DEPOSITIONAL SETTING OF THE TRIASSIC DOCKUM GROUP, TEXAS PANHANDLE - EASTERN NEW MEXICO[1]

by

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ABSTRACT

The upper Triassic Dockum Group accumulated in relict Paleozoic basins defined in Texas by the Amarillo Uplift on the north and the Glass Mountains on the south. These basins were reactivated during the late Paleozoic or early Mesozoic by tectonic activity that was probably related to the opening of the Gulf of Mexico. As basins subsided and some relict positive elements were uplifted, sedimentation rates increased.

More than 2,000 ft (610 m) of terrigenous clastics, derived chiefly from Paleozoic sedimentary rocks, accumulated within the basin. Source areas were in Texas, Oklahoma, and New Mexico; sediment transport was from the south, east, north, and west. The Dockum Group accumulated in a variety of depositional environments including (1) braided and meandering streams; (2) alluvial fans and fan deltas; (3) distributary-type lacustrine deltas (high-constructive elongate deltas); (4) ephemeral and relatively long-lived lakes; and (5) mud flats.

Alternation of wet and dry climate caused cyclic sedimentation in the Dockum. The main control on climate was most likely tectonism. During wet periods, lake level was relatively stable. Meandering streams supplied sediment to high-constructive elongate deltas in the central basin area of Texas and New Mexico, whereas braided streams and fan deltas were dominant depositional elements along southern and northern basin margins. Lake area and depth decreased when dry conditions prevailed. Under these conditions, base level was lowered, valleys were cut into older Dockum deposits, and small fan deltas were built into ephemeral lakes; evaporites, calcretes,

silcretes, and soils developed upon emergent surfaces ranging from floors of ephemeral lakes to delta platforms.

INTRODUCTION

The Triassic Dockum Group in Texas, New Mexico, Colorado, Kansas, and Oklahoma underlies an area of some 96,000 mi^2 (246,050 km^2). Terrigenous clastic rocks that make up the Dockum range in thickness from a few hundred feet to more than 2,000 ft (610 m). Dockum strata consist of (1) reddish brown mudstone, siltstone, sandstone, and conglomerate, and (2) grayish green siltstone, sandstone, and conglomerate.

Depositional systems that have been recognized in the Dockum are (1) braided and meadering streams, (2) alluvial fans, (3) fan deltas, (4) high-constructive elongate deltas, (5) lacustrine, and (6) valley-fill. Beach and shoreface deposits are rare, but have been recognized in Texas and New Mexico. Silcretes and calcretes were developed locally during accumulation of the Dockum Group.

More than 200 measured sections were used in the outcrop studies. Surface and subsurface studies cover all, or parts of, 55 counties in the Texas Panhandle and eastern New Mexico. Subsurface control consists of 2,000 gamma-ray logs; borehole cuttings from several wells, and continuous cores supplement the gamma-ray log data.

Methods used in facies analyses include mapping of sandstone percentages, studies of stratification types (in outcrop and in cores), determination of textural trends, and petrographic and mineralogic studies.

STRUCTURE AND CLIMATE

By the end of Late Permian time the Paleozoic structural basins of West Texas and eastern New Mexico were almost filled with sediment. The Late Permian landscape was dominated by ephemeral streams, sabkhas, salinas, expansive dune fields, and a shallow hypersaline sea (Gustavson and others, 1980; Presley, 1979, 1980; Handford and others, 1981). The arid Late Permian climate was gradually replaced by increasingly wet conditions during the Triassic. Although an erosional unconformity exists between Permian and Triassic strata within the northern and southern parts of the basin, sedimentation was continuous from Late Permian time through Late Triassic time within the east- and west-central parts of the basin.

Contrasting depositional styles of Permian and Triassic rocks possibly resulted from reactivation of relict Paleozoic structural elements and an increase in rainfall resulting from the opening of the Gulf of Mexico during Late Paleozoic or Early Mesozoic time.

Assuming that the Gulf of Mexico originated during the Late Paleozoic or Early Mesozoic time then a mechanism was operative at that time to rejunevate relict structural elements and to progressively change a dry climate to a wet climate. A change in climate and uplift is recorded in a shift (1) from sediment transport to the east (Quartermaster Formation) to a transport direction to the west (Dockum Group), and (2) a change from sabkha-tidal flat deposition (Permian) to a fluvial-deltaic-lacustrine regime (Dockum) through a stratigraphic interval of several tens of feet (a few meters).

Deposition of the Triassic Dockum Group was indirectly related to the tectonic events that produced the Ouachita-Marathon Foldbelt and directly related to a broad domal uplift and resulting block faulting that created the proto Gulf of Mexico. The timing of the events and the mechanisms that produced these tectonic elements are topics that are still being researched (Pilger, 1980).

Regional uplift, doming, and rifting that produced the Gulf of Mexico (Walper and Rowett, 1972; Wood and Walper, 1974; Pilger, 1978; Belcher, 1979; Buffler and others, 1980) was accompanied by erosion of uplifted areas and deposition of continental sediments and volcanic rocks in graben. Block faulting was aligned parallel to the newly formed oceans and extended from northern Mexico through Texas into the Florida area, then northward along eastern North America (figure 1). Graben were sites of alluvial fan, braided alluvial plain, flood plain, and ephemeral and perennial lake deposition (Scott and others, 1961; Hubert and others, 1978; Belcher, 1979). A north and west slope toward the continental interior was produced in the Texas area by the domal uplift (figure 2).

The uplift possibly initiated Triassic sedimentation in parts of northern Mexico and southwestern United States prior to significantly affecting the Texas-eastern New Mexico region. Moenkopi Formation (Lower Triassic) accumulated in a basin whose eastern limit approximated the Arizona-New Mexico border (Green, 1956; Robertson, 1956; Sirrine, 1956; Woodyard, 1956). Early Triassic sedimentation is recorded in Texas by the Bissett Formation in the Glass Mountains area (King, 1935). The largest volumes of Triassic deposits that accumulated in Texas-eastern New Mexico (the Dockum Group) are said to be Late Triassic in age (Cope, 1875; Gregory, 1956, 1962, 1969; Colbert and Gregory, 1957; Colbert, 1972; Dunay, 1972; Chatterjee, 1978; Elder, 1978).

During Late Permian time the west Texas-eastern New Mexico area was an interior desert of the supercontinent Pangea. Paleolatitude maps (Van der Voo and French, 1974; Van der Voo and others, 1976), generated from paleomagnetic and sea-floor spreading data, indicate a southward migration of the paleoequator for the Late Permian, Early Triassic, Late Triassic interval (figures 3, 4, and 5). In the Colorado Plateau area, Paleozoic and Early Mesozoic winds were generally from the north (Poole and Williams, 1956; Poole, 1962). This belt of northerlies may represent an ancient tradewind belt extending from the equatorial zone to Latitude 43°N and beyond, or perhaps the persistent northerly winds resulted from a relatively stable high-pressure cell that was situated over the Late Paleozoic-Middle Mesozoic sea to the west (Poole and Williams, 1956; Poole, 1962). Clockwise movement of air around such a high-pressure center would result in perennial northerlies along the eastern part of the high pressure system; winds that affected the Texas area should have been from the north.

Domal uplift and rifting that created the Gulf of Mexico changed the climate and depositional regime of the Texas-eastern New Mexico area during Triassic time. Climatic conditions that prevailed along the continental margin within the block faulted regions have been attributed to range from (1) subhumid to humid with seasonal rainfall in northern Mexico during accumulation of La Boca Formation (Belcher, 1979), (2) tropical or subtropical with ample rainfall but with a distinct dry season during deposition of the Eagle Mills Formation (Scott and others, 1961), to (3) tropical semi-aridity with seasonal precipitation of 4.0 to 19.0 inches (10 to 48 cm) during deposition of the Newark Group (Hubert and others, 1978) (figure 6).

A climatic gradient existed between the source area and depositional site of the Dockum (figure 2). The uplands adjacent to the evolving Gulf of Mexico received the maximum rainfall. These uplands were densely vegetated. Rainfall progressively decreased from the vegetated uplands to the depositional basin, and consequently near the basin margin vegetation was chiefly restricted to stream courses. A similar decrease in rainfall from a highland source area to a basin margin was reported for the modern Lake Rudolf and the Oma delta of Ethiopia (Butzer, 1971); rainfall in the vegetated highlands is 60 to 80 inches (150 to 200 cm) per year whereas at the shores of Lake Rudolf rainfall is about 14 inches (35 cm) per year.

