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SANDSTONE DISTRIBUTION AND LITHOFACIES OF THE TRIASSIC DOCKUM GROUP, PALO DURO BASIN, TEXAS

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ABSTRACT

The Triassic Dockum Group in the Palo Duro Basin consists of many interbedded sequences of coarse- to fine-grained terrigenous clastic sedimentary strata. Four sandstone-dominated progradational sequences appear in the lower Dockum section. Sandstone in the first unit has a relatively uniform distribution across the basin, owing to deposition by broad alluvial fans and fan deltas. Sandstones in the remaining units and the upper Dockum are unevenly distributed owing to deposition by deltaic and fluvial systems. Sediment sources for Triassic strata in the Palo Duro Basin, according to net-sandstone trends, indicate deposition from the west, north, and east for the basal unit, dominantly from the east for units 2 and 3, and mixed western and eastern sources for unit 4 and the upper Dockum. Net-sandstone distribution patterns and lithofacies trends suggest proximal depositional environments in the present eastern and northeastern Dockum and more distal environments to the west and southwest. Paleodip was apparently from east to west over most of the Texas side of the basin, possibly changing in the area of the Texas-New Mexico border. Basement structural elements within the basin were subtly active during deposition and influenced the local accumulation of sandstone.

Nine lithofacies in the Dockum can be recognized from core. Two lacustrine system lithofacies are identified by claystone, mudstone, and siltstone lithologies. In places these intervals are thick and commonly contain features indicative of subaerial exposure and weathering. Four lithofacies may have been deposited in deltaic environments. Thick siltstone sequences and interbedded siltstone and sandstone sequences represent distal and proximal delta-front deposits, whereas mudstone was deposited on deltaic mudflats. Interbedded, organic-rich siltstone and sandstone accumulated in swamps on abandoned delta platforms. Two fluvial lithofacies,

including delta-distributary-channel fill deposits, are represented by relatively thick sandstone and conglomerate. Fluvial lithofacies include bed-load and mixed-load systems. An eolian-flat lithofacies may have formed on distal alluvial-fan sediments.

INTRODUCTION

The Upper Triassic Dockum Group is present over a wide area, extending from West Texas to south-central Colorado. In the Palo Duro Basin of the Texas Panhandle, Dockum Group strata occur over approximately 12,000 mi^2 in a 15-county area. The basin is geologically bordered by the Amarillo Uplift to the north, the Matador Arch to the south, and broad structural saddles to the east and west. The study area covers the defined basin to the north and south and extends to the Caprock Escarpment to the east and the Texas-New Mexico border to the west. Thickness of Dockum strata ranges from less than 100 ft in the north to greater than 1,800 ft in the southwest. Dominant lithologies consist of mudstone, siltstone, sandstone with minor conglomerate, and claystone deposited in fluvial, deltaic, and lacustrine depositional environments.

The Palo Duro Basin is being evaluated as a potential host for a high-level nuclear waste repository in bedded salts in the Permian San Andres Formation. Because of the Dockum's stratigraphic position superjacent to the Permian strata, which include the potential host salt beds, knowledge of the Dockum sediments and their water-bearing character is important. Water from the Triassic sediments represents a potential threat to the integrity of a salt-hosted repository if a conduit for water movement to the repository horizon exists or is later created. Additionally, the Dockum contains the locally productive Santa Rosa aquifer. As the overlying Ogallala aquifer becomes depleted, the Santa Rosa aquifer will likely be more extensively exploited for domestic and agricultural water supplies. Engineering designs of repository shafts and sealing methods for boreholes will also be influenced by the composition and induration of the sediments as well as by their water-bearing properties.

The objectives of this study are to (1) describe and interpret the lithologies, (2) determine the distribution of major lithofacies within the basin, and (3) detect changes in the sandstone trends and thicknesses, which may indicate changes of or in the source areas, sediment transport direction, and syndepositional tectonic activity in the basin.

