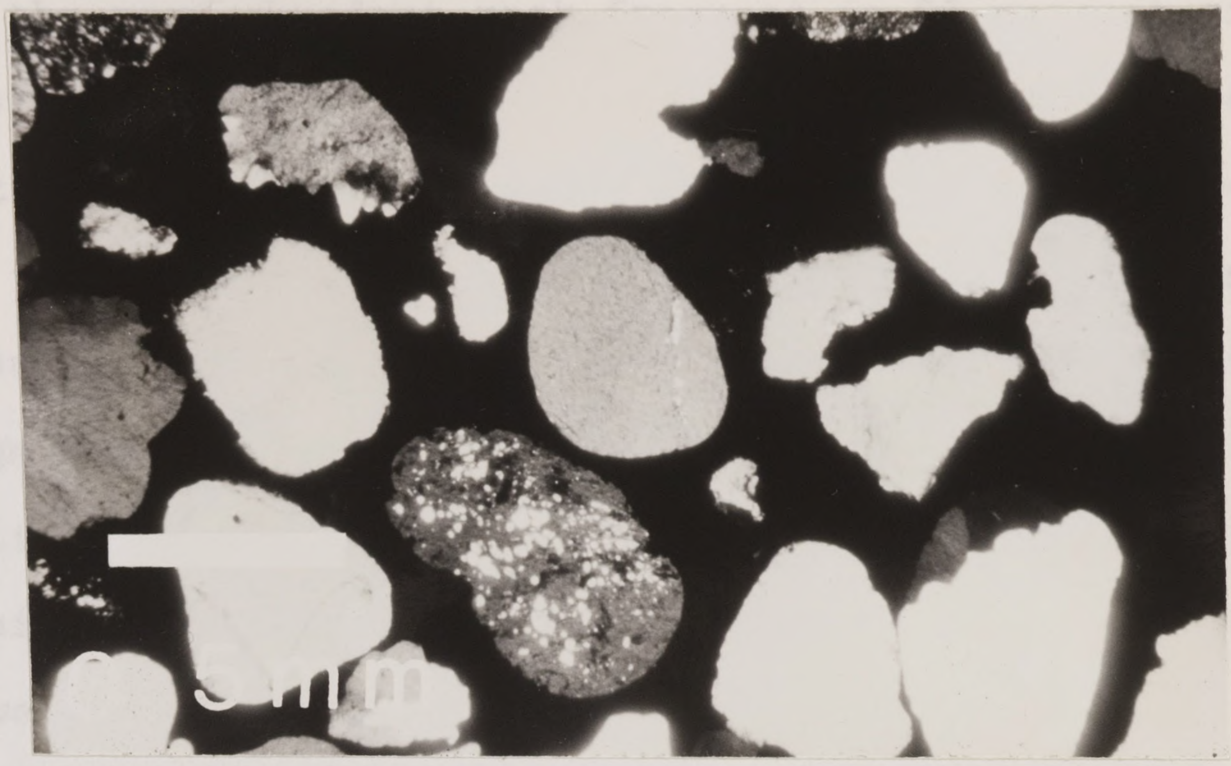


Figure 50. Rounded quartz and chert medium to coarse sand is common in the lower unit of the first progradational sequence. Scale is 0.5 mm.

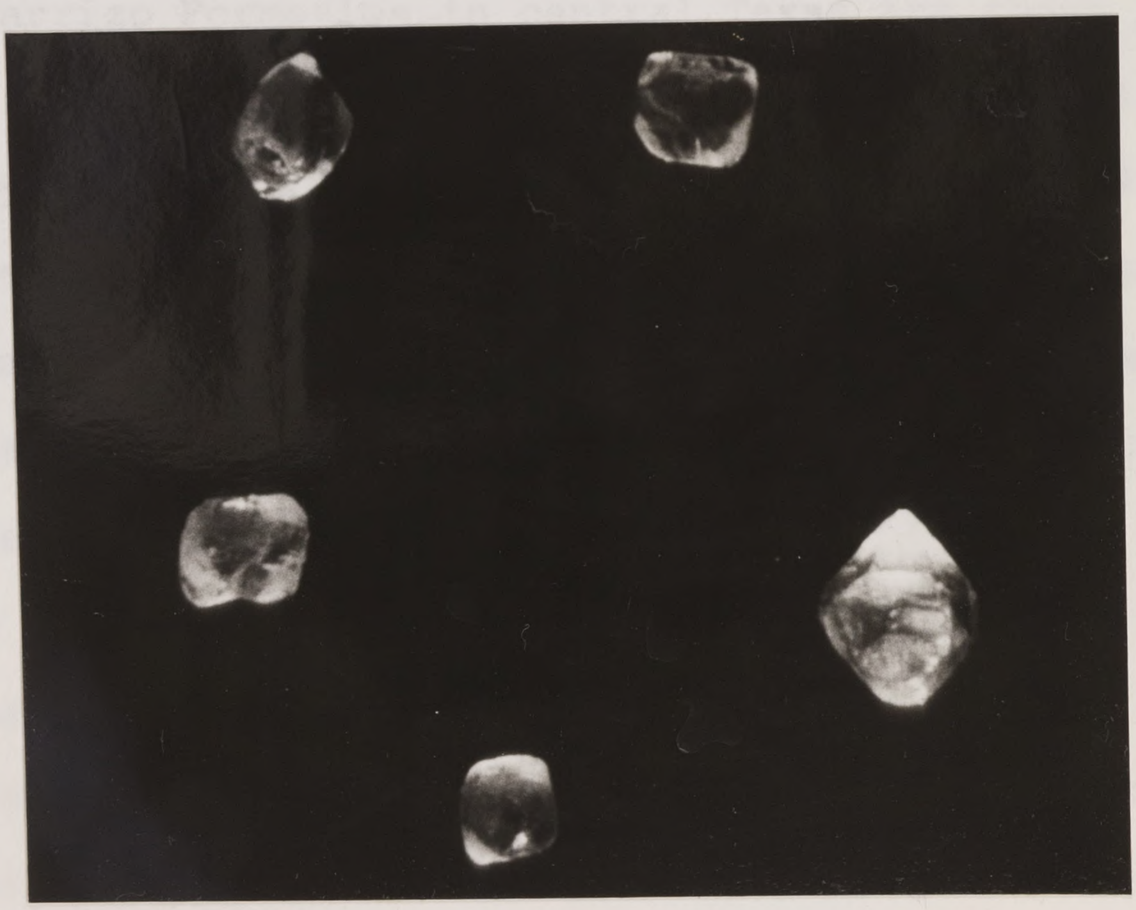


Figure 51. Euhedral quartz crystals are silt to very fine sand sized in the lower unit of the first progradational sequence.

Chert is the most abundant rock fragment in 83 percent of the sandstone samples from the first progradational sequence. This contrasts with the abundance of carbonate rock fragments in the Dockum as a whole. (In 55 percent of Dockum sandstones carbonate rock fragments are the most abundant rock fragment). Also, silt to very fine quartz sand in the lower unit is commonly euhedral and bipyramidal (Figure 51). These grains show some abrasion, but sharp lines still remain between crystal faces. Most of these crystals are very clear, but some have hematite coats. Bipyramidal quartz is commonly cited as an indicator of a volcanic source (Folk, 1974b). Euhedral volcanic quartz phenocrysts from the Carrizo Formation in central Texas are shown in Figure 52. They are embayed and have rounded boundaries between crystal faces. Folk (pers. communication, 1978) stated that euhedral quartz from the Dockum probably originated from transportation and disaggregation of sedimentary quartz nodules. Several lines of evidence support Folk's interpretation: (1) quartz-replaced evaporite nodules which occur at the top of the lower unit contain euhedral quartz crystals and anhydrite inclusions; (2) cores from Permian San Andres Formation in north-central Texas contain partially silicified evaporite nodules (de Mejia, 1977); (3) some medium and coarse quartz sand in the lower unit also contain anhydrite inclusions; and (4) whereas

Figure 52. Euhedral embayed quartz phenocrysts from the Carrizo Formation in central Texas.

volcanic quartz is characteristically embayed and rounded, sedimentary quartz crystals lack embayments.

MIDDLE UNIT

The middle unit, which consists of two to five lacustrine mudstone packages that are interbedded with paleocaliches (Figure 48), is the thickest unit of the first progradational sequence. The lateral and vertical trends in composition, sedimentary structures and depositional facies are shown in Figures 46 and 47. An isopach of the middle mudstone unit is shown in Figure 53. Two lobes of mudstone accumulation occur in the northwest and southeast sectors of the study area. Mudstone thickness decreases toward the southwest. This depositional pattern suggests that two sub-basins existed in the study area. Although the total thickness of rock in the Dockum basin increases to the west beneath the High Plains, sub-basins may have been locally important areas of sediment accumulation.

UPPER UNIT

The upper unit caps the first progradational sequence. It is an upward coarsening sequence of fan delta front, distributary channel, and delta platform siltstone-sandstone-conglomerate; white, very fine to fine sandstone

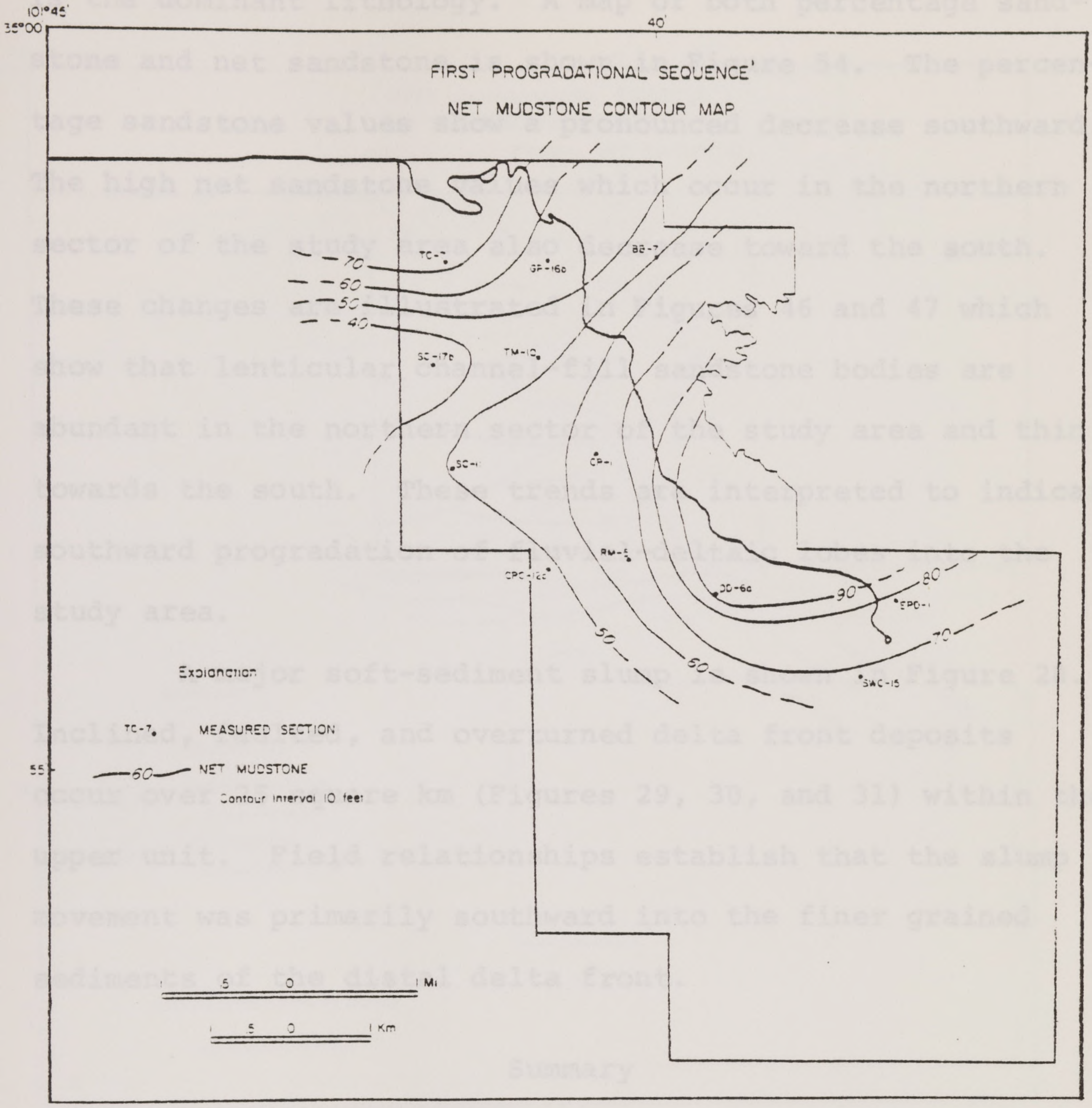


Figure 53. Thickness of mudstone in the middle unit of the first progradational sequence.

is the dominant lithology. A map of both percentage sandstone and net sandstone is shown in Figure 54. The percentage sandstone values show a pronounced decrease southward. The high net sandstone values which occur in the northern sector of the study area also decrease toward the south. These changes are illustrated in Figures 46 and 47 which show that lenticular channel-fill sandstone bodies are abundant in the northern sector of the study area and thin towards the south. These trends are interpreted to indicate southward progradation of fluvial-deltaic lobes into the study area.

A major soft-sediment slump is shown in Figure 28. Inclined, faulted, and overturned delta front deposits occur over 25 square km (Figures 29, 30, and 31) within the upper unit. Field relationships establish that the slump movement was primarily southward into the finer grained sediments of the distal delta front.