DEPOSITIONAL REGIME

The Triassic Dockum Group accumulated in a continental basin; fluvial, deltaic, and lacustrine systems were operative within the basin (McGowen, Granata, and Seni, 1979; Seni, 1979; Boone, 1979; Granata, 1981; Gawloski, 1981). Large lakes, such as the ones in which the Dockum accumulated, are primarily tectonic in origin (Collinson, 1978). During the Triassic two styles of tectonism produced lakes (basins). The first type is block faulting or rifting; Modern analogues are lakes that occur along the east African Rift and the Dead Sea. The second type is the long-lasting sag that persists over long periods of geologic time; Modern examples are Lake Chad in Africa and Lake Eyre in Australia.

The tectonic regime under which the Dockum accumulated, was domal uplift in part of the source area accompanied by sag in the relict Palo Duro-Permian Delaware Basin area which produced a shallow expanding basin (figure 7). This regional topography was responsible for high, seasonal rainfall in the uplands with associated, dense and progressively drier areas and sparser vegetation toward the depositional basin. Deep weathering in the source area produced soils that were rich in hydrated iron oxide (exposed Permian strata also were mostly red). These "red" soils were eroded and transported to the basin where part of the debris accumulated as elongate deltas and fan deltas. The lake shoreline probably migrated considerable distances yearly because of shallow conditions along the basin edges coupled with highly variable seasonal runoff. In this way, lake area and depth decreased periodically as a consequence of sedimentation and because of a change from wet to dry climate.

Accumulation of the Dockum progressed under alternating wet and dry climatic conditions. Under wet conditions lake area and depth were at a maximum and the dominant fluvial systems were meandering streams, although braided streams continued to transport debris to the southern and northern parts of the basin. With the onset of dry conditions lake level dropped, stream courses were incised, and braided streams became the dominant fluvial system.

PALEOGEOGRAPHY

The Dockum Group has been arbitrarily divided into a upper and a lower section (McGowen, Granata, and Seni, 1979; Granata, 1981). With the exception of the Tucumcari Basin in New Mexico the upper Dockum is entirely in the subsurface (Granata, 1981). Reconnaissance outcrop study was made along the Dockum basin in Texas and New Mexico, and detailed outcrop studies were made in select areas (figure 8). Interpretation of outcrop data, with respect to depositional facies, served as a guide to interpreting the subsurface data. Regional sedimentological trends of the Dockum were determined by integrating outcrop and subsurface data.

Within the southeast and northwest corners of the basin there are some Dockum deposits that appear to predate the early, major, influx of sediment into the basin (figure 9). A deltaic sequence about 100 ft (30 m) thick prograded from the southeast into the Midland Basin at a time when the Midland Basin was receiving mostly lacustrine muds. Sediment supplied to the delta was derived from doming along the Marathon Fold Belt; this area later supplied thick fan/fan delta systems.

Braided stream deposits in the northwestern part of the basin form the lowest member of the Santa Rosa Sandstone, which predates the major onset of Dockum sedimentation. Braided stream deposits formed a relatively small alluvial apron around low lying structural/topographic features (figure 9).

During accumulation of the lower Dockum the lacustrine environment expanded northward into the Palo Duro Basin (figure 10). In the east- and west-central parts of the basin the Dockum is characterized by generally fine-grained sedimentary rocks, including meanderbelt sandstones and overbank mudstones, lacustrine deltaic sandstones and mudstones, and lacustrine mudstones. The initial extent of the lacustrine environment and delta progradation probably was restricted to the Midland Basin; subsequent lacustrine expansion covered most of the present limits of the Dockum.

Fan and fan delta systems developed in the southern end of the basin. These coarse-grained deposits were separated from the fine-grained deposits in the east-central basin area by the Sterling-Howard High (figure 10). These fan and fan delta deposits compose the greatest thickness of sand contained within the Dockum. The sediment source for these fans and fan deltas was the domal uplift along the Marathon Fold Belt.

Thin delta and fan delta facies accumulated in small lakes in the northeast part of the basin; there, small lacustrine areas were by-passed by fluvial systems which discharged into larger lakes. Regional expansion of the lacustrine environment at a later date resulted in widespread deltation over the northeast area.

Minor alluvial fans or alluvial plains developed in the north-central part of the basin south of the Amarillo Uplift-Bravo Dome area. Lacustrine mudstones which succeed alluvial fan or alluvial plain deposits suggest a regional expansion of the lacustrine environment.

Coarse-grained meanderbelt sandstones in the basal part of the Dockum cover a large area to the north and northwest of the Matador Arch. Lacustrine and deltaic sediments which overlie the fluvial sandstones provide further indication of an expansion of the lake environment.

Most of the upper Dockum, which is overlain by Jurassic, Cretaceous, and Pliocene deposits, is entirely within the subsurface. Fluvial-deltaic deposits compose the upper Dockum in the east- and west-central parts of the basin (figure 11). The major source of upper Dockum sediment was west of the basin, but alluvial fan and fan delta systems continued to be operative in the southern part of the basin, and high sand, fluvial-deltaic systems were operative in the northeastern and north central parts of the basin.

Upper Dockum in northeastern New Mexico is characterized by an increase in deltaic sediment which is underlain and overlain by lacustrine mudstone. The youngest upper Dockum sequence occurs in northeastern New Mexico. Here, the Dockum is made up of lacustrine mudstone and shoreface sandstone with features indicative of dry climate and a slow sedimentation rate.

DEPOSITIONAL SYSTEMS

Triassic sediment fill of the Dockum basin reflects an overall expanding lacustrine environment punctuated by a fluctuating base level. Base level changes probably resulted from a combination of tectonic activity and climatic cycles (McGowen, Granata, and Seni, 1979).

Bissett Formation (Glass Mountains Area)

The oldest Triassic deposits in Texas are in the Glass Mountains area (King, 1930, 1935, 1937). Some 300 to 800 ft (91 to 244 m) of conglomerate, sandstone, shale, limestone, and dolomite compose the Triassic Bissett Formation (figure 12). The Bissett had a local source (the Marathon Fold Belt) dominated by limestone and dolomite derived from the Capitan and Word Formations (King, 1930). Sediment was transported northward by braided streams which constructed fan deltas which prograded into a lacustrine environment.

Dockum Group

Dockum deposits (Late Triassic in age) are distinctly younger than the Bissett Formation. In certain parts of the Dockum basin (for example, the relict Midland Basin) sedimentation was continuous from Permian through Triassic time. The oldest Dockum deposits accumulated in the relict Midland Basin and in northeastern New Mexico (figure 9). As the lacustrine environment expanded northward the relict Palo Duro Basin began to receive Dockum deposits.

As previously mentioned, sedimentation of the Dockum Group progressed under alternating wet and dry climatic conditions. Under wet conditions lake area and depth were at a maximum and the dominant fluvial systems were meandering streams although braided streams transported debris to the southern and northern parts of the basin. With the onset of dry conditions lake level dropped, stream courses were incised, and braided streams became the dominant fluvial system.

Depositional systems that were operative during wet climatic cycles include meandering and braided streams, high-constructive elongate deltas (Scott and Fisher, 1969), fan deltas, interdeltaic mudflats and beaches, and lakes (figure 13).

Depositional (and erosional) systems that characterized the Dockum during a dry climatic cycle are incised valleys, braided streams, fan deltas, interdeltaic mudflats, and lacustrine (figure 14).

At any particular site the depositional style of the Dockum was altered as a consequence of cyclical changes in climate. However, variations in depositional style for northern, central, and southern parts of the basin were dictated by expansion of the lacustrine basin through time, by uplift (rejuvenation) of relict structural elements, and by size of drainage basins. In general, the central parts of the basin were fed by relatively large meandering streams, which built distributary-type deltas into a lake. Since the distance from basin margin to the highlands (presumed to be the Ouachita Fold Belt on the Texas side) was on the order of 250 mi (403 km) the drainage basin area was large. The northern and southern parts of the basin were fed by relatively high-gradient, braided streams which headed in highlands some 40 to 50 mi (64 to 80 km) from the basin margin; drainage basins in those areas were small.

North of the Matador Arch (Palo Duro Basin Area) fluvial deposits dominate Dockum outcrops; however, deltaic and lacustrine facies compose a large part of the Dockum in stratigraphically higher parts of the section (Boone, 1979; Granata, 1981; McGowen, Granata, and Seni, 1979; Seni, 1979). Lower Dockum deposits are well exposed in northeastern New Mexico, Palo Duro Canyon, Tule Canyon, and in the Silverton-Quitaque area (figure 8). Similar deposits in the southern part of the basin are entirely within the subsurface.