METHODS

Data were gathered from outcrops, geophysical well logs, Department of Energy - Stone and Webster Engineering Corporation (DOE-SWEC) and Department of Energy - Gruy Federal (DOE-GF) core, and work by previous authors. All gamma-ray well logs penetrating the Dockum section were used, except those from Lamb and Potter Counties, where well density was too great for the base map scale. A total of 350 wells were utilized in this study. Data gathered from well logs were used to construct structure, isopach, lithologic cross sections, and net- and percent-sandstone maps of selected intervals. Structural and lithologic cross sections were used in construction of lithofacies cross sections and maps to help determine paleogeography. The usefulness of many wells was diminished because surface casing extending through the Dockum caused attenuation of gamma rays and a corresponding decrease in character and sensitivity of log response. Nevertheless, these wells were useful for picking formation contacts.

Outcrops were measured, described, and interpreted along the Eastern Escarpment, in the Canadian River Valley, and along the Western Escarpment in eastern New Mexico. Interpretations were used for local facies and depositional systems analysis. These interpretations were projected into the subsurface to the nearest well log or facies cross section and incorporated into the subsurface analysis of the Dockum. Outcrops previously described and interpreted by Granata (1981) in eastern New Mexico, by Boone (1980) in Tule Canyon, and by Seni (1978) in Palo Duro Canyon were used to augment outcrop data.

Four DOE wells recovered cores from the Dockum (fig. 1). Cores were described and interpreted to provide subsurface lithologic and facies control points. Gamma-ray logs were compared to the core logs to help make accurate interpretations of gamma-ray responses to lithologies. Thin section analyses, clay mineralogy studies, and scanning electron microscopy studies were made of selected core samples.

REGIONAL SETTING

The Dockum Group is present over a 96,000 mi^2 area of western and northwestern Texas, eastern and northern New Mexico, western Oklahoma, southeastern Kansas, and southeastern Colorado. Sediments are preserved in several basins including the Midland, Palo Duro, Dalhart, Tucumcari, Raton, and Denver Basins. Thickest preserved sediments, more than 2,000 ft thick, are in the Midland Basin (McKee and others, 1959; Granata, 1981).

Regional subsurface work by McGowen and others (1979) and Granata (1981) shows that the base of the Dockum strata has a closed-basin geometry in which sediments are largely confined to the relict Permian structural basin. Deepest and thickest sediments lie in the Midland Basin, suggesting that the Dockum depositional basin was roughly equivalent to the ancient Permian Basin. During Triassic time, the Palo Duro Basin was a shallow northern extension of the deeper Midland Basin. It was separated from the Midland Basin by the Matador Arch and bordered on the east by the Eastern Shelf and Hardeman Basin, on the north by the Amarillo Uplift and Bravo Dome, and on the west by a shallow shelf and Tucumcari Basin. Percent-