Summary

An upward coarsening sequence of lacustrine and fluvial-deltaic environments characterized the first progradational sequence of the Dockum Group in the study area. A sandstone percent map for the entire first progradational sequence is shown in Figure 55. A fan-shaped contour pattern outlines the area of highest percentage sandstone in

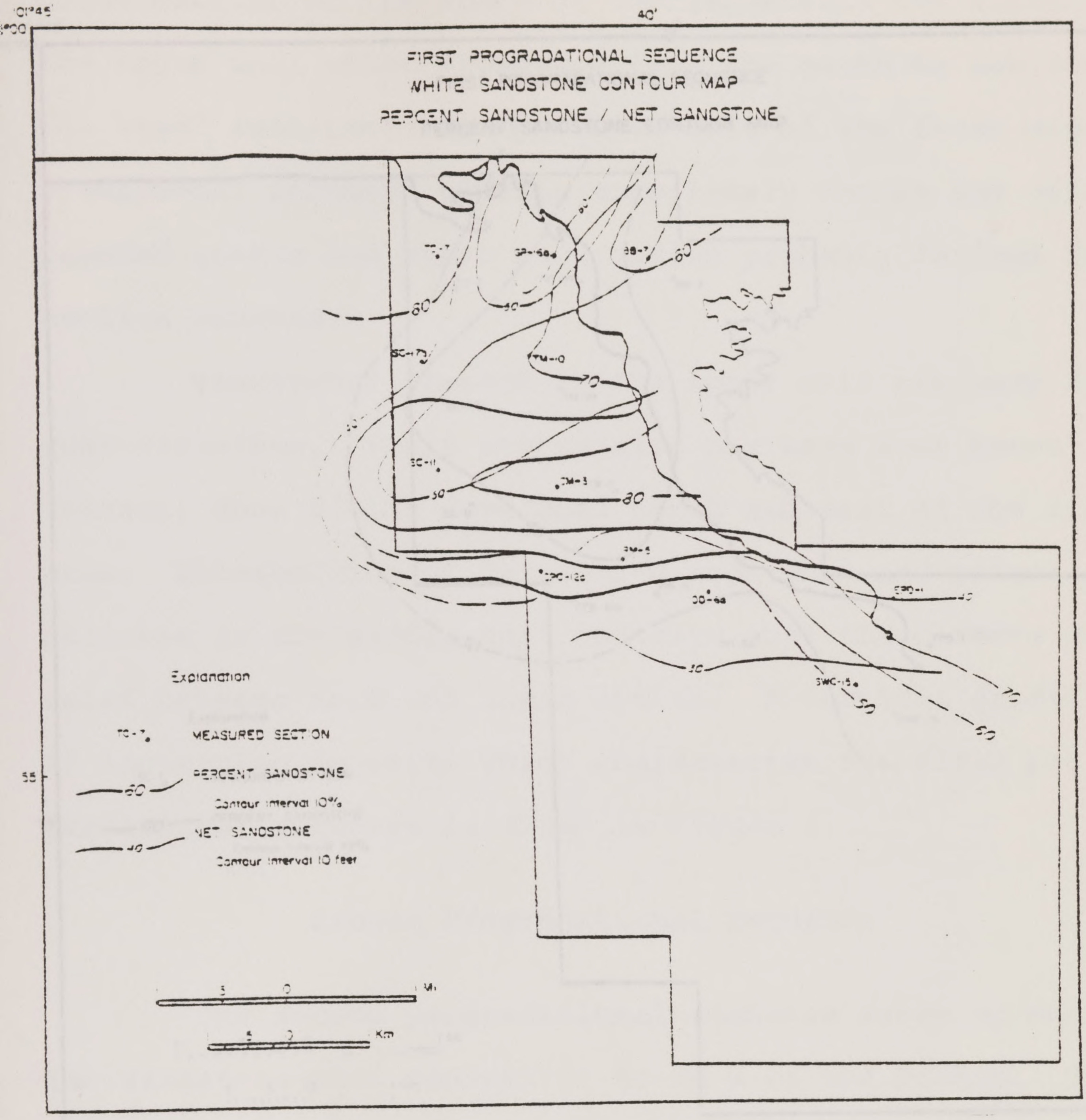


Figure 54. Percentage sandstone and net sandstone in the upper unit of the first progradational sequence.

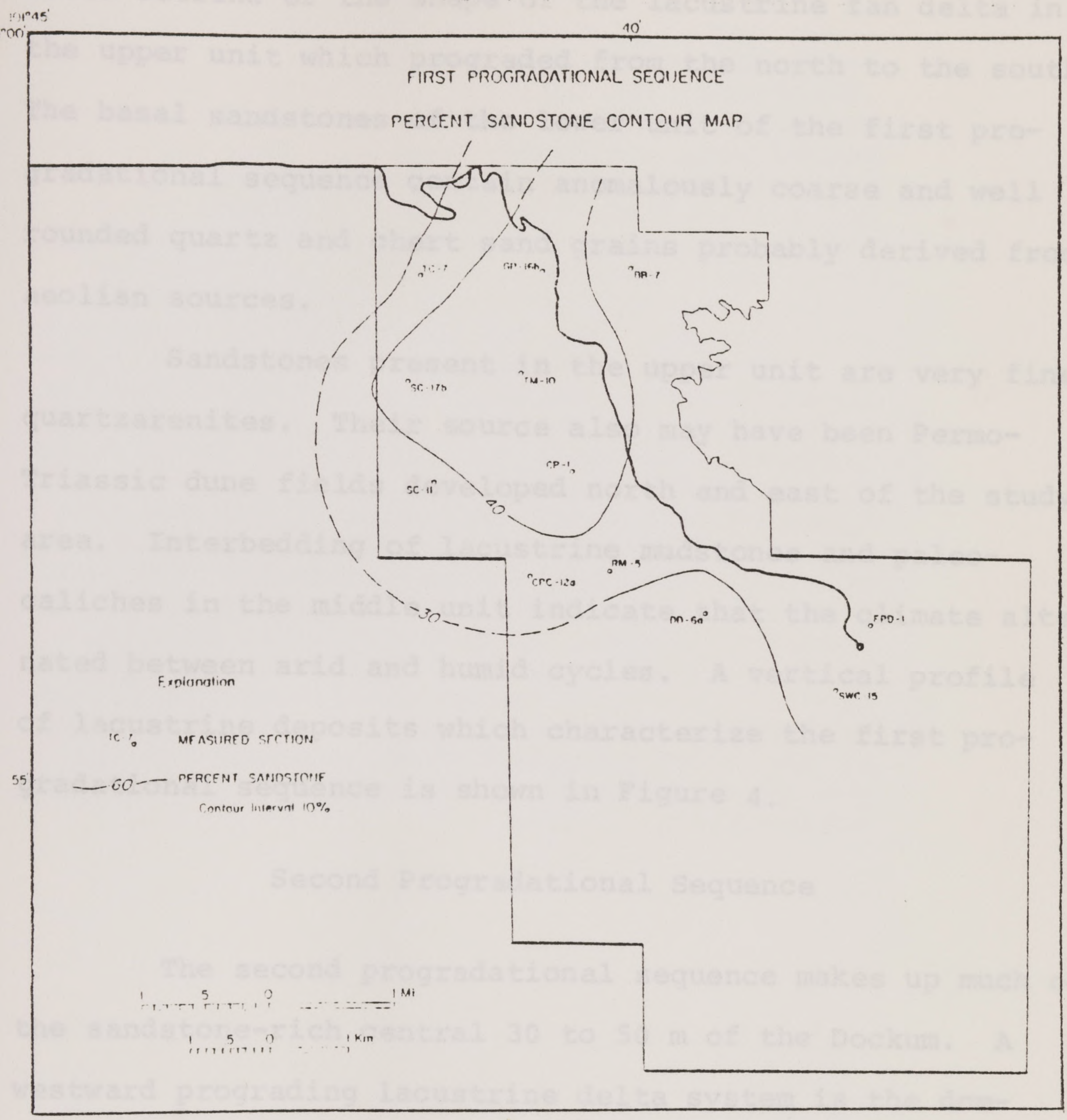


Figure 55. Percentage sandstone in the total first progradational sequence.

the northern part of the study area. This contour is a broad outline of the shape of the lacustrine fan delta in the upper unit which prograded from the north to the south. The basal sandstones of the lower unit of the first progradational sequence contain anomalously coarse and well rounded quartz and chert sand grains probably derived from aeolian sources.

Sandstones present in the upper unit are very fine quartzarenites. Their source also may have been Permo-Triassic dune fields developed north and east of the study area. Interbedding of lacustrine mudstones and paleo-caliches in the middle unit indicate that the climate alternated between arid and humid cycles. A vertical profile of lacustrine deposits which characterize the first progradational sequence is shown in Figure 4.

Second Progradational Sequence

The second progradational sequence makes up much of the sandstone-rich central 30 to 50 m of the Dockum. A westward prograding lacustrine delta system is the dominant depositional element in the second progradational sequence. A series of measured sections along strike (Figures 56 and 57) illustrate lateral and vertical trends in texture, sedimentary structures, and depositional facies of the delta system and show the relationship between the

Figure 56. Second progradational sequence strike section is exposed along the eastern margin of Palo Duro State Park. This figure illustrates the facies tract and sedimentary structures, and Figure 57 illustrates the texture. Two nearly continuous sandstone-conglomerate sheets, which cap the second progradational sequence, were deposited in sandstone-rich delta platform braided stream and distributary channel environments. The progradational sequence is composed in ascending order of: lacustrine burrowed mudstone (pro delta), and delta front siltstone-sandstone-conglomerate. The two laterally and temporally equivalent lacustrine fan deltas were separated by finer grained interdeltaic mudflat or embayment. The southern flank of the southern lacustrine delta is truncated by a thick valley-fill sequence which formed in response to diminished lake depth and area. The valley-fill sequence is composed of basal braided stream and delta distributary sandstone-conglomerate. The valley-fill sequence comprises a transgressive sequence encased within an overall progradational sequence. A subsequent expansion of lake area caused the lacustrine deltas to founder. Fine-grained lacustrine mudstones of the third progradational sequence overlie the second progradational sequence. Vertical exaggeration is 128x.

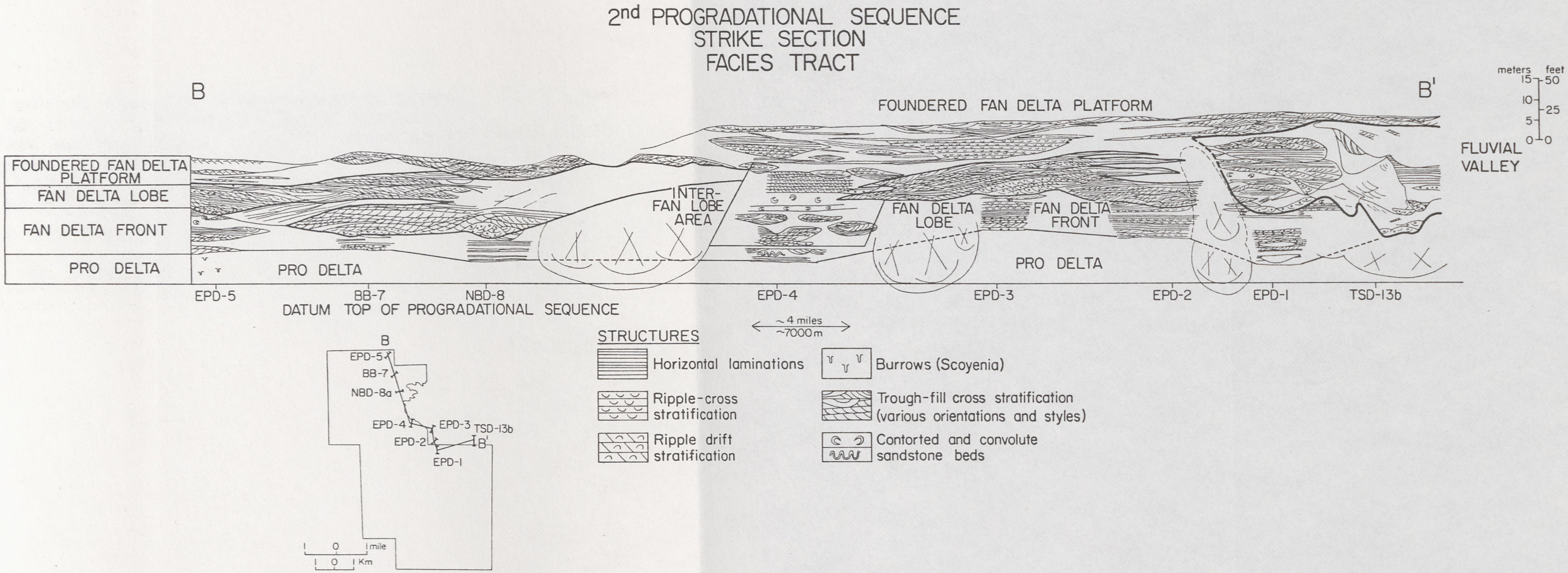

2nd PROGRADATIONAL SEQUENCE
STRIKE SECTION
FACIES TRACT
B
B'
FOUNDERED FAN DELTA PLATFORM
FOUNDERED FAN DELTA PLATFORM
FAN DELTA LOBE
FAN DELTA FRONT
PRO DELTA
PRO DELTA
INTER-FAN LOBE AREA
FAN DELTA LOBE
FAN DELTA FRONT
PRO DELTA
FLUVIAL VALLEY
meters feet
15 50
10 25
5
0 0
EPD-5
BB-7
NBD-8
EPD-4
EPD-3
EPD-2
EPD-1
TSD-13b
DATUM TOP OF PROGRADATIONAL SEQUENCE
~4 miles
~7000 m
STRUCTURES
Horizontal laminations
Ripple-cross stratification
Ripple drift stratification
Burrows (Scoyenia)
Trough-fill cross stratification (various orientations and styles)
Contorted and convolute sandstone beds
B
EPD-5
BB-7
NBD-8a
EPD-4
EPD-3
TSD-13b
EPD-2
B'
EPD-1
0 1 mile
0 1 Km

Figure 56

Figure 57. Second progradational sequence strike section is exposed along the eastern margin of Palo Duro State Park. Figure 57 illustrates texture and depositional facies for the same areas as Figure 56.