South of the Matador Arch (Midland Basin area) fluvial, deltaic, and lacustrine facies that developed during both wet and dry cycles are locally well exposed on the Texas side of the basin from Dickens County through Mitchell County (figure 8).

Northeastern New Mexico

Formal stratigraphic nomenclature (figure 15) was not used, for the most part, in the regional and detailed study of the Dockum Group. In northeastern New Mexico there is a close correlation of genetically related depositional facies and formal stratigraphic units (figure 16). Approximately 1,650 ft (503 km) of Dockum consisting of the Santa Rosa Sandstone, Chinle Formation, and Redonda Formation were studied by Granata (1981). In ascending order the members of the Santa Rosa Sandstone (figure 17) accumulated in alluvial fan, meandering bed-load streams (Morton and McGowen, 1980), lacustrine, and fan delta environments. The Chinle Formation accumulated in lacustrine and deltaic environments (figure 18). The Redonda Formation, which accumulated in lacustrine, shoreface, and beach environments (figure 19), possibly accumulated in the Tucumcari Basin and was not directly related to older Dockum deposits that accumulated in the relict Palo Duro Basin to the east.

Palo Duro-Tule-Caprock Canyons Area

The Dockum in Palo Duro Canyon, Tule Canyon, and Caprock Canyons area exhibits similar depositional trends (figures 20, 21, and 22). Only the lower Dockum is exposed in this area and its thickness is between 350 and 500 ft (107 to 152 m).

An unconformity exists between the Dockum and upper Permian strata in the Palo Duro Canyon State Park area (Seni, 1978). The contact between the Dockum and the upper Permian is gradational in the Tule Canyon area (Boone, 1979). In the Caprock Canyons area there is a change in depositional style and direction of sediment transport that occurs several tens of feet below the boundary between the Dockum and upper Permian strata as mapped by Barnes and Eifler (1967).

The upper Permian Quartermaster Formation in the Caprock Canyons area consists of approximately 300 ft (107 m) of red, predominantly sandstone, minor siltstone, and rare mudstone. Sediment source for the Quartermaster was to the west as suggested by paleocurrent indicators. A tentative interpretation is that the Quartermaster Formation in the Caprock Canyons area is a fan delta system (Gustavson and others, 1981). The Quartermaster exhibits an upward increase in grain size and in scale of sedimentation units. Overall, the Quartermaster Formation is a progradational sequence (units 2a, b, c, figure 22). The lower part of the Quartermaster consists of thin beds of red mudstone, siltstone, and very fine-grained sandstone. Primary sedimentary structures are ripple drift, ripple cross-laminae, and parallel laminae; soft sediment deformation includes load casts, convolute bedding, and injection features (unit 2a, figure 22). Next in the succession (unit 2b, figure 22) is a zone of foresets that is several tens of feet thick (foresets grade laterally into units 2a and 2c). The uppermost unit (unit 2c, figure 22) consists of red, moderately sorted, fine- to coarse-grained, subround to very well-rounded, quartz arenite. Within unit 2c there are some broad, thin, channel-fill deposits; primary sedimentary structures (where observed) are trough-fill cross-strata and foreset cross-strata.

The vertical succession of facies in the Dockum Group (figures 20, 21, and 22) in the Palo Duro Canyon, Tule Canyon, and Caprock Canyons area records the depositional and erosional events in an expanding continental basin (Seni, 1978; McGowen, Granata, and Seni, 1979; Boone 1979; Granata, 1981). In general, the Dockum in this area can be divided into three broad genetic packages: (1) a lower braided stream-fan delta-lacustrine unit; (2) a middle valley-erosion and valley-fill unit; and (3) and upper fan delta-lacustrine sequence.

The lower 100 ft (30 m), or so, of the Dockum in the Caprock Canyons area is interpreted as distal (unit 3a, figure 22) and proximal (3b, figure 22) braided stream facies. Braided stream deposits are capped by as much as 3.0 ft (1.0 m) of white to light-gray chert and opaline-cemented quartz arenite which are interpreted to be a silcrete. In the Tule Canyon area (figure 21) the lower 200 ft (61 m) of the Dockum represent a fan delta system (Boone, 1979). In Palo Duro Canyon State Park the lower part of the Dockum Group (figure 20) consists of 200 to 300 ft (61 to 91 m) of fan delta and lacustrine deposits (Seni, 1978; McGowen, Granata, and Seni, 1979; Gustavson and others, 1981). Numerous braided stream systems possibly were operative within this area. During accumulation of the lower part of the Dockum a deeper part of the basin existed in the Palo Duro Canyon area than in the Tule Canyon and Caprock Canyons areas as shown by the relatively thick lacustrine deposits (unit 2, figure 20).

A change in the base level, resulting from a decrease in rainfall or uplift in the Ouachita Foldbelt, caused erosion of valleys ranging in width from 0.5 to 0.75 mi (0.8 to 1.2 km) and in depth from 45 to more than 200 feet (14 to 61 m). Valley fill, which is complex, generally exhibits an overall fining-upward texture. Locally, sandstone boulders (derived from older Dockum deposits) occur at the base of the valley-fill sequence. The lower conglomeratic valley fill was laid down by braided streams; at the mouth of the valley small fan deltas prograded into shallow lakes (Seni, 1978). Valleys were back-filled when lake level began to rise with a change to wetter climatic conditions. An overall transgressive sequence is recorded in the valley-fill within Palo Duro Canyon State Park (Seni, 1978). Here, fluvial deposits are succeeded by delta plain, delta front, and lacustrine deposits. Valley fill in Tule Canyon was emplaced entirely by fluvial systems (Boone, 1979). Both bed-load and suspended-load deposits constitute valley-fill deposits in the Caprock Canyons area. Documentation of valley-fill deposits is possible only where outcrops are laterally and vertically extensive.

Above the valley-fill sequence, the Dockum ranges in thickness from 130 to 320 ft (40 to 98 m). Part of the difference in thickness of the Dockum which lies between the valley-fill and Ogallala Formation is attributable to pre-Ogallala erosion. With the exception of the Tule Canyon area, most of the Dockum lying between the valley-fill horizon and base of the Ogallala accumulated in braided stream, fan delta, and lacustrine environments. In the Tule Canyon area the fill within the Dockum valleys does not exhibit a fining upward sequence (fluvial-deltaic-lacustrine facies) as does the fill of valleys in Palo Duro Canyon. Instead, the fill within the Dockum valleys in Tule Canyon is conglomerate and sandstone laid down by ephemeral streams. In the Tule Canyon area valley fill is succeeded by sandstone that was deposited by meandering bed-load streams (the term is synonymous with coarse-grained meanderbelt systems), which is, in turn, overlain by a "lobate delta system" (Boone, 1979). Similar deltaic sequences, interpreted as fan deltas, are present in Palo Duro Canyon area (Seni, 1978; Gustavson and others, 1981) and in the Caprock Canyons area (Gustavson and others, 1981). Deltaic sequences are similar in each of the three areas; however, differences exist with respect to thicknesses and numbers of sequences (figures 20, 21, and 22). In general, each sequence is characterized by an upward increase in grain size and scale of sedimentation units. Two broad depositional facies constitute these fan delta systems, (1) a lower delta foreset (delta front) sequence, and (2) an upper delta platform (delta plain) sequence. Delta foresets consist of reddish-brown mudstone, siltstone, sandstone, and granule lithoclast conglomerate. Primary sedimentary structures are dominantly parallel-inclined laminae (wedge sets) and ripple cross-laminae, with minor trough-fill cross-strata and foreset cross-strata. Foresets dip up to 15 degrees; soft sediment deformation is common in the delta foresets. Delta platform deposits are, in places, gradational into the coarser-grained delta foresets, but most commonly there is an erosional relationship between delta foresets and delta platform deposits. Delta platform deposits were laid down by braided stream systems. Most commonly, delta platform deposits are yellowish-brown, calcitic, poorly-sorted, sandy, granule to pebble, lithoclast conglomerate. Primary sedimentary structures are dominantly trough-fill cross-strata, with minor foreset cross-strata and ripple cross-laminae.

South of Matador Arch

South of the Matador Arch (Midland Basin area) the depositional style of the Dockum was somewhat different from that to the north of the Matador Arch (Palo Duro Basin area). Wet and dry climatic cycles, which possibly were controlled by tectonism, strongly influenced sedimentation in this area.

Cyclic sedimentation began after accumulation of the basal Dockum, which is a progradational sequence recognizable in outcrop and traceable westward into the subsurface (McGowen, Granata, and Seni, 1979). Basal Dockum deposits, which accumulated during expansion of the Dockum lacustrine environment, are characterized by a progradational sequence comprising (1) basal lacustrine-deltaic mudstone and siltstone units, (2) thin, middle deltaic units, and (3) an upper thick fluvial sandstone.