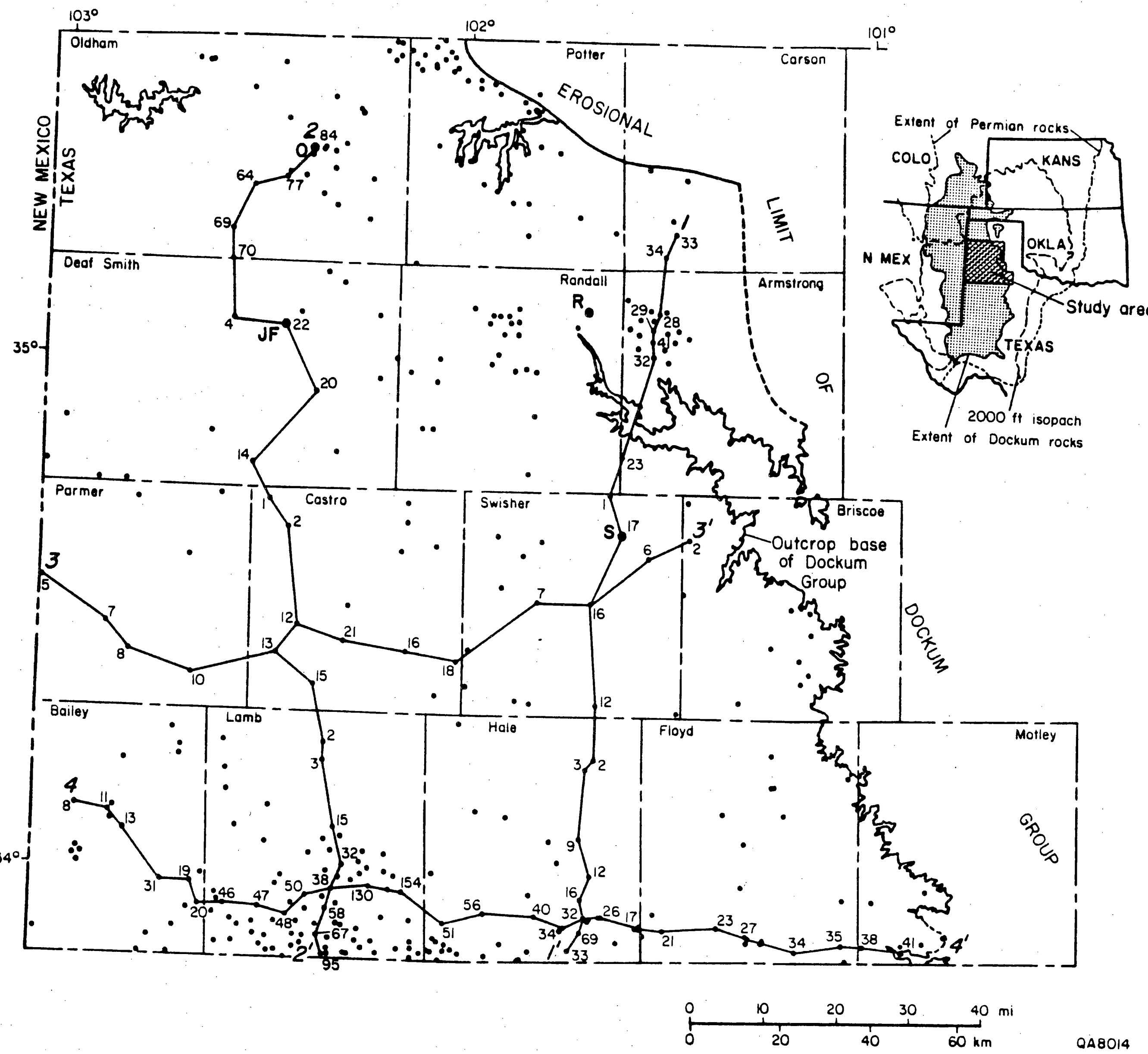

Figure 1. Location of study area in the Texas Panhandle showing the eastern erosional boundary of Dockum Group strata and cross sections used in this report. Circles mark locations of Department of Energy - Stone and Webster and Department of Energy - Gruy Federal wells that cored the Dockum: Rex White No. 1 (R), Grabbe No. 1 (S), J. Friemel No. 1 (JF), and Mansfield No. 1 (O). The extent of Dockum Group rocks in relation to Permian rocks is shown in the inset map (modified from McKee and others [1959] and McKee and others [1967]).

sandstone maps by Granata (1981) show widespread areas of low sandstone percent (high mudstone percent) just south of the Matador Arch in the Midland Basin, suggesting that, compared to the Palo Duro Basin, these areas were more removed from source areas. McGowen and others (1979) proposed that Dockum sedimentation was associated with and initiated by uplift, doming, and rifting due to the opening of the Gulf of Mexico. These events reactivated source areas in the Ouachita Tectonic Belt and in the Ancestral Rockies, including parts of the Wichita-Amarillo Uplift trend; initiated subsidence of the Dockum depositional basin; and caused a change from the arid Permian climate to more humid conditions. The uplifting effectively closed the Permian seaway, resulting in a closed, fresh-water, continental basin during Dockum deposition. Although structures along the Matador Arch and within the basin did not greatly affect sedimentation (McGowen and others, 1979), local structural influences on percent- and net-sandstone patterns, lithologic distribution, and thicknesses of sediment are apparent.