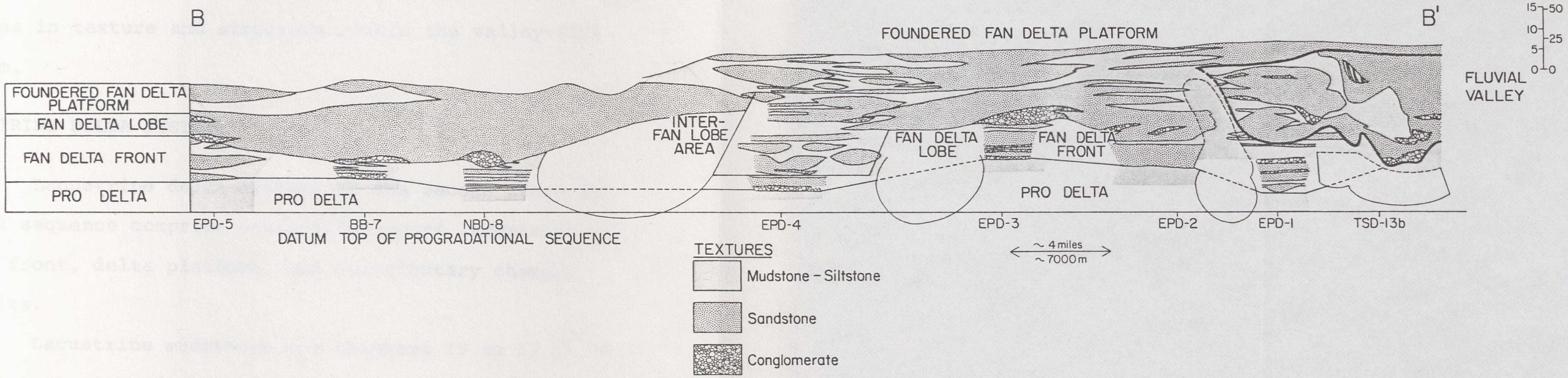

B
B'
FOUNDERED FAN DELTA PLATFORM
FOUNDERED FAN DELTA PLATFORM
FAN DELTA LOBE
FAN DELTA FRONT
PRO DELTA
PRO DELTA
INTER-FAN LOBE AREA
FAN DELTA LOBE
FAN DELTA FRONT
PRO DELTA
FLUVIAL VALLEY
meters feet
15 50
10 25
5
0 0
EPD-5
BB-7
NBD-8
EPD-4
EPD-3
EPD-2
EPD-1
TSD-13b
DATUM TOP OF PROGRADATIONAL SEQUENCE
~ 4 miles
~ 7000 m
TEXTURES
Mudstone – Siltstone
Sandstone
Conglomerate

Figure 57

delta system and the valley-fill system. The delta system is truncated in the northern and southern sectors of the study area by two valley-fill sequences. Small fan deltas were constructed at the valley mouth. Subsequent expansion of lake area produced flooding in the valley which ultimately was filled by a transgressive fluvial-deltaic-lacustrine sequence. A dip-oriented series of cross-sections (Figure 58) illustrate down dip facies variation and changes in texture and structure within the valley-fill system.

LACUSTRINE DELTA SYSTEM

Lacustrine delta systems of the second progradational sequence comprise coarsening-upward lacustrine and delta front, delta platform, and distributary channel deposits.

Lacustrine mudstones are thickest (9 to 13 m) in the western part of the study area (Figure 34) and thin toward the east (less than 1 to 6 m). Valley incision, caused by lowering of base level, entirely removed lacustrine mudstone at two locations (Figure 2, RM-5b, DD-6). Thick lacustrine mudstones in the west are laterally equivalent to thick deltaic deposits in the eastern part of the study area. Lacustrine mudstones contain isolated carbonate nodules that may represent paleocaliche. Arid conditions, which caused a decrease in lake volume and valley

Figure 58. Dip-oriented perspective series of strike sections within the second progradational sequence which show a down dip facies change from fluvial valley-fill to lake margin and lake center deposition. A transgressive fluvial valley-fill sequence (TSD-13b) formed in response to diminished lake depth and area. A narrow 100-1000 m wide valley is filled predominantly with thick fluvial and deltaic channel sandstone bodies. High net sandstone and high percentage sandstone values are associated with east-west oriented valley fill. A transgressive fluvial-deltaic sequence (RM-5, 5b) was deposited down dip, and west of the fluvial valley fill in a broader (500-5000 m), shallow (5-15 m) valley. Thin sandstone-conglomerate sheets were deposited on progradational fan delta platforms west of the broad, ill-defined valley mouth. These thin sandstone-rich fan delta pinch out into fine-grained lacustrine mudstones that are 3-8 km west of the fluvial valley-fill. Throughout the study area the second progradational sequence is overlain by fine-grained lacustrine mudstones which comprise the base of the third progradational sequence.

2nd PROGRADATIONAL SEQUENCE
DIP SECTION FACIES TRACT

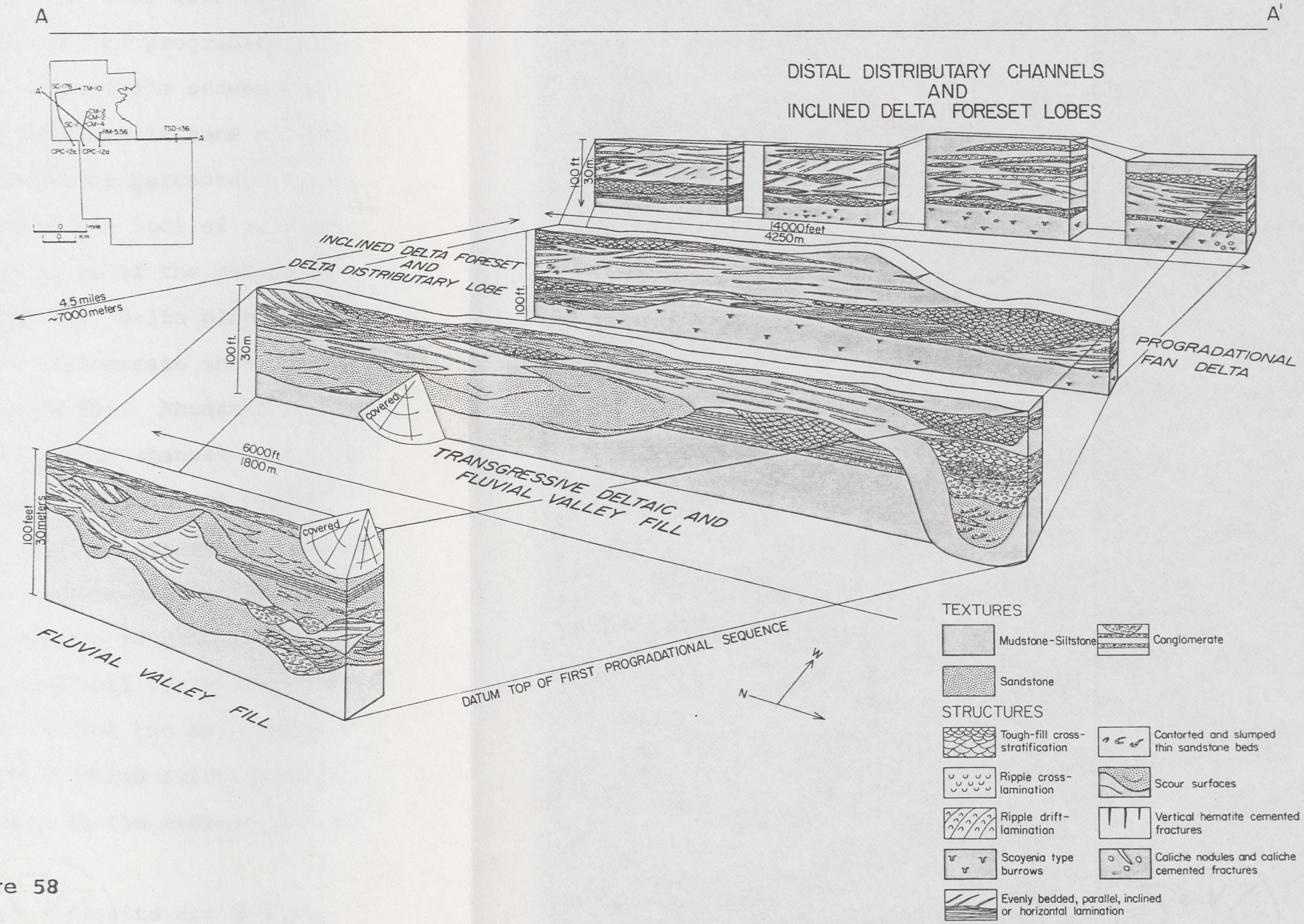


Figure 58

incision, possibly contributed to caliche development.

Framework lithofacies of the main lacustrine delta are thick sandstone-conglomerate sheets exposed along the eastern margin of the study area. Three or four delta platform sheets occupy part of the second progradational sequence. A sandstone percentage map of the second progradational sequence indicates a decrease in sand content to the west (Figure 59). High sandstone percentage areas with an east-west orientation record the loci of valley-fill. Examples of delta front deposits of the second sequence are shown in Figures 22 and 23. Delta platforms are composed of lobate sandstone-conglomerate sheets which overlie delta front deposits (Figure 60). Abundant trough-fill cross-stratification and lenticular channel-fill sandstone bodies within broad sandstone-conglomerate sheets (Figures 39 and 40) suggest that delta platforms are products of braided stream processes. Delta platforms are predominantly composed of sand and granule to pebble gravel, and are fan-shaped. Lateral and vertical variations in thickness, texture, and structure of the two main delta lobes are shown in Figures 56 and 57 which illustrate strike relationships of the two main lobes in the eastern part of the study area.

Two thinner delta platform deposits are exposed west of the main lobes on Timber Mesa and Capitol Peak Mesa

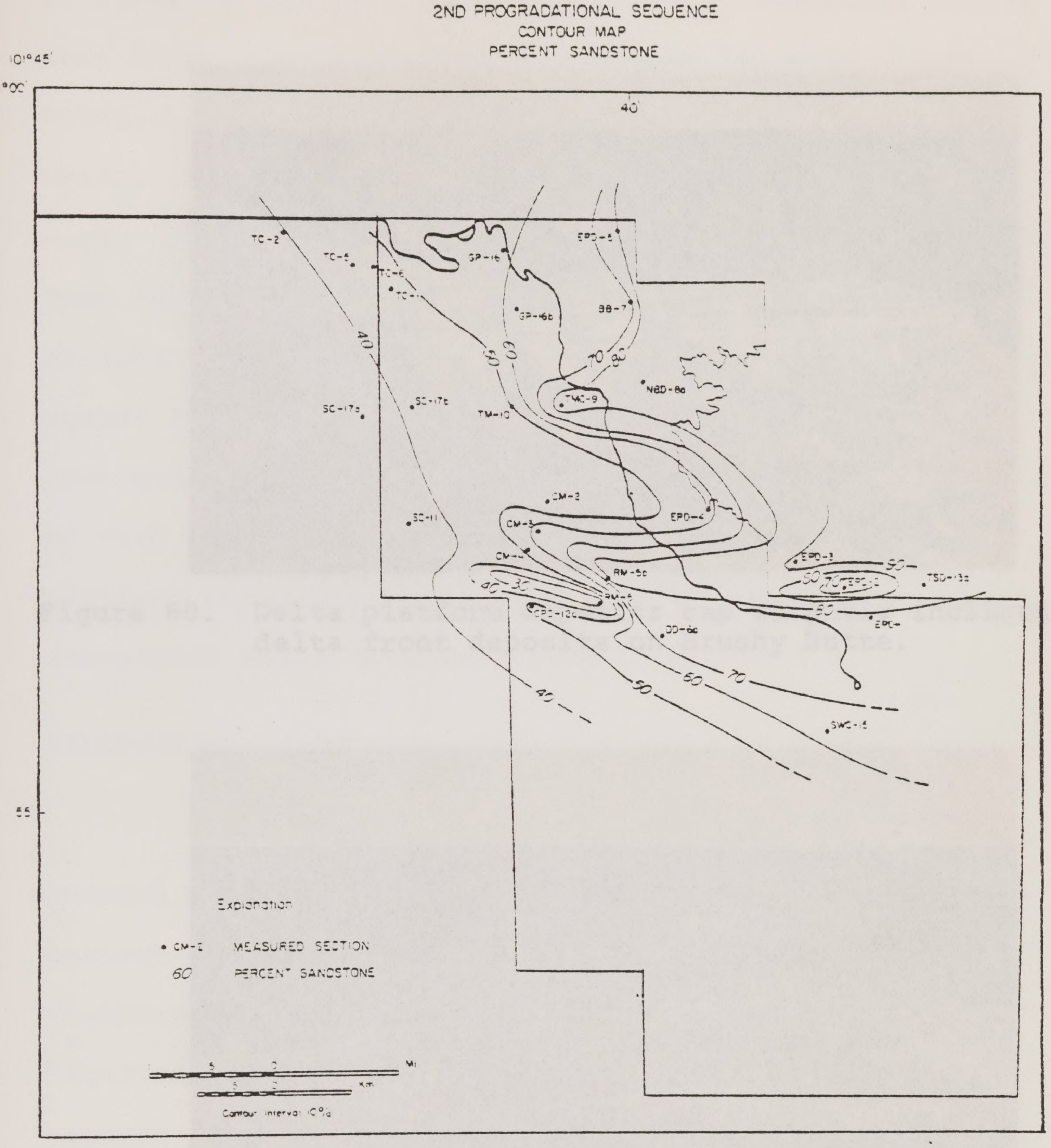


Figure 59. Percentage sandstone in the second progradational sequence.

Figure 60. Delta platform deposits cap slightly inclined delta front deposits on Brushy Butte.

Figure 61. Fan-shaped, westward dipping and thinning delta platform deposits on Timber Mesa. View south.

(Figures 38 and 44). Three-dimensional exposures reveal that these sheets dip and thin toward the west (Figure 61). Distributary channel sandstone bodies in the west are laterally equivalent to delta platform sheet sandstones in the east. The delta exposed on Capitol Peak Mesa is down dip from thick channel-fill sandstone-conglomerate that constitute the basal valley-fill sequence. A small (1 to 3 square km) shallow-water fan delta (see Figure 19) is interpreted to have formed during rapid progradation associated with base level lowering produced by an arid cycle. A vertical profile of a typical shallow-water (1 to 10 m). lacustrine delta is illustrated in Figure 5 .