Cyclic sedimentation was controlled by alternating wet and dry climatic conditions and fluctuations in lake area and depth. During wet periods lake level and area were maximum, meandering streams were the dominant fluvial system, and high-constructive elongate deltas prograded the shoreline (figure 13). Dry periods produced a drop in lake level (a change in base level), the cannibalization of deposits that were laid down during a wet cycle, and progradation of lake shorelines by small fan deltas (figure 14).

Wet-Cycle Facies

Two depositional systems comprise Dockum deposits that accumulated during a wet cycle (figure 13). These are a lower delta system and an upper fluvial system. The delta system is a coarsening-upward sequence beginning with mudstone/siltstone and terminating with fine-grained sandstone. In erosional contact with deltaic deposits are fining-upward, thick, conglomeratic sandstone and sandstone laid down by meandering streams.

Complete progradational sequences are rare because of erosion by superposed meandering fluvial systems (figures 23, 24). Facies that constitute the delta systems are lacustrine and prodelta, delta front, channel-mouth bar, distributary channel-fill, and crevasse splay. Delta sequences in outcrop are 20 to 50 ft (6.0 to 15 m) thick.

Thin, reddish-brown, parallel-laminated mudstone makes up the lacustrine-prodelta facies. This facies is commonly gradational below with mudstones of low-stand (dry cycle) origin. Sedimentary structures are thin, horizontal to wavy laminae, exhibiting local soft-sediment deformation. Parallel-laminated mudstone, which records initial lacustrine or prodelta sedimentation, grades upward into delta-front siltstone and sandstone.

Delta-front siltstone and sandstone facies are mostly grayish-green with reddish-brown being dominant in the lower few feet of the unit. Bedding may be approximately horizontal or inclined in the direction of sediment transport. A few thin, low-angle foreset cross-strata and trough-fill cross-strata are associated with inclined beds. Thickness of sedimentation units, scale of sedimentary structures, and grain size increases upward. Foreset cross-strata and trough-fill cross-strata are best developed near the tops of these sequences.

Small washout channels are rare to common (figure 24). Channels, 1 to 2 ft (0.3 to 0.6 m) deep and 15 to 45 ft (4.6 to 13.7 m) wide, are filled with parallel-laminated and low-angle foreset cross-stratified, fine-grained sandstone.

Delta-front siltstone and sandstone are locally burrowed. Dominant burrow type is unornamented, small in diameter (0.25 inch; 6.0 mm), and may be oriented perpendicular or parallel to bedding. Ophiomorpha are present but rare. Other biological constituents are bone fragments and unidentified molluscan shell fragments. Comminuted plant debris is common. Carbonized plant debris in conjunction with biotite forms some distinct dark laminae within this facies.

The thickness of inclined bedded units suggests that water depths were 10 to 15 ft (3.0 to 4.6 m). Horizontally bedded delta-front deposits probably accumulated in less than 10 ft (3.0 m) of water.

Channel-mouth bar sandstones are gradational below with delta-front deposits and are in erosional contact with overlying distributary channel-fill facies (figure 24). Lower parts of this facies generally consist of low-angle, foreset cross-stratified, very fine-grained to fine-grained sandstone. Uppermost deposits comprise foreset cross-stratified and trough-fill cross-stratified sandstone. Thickness of this sequence is 5 to 10 ft (1.5 to 3.0 m). Very fine- to fine-grained sandstone composing the facies displays no vertical textural trend. Bioturbation of channel-mouth bar facies is rare, as are fragments of bone and shell. Preservation potential is low because distributary channels commonly cut entirely through this facies into the underlying delta front sandstones.

Distributary channel-fill conglomerate and sandstone bodies range from 5 to 15 ft (1.5 to 4.6 m) thick and 30 to 200 ft (9.0 to 61 m) wide. Multiple, superposed channel-fill units are 25 to 35 ft (7.6 to 11 m) thick and up to 1,300 ft (396 m) wide. Individual channels have parabolic cross sections; some are symmetrically filled indicating a straight channel pattern.

Large distributary channel systems eroded through channel-mouth bar facies into subjacent delta-front facies. Large channels were filled, for the most part, with trough-fill cross-stratified, fine-grained sandstone. Foreset cross-stratified, lithoclast conglomerate floors many small channel-fill sequences. Conglomerates are commonly overlain by alternating parallel-laminated sandstone and siltstone; laminae conform to the channel configuration. Parallel-laminated or massive mudstone overlies sandstone-siltstone units.

Conglomerate-filled crevasse channels are present but are limited in distribution; maximum thickness of these channel deposits is about 15 ft (4.6 m). Crevasse channels are associated with both distributary channels and meandering streams. Materials that fill crevasse channels were derived from (1) the bed load and suspended load of rivers and distributaries, (2) the many environments which the crevasse cuts across, and (3) plants and animals. Proximal fill of crevasse channels is typically unsorted cobble to boulder lithoclast conglomerate; the more distal parts of the fill consist of trough-fill and foreset cross-stratified conglomeratic fine- to coarse-grained sandstone. Primary sedimentary structures are poorly defined in the proximal fill. Obvious structures are large-scale and can be identified only as cut-and-fill; some pebble conglomerate units exhibit trough-fill cross-strata. Shells of Unio (a fresh-water clam), bone fragments, and plant debris are rare to abundant.

Meandering fluvial sandstone sequences commonly cap the high-constructive, elongate delta systems (figures 23, 24). Maximum thickness of composite fluvial sandstone bodies is approximately 85 ft (26 m); maximum is about 6 mi (10 km). These sandstones are products of multiple depositional events, and complete fluvial sequences are rarely preserved. Single genetic sandstone bodies range in thickness from 20 to 40 ft (6.0 to 12 m). Accretionary grain, a feature that results from point-bar migration, is exhibited by some of the sandstones.

Both coarse-grained (McGowen and Garner, 1970; Levey, 1976) and fine-grained point-bar deposits (Bernard and others, 1970) occur in Dockum meanderbelt sequences. Modern streams have been classified according to channel pattern (straight, braided, meandering) by Leopold, Wolman, and Miller (1964) and by sediment load (suspended-, mixed-, bed-load) by Schumm (1968, 1972). Various models have been proposed for meandering stream deposits, for example fine-grained point bar (Bernard and Major, 1963; Bernard and others, 1970) and coarse-grained point bar (McGowen and Garner, 1970; Levy, 1976). Galloway (1977, 1979) found some existing models to be inadequate when applied to the geologic record. Morton and McGowen (1980) attempted to combine data on channel patterns, sediment load, and stratification types to more clearly define the fine-grained and coarse-grained point bar models. Redefinition of these models resulted in part from problems arising from studies of Dockum fluvial deposits which exhibited a succession of stratification types characteristic of coarse-grained point bars, but were composed almost exclusively of sand-sized particles. Hence, the change in terms; mixed-load, fine-grained meanderbelt systems seems more appropriate than fine-grained point bar sequence, and bed-load meanderbelt system seems more appropriate than coarse-grained point bar sequence. A succession of sedimentary structures similar to those found in Modern bed-load meanderbelt systems (figure 25) consists of the following (in ascending order): (1) massive or trough-fill cross-stratified conglomerate or conglomeratic fine-to medium-grained sandstone; (2) alternating foreset and trough-fill cross-stratified granule-bearing fine-grained sandstone; (3) either simple low-angle foresets 5 to 9 ft (1.5 to 2.7 m) thick or an interval of compound foresets of comparable thickness; and (4) parallel-laminated and ripple cross-laminated siltstone and very fine-grained sandstone that alternate with parallel-laminated or massive mudstone.

Deposits of mixed-load meanderbelt systems (figure 26) vary slightly from those of the bed-load meanderbelt systems. Thick foresets or compound foresets are absent in fine-grained point-bar deposits. Parallel-horizontal or parallel-inclined laminae composed of very fine-grained to fine-grained sandstone typify upper point bars in mixed-load meanderbelt systems. Other stratification types such as thin foreset cross-strata, trough-fill cross-strata, and ripple cross-laminae also occur within the upper point-bar facies of mixed-load fine-grained meanderbelt sandstones.