Studies by numerous workers agree that Dockum sediments accumulated in an intracratonic continental setting. The most recent published information by McGowen and others (1979, 1983) and unpublished Master's theses by Seni (1978), Boone (1979), and Granata (1981) describe the Dockum as consisting of fine- to coarse-grained clastic sediments deposited in fluvial, deltaic, and lacustrine environments. Outcrop data on delta-foreset beds in Palo Duro and Tule Canyons indicate relatively shallow water depths, ranging from 3 to 30 ft in the lower part of the section to 30 to 60 ft higher in the section (Seni, 1978; Boone, 1979). In such a shallow basin even small fluctuations in lake level would affect large areas, producing rapid changes in depositional style and abrupt associations of usually unrelated lithofacies. Such associations have been noted previously in outcrop by McGowen and others (1979) and in core by this author.

Throughout most of the Palo Duro Basin, the Dockum Group is erosionally overlain by the Neogene Ogallala Formation (fig. 2). Erosion prior to and contemporaneous with Ogallala deposition locally cut valleys as much as 150 ft deep into Dockum strata. Erosion probably removed units of Cretaceous and Jurassic age in the northern part of the basin, leaving only a thin Cretaceous cover in the southern basin area. Inliers of Lower Cretaceous Edwards Limestone crop out in central Floyd County (Barnes, 1968), probably representing the Cretaceous units in the subsurface that were recognized on geophysical well logs. The contact between the Edwards and the Dockum is unconformable.

The Upper Permian Dewey Lake Formation underlies the Dockum throughout most of the study area; locally the Dockum may rest on the Permian Alibates Formation (fig. 2). McGowen and others (1979, 1983) and Granata (1981) thought that both conformable and unconformable contacts are present between the Dockum and Dewey Lake in the subsurface, gradational contacts being more common toward the center of the Dockum basin. In Palo Duro Canyon State Park, the contact between the Permian and Triassic units is unconformable and locally angular. In Tule Canyon, Boone (1979) reported a gradational contact between the Permian Quartermaster Formation, which includes the outcrop equivalent of the Dewey Lake, and the Dockum. However, a basinwide unconformity has been suggested on the basis of the absence of Lower and Middle Triassic fossils within the Dockum sediments (Reeside, 1957).

Formation nomenclature in the Dockum Group originated from outcrop work in a number of localities and can be extended with confidence only a short distance into the subsurface. Outcrop formation names vary from area to area. Granata (1981) and Fink (1963) showed the stratigraphic relationships of the various component formations of the Dockum. Because of this conflicting nomenclature, formal formation names will be avoided in this report in favor of grouping by genetic association.

SYSTEM	FORMATION		GENERAL LITHOLOGY AND DEPOSITIONAL SETTING
QUATERNARY	Tahoka Double Lakes Blackwater Draw Tule Blanco		Fluvial, lacustrine, and eolian clastics
TERTIARY	Ogallala		Fluvial, lacustrine, and eolian clastics
CRETACEOUS	Undifferentiated		Marine limestone and clastics
TRIASSIC	Dockum Group	Chinle Trujillo Tecovas	Fluvial, deltaic, and lacustrine clastics
PERMIAN	Dewey Lake		Marine halite, anhydrite, dolomite, limestone, and clastics
	Alibates		
	Salado / Tansill		

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Figure 2. Stratigraphic column of the Upper Permian to Recent in the Palo Duro Basin (after Handford and Dutton [1980] and Barnes [1967, 1977, 1983]).

GENERAL SUBSURFACE SETTING

Subsurface studies of Dockum Group strata incorporate data from gamma-ray geophysical logs and four DOE cores. These data were used to determine upper and lower formation boundaries and informal unit subdivisions and to make lithologic interpretations. Core was compared to gamma-ray logs to enhance accurate interpretation of log responses and to provide a guide for noncored wells. Methods for placement of the sandstone-siltstone lines follow those used by Granata (1981).

The lower contact of the Triassic is not easily identified in the subsurface. In the Midland Basin, an abrupt increase in gamma-ray activity in the strata above the Rustler Formation (the Alibates equivalent) is generally thought to be the contact between the Upper Permian Dewey Lake and the Triassic Dockum (Herald, 1957). Granata (1981) also used this gamma-ray increase horizon, interpreting it as being due to an increase in mud content corresponding to the initiation of Triassic lacustrine deposition. Two new lines of evidence indicate that these interpretations incorporate portions of the Dewey Lake Formation into the basal Dockum.