VALLEY-FILL SEQUENCE

There are two east-west oriented valley-fill sequences within the second progradational sequence. The contact between the southern valley-fill sequence and the southern lobe of the main lacustrine delta is shown in Figure 62. Part of the northern valley-fill sequence is exposed in a road cut along the Palo Duro State Park road near the northwest end of the Palo Duro State Park. Here, the valley-fill is made up of four to six major sandstone bodies and numerous smaller conglomerate lenses. Excellent dip exposures of the southern valley-fill sequence are displayed over a distance of five kilometers in can-

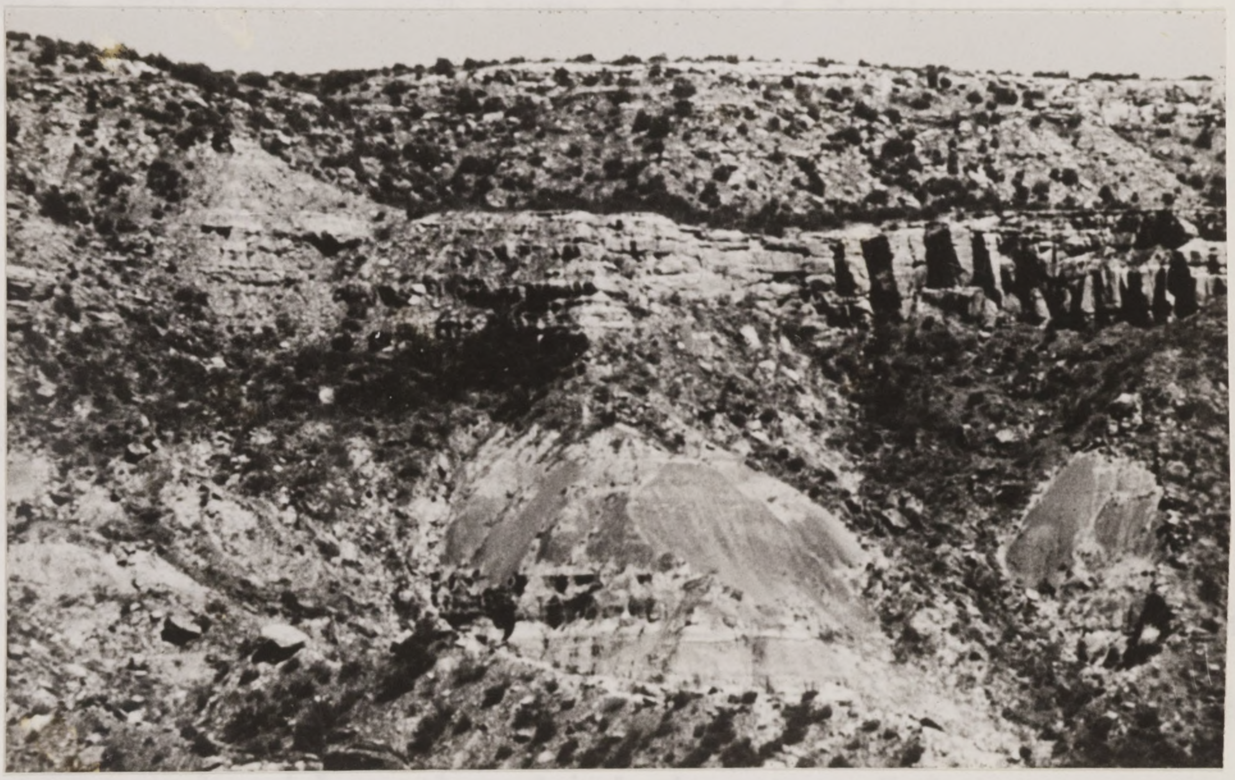


Figure 62. View east of the contact between the valley-fill sequence to the south (right), and the lacustrine delta sequence to the north (left). The thick sandstone and conglomerate section on the right is exposed at EPD-1 and is approximately 40 m (130 ft) thick.

yons north of Mesquite Park and in Tub Springs Draw (Figures 41 and 42).

Lateral and vertical lithofacies relationships of this sequence are illustrated in Figure 58. A vertical succession of valley-fill facies (Figure 7) indicates that the valley-fill sequence was constructed in three stages. First, lake area and depth were reduced during an arid cycle, resulting in increased stream gradient and valley incision. A second stage is recorded in braided stream deposits that accumulated on the valley floor. These streams were confined within the valley 1000 to 2000 m wide. The depth of the valley may have been 5 to 15 m. A shallow lake existed at the valley mouth where braided streams constructed a small fan delta which is exposed now on Capitol Peak Mesa. A third stage records valley aggradation during a humid cycle which increased lake area and depth thereby drowning the valley. Braided streams within the valley were succeeded by delta distributaries (Figure 43). Deposition accompanying the three stages produced a transgressive sequence. Lacustrine expansion overwhelmed fluvial input. As a result deltaic environments migrated updip, covering the fluvial deposits.

PALEOCURRENT ANALYSIS

Paleocurrent analysis provides additional data which support the interpretation of westward progradation of fluvial-deltaic lithofacies. Paleocurrent analysis attempts to measure the dip direction of paleoslope. Paleoslope indicators vary from measurements of channel orientation to measurements of the orientation of small-scale stratification. For instance, channel orientation is a better indicator of paleoslope than ripple cross-stratification which reflects only local hydrodynamic conditions. Depositional environments also vary with respect to their ability to reflect true regional paleoslope. Distributary channel and crevasse splays may be oriented at high angles to main flow and regional dip. Paleocurrent indicators within distributary channels and crevasse splays would not reflect true regional paleoslope. In the study area, fan delta-delta platform deposits are composed of trough-fill cross-stratification produced by downstream migration of dune bedforms. In this environment dune bedforms developed in braided streams whose trends range from parallel to regional paleoslope to more than 30 degrees from regional paleoslope. Paleocurrent indicators from fan delta-delta platform facies are better indicators of true paleoslope than distributary channel or crevasse splay facies. Paleocurrent analyses in the study area support these general observations.

Directional features were determined for various genetic units within the second progradational sequence by measuring plunge direction of axes of trough-fill cross-stratification. Measurements were taken only from bedding plane surfaces which clearly indicate the direction of dune migration (Figure 63). Trough axes of distributary channel, fan delta-delta platform, and crevasse splay deposits were measured from Lithofacies 6, 7, and 8. These data are shown in Figure 64. Distributary channel and crevasse splay environments have considerable scatter of trough axes orientation. Measurements from fan delta-delta platform fluvial deposits show the narrowest distribution of trough axes orientation. This distribution indicates that progradation of these environments was down paleoslope toward the west-southwest.

Third Progradational Sequence

The third progradational sequence is the last genetic sequence exposed in the study area. Lithofacies 4 is most characteristic of this sequence. A vertical profile through sequence 3 contains, in ascending order: lacustrine burrowed mudstones (Lithofacies 1); delta front siltstone-sandstone-conglomerate (Lithofacies 3, 4, and 6); and fluvial-deltaic platform sandstone-conglomerate (Lithofacies 7). This same vertical sequence is repeated resulting in 2 superposed progradational cycles within the

Figure 63. Current indicators were taken only from bedding planes which show the plunge axes of trough-fill cross-stratification.

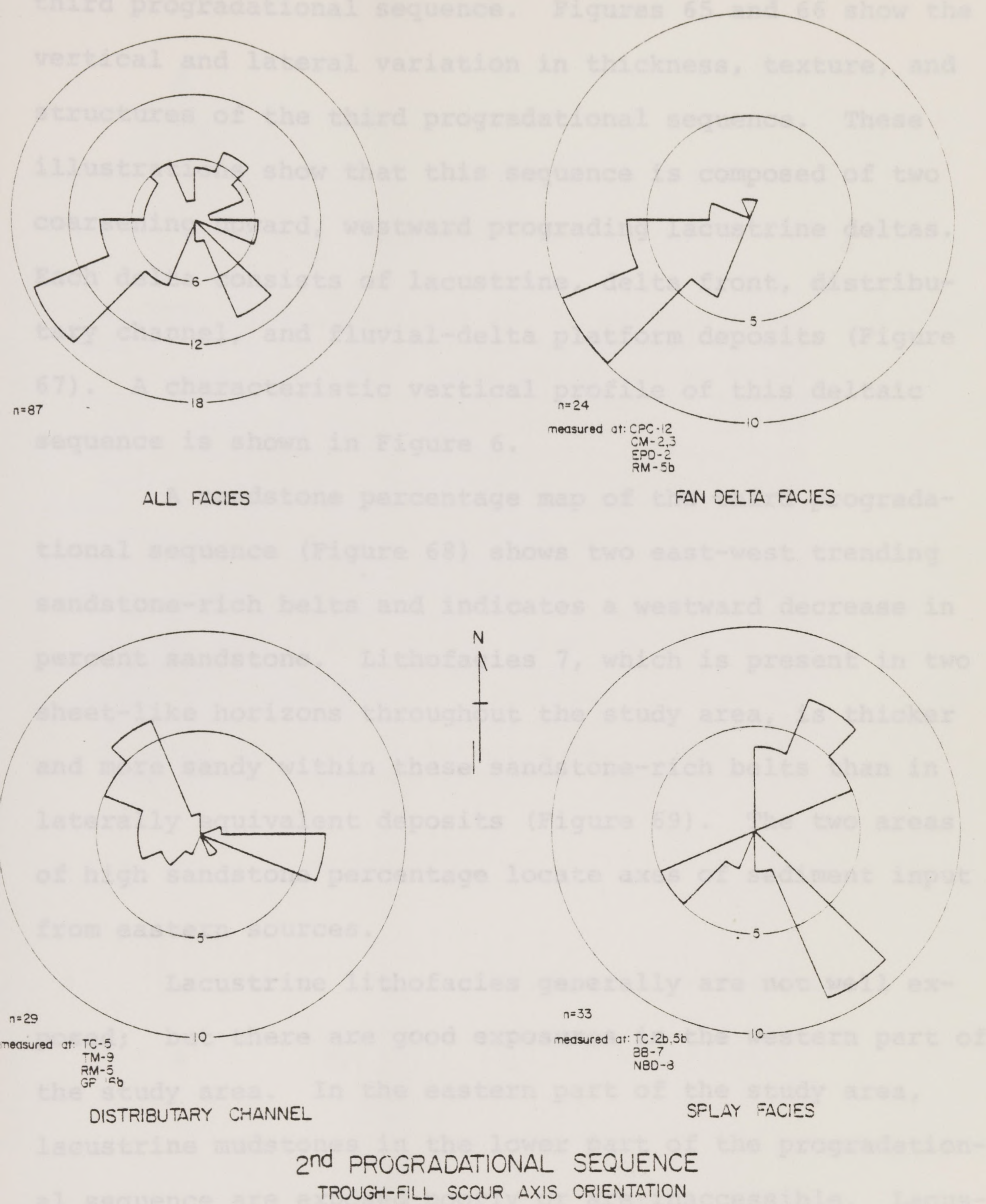


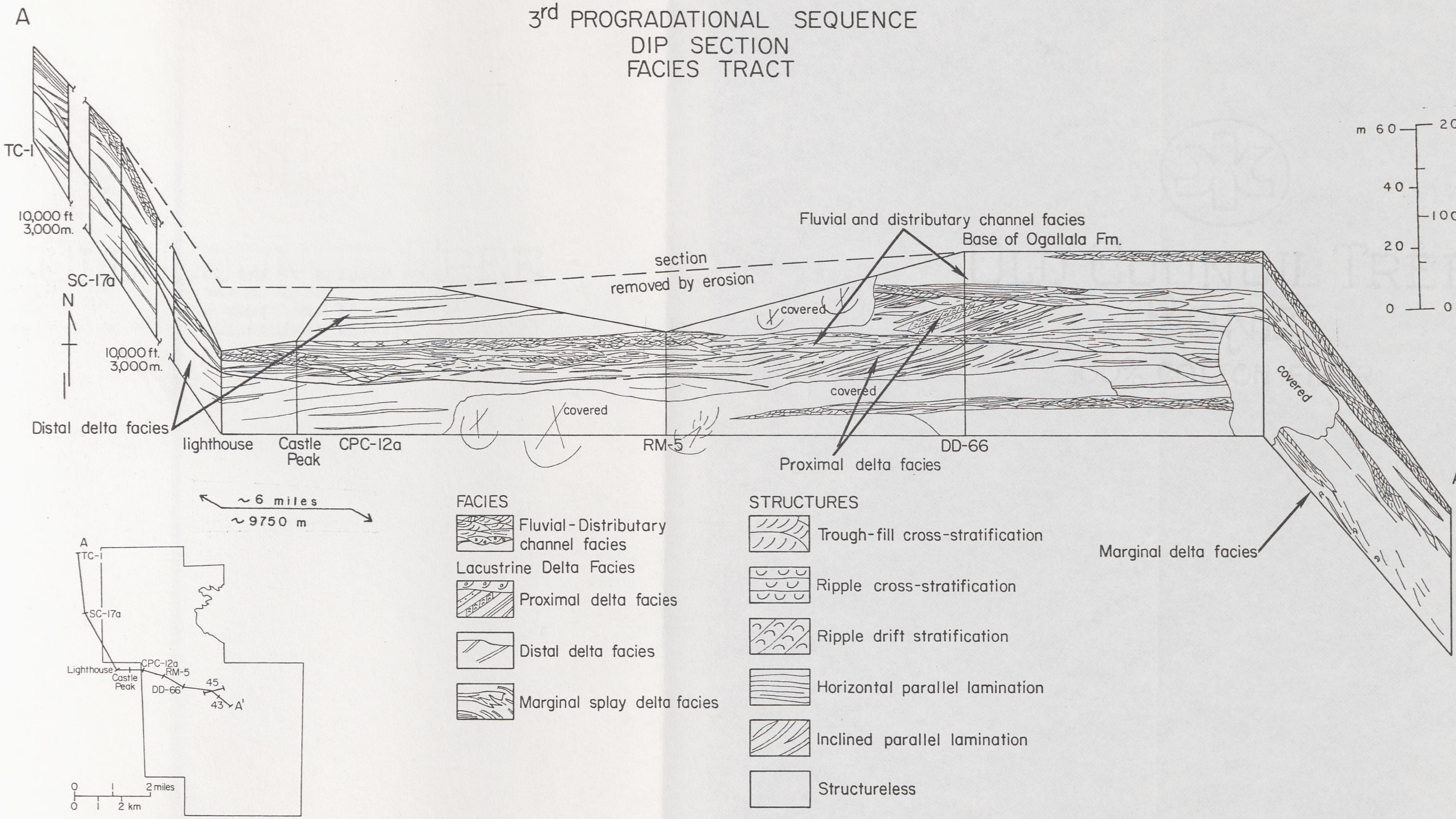
Figure 64. Current directions in the second progradational sequence based on the plunge direction of axes of trough-fill cross-stratification.

third progradational sequence. Figures 65 and 66 show the vertical and lateral variation in thickness, texture, and structures of the third progradational sequence. These illustrations show that this sequence is composed of two coarsening upward, westward prograding lacustrine deltas. Each delta consists of lacustrine, delta front, distributary channel, and fluvial-delta platform deposits (Figure 67). A characteristic vertical profile of this deltaic sequence is shown in Figure 6.