Meander cutoffs and abandoned stream courses are common in the Dockum. Abandoned channels are filled with mudstone and sandstone. Mudstone lenses, 15 to 30 ft (4.6 to 9.0 m) thick, are reddish-brown and dark-greenish gray. Reddish-brown mudstones, which are massive or parallel-laminated, contain (1) lenses of ripple cross-laminated siltstone and very fine-grained sandstone and (2) very fine-grained sandstone wedges that thicken toward neck cutoffs. Dark-greenish-gray mudstones are generally massive and contain a few parallel-laminated horizons consisting of a high percentage of siltstone and plant debris. Some irregular masses of very fine-grained sandstone occur within gray mudstones; these discontinuous sandstone bodies were deposited as rippled sands that foundered into a "soupy" mud substrate. Rare to common coprolites and carbonized plant material (mostly leaves and twigs) have been observed in some gray mudstones.

Dry-Cycle Facies

During the dry climatic cycles the dominant depositional environments were small, shallow lakes, small fan deltas, interdeltaic mudflats, and ephemeral streams that were confined to headwardly eroding valleys (figure 14). Three depositional systems comprise Dockum deposits that accumulated during a dry cycle. These are lacustrine, fan delta, and ephemeral stream systems (figures 23, 27). Component facies are lacustrine and prodelta, delta foreset, delta platform, mudflat, and valley fill. Single deltaic sequences comprising foresets and delta platform are about 10 ft (3.0 m) thick, whereas multiple sequences are several tens of feet thick. Lacustrine and prodelta facies are 5 to 10 ft (1.5 to 3.0 m) thick, and valley-fill deposits are a maximum of 50 ft (15 m) thick.

Reddish-brown mudstone and siltstone compose lacustrine and prodelta deposits. Several mudstone and siltstone types make up these deposits. Burrowed mudstones are grayish and purple. These mudstones indicate slow rates of sedimentation. All burrows are attributed to worms. _Scoyenia_ and _Teichichnus_ were produced by polychaetes; the critter that produced small diameter (2 to 5 mm), nondescript burrows is unknown. Massive, reddish-brown, lacustrine and prodelta mudstones commonly have grayish-green reduction patches and slickensides. Near the transition from lacustrine to delta foreset deposits the dominant sediment type is reddish-brown, parallel-laminated mudstone and siltstone, and grayish-green, well-sorted, calcitic, ripple cross-laminated siltstone.

Delta foresets are made up of reddish-brown mudstone, siltstone, sandstone, and lithoclast conglomerate. Foresets range in thickness from 2 to 10 ft (0.6 to 3.0 m). Dips of foresets range from 4 degree to 16 degrees. Outcrops oriented approximately perpendicular to transport direction exhibit horizontal or broadly convex upward stratification. Most foreset sequences display (1) a downcurrent decrease in grain size, dip angle, and bedding thickness, (2) conglomerate lenses that are thickest near tops of foresets but generally pinch out before reaching the toe, and (3) soft-sediment deformation that is normally confined to sandstone units.

Delta foresets are capped by lithoclast conglomerate and sandstone that were deposited by braided streams. Conglomerate, the dominant textural type, was derived from Triassic mudstone, siltstone, sandstone, caliche, wood debris, bone fragments, and Unio shells.

Two geometric types, sheet and channel-fill, compose the delta-platform fluvial facies. Sheetlike conglomerate beds, 1 to 5 ft (0.3 to 1.5 m) thick conformably overlie delta foresets. Some of the conglomerate beds grade basinward into delta foresets. Conglomerate sheets consist of alternating granule to pebble conglomerate and very fine- to very coarse-grained sandstone. Sedimentary structures in conglomerates are trough-fill cross-strata, minor foreset cross-strata, and parallel bedding. Sedimentary structures in sandstones are trough-fill cross-strata and parallel laminae. Upper surfaces of some sheet conglomerates contain Ophiomorpha and rare to abundant, randomly oriented, juvenile and adult, articulated, and disarticulated Unio.

Channel-fill conglomerates accumulated in two types of channels. The first type is representative of relatively deep (15 ft; 4.6 m) and narrow (generally less than 100 ft; 30 m) incised straight feeder channels that were alternately active and abandoned. The first channel type was filled with conglomerate, sandstone, and siltstone. Conglomerate beds are a few inches (few cm) to about 3.0 ft (0.9 m) thick and are either structureless or display indistinct parallel bedding and trough-fill cross-strata. A second type of channel-fill conglomerate accumulated within the more-or-less continuously active channels which were the feeder systems for sheet conglomerates and delta foresets. Maximum thickness of these channel-fill conglomerates is 15 ft (4.6 m); these channel-fill bodies exhibit width-thickness ratios of about 25 to 1.0. Channels were filled chiefly with trough-fill cross-stratified granule to cobble lithoclast conglomerate; wood, bone fragments, and disarticulated and fragmented _Unio_ are rare to common in the second type of channel-fill deposit.

Mudflat deposits apparently accumulated upon abandoned fan-delta platforms, between contemporaneous deltas, and in desiccating ponds and lakes. Green, brown, and purple mudstone facies contain traces of evaporites, including mud-filled chert nodules and lentil-shaped gypsum crystals. Desiccation cracks and desiccation breccia are characteristic of mudflat deposits. Some of the desiccation cracks are filled with calcite.

Lowering of base level during dry cycles caused entrenchment of existing streams and created new headwardly eroding streams. The net result was development of numerous valley, the maximum depths of which were about 50 ft (15 m). Valley-fill deposits are characterized by a complex sequence of terrigenous clastics that record many depositional and erosional events (figure 28). The deposits range in texture from mudstone to cobble conglomerate. Valleys were filled with debris that was transported down the valley by braided and meandering streams, eroded from valley walls by slope wash, and deposited from suspension as the valley was invaded by lake waters.

Sediment that was eroded from older Dockum deposits, through entrenchment of older streams and by headwardly eroding streams, was the major sediment source from which small fan deltas were constructed.

SUBSURFACE

For the purpose of subsurface mapping the Dockum was divided into informal "lower Dockum" and "upper Dockum" units. The lower Dockum is an overall fining-upward sequence. The boundary between the lower and upper Dockum is a regional approximation of a vertical lithologic change (McGowen, Granata, and Seni, 1979; Granata, 1981).

Sandstone map patterns, proportion of sandstone to mudstone, gamma log characteristics, and adjacent outcrop data were used to interpret depositional systems. The depositional model generated from outcrop work (McGowen, Granata, and Seni, 1979) includes shoreline progradation during wet climatic cycles, followed by a decrease in lake size and erosion resulting from dry climatic cycles. During dry cycles the small depositional systems (e.g., fan deltas) were constructed of materials cannibalized from the previous wet cycle deposits, and consequently appear as fine-grained rocks on gamma logs. Consequently, the dry cycle depositional systems were not detected by regional subsurface techniques. Only the quartzose sandstones were mapped; therefore, the sandstone percentage maps are mainly a record of the coarse fraction of Dockum deposits that accumulated during a wet climatic cycle.

Lower Dockum Depositional Patterns

The lower Dockum is up to 1,200 ft (365 m) thick (figure 29), about an order of magnitude thicker than individual depositional systems (Granata, 1981). Lithofacies maps of such a unit reflect the cumulative effects of several superimposed depositional features. Vertical persistence, or stacking effect, of Dockum depositional systems was minimal. This is in strong contrast with vertical stacking of fluvial and deltaic facies in the Pennsylvanian and Permian of north-central Texas (Galloway and Brown, 1972; Galloway and Brown, 1973; Brown and others, 1973). Therefore, depiction of some individual depositional patterns is not evident in subsurface maps of the Dockum.

Regional and local detailed outcrop study of the lower Dockum (McGowen, Granata, and Seni, 1979) indicate that the gradients of streams flowing into the Dockum basin were generally very low, the lakes were shallow, and any change in water level affected broad areas adjacent to the lake. Hence, lake level oscillations produced both changes in facies tracts and in depositional systems. Possibly the main reason that sandstone percentage maps exhibit any pattern from which an interpretation can be made is that lake expansion occurred after an early progradational event. This transgression resulted in mud and silt accumulation over sandy peripheral deposits (Granata, 1981). Although the lower Dockum interval is thick, the map pattern was affected by relatively few sand dispersal systems. Sediment distribution patterns are not indicative of individual depositional systems, instead they reflect the dispersal mechanisms (transport axes).

East- and West-Central Basin Area

The Dockum in the east-central basin area contains more mudstone and siltstone than the Dockum at the north and south ends of the basin. Large watersheds in the central part of the Dockum Basin derived part of their sediment load as far away as the Ouachita Fold Belt. Most of the sediment was from older sedimentary rocks. Low-gradient streams transported sediment to the basin.