A sandstone percentage map of the third progradational sequence (Figure 68) shows two east-west trending sandstone-rich belts and indicates a westward decrease in percent sandstone. Lithofacies 7, which is present in two sheet-like horizons throughout the study area, is thicker and more sandy within these sandstone-rich belts than in laterally equivalent deposits (Figure 69). The two areas of high sandstone percentage locate axes of sediment input from eastern sources.

Lacustrine lithofacies generally are not well exposed; but there are good exposures in the western part of the study area. In the eastern part of the study area, lacustrine mudstones in the lower part of the progradational sequence are exposed poorly or are inaccessible. Lacustrine mudstones thicken to the west where they comprise one or two burrowed horizons that are 2 to 10 m thick.

Figure 65. Fence diagram of the third progradational sequence exposed in the central and western portions of the study area. This figure illustrates sedimentary structures and depositional facies. Figure 66 illustrates texture. Two, superposed lacustrine deltas prograded to the west across the study area. Each lacustrine delta is composed in ascending order of: lacustrine mudstone, deltaic siltstone-sandstone-conglomerate, and fluvial sandstone-conglomerate. Parallel, foreset inclined, wedge-shaped sedimentation units that were deposited proximal delta (delta front) facies are highly characteristic of deltaic deposits of the third progradational sequence. The thickness of these delta foresets is from 8 to 15 m, indicating that deposition occurred in water at least 8 to 15 m deep. Vertical exaggeration is 44x.



A
3rd PROGRADATIONAL SEQUENCE
DIP SECTION
FACIES TRACT
TC-1
10,000 ft
3,000m.
SC-17a
N
10,000 ft.
3,000m.
Distal delta facies
lighthouse
Castle Peak
CPC-12a
section removed by erosion
covered
RM-5
Fluvial and distributary channel facies
Base of Ogallala Fm.
covered
DD-66
Proximal delta facies
covered
m 60
40
20
0
200 ft
100
0
A'
Marginal delta facies
~6 miles
~9750 m
FACIES
Fluvial-Distributary channel facies
Lacustrine Delta Facies
Proximal delta facies
Distal delta facies
Marginal splay delta facies
STRUCTURES
Trough-fill cross-stratification
Ripple cross-stratification
Ripple drift stratification
Horizontal parallel lamination
Inclined parallel lamination
Structureless
A
TC-1
SC-17a
Lighthouse
Castle Peak
CPC-12a
RM-5
DD-66
45
43
A'
2 miles
2 km

Figure 65

Figure 66. Fence diagram of the third progradational sequence exposed in the central and western portions of the study area. This figure illustrates texture for the same area as Figure 65.

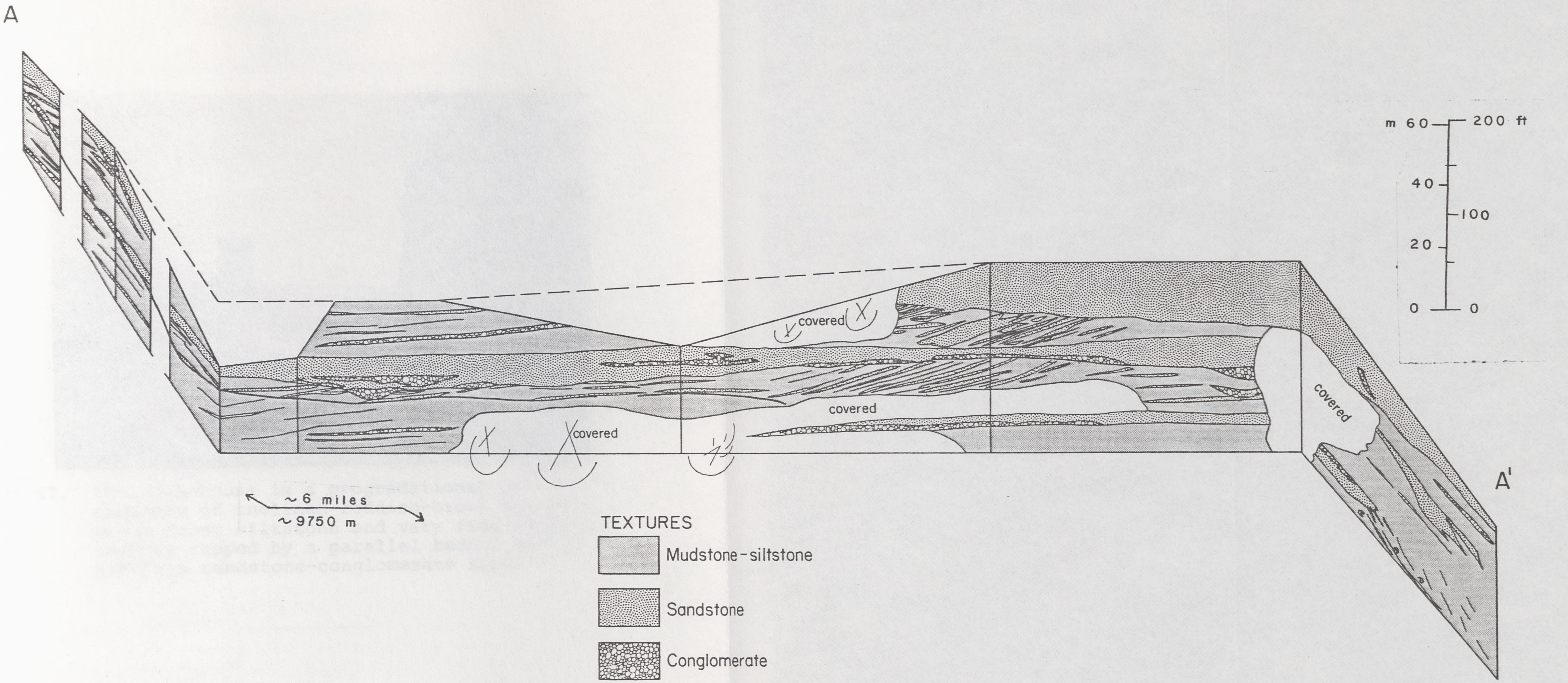

A
A'
covered
covered
covered
covered
m 60
40
20
0
200 ft
100
0
~6 miles
~9750 m
TEXTURES
Mudstone-siltstone
Sandstone
Conglomerate

Figure 66

Figure 67. The Lighthouse is a progradational deltaic sequence of inclined reddish-brown and gray delta front siltstone and very fine sandstone that is capped by a parallel bedded delta platform sandstone-conglomerate sheet.

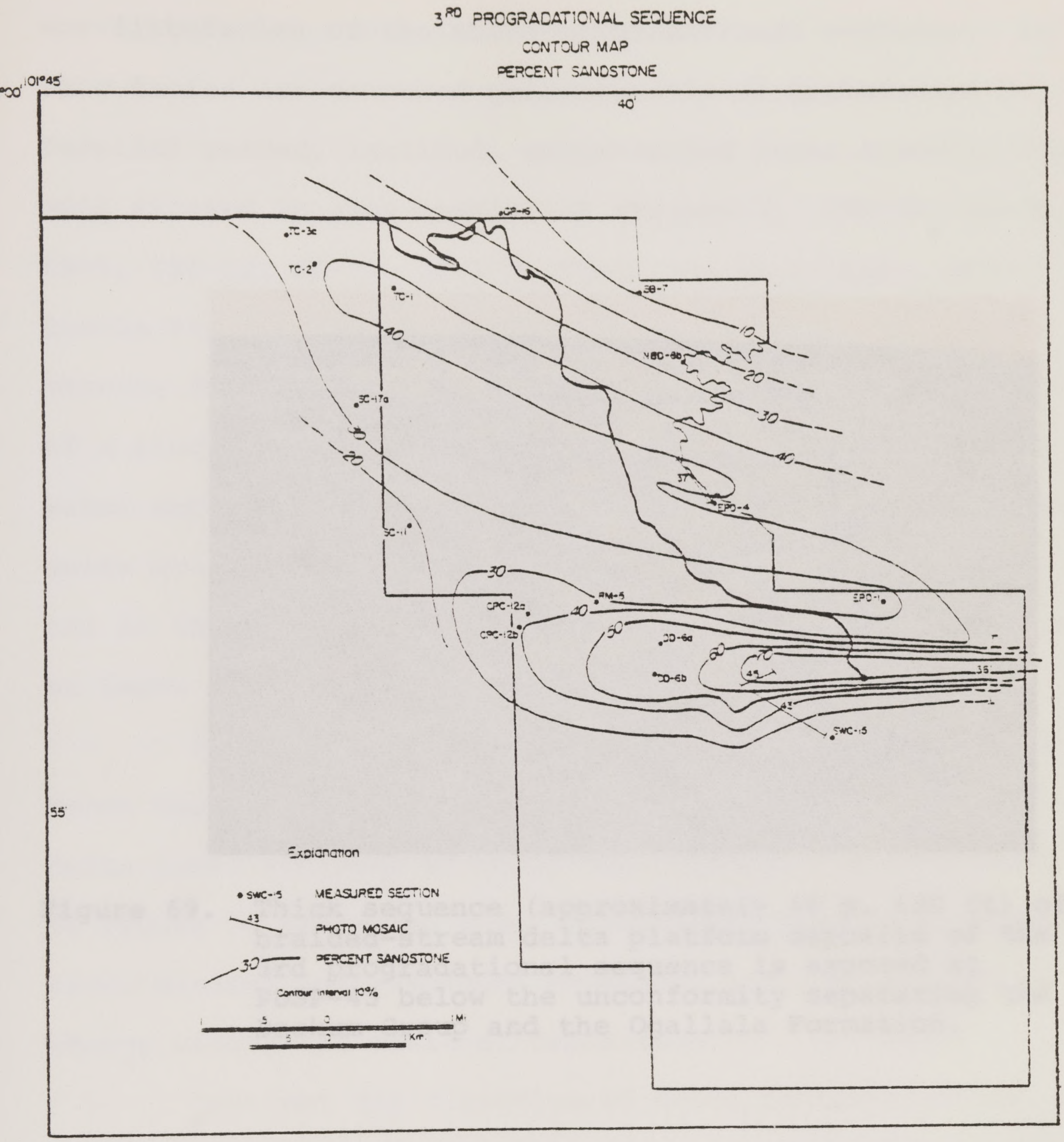


Figure 68. Percentage sandstone in the third progradational sequence.

Figure 69. Thick sequence (approximately 40 m, 130 ft) of braided-stream delta platform deposits of the 3rd progradational sequence is exposed at PDSP-45 below the unconformity separating the Dockum Group and the Ogallala Formation.

Deltaic deposits (Figure 32) constitute the thickest lithofacies of the third progradational sequence. Deltaic facies are composed predominantly of Lithofacies 4. Parallel bedded, inclined, wedge-shaped delta foresets are well exposed in many localities (Figure 2, NBD-8b, DD-6b, RM-5, CPC-12, SC-11, SC-17b, TM-1, the Lighthouse, and Castle Peak). Delta foresets were constructed at the advancing front of some lacustrine deltas. Vertical height of a single continuous foreset unit indicates a minimum water depth in which the unit was deposited. Some foreset units are 8 to 15 m high, indicating that lacustrine deltas in the third progradational sequence were deposited in at least 8 to 15 m of water.

The high dip angle (4 to 15 degrees) of the delta front deposits indicates there was minimal reworking of delta front sediment by waves and currents. A high angle of repose is preserved under conditions of rapid sedimentation, minimal soft-sediment movement, and low-physical energy within the basin of deposition.

Apparent dip direction of delta foresets in the study area varies widely. Factors which influence apparent dip direction as observed on an outcrop face include true dip direction, and the strike of the outcrop face. Apparent dip may change with variations in true dip. Coalescence of many laterally equivalent delta front lobes could cause the true dip angle and orientation to vary. Variations in outcrop strike causes apparent dip angle and direction to change. An outcrop which faces north and strikes east-west will show foresets with an apparent dip east or west regardless of true dip direction. If the true dip direction is normal to the strike of the outcrop, then dipping foresets will appear horizontal. Measurements taken from sedimentary structures exposed in two-dimensional vertical outcrops are not valid indicators of true dip. Lithofacies geometry and trends in sandstone percentage were used as a means to determine the westward deltaic progradation.

Distributary channel-fill and channel mouth bar deposits overlie delta front foresets. Laterally equivalent to thick sequences of delta front and delta platform deposits are prograding lobate crevasse splay deposits of thin conglomeratic sheets and channels (Figure 65), and laterally equivalent fine-grained foreset lobes (Figure 70). Marginal crevasse channels and splays are common features of the Dockum lacustrine deltas. In one location (Figure 2, PDSP-43) crevasse splays are vertically stacked. On a large scale, the lithofacies tract is very similar to the vertical profile of prograding lacustrine deltas with prominent delta front foresets. The inclined foreset lobes indicates that crevasse splays prograded into low physical-energy water bodies, possibly an embayment.

Figure 70. Crevasse splay deposits at PDSP-43 are exposed 300 m (1000 ft) south of PDSP-45 (see Figure 69). Crevasse splay deposits comprise thin conglomeratic sheets and lobate inclined foreset lobes.

Delta platform sheet deposits occur at two horizons which cap delta front foresets. These sheets are products of braided stream processes that operated on coarse-grained delta platforms. Areas where delta platform deposits thicken (Figure 69) are outlined by high percentage sandstone values (Figure 68), which delineate axes of sediment input. Sediment sources for delta platforms included Permian and older Triassic deposits that lay to the east. Two lacustrine delta lobes were fed by westward-flowing streams. The lower delta lobe prograded to the west across the study area. An increase in lake area and depth, or possibly an upstream river avulsion and continued basin subsidence, caused the lower delta to founder. Lacustrine mudstones accumulated upon the lower delta platform. Dockum deposition in the study area ended with another cycle of westward deltaic progradation into water 10 to 20 m deep.

DEPOSITIONAL HISTORY

A complex depositional history is indicated for the Dockum Group in the study area. Each of the three genetic sequences comprises similar vertical lithofacies suites. Each sequence is a progradational coarsening upward lacustrine, fluvial-deltaic assemblage. One progradational sequence contains an incised, fining upward transgressive sequence. There are lateral facies variations and thickness relationships among lithofacies of different progradational sequences. Each sequence is characterized by a predominant lithofacies. The first progradational sequence is characterized by thick lacustrine mudstones (Lithofacies 1) and paleocaliche horizons (Lithofacies 2). The second progradational sequence contains localized, transgressive valley-fill sequences (Lithofacies 8). The third progradational sequence is characterized by two cycles of thick, delta foresets (Lithofacies 4).

Interbedded lacustrine mudstones and paleocaliches of the first sequence are indicative of alternating humid and arid climatic cycles. During humid cycles lakes were continuous and may have been open lakes. Braided streams transported very fine to coarse well rounded quartz and chert sand from aeolian dune fields, and lacustrine deltas were constructed in the study area. During arid cycles, ephemeral lakes and paleocaliches developed on mudflats and/or in a shallow subsurface diagenetic environment.

The progradational lacustrine delta which caps the first sequence had a northern sediment source. This contrasts with the two overlying sequences which have eastern sources. The sandstones of the first progradational sequence are mineralogically mature (Appendix 2). Distributary channel and delta platform sandstones are predominantly very well sorted quartzarenites. The coarse well rounded quartz and chert sandstones of the basal sandstones indicate that these rocks were derived from aeolian sands. Permo-Triassic dune fields were present north and east of the study area.

The second progradational sequence mostly comprises shallow water lacustrine deltas. The second sequence includes thick transgressive valley-fill deposits. There are paleocaliches within the basal lacustrine mudstones of the second progradational sequence. Paleocaliche and valley scour indicate that arid climate cycles alternated with humid climatic conditions that were favorable for development of shallow water lacustrine deltas.

Paleocurrent and petrographic analyses indicate that eastern sediment source areas were underlain predominantly by sedimentary terrains. Texture and composition of sandstones from the second progradational sequence indicate that sands were not derived from aeolian sources. A mixed sedimentary terrain is indicated by the abundance of sedimentary rock fragments (mudstone, caliche, chert) and fresh and weathered feldspars. The valley-fill sequence also was derived from eastern sedimentary sources. Granule to pebble chert conglomerate is abundant in the valley-fill deposit, but chert conglomerate is not found in other strata of the second progradational sequence.

A fundamental change in the character of deltaic lithofacies occurs within the third progradational sequence, which is characterized by parallel-bedded, inclined, wedge-shaped delta foresets. Delta foresets accumulated at the advancing front of westward prograding lacustrine deltas. Continuous foresets are from 8 to 15 m thick, and they probably accumulated in water that was at least 8 to 15 m deep. Caliche horizons were not observed in the third progradational sequence. The underlying genetic sequence only contains indicators of shallow water depth. The third progradational sequence contains evidence of stable, relatively deep (10 to 20 m) water lakes without the intervening arid conditions which characterize the underlying progradational sequences.

The provenance of fluvial sandstones in the third progradational sequence was similar to that of the second progradational sequence.

CONCLUSIONS

1) Upper Triassic Dockum Group rocks in the study area are continental lacustrine, fluvial-deltaic deposits.

2) Three progradational genetic sequences are recognized which consist in ascending order of: lacustrine mudstone, deltaic siltstone-sandstone-conglomerate, and fluvial sandstone-conglomerate.

a) The first progradational sequence is typified by thick burrowed lacustrine mudstones and thin paleocaliche horizons. Mudstones and caliche are capped by a fan-shaped, shallow-water, lacustrine delta that prograded southward. Abundant slump structures occur over 25 square km in the front of the lacustrine delta. Permo-Triassic dune sands north and east of the study area were the source of some sands for the first sequence. During deposition of the first sequence climatic conditions alternated between arid and humid.

b) The second progradational sequence is characterized by several shallow-water, lacustrine deltas. Rapid progradation of small fan deltas ensued when base level was lowered during an arid cycle. Lower lake level increased local gradient and caused valley incision. Subsequent increase in lake area and depth drowned the valley which ultimately was filled with a transgressive fluvial, deltaic, and lacustrine sequence. A series of fan-shaped, shallow-water deltas prograded toward the west. Mixed sedimentary source terrains lay east of the study area. The climate during deposition of this sequence alternated between arid and humid conditions.

c) The third progradational sequence is characterized by thick, parallel-bedded, inclined, delta front foresets deposited at the margins of relatively deep-water (10 to 20 m) lacustrine deltas. Continuous foresets are 8 to 15 m thick indicating that deltas prograded into water at least 8 to 15 m deep. Lobate, lacustrine deltas prograded westward. Mixed sedimentary source terrains were east of the study area.

3) Ephemeral lakes characterized the first and second progradational sequences. Lacustrine fan deltas formed in shallow-water 1 to 10 m deep. The third progradational sequence was deposited in more stable deep-water (10-20 m) lake. A vertical sequence through Dockum Group rocks in the Palo Duro Canyon area reveals a change from alternating humid and arid conditions of the first and second progradational sequences toward continuously humid conditions which prevailed during deposition of the third progradational sequence.

APPENDIX I

URANIUM DATA

SAMPLE NAME	GENETIC SEQUENCE	DEPOSITIONAL ENVIRONMENT	TEXTURE	U_3O_8 ppm *
CPC-12-1a	1st G.S.	soil zone	qtz. geode	1
CPC-12-1a	1st G.S.	soil zone	qtz. geode	less than 1
TMC-5-1	2nd G.S.	lacustrine-interdistrib.	mudstone	1
TMC-5-2a	2nd G.S.	splay	conglomer.	1
TMC-5-2b	2nd G.S.	interdistrib.	mudstone	2
TMC-5-2c	2nd G.S.	splay	conglomer.	2
TMC-5-3a	2nd G.S.	lacustrine-interdistrib.	mudstone	1
TMC-5-3b	2nd G.S.	lacustrine-interdistrib.	mudstone	1
TMC-5-3c	2nd G.S.	lacustrine-interdistrib.	mudstone	less than 1
TMC-5-4a	2nd G.S.	distrib. channel base	sandstone	less than 1
TMC-5-4aw	2nd G.S.	distrib. channel base	lignitized log	40
TMC-5-4y	2nd G.S.	distrib. channel base	sulfate minerals on log	14
TMC-5-4b	2nd G.S.	distrib. channel-fill	sandstone	less than 1
TMC-5-4c	2nd G.S.	distrib. channel-fill	sandstone	1
TMC-5-4d	2nd G.S.	distrib. channel top	sandstone	1
TMC-5-5a	2nd G.S.	interdistrib.	mudstone	less than 1

*Analyzed nitric acid soluble uranium with Jarrell-Ash fluorometer at Bureau of Economic Geology Mineral Studies Lab.

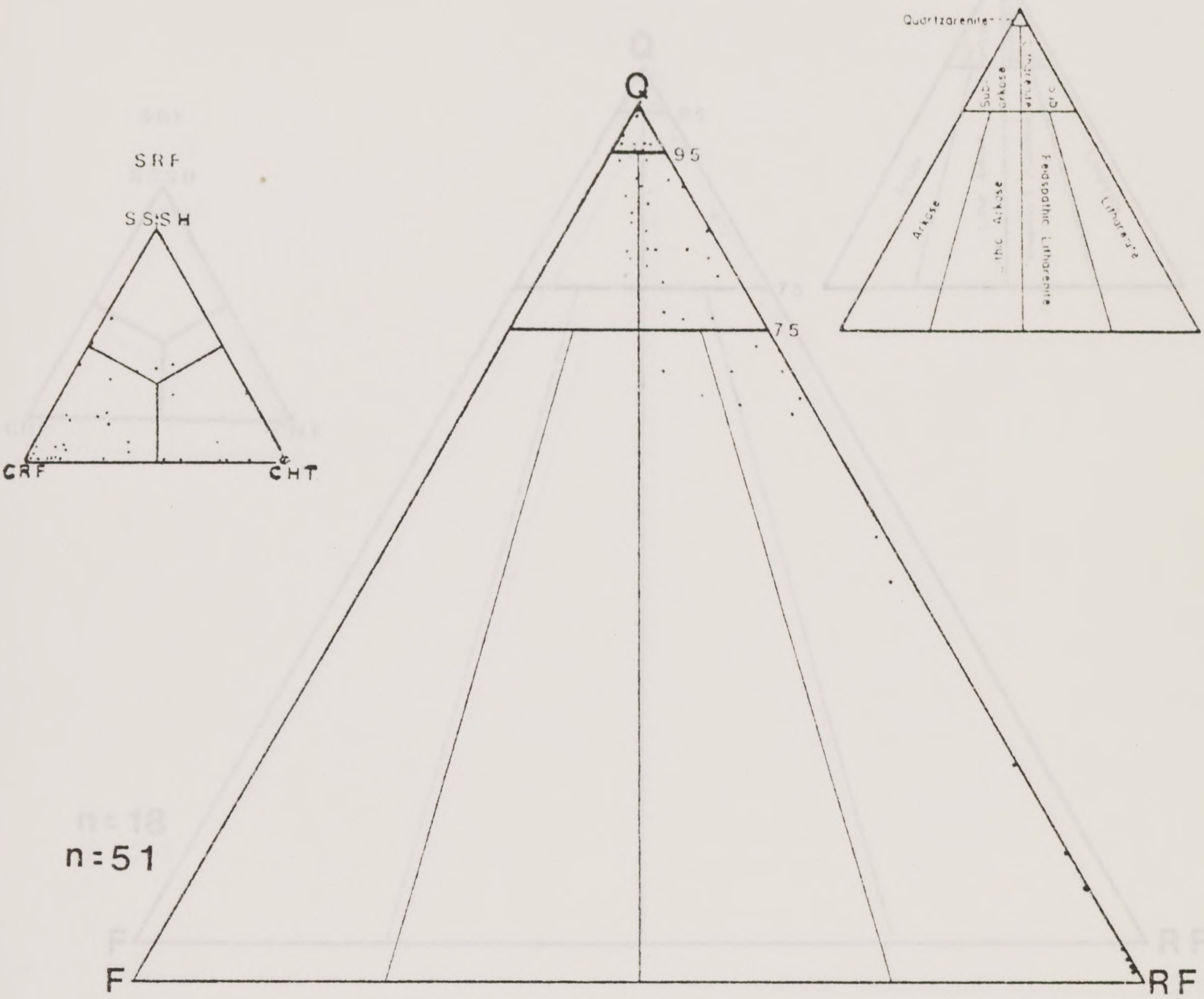
SAMPLE NAME	GENETIC SEQUENCE	DEPOSITIONAL ENVIRONMENT	TEXTURE	U_3O_8 ppm
TMC-5-5b	2nd G.S.	interdistrib.	mudstone	3
TMC-5-5c	2nd G.S.	interdistrib.	mudstone	2
TMC-5-5d	2nd G.S.	interdistrib.	mudstone	4
TMC-5b-3a	2nd G.S.	splay	mudstone	2
TMC-5b-3b	2nd G.S.	splay	sandstone	less than 1
TMC-5b-3c	2nd G.S.	splay	sandstone	less than 1
TMC-5b-3d	2nd G.S.	splay	sandstone	1
TMC-5c-a	2nd G.S.	distrib. channel-fill	conglomer.	3
TMC-5c-b	2nd G.S.	distrib. channel-fill	mudstone	less than 1
TMC-5c-c	2nd G.S.	distrib. channel-fill	mudstone	3
TMC-5c-d	2nd G.S.	distrib. channel-fill	mudstone	1
TMC-5d-e	2nd G.S.	distrib. channel-fill	mudstone	less than 1
TMC-5d-f	2nd G.S.	distrib. channel-fill	mudstone	1
TMC-6-1a	2nd G.S.	lacustrine	mudstone	2
TMC-6-1b	2nd G.S.	lacustrine	mudstone	less than 1
TMC-6-1c	2nd G.S.	lacustrine	mudstone	less than 1
TMC-6-1d	2nd G.S.	lacustrine	mudstone	less than 1
TMC-6-2	2nd G.S.	splay	conglomer.	3
TMC-6-2b	2nd G.S.	splay	conglomer.	1
TMC-6-3	2nd G.S.	interdistrib.	mudstone	3

SAMPLE NAME	GENETIC SEQUENCE	DEPOSITIONAL ENVIRONMENT	TEXTURE	U_3O_8 ppm
TMC-6-5a	2nd G.S.	fluvial channel-fill	sandstone	2
TMC-6-5b	2nd G.S.	fluvial channel-fill	sandstone	2
TMC-6-6a	2nd G.S.	fluvial channel-fill	conglomer.	less than 1
TMC-6-6b	2nd G.S.	fluvial channel-fill	conglomer.	1
TMC-6-10-11a	2nd G.S.	interdistrib.	mudstone	1
TMC-6-10-11b	2nd G.S.	interdistrib.	mudstone	less than 1
TMC-6-11a	2nd G.S.	delta front	mudstone	1
TMC-6-11b	2nd G.S.	delta front	sandstone	2
TMC-6-11b2	2nd G.S.	distrib. channel-fill	sandstone	less than 1
TMC-6-11c1	2nd G.S.	delta front	sandstone	less than 1
TMC-6-11d	2nd G.S.	fluvial channel-fill	sandstone	less than 1
TMC-7-1a	3rd G.S.	lacustrine	mudstone	1
TMC-7-1b	3rd G.S.	lacustrine	mudstone	3
TMC-7-1c	3rd G.S.	lacustrine	mudstone	less than 1
TMC-7-1d	3rd G.S.	lacustrine	mudstone	2
TMC-7-2	3rd G.S.	delta front-splay	mudstone	2
TMC-7-3	3rd G.S.	delta front-splay	sandstone	2
TMC-7-4	3rd G.S.	delta front-splay	sandstone	1