Sediment entered the basin by way of mixed-load, meandering fluvial systems (McGowen, Granata, and Seni, 1979; Morton and McGowen, 1980). High constructive elongate deltas (classification of Scott and Fisher, 1969) prograded the lake shoreline.

A sandstone percentage map (figure 30) shows two lobes of high sand along the eastern margin of the basin; these are inferred to be shallow lacustrine deltas constructed by mixed-load meandering streams.

Sandstone distribution in the west-central part of the basin is similar in pattern to that of the east-central basin (figure 30). Gamma logs from wells in the west-central area show a basal mudstone succeeded by a "coarsening-upward" sandstone which is overlain by a dominantly mudstone section.

This vertical succession suggests (1) an initial progradation consisting of deltaic and meandering stream deposits and (2) a succeeding transgression on finer-grained sediment toward the lake margin.

South Basin Area

At the southern end of the basin (in Upton County) the Dockum, which is about 75 percent sandstone (figure 30), attains a thickness greater than 600 ft (183 m). Gamma log signature of the sandstones is a blocky pattern;

similar blocky patterns have been reported on electric logs for Paleozoic fan delta deposits in north Texas (Erxleben, 1975; Handford and Fredericks, 1980; Dutton, in press). Thick, blocky sandstones extend as far north as Midland County. Based on log characteristics, large sandstone volume, and a probable nearby source area, these deposits are considered to be a fan delta system.

Northeast Basin Area

The Amarillo-Wichita Uplift was the major sediment source for sandstone in the northeast part of the basin. Higher sandstone percentage than for the east- and west-central parts of the basin indicate that the northeastern depositional site was nearer a sediment source. Depositional systems described by Seni (1978), Boone (1979), and Gustavson and others (1981) from outcrops along the northern part of the basin are predominantly fluvial and deltaic. The presence of both lacustrine deltas (Seni, 1978) and fluvial systems (Boone, 1979; Gustavson and others, 1981) within similar (lower) horizons of the Dockum in outcrop some 20 to 50 mi (32 to 80 km) apart indicates that lacustrine environments were not widespread in this part of the basin. Thicker delta foresets in the upper part of the Dockum, in outcrop, suggest the lacustrine environments expanded during accumulation of the upper part of the lower Dockum.

North Basin Area

South of the Bravo Dome and the western end of the Amarillo Uplift the lowermost Dockum is inferred to be mostly alluvial fan deposits. Lobes of high-percent sandstone (figure 30) south of the uplift may correspond to the extent of this system.

The Bravo Dome and western Amarillo Uplift were not major sediment sources for these deposits as the volume of Permian rock removed from these structural highs is small compared to the volume of Dockum in this part of the basin (Granata, 1981).

Northwest Basin Area

Subsurface data are sparse for the northwest basin area. A bed-load meanderbelt system (Middle Santa Rosa Sandstone) crops out over a wide area in De Baca, Guadalupe, San Miguel, and Quay Counties, New Mexico. This sandstone extends to the southeast in the subsurface into Cochran, Hockley, and southern Lamb Counties, Texas, and into Roosevelt County, New Mexico along the Paleozoic Matador Arch (figure 30). The elongate sandstone trend terminates abruptly at the Matador Arch; this abrupt change suggests that the elongate fluvial system terminated at the margin of the lacustrine system.

In outcrop, in New Mexico, the bed-load meanderbelt system is overlain by deltaic deposits which are overlain by about 200 feet (61 m) of lacustrine mudstone (Granata, 1981). This transgressive sequence records expansion of the lacustrine environment from base to top of the lower Dockum.

Upper Dockum Depositional Patterns

In the northwest part of the Midland Basin the upper Dockum attains a thickness of 1,000 ft, or 305 m (figure 31). A large amount of erosional truncation of the upper Dockum occurred along the eastern side of the basin. Upper Dockum does not crop out along the eastern side of the High Plains; it is overlapped by the Pliocene Ogallala Formation. In New Mexico, the upper Dockum in subsurface corresponds to the outcrop interval beginning at the base of the Cuervo Sandstone Member of the Chinle Formation and extending to the top of the Redonda Formation (Granata, 1981).

East- and West-Central Basin Area

Peripheral filling of the basin is evident from sandstone trends of the upper Dockum (figure 32). The dominant depositional feature of the upper Dockum is the major lobate trend along the western part of the basin. Sandstone trends illustrate that, at this time, western sediment sources were prevalent over eastern sources. The distribution pattern suggests a fluvial-deltaic system.

Northwest Basin Area

The Redonda Formation represents the youngest strata of the Dockum Group. In the subsurface the sandstones of the Redonda are not distinguishable from those of the Chinle Formation. In outcrop, the extent of the Redonda Formation approximates the area of the Tucumcari Basin. The cyclical mudstone-sandstone of the Redonda overlies a soil horizon developed on Chinle mudstone. The Redonda comprises lacustrine mudstone and shoreface sandstone (Granata, 1981).

HISTORICAL SUMMARY

The Triassic Dockum Group represents the final fill of the Permian Basin complex, a structural basin whose origin dates from the Late Mississippian-Early Pennsylvanian. By Late Permian time the Permian Basin had been almost completely filled with sediment and the shoreline had migrated southward (Hills, 1972), leaving the Dalhart and Palo Duro Basins as virtually barren desert areas. Depositional environments that existed during the Late Permian were continental dune fields, ephemeral streams, alluvial fans and fan deltas, continental and coastal sabkhas, and shallow hypersaline seas in which carbonates and evaporites accumulated.

As the Permian seaway migrated southward, previously deposited Permian carbonates, evaporites, and terrigenous clastics were eroded and debris derived therefrom was transported to the relict Permian sea. Within the Midland Basin sedimentation was continuous from Late Permian through Triassic time.

The desert regime of the Late Permian, and perhaps Early-Middle Triassic as well (Upper Triassic Dockum is in gradational contact with the Upper Permian Pierce Canyon, Dewey Lake, and Quartermaster Formations), was gradually replaced by fluvial conditions of the Late Triassic. A major climatic change was brought about by tectonism which produced the Gulf of Mexico via the break up of Pangea during Late Paleozoic-Early Mesozoic time. Relict Paleozoic structural elements were reactivated to some degree; some former highs were elevated, and former lows were depressed somewhat.

The result of this tectonic activity and change in climatic regime was the onset of Triassic sedimentation (at or near sea level) adjacent to the reactivated Glass Mountains (deposition of the Bissett Formation). Through time large fluvial systems developed in the east- and west-central Dockum basin area; the relict Midland Basin became the site of an expanding lacustrine environment whose shoreline was prograded through deltation. The oldest Dockum deposits accumulated in the relict Midland Basin. As the Triassic lacustrine basin expanded northward the Palo Duro and Dalhart Basins began to receive Dockum sediment. In much of the Palo Duro-Dalhart Basin area the Dockum Group is in erosional contact with Permian strata.

Most of the sediment that composes the Dockum was derived from Paleozoic sedimentary rocks that literally surrounded the Dockum Basin in Texas, New Mexico and Oklahoma. Petrography of sandstones in conjunction with paleocurrent data document the multiple sediment source areas.

Contrasting depositional styles between the (1) southern and northern and (2) central basin areas are primarily a function of tectonism and secondarily a function of climate. Alluvial fans and fan deltas were the dominant depositional systems at the south end of the basin near the Marathon Fold Belt, and at the north end of the basin near the Wichita-Amarillo Mountain System. Within the east- and west-central parts of the basin meandering streams and high constructive elongate deltas were the dominant depositional elements during periods of high rainfall. A shift from wet to dry climatic conditions affected the overall depositional regime within the Dockum Basin. Evidence of dry conditions within the northern part of the basin is the presence of thick valley-fill deposits and soils (silcrete and calcrete) that developed under a dry evaporitic regime. Within the central basin area the dry climatic cycles are recorded by thin valley-fill sequences, small fan deltas composed of reworked older Dockum deposits, and gypsum (anhydrite) and chert associated with desiccation features.

The Dockum was subjected to prolonged erosional events during parts of the Jurassic, Cretaceous, and Tertiary periods; consequently, the former areal extent of the Dockum is not precisely known.

ECONOMIC POTENTIAL

Ground water and uranium are the two possible economic resources of the Dockum Group. With the depletion of the ground water in the Ogallala

Aquifer interest in the Dockum may be renewed. Uranium occurrences in the Dockum have been known for years, and with increasing demands for energy in the United States the uranium-bearing potential of the Dockum has recently been reevaluated (McGowen, Granata, and Seni, 1979; Amaral, 1979; McGowen and others, 1980; Seni and others, 1980).