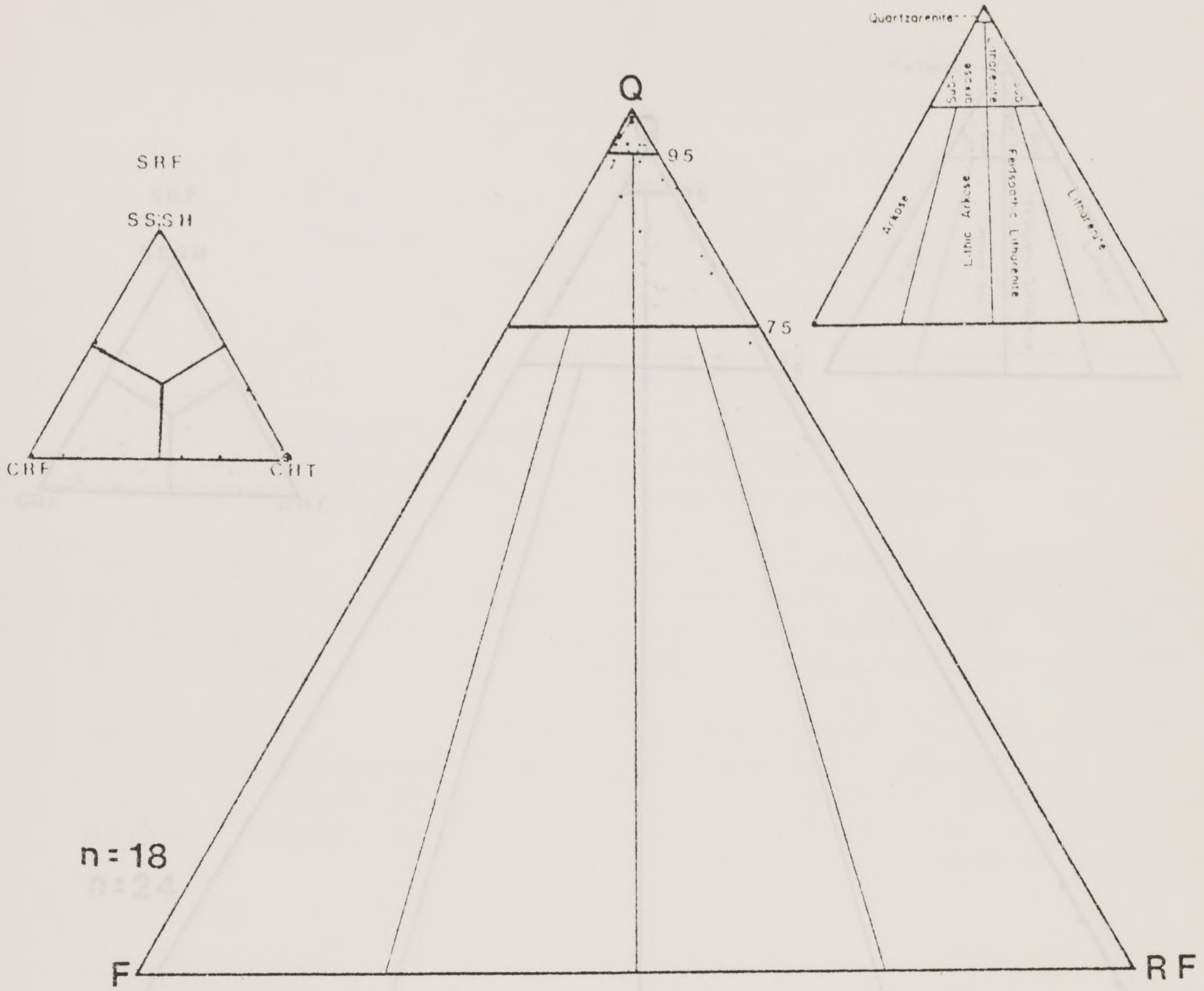
SAMPLE NAME	GENETIC SEQUENCE	DEPOSITIONAL ENVIRONMENT	TEXTURE	U_3O_8 ppm
TMC-7-5	3rd G.S.	delta platform	conglomer.	7

APPENDIX II

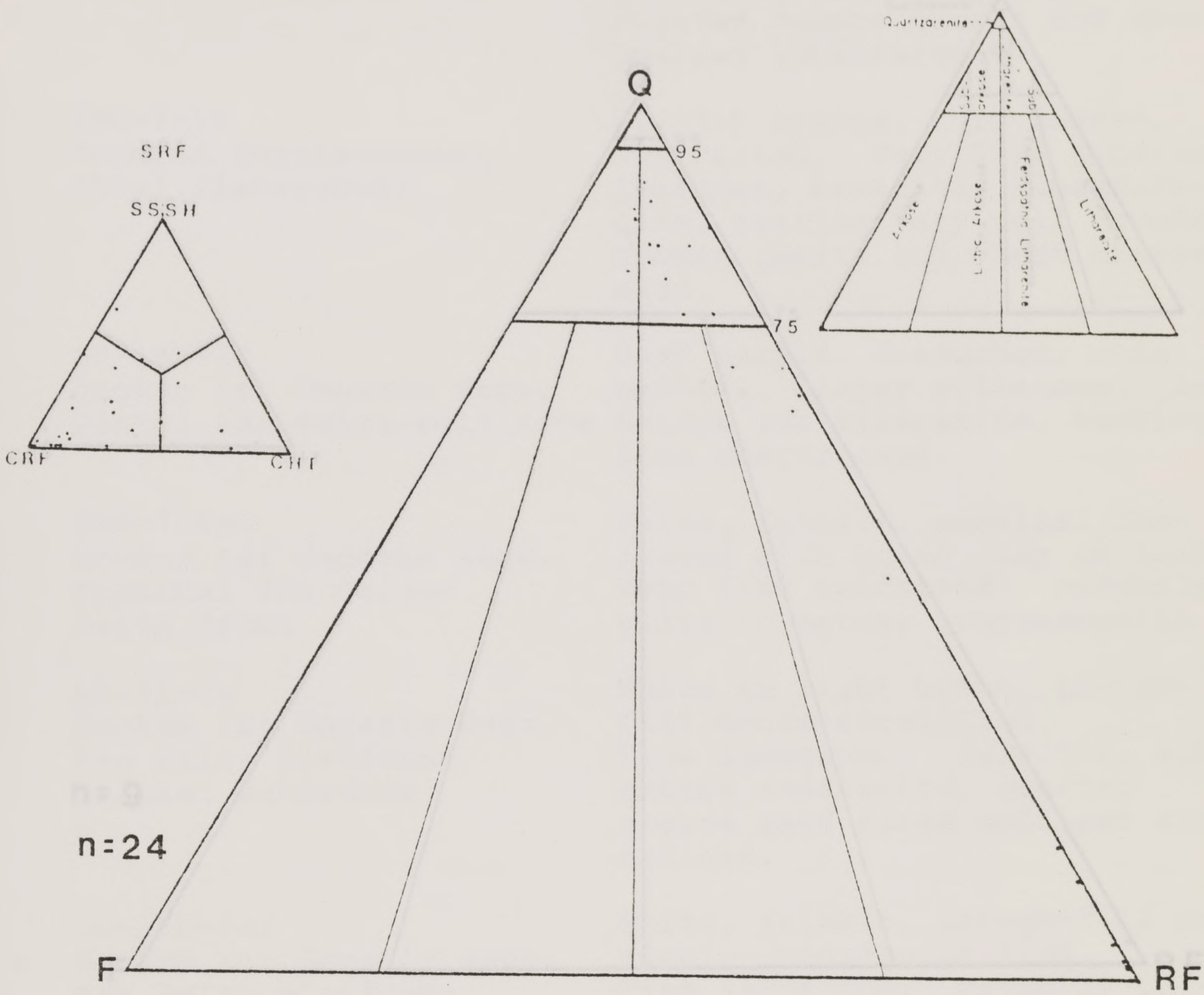
PETROGRAPHIC DATA



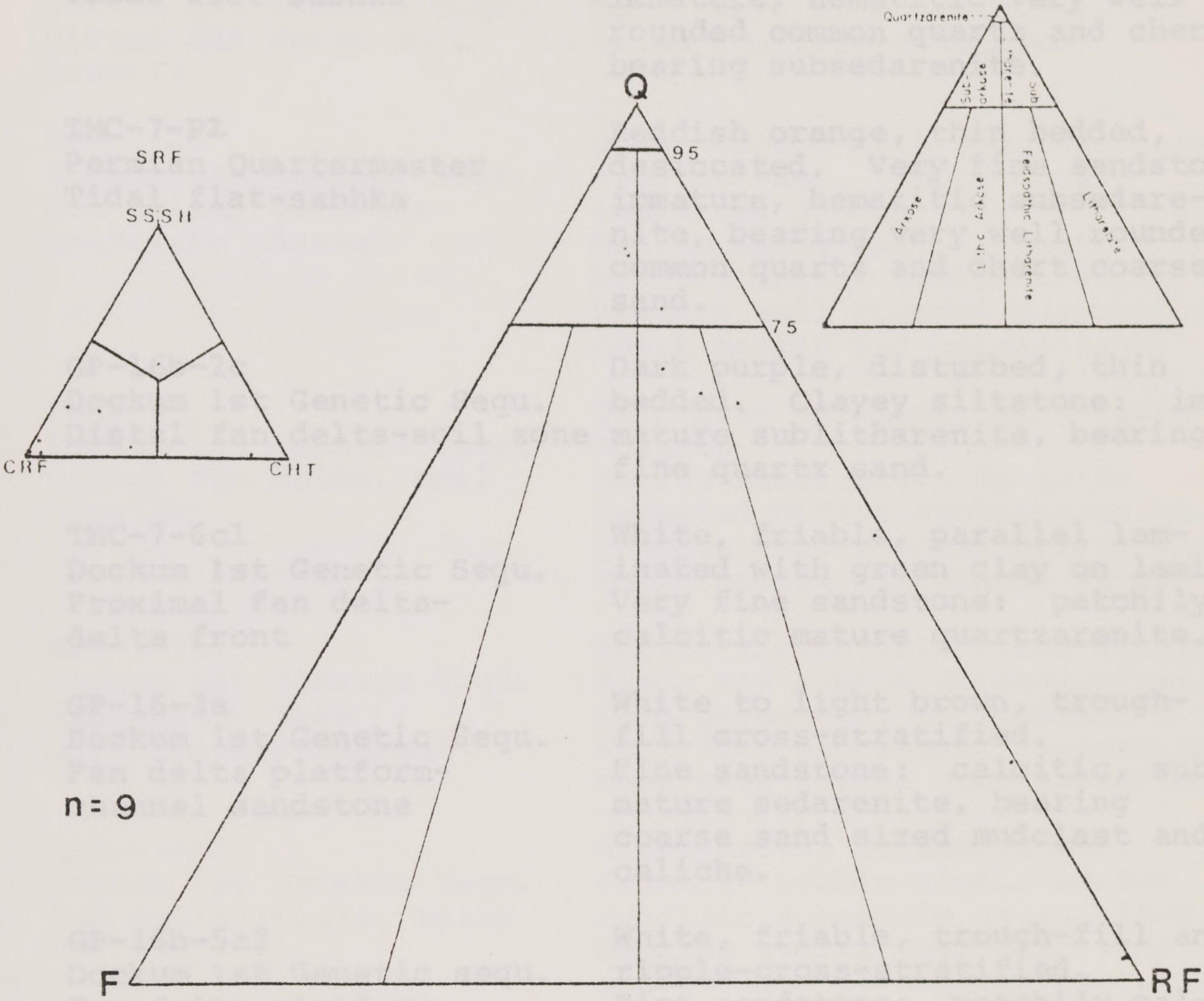
Plot of all Triassic Dockum Group thin section samples after classification by Folk, Andrews, and Lewis (1970). Q = quartz, RF = rock fragment, F = feldspar, SRF = sedimentary rock fragment, SS:SH = sandstone:shale fragment, CHT = chert rock fragment, CRF = carbonate rock fragment, n = number of samples.



Plot of Triassic Dockum thin section samples from the first progradational sequence.



Plot of Triassic Dockum thin sections from the second progradational sequence.



Plot of Triassic Dockum Group thin sections from the third progradational sequence.

REFERENCE NUMBER GENETIC SEQUENCE FACIES-ENVIRONMENT	PETROGRAPHIC DESCRIPTION: MICROSCOPIC AND MACROSCOPIC after Folk and others (1970)
TMC-7-P1 Permian Quartermaster Tidal flat-sabhka	Reddish orange, thin bedded, desiccated. Very fine sandstone: immature, hematitic very well rounded common quartz and chert-bearing subsedarenite.
TMC-7-P2 Permian Quartermaster Tidal flat-sabhka	Reddish orange, thin bedded, desiccated. Very fine sandstone: immature, hematitic subsedarenite, bearing very well rounded common quartz and chert coarse sand.
GP-16b-2c Dockum 1st Genetic Sequ. Distal fan delta-soil zone	Dark purple, disturbed, thin bedded. Clayey siltstone: immature sublitharenite, bearing fine quartz sand.
TMC-7-6c1 Dockum 1st Genetic Sequ. Proximal fan delta-delta front	White, friable, parallel laminated with green clay on laminae. Very fine sandstone: patchily calcitic mature quartzarenite.
GP-16-3a Dockum 1st Genetic Sequ. Fan delta platform-channel sandstone	White to light brown, trough-fill cross-stratified. Fine sandstone: calcitic, submature sedarenite, bearing coarse sand sized mudclast and caliche.
GP-16b-5a2 Dockum 1st Genetic sequ. Fan delta platform-channel sandstone	White, friable, trough-fill and ripple-cross-stratified. Fine sandstone: patchily calcitic mature quartzarenite.
GP-16b-5d2 Dockum 1st Genetic Sequ. Fan delta platform-channel sandstone	White, parallel laminae scoured by trough-fill cross-stratification. Fine sandstone: patchily calcitic mature quartzarenite.
GP-16b-5d4 Dockum 1st Genetic Sequ. Fan delta platform-channel sandstone	Light brown, trough-fill and ripple cross-stratified. Very fine sandstone: friable mature quartzarenite.