Uranium has been reported from outcrops of the Triassic Dockum Group in many areas of Texas. Numerous deposits were discovered during the flurry of exploration activity in the 1950's, notably in the Post area of Garza County, Tule Canyon area in Briscoe County, and the Quitaque area in Briscoe County (Hays, 1956).

Renewed interest in and exploration for uranium was brought about by the "energy crisis" of the 1970's. Results of some of these efforts (McGowen, Granata, and Seni, 1979; Amaral, 1979; McGowen and others, 1980; Seni and others, 1980) support conclusions drawn from previous efforts. The Dockum Group contains numerous, small, high concentrations of uranium that, because of their size, are not, at the present, economic deposits.

The more recent studies (McGowen, Granata, and Seni, 1979; McGowen and others, 1980; Seni and others, 1980) demonstrate that there is a relationship between depositional facies and uranium occurrence, and that there is a relationship between Pleistocene lake deposits, the Ogallala ground-water system, and uranium occurrence in the Dockum.

Numerous depositional facies were recognized in the Dockum outcrops and almost all of these facies contain uranium. Uranium occurrences are common in meandering-stream, delta-front, and crevasse-splay deposits. Uranium occurs most frequently in meandering-stream deposits, but the highest concentrations (greater than 8,000 ppm) occur in crevasse-splay deposits (McGowen and others, 1980). Without exception, these areas of high uranium concentrations are in close proximity to (1) Pleistocene lake deposits that contain high uranium concentrations and (2) area of high uranium counts in Ogallala ground water.

Regional ground-water geochemical data (Butz and others, 1979; McGowen and others, 1980) show that the high concentrations of uranium in the Dockum and Ogallala have similar trends, suggesting that their respective aquifers are physically connected and that the waters are genetically related.

It is postulated that uranium contained in ground water of the Ogallala and Dockum was derived from volcanic ash within the overlying Pleistocene deposits. Ground water, charged with uranium, moved downward from the Pleistocene through the Ogallala into Dockum (and upper Permian) strata. Upon reaching upper Permian strata, ground water moved updip through permeable carbonates, sandstones, and siltstones; brines derived from solution of salts within the Permian are currently being discharged into present drainage systems.

By approximately 600,000 years B.P., the time when the Pearlette ash was accumulating, the Ogallala had been eroded westward to near the middle of Kent County (figure 33). Eastward beyond this point, volcanic ash fell upon Permian outcrops. The present areas of discontinuous uranium anomalies were overlain 600,000 years B.P. by the Ogallala Formation. Pleistocene lakes that formed on the Ogallala surface were sites of uranium concentration. The present patchy distribution of ground-water anomalies probably reflects the position of those lakes; ground-water movement was downward into Dockum and Permian strata.

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FIGURE CAPTIONS

1. Structural elements and major stratigraphic elements, Late Triassic, southeastern United States (modified from Scott and others, 1961; Wood and Walper, 1974; Hubert and others, 1978; Belcher, 1979).
2. Southeast-northwest schematic cross section contrasting the structural and depositional styles of the Eagle Mills Formation and the Dockum Group.
3. Paleo-Latitude map during Late Permian time (after Van der Voo and French, 1974).
4. Paleo-Latitude map during Early Triassic time (after Van der Voo and French, 1974).
5. Paleo-Latitude map during Late Triassic time (after Van der Voo and French, 1974).
6. Late Triassic climatic zones. Shows distribution of climate sensitive rocks which are coal (C), dune sandstone (D), and evaporites (E). (After Hubert and others, 1978).
7. Paleozoic structural elements that indirectly affected Dockum sedimentation (A), and major geologic elements that, during Triassic time, directly affected Dockum sedimentation (B.) (Modified from Granata, 1981).
8. Areas of detailed outcrop study. A. Northeastern New Mexico (Granata, 1981). B. Palo Duro Canyon (Seni, 1978). C. Tule Canyon (Bone, 1978). D. Area south of the Matador Arch (McGowen and others, 1979).
9. Paleogeography during initial Dockum sedimentation (modified from Granata, 1981).

10. Paleogeography during accumulation of lower part of Dockum Group (modified from Granata, 1981).
11. Paleogeography during accumulation of upper part of Dockum Group (modified from Granata, 1981).
12. Vertical succession of lithofacies, Bissett Formation (constructed from physical descriptions of King, 1930).
13. Sediment dispersal system during a wet cycle: meandering streams, lacustrine deltas, and shallow lakes. Facies tract and cross sections are generalized from field observations. Cross section A-A' represents coarse-grained meanderbelt sequence, and B-B' is a fine-grained meanderbelt sequence. Large distributary channel, and channel-fill deposits are shown by C-C'. Small distributary channels, channel-mouth bar, and delta-front deposits are shown by D-D'. Where deltas prograded into relatively deep water, the delta front is represented by siltstone, sandstone, and conglomerate foresets that interfinger with prodelta deposits (E-E'). Cross sections F-F' and G-G' represent fill of crevasse channel and crevasse splay, respectively (after McGowen and others, 1979).
14. Sediment dispersal systems during a dry cycle: headwardly-eroding streams, braided streams, small fan deltas, and ephemeral lakes. Facies tract and cross sections are generalized from field observations. Cross section A-A' is a valley-fill sequence consisting of braided-and meandering-stream deposits, slopewash, and lacustrine mudstone and siltstone. Braided feeder channel-fill sequence near the apex of a small fan delta is shown by cross section B-B'; the fill is chiefly trough-fill cross-stratified lithoclast conglomerate. Delta platform,

delta margin, and delta foresets are shown in cross section C-C' which is parallel to flow direction. Cross section D-D' is across the distal part of a small fan delta; this section shows foresets to be broadly convex upward (after McGowen and others, 1979).

15. Formal stratigraphic terminology of the Dockum Group (modified from Granata, 1981).
16. Formal stratigraphic terminology, depositional systems, and lithofacies of the Dockum Group, Northeastern New Mexico (modified from Granata, 1981).
17. Stratigraphic units, depositional systems, and lithofacies, Santa Rosa Sandstone (modified after Granata, 1981).
18. Stratigraphic units, depositional systems, and lithofacies, Chinle Formation (modified from Granata, 1981).
19. Stratigraphic units, depositional systems, and lithofacies, Redonda Formation (modified from Granata, 1981).
20. Depositional systems and lithofacies; generalized from several measured sections in Palo Duro Canyon State Park (modified from Seni, 1978; McGowen and others, 1979; Gustavson and others, 1981).
21. Depositional systems and lithofacies; generalized from several measured sections in Tule Canyon (after Boone, 1978).
22. Depositional systems and lithofacies; Caprock Canyons area (modified from Gustavson and others, 1981).
23. Cross section of the uppermost Dockum in outcrop in southwest Garza County, Texas. A. Two-dimensional geometry and lithofacies. B. Two-dimensional geometry and depositional facies.
24. Progradational sequence, Slaughter Ranch, southwestern Garza County, Texas (Middle Creek 7.5-minute quadrangle). High-stand and low-stand

deposits represented in section. Units 1 through 4 are low-stand deposits, and units 5 through 15 are high-stand deposits; a transition occurs from low-stand to high-stand facies. Low-stand deposits (units 1 through 4) are components of fan deltas. For example, unit 1 and upper part of unit 2 are delta foresets consisting of reddish-brown mudstone, siltstone, very fine sandstone, and intrabasinal conglomerate; primary sedimentary structures are parallel inclined laminae, ripple cross-laminae, trough-fill cross-stratified, and low-angle delta foresets; small diameter (0.06 to 0.12 inch) burrows present. Lower part of unit 2 is a multiple channel-fill sequence (straight feeder channel) consisting of reddish-brown and greenish-gray very fine sandstone and granule to pebble intrabasinal conglomerate; primary sedimentary structures are massive conglomerate, parallel and ripple cross-laminated sandstone. Delta platform (middle part of unit 2 and units 3 and 4) consists of reddish-brown, very fine sandstone and granule to pebble intrabasinal conglomerate; sedimentary structures are high- and low-angle foreset cross-strata, wavy parallel laminations (wave length: 8 ft; amplitude: 0.5 ft), parallel laminae with mud drapes (Unio in unit 3), combined flow ripples (unit 4), and soft-sediment deformation (unit 4). Interdeltaic deposits (lower part of unit 5) are moderate-brown to reddish-brown, coarse siltstone and very fine sandstone; sedimentary structures are alternating parallel and ripple cross-laminae. High-stand deposits represented by lacustrine deposits (lower part of unit 5) consist of reddish-brown and red-purple claystone, mudstone, and siltstone (silt content increases upward); primary sedimentary structures are parallel laminae, sequence is mostly massive; burrows are common (Scoyenia and Teichichnus). Mudflat deposits (upper part of unit 5) consist of reddish-brown, red-purple, and green desiccated mudstone with caliche nodules and burrows in lower part. Lacustrine deposits (uppermost part of unit 5) consist of reduced grayish-green massive mudstone. Distal delta front (units 6 and 7) and proximal delta front (unit 8). Distal delta front is greenish-gray biotite-bearing coarse siltstone to very fine sandstone; primary sedimentary structures are alternating parallel laminae and ripple cross-laminae with washout channels (unit 7) 10 ft wide by 3 ft deep. Proximal delta front is grayish-green biotite-bearing very fine to fine sandstone; primary sedimentary structures are parallel laminae. Distributary channel fill (units 9 through 14) comprises greenish-gray granule to pebble intrabasinal conglomerate, conglomeratic fine sandstone, fine sandstone, and moderate-brown to reddish-brown mudstone, siltstone, and very fine sandstone; primary sedimentary structures are trough-fill cross-strata, high-angle foresets, parallel laminae (conform to channel floors), ripple drift, ripple cross-laminae, and settle-out mud and silt laminae. Meanderbelt deposits (unit 15) complete high-stand sequence. Unit 15 is composed of greenish-gray granule to pebble intrabasinal conglomerate and fine sandstone, light-gray to yellowish-light gray coarse siltstone to medium sandstone; primary sedimentary structures are massive conglomerate, thin trough-fill cross-strata, parallel inclined laminae, medium-scale trough-fill cross-strata, high-angle foreset cross-strata, and wavy parallel laminae (after McGowen, Granata, and Seni, 1979).

25. Bed-load meanderbelt sequence, Dalby Ranch, central Garza County, Texas (Justiceburg Northwest 7.5-minute quadrangle). Meanderbelt

sandstone caps escarpments in area. Approximately 50 ft of reddish-brown lacustrine mudstone (mostly associated with low-stand, arid phase, and in part equivalent to unit 1 of figure 14, and units 1 and 2 of figure 19) underlies thin progradational siltstone and sandstone (top of unit 1, and unit 2). Splay deposit (in part equivalent to units 5 through 8, figure 14) overlies thin progradational sequence. Coarse-grained meanderbelt sandstone (unit 5) in erosional contact with splay unit. Meanderbelt comprises channel lag (unit 5a), trough-fill cross-stratified granule to pebble intrabasinal conglomerate; lower and middle point bar (units 5b and c), trough-fill and foreset cross-stratified fine to medium sandstone; and upper point bar (chute bar, unit 5d), compound foresets, some ripple cross-laminae, and trough-fill cross-stratified fine- to medium-grained sandstone. Overbank deposits (units 6, 7, and 8) consist of ripple cross-laminated coarse siltstone to very fine sandstone and massive sandy mudstone (after McGowen, Granata, and Seni, 1979).

26. Mixed-load meanderbelt sequence, Dalby Ranch, central Garza County, Texas (Justiceburg Northwest 7.5-minute quadrangle). Meanderbelt sandstone caps escarpment. Meandering stream cut into deltaic deposits. Unit 1 is lacustrine-prodelta mudstone. Unit 2 is a delta-front sequence equivalent to units 2 through 8 (figure 14). Units 4 through 13 are components of a fine-grained meanderbelt sequence. Unit 4 is yellowish-brown granule to cobble channel-lag conglomerate with lenses of medium- to coarse-grained sandstone. Units 5 through 10 are point-bar deposits that exhibit general upward decrease in grain size and thickness of sedimentation units; vertical succession of stratifica-

tion types is trough-fill cross-strata (units 5 and 6), parallel inclined laminae and foreset cross-strata (top unit 6), foreset cross-strata, parallel inclined laminae, and trough-fill cross-strata (unit 7), foreset cross-strata and trough-fill cross-strata (unit 8), ripple cross-laminae, and wavy laminae (unit 9), trough-fill cross-strata, wavy laminae, and foreset cross strata (unit 10). Unit 11 is abandoned channel fill (mudstone mostly massive). Siltstone lenses within mudstone are ripple cross-laminated and contain abundant carbonized plant leaves and stems. Units 12 and 13 are ripple cross-laminated, massive, and parallel-laminated overbank mudstone, siltstone (z), and sandstone (after McGowen, Granata, and Seni, 1979).

27. Facies developed during low stand, southeastern Garza County, Texas (Macy Ranch, Grassland Southeast 7.5-minute quadrangle). Seven facies depicted in outcrop sketch: delta foresets, mudflat, feeder chanel, crevasse channel, levee, abandoned channel fill, and delta platform. Delta foresets have apparent dips of 9° to 15° and consist of parallel-laminated mudstone, siltstone, very fine sandstone, and granule conglomerate. Lateral to upper parts of some foresets are mudflat deposits consisting of burrowed, ripple cross-laminated, contorted, and desiccated claystone, siltstone, and very fine sandstone. Feeder channels are filled at base (see unit 2) with parallel-laminated, contorted foreset crossbeds and ripple-drift siltstone to granule conglomerate. Most feeder channels are filled with coarse sandstone to cobble intrabasinal conglomerate; sedimentary structures are trough-fill cross-strata 15 to 30 ft wide and 1 to 3 ft thick at base. Crevasse channel characterized by multiple scour-and-fill events; fill

is muddy fine sandstone to granule conglomerate; sedimentary structures are parallel laminae, foreset cross-strata poorly defined trough-fill cross-strata, and ripple cross-laminae. Levee deposits are wedge shaped (thickest at east and pinch out to west); sediment is clayey siltstone to very fine sandstone; sedimentary structures are parallel laminae and ripple cross-laminae. Abandoned channel fill is about 12 ft thick composed of trough-fill cross-stratified fine sandstone to granule conglomerate, with central part filled with ripple cross-laminated clayey coarse siltstone to muddy very fine sandstone, and channel margin of fill composed of alternating ripple cross-laminated siltstone to very fine sandstone and massive to burrowed muddy very fine sandstone. Uppermost unit is delta platform consisting of trough-fill cross-stratified coarse sandstone to granule conglomerate, parallel-laminated very fine to fine sandstone, and massive pebble intrabasinal conglomerate with Unio and sand-filled burrows on bedding surfaces; this unit grades into delta foresets to the west (after McGowen, Granata, and Seni, 1979).

28. Valley-fill and lacustrine deposits, Slaughter Ranch, southwest Garza County, Texas (Middle Creek 7.5-minute quadrangle). Represented in outcrop sketch are valley-fill deposits (units 1 through 19), lacustrine deposits (units 20 through 24), and soil (top unit 24 and unit 25). At least three sedimentary sequences are represented in valley fill: units 1 through 3 (base not exposed), characterized by intrabasinal conglomerate, fine sandstone, and siltstone; conglomerates, mostly lenses of trough-fill and foreset cross-strata; Unio fragments abundant in some conglomerates; fine sandstones contain parallel and

ripple cross-laminae, trough-fill and foreset cross-strata, and soft-sediment deformation; siltstone is parallel laminated and ripple cross-laminated. Units 4 through 16 (sequence bounded by erosional surfaces) consist of mudstone, siltstone, and very fine to fine sandstone with a few lenses of granule conglomerate; primary sedimentary structures are trough-fill cross-strata, low-angle foreset crossbeds, parallel inclined laminae, ripple drift, ripple cross-laminae, and starved ripples; post-depositional features are desiccation cracks and faults with little displacement. Units 17 through 19 (erosional at base, gradational at top into lacustrine deposits) consist of siltstone, very fine to fine sandstone, and granule to pebble intrabasinal conglomerate; sedimentary structures are trough-fill cross-strata, parallel inclined laninae, and ripple cross-laminae. Lacustrine deposits (units 20 through 24) consist of mudstone, siltstone, and very fine sandstone; primary sedimentary structures are parallel laminae and ripple cross-laminae; burrows are common in unit 22 (Teichichnus occurs near top of unit). Postdepositional features in mudstones (units 23 and 24) are slickensides, reduction patches, and pyrite-filled fractures. Top of unit 24 and unit 25 comprise soil (after McGowen, Granata, and Seni, 1979).

29. Isopach map of lower Dockum (modified from Granata, 1981).
30. Sandstone percentage map of lower Dockum (modified from Granata, 1981).
31. Isopach map of upper Dockum (modified from Granata, 1981).
32. Sandstone percentage map of upper Dockum (modified from Granata, 1981).