GP-16b-2b Dockum 1st Genetic Sequ. Fan delta front	Light gray, friable, structureless. Medium sandstone: mature bimodal, sublitharenite, bearing very well rounded common quartz and chert coarse sand.
EPD-1-2a Dockum 1st Genetic Sequ. Distal fan delta-soil zone(?)	Gray, thin bedded, disturbed. Muddy very fine sandstone: calcitic immature subarkose.
EPD-1-2b Dockum 1st Genetic Sequ. Fan delta, thin distributary channel	Gray, trough-fill cross-stratified at base, ripple cross-laminated at top. Medium sandstone: slightly baritic mature sublitharenite, bearing well rounded quartz and chert medium and coarse sand.
PDSP-1c Dockum 1st Genetic Sequ. Distal fan delta, soil zone(?)	Dark gray to black, fist-sized nodule. Medium sandstone: Mn-oxide cemented mature sublitharenite, bearing well rounded quartz and chert medium and coarse sand.
EPD-1-6b1 Dockum 1st Genetic Sequ. Fan delta, thin distributary channel	White, trough-fill cross-stratified, and ripple cross-laminated with green clay on laminae. Very fine sandstone: supermature very well sorted quartzarenite.
EPD-1-6b2 Dockum 1st Genetic Sequ. Fan delta-frontal splay	Light brown, structureless. Granular pebble conglomerate: calcitic submature calclithite, bearing quartz very fine sand, and rounded to angular septarian fractured--calcite and dolomite filled caliche granules and pebbles.
EPD-4-F1, EDP-4-F2, Dockum 1st Genetic Sequ. Caliche horizon on lacustrine mudstone	Reddish brown to light red carbonate-replaced mudstone: predominantly microspar, fractures 0.5 to 1 mm, filled with dolomite, and calcite; fracture-fill rarely opal; euhedral scalenahedrons of calcite projecting into voids are coated

	with alternating bands of dolomite and calcite spar; quartz silt and clay minerals are common toward exterior of pisolitic nodule; silt grains float in microspar (crystals 5 to 15 mm) matrix; short distance transport (0.5 to 5 mm) of quartz silt during nodule growth has produced "comet tails" of sparry calcite in areas through which the silt was moved.
CPC-12-2f, PDSP-1 Dockum 1st Genetic Sequ. Caliche nodule horizon lacustrine mudstone	Dark yellowish orange, carbonate-replaced mudstone nodule: predominantly microspar, euhedral calcite spar occurs in nodule center; outer surface of nodule mimics fabric of mudstone, <u>Scoyenia</u> and <u>Teichichnus</u> trace fossils are preserved.
EPD-1-6c Dockum 1st Genetic Sequ. Fan delta platform-distributary channel	White, structureless. Very fine sandstone: calcitic mature quartzarenite, bearing fresh orthoclase.
GP-16-5a1 Dockum 2nd Genetic Sequ. Fluvial(?)-distributary channel	White to light brown, trough-fill cross-stratified to structureless. Fine sandstone: calcitic mature sublitharenite, bearing fresh, weathered, and calcitized feldspar grains.
EPD-1-8a Dockum 2nd Genetic Sequ. Lowest progradational sequence-distributary channel	White to light brown, inclined parallel laminae. Fine sandstone: calcitic mature chert-bearing subarkose.
GP-16b-5b Dockum 1st Genetic Sequ. Distributary channel	White to light gray, ripple cross-laminaed, with gray clay on laminae. Fine sandstone: calcitic mature quartzarenite, bearing well-rounded caliche and fresh feldspar.

TSD-13-2a Dockum 2nd Genetic Sequ. Basal channel lag- fluvial valley-fill	Light gray to brown, large trough-fill cross-stratification. Sandy pebble conglomerate: submature poorly sorted sublitharenite, bearing well rounded quartz and chert medium sand to granule conglomerate.
TDS-13-2b Dockum 2nd Genetic Sequ. Fluvial channel-fill	Light gray to brown, trough-fill cross-stratified. Medium sandstone: calcitic mature sublitharenite, bearing chert coarse sand.
EPD-3-3 Dockum 2nd Genetic Sequ. Distributary channel- channel mouth bar	Light grayish green, parallel inclined laminae, with gray clay on laminae. Fine sandstone: calcitic mature subarkose, bearing fresh and weathered orthoclase, chert, and caliche.
EPD-3-3b Dockum 2nd Genetic Sequ. Upper distributary channel channel mouth bar	Grayish green, trough-fill cross-stratified. Coarse sandstone: calcitic slightly opal cemented supermature calclithite.
EPD-3-4a Dockum 2nd Genetic Sequ. Basal part fan delta platform	Grayish green, crudely parallel laminated, and trough-fill cross-stratified. Sandy granule conglomerate: calcitic submature calclithite, bearing quartz medium sand and very well rounded caliche sand to granule conglomerate.
GP-16b-2f, GP-16b-3b2 Dockum 1st Genetic Sequ. Desert pavement(?) desiccated mudflat	Grayish brown to black, Mn-oxides. Pebble conglomerate: immature, calcitic sedarenite, bearing Mn-replaced caliche coarse sand to pebble gravel.
DD-6-2c, EPD-1-3t Dockum 1st Genetic Sequ. Desert pavement(?) desiccated mudflat	Dark yellowish orange sandy caliche pebble conglomerate: calcitic, slightly Mn-oxides cemented submature calclithite, bearing subangular to rounded

	septarian fractured caliche coarse sand to pebble gravel.
TMC-5-4a Dockum 2nd Genetic Sequ. Distributary channel lag	Gray, trough-fill cross-stratified. Very coarse sandstone: calcitic mature calclithite, bearing quartz very fine sand.
TMC-5-4b Dockum 2nd Genetic Sequ. Middle part of distributary channel	Grayish, brown, trough-fill cross-stratified. Medium sandstone: calcitic mature calclithite.
TMC-5-4c Dockum 2nd Genetic Sequ. Middle part of distributary channel	Light gray, foreset cross-stratified. Granular fine sandstone: calcitic mature feldspar-bearing sublitharenite.
TMC-5-4d Dockum 2nd Genetic Sequ. Upper part of distributary channel	Grayish light brown, trough-fill cross-strata. Very fine sandstone: calcitic mature subarkose, bearing caliche and mudclast sand.
EPD-5-1a Dockum 2nd Genetic Sequ. Base of fan delta platform	Grayish green, trough-fill cross-stratified. Granular pebble conglomerate: calcitic submature calclithite, bearing quartz medium sand.
EPD-5-1b Dockum 2nd Genetic Sequ. Middle part of fan delta platform	Grayish green, trough-fill cross-stratified. Fine sandstone: calcitic mature subsedarenite, bearing seritized and calcitized feldspar.
EPD-5-1c Dockum 2nd Genetic Sequ. Upper part of fan delta platform	Grayish green parallel laminated and trough-fill cross-stratified. Fine sandstone: slightly calcitic mature very well sorted subsedarenite, bearing fresh and weathered feldspar.
GP-16b-9a Dockum 2nd Genetic Sequ. Distributary channel lag	Greenish light brown, trough-fill cross-stratified. Fine sandstone: calcitic submature calclithite, bearing very

	well rounded caliche coarse to very coarse sand, and calcitized feldspar.
GP-16b-9b Dockum 2nd Genetic Sequ. Middle part of distributary channel	Greenish light brown parallel, horizontal to slightly inclined laminae. Fine sandstone: calcitic mature sublitharenite, bearing orthoclase and microcline.
GP-16b-9c Dockum 2nd Genetic Sequ. Middle part of distributary channel	Grayish light brown, structureless. Fine sandstone: calcitic mature sublitharenite, bearing seritized orthoclase and fresh microcline.
GP-16b-9d1 Dockum 2nd Genetic Sequ. Upper part of distributary channel	Light brown, parallel laminated and small scale trough-fill cross-stratified. Medium sandstone: calcitic mature calclithite, bearing chert and fresh fractured microcline.
GP-16b-7a Dockum 2nd Genetic Sequ. Lowest progradational sequence-fluvial channel lag	Reddish brown, crudely parallel laminated. Granular pebble conglomerate: calcitic slightly dolomitic submature calclithite, bearing hematitic SRF.
TMC-6-2a Dockum 2nd Genetic Sequ. Lowest progradational sequence-fluvial channel lag	Grayish green, trough-fill cross-stratified. Granular pebble conglomerate: calcitic submature calclithite, bearing quartz medium sand and chert coarse sand.
TMC-6-6a Dockum 2nd Genetic Sequ. Fluvial channel	Grayish light brown, trough-fill cross-stratified. Medium sandstone: calcitic mature sublitharenite, bearing well rounded quartz and chert medium sand.
TMC-6-3 Dockum 2nd Genetic Sequ. Upper part of fluvial channel	Grayish green, structureless. Fine sandstone: calcitic mature sublitharenite, bearing fresh feldspar.

EPD-1-12b Dockum 2nd Genetic Sequ. Fluvial channel-fill	Grayish green, parallel laminated. Very fine sandstone: calcitic mature sublitharenite.
EPD-1-12d Dockum 2nd Genetic Sequ. Upper part of fluvial channel	Grayish light brown, structureless. Fine sandstone: calcitic mature SRF-bearing subarkose.
EPD-1-14b1 Dockum 3rd Genetic Sequ. Sheet-like fluvial basal channel lag	Light gray, small scale trough-fill cross-stratified. Coarse sandstone: calcitic submature calclithite, bearing quartz fine sand.
EPD-1-14b2 Dockum 3rd Genetic Sequ. Upper part of sheet-like fluvial channel-crevasse splay	Light gray, trough-fill cross-stratified. Fine sandstone: calcitic mature SRF-bearing subarkose.
EPD-1-15b Dockum 3rd Genetic Sequ. Crevasse splay	Grayish light brown, low-angle, continuous, trough-fill cross-stratified and parallel laminated. Very fine sandstone: calcitic mature SRF-bearing subarkose.
EPD-1-15d1 Dockum 3rd Genetic Sequ. Sheet-like braided fluvial(?)-crevasse splay	Grayish green, trough-fill cross-stratified. Very fine sandstone: calcitic mature feldspathic litharenite, bearing fresh and weathered orthoclase, microcline, and volcanic rock fragments(?).
EPD-1-15d2 Dockum 3rd Genetic Sequ. Upper part of sheet-like braided fluvial(?)-crevasse splay	Greenish light brown, trough-fill cross-stratified. Very coarse sandstone: calcitic submature calclithite, bearing volcanic rock fragments and very well rounded caliche very coarse sand.
TMC-1-2 Dockum 3rd Genetic Sequ. Delta front	Grayish green, parallel inclined and horizontal laminated. Fine sandstone: calcitic mature calclithite, bearing fresh and leached feldspar and rounded caliche coarse sand.

TMC-1-5 Dockum 3rd Genetic Sequ. Sheet-like braided fluvial channel	Grayish green, trough-fill cross-stratified. Granule conglomerate: calcitic submature calclithite, bearing feldspar and quartz very fine sand.
DD-6b-4a Dockum 3rd Genetic Sequ. Distributary channel	Brownish gray, trough-fill cross-stratified. Granular fine sandstone: calcitic submature feldspathic litharenite, bearing fresh and altered feldspar, volcanic rock fragments, and rounded caliche granules.
DD-6b-4b Dockum 3rd Genetic Sequ. Fluvial channel	Grayish light brown, structureless. Fine sandstone: slightly calcitic mature sublitharenite, bearing fresh and leached feldspar and volcanic rock fragments.
GP-16b-4a2, GP-16b-3c2 Dockum 1st Genetic Sequ. Soil zone on lacustrine mudstone	Grayish dark yellowish orange carbonate-replaced mudstone: semi-pisolitic morphology; fractures (0.5 mm to 2 cm) filled with soil; Mn-oxide cements line the inside of fractures; Mn-oxide dendrites common; coarsely crystalline (0.5 mm to 2 cm) calcite spar and dolomite fill fractures.
EPD-1-2c1, EPD-1-3a1, EPD-4-F, GP-16b-3c3 Dockum 1st Genetic Sequ. Highly desiccated soil zone	Dark red mudstone: highly fractured (0.1 mm to 1 cm); fractures filled with dolomite, calcite spar, and opal; mudstone is predominantly hematite; quartz silt common; opal occurs as fracture linings, and as spheres 0.1 to 0.2 mm; sparry calcite and dolomite are intergrown.
CPC-12-1a, CPC-12-1b CPC-12-1c, SC-17-2b Dockum 1st Genetic Sequ. Distal fan delta-soil zone	Quartz nodules: megaquartz spherules (2-10 mm) occur at nodule rim, they contain abundant anhydrite inclusions and

	vacuoles; toward nodule center megaquartz crystals increase in size, and are inclusion free; quartz crystals that project into central void often have pseudo cubic terminations; nodules with central void may have gray or red (hematitic) chalcedony in optical continuity with megaquartz; soil, barite, and managnite may occur as secondary minerals filling the central void.
SC-17-2a, CPC-12-1b3 Dockum 1st Genetic Sequ. Distal fan delta-soil zone	Reddish brown chert nodules: light brown microcrystalline quartz matrix contains abundant quartz silt to medium sand; outer surface of nodules is fractured, fissures are 1 mm to 3 cm long, 0.1 to 2 mm wide, and 0.1 to 4 mm deep; some interior fractures are healed with coarser microcrystalline quartz and small (0.05 mm) megaquartz spherules, some grade into chalcedony; open fractures are lined with alternating bands (0.05-0.1 mm) of quartzine and chalcedony.

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