Recently acquired core from the Permian-Triassic contact interval exposes a problem with previous interpretations of the gamma-ray log responses. In the Rex White No. 1 well (fig. 1) the basal Dockum contact is placed at the base of a prominent erosional surface separating an orangish-red, moderately clean siltstone below from a muddy, poorly lithified, medium-to-coarse sandstone. This contact is about 60 ft above a sharp rise in gamma-ray activity in the post-Alibates strata that marked the contact according to previous studies. In core, the point at which the increase in gamma-ray activity begins corresponds to the point at which gypsum-filled veins and fractures end. No other significant lithologic variations are noted, and no evidence of scour or erosion is present. Because gypsum is a low emitter of gamma rays, the high concentration of gypsum (between 10 and 40 percent) in the lower sediments significantly reduces the number of gamma rays that would normally be emitted, in effect attenuating the normal emission and causing a lower than normal response to be recorded. Absence of gypsum allows the normal gamma-ray response of the sediment to be recorded. As additional evidence in support of this hypothesis, gamma-ray logs for Stone and Webster Engineering Corporation (SWEC) wells Mansfield No. 1 and J. Friemel No. 1 (fig. 1) show no gamma-ray increases in post-Alibates strata, and the corresponding cores show no gypsum-filled veins. As a result of these findings, the base of the Triassic on gamma-ray logs is defined as the base of the first major sandstone bed above the Permian Alibates Formation, unless core data suggest otherwise.

Two ash beds in the Quartermaster Formation (which contains the outcrop equivalent of the Dewey Lake Formation) have recently been mapped in Palo Duro Canyon and Caprock Canyons State Parks. These beds were correlated with core in the Rex White No. 1 and Grabbe No. 1 wells by Fracasso and Kolker (1985). In both cores, the upper ash bed is at least 20 ft below the base of the Dockum, as defined in this report, and within the Permian Dewey Lake high gamma-ray zone previously interpreted as Triassic. The ash beds thus provide a lowest horizon for the basal Triassic boundary in core. The lower bed has been dated by K/Ar methods on separated biotite to be from 251 ± 4 to 261 ± 9 m.y. old. This is much older than the 230 m.y. age for the Permian-Triassic boundary as defined by van Eysinga (1978) and slightly older than the 245 m.y. age placed on the boundary by Palmer (1983). A Late Permian age for this interval is thus indicated. The upper bed was not dated because of insufficient sample. The age of the ash beds and their correlation into the subsurface preclude the possibility of an Early or Middle Triassic age for the "high-gamma" interval of the Dewey Lake Formation.

In the Palo Duro Basin, structural elevation on the base of the Dockum shows a gradual south-to-southwest dip of less than 1^{o} (fig. 3). Dips reverse to the north in Oldham, Potter, and Carson Counties because of structure modification along the trend of the Amarillo Uplift, possibly accentuated by salt dissolution. Throughout the central basin area, the basal structure appears fairly regular and uniform; however, this is most likely a function of sparse well control. To the north and south in the more structurally active areas, contours show structural highs and lows (fig. 3) and corresponding section thins and thicks (fig. 4). The total isopach (fig. 4) reflects the overall basin geometry by thickening to the southwest. Discussion of structural influences on deposition follows in the "Structure and Tectonics" section of this report.

The subsurface Dockum is divided into two informal units, the upper and lower Dockum. The boundary is based on regional correlations by Granata (1981) and is placed at the base of a regional progradational episode defined by an increase in sandstone content at about the middle of the Dockum section in the Midland Basin.

The upper Dockum is present only in the central and western portions of the Palo Duro Basin (fig. 5). Post-Triassic erosion has removed an unknown thickness of this interval and truncated it to the east. The upper Dockum does not crop out along the Eastern Escarpment, although its equivalent, the Chinle Formation, is exposed over wide areas of eastern New Mexico. An isopach map of the upper Dockum reflects pre-Ogallala erosion showing isopach thins extending westward from the eastern erosional limit. These correlate with entrenched valley systems mapped by Seni (1980). An east-to-west-trending isopach thin in Parmer County lies along the trend of the pre-Ogallala valley systems. The thick in Bailey County (fig. 5) is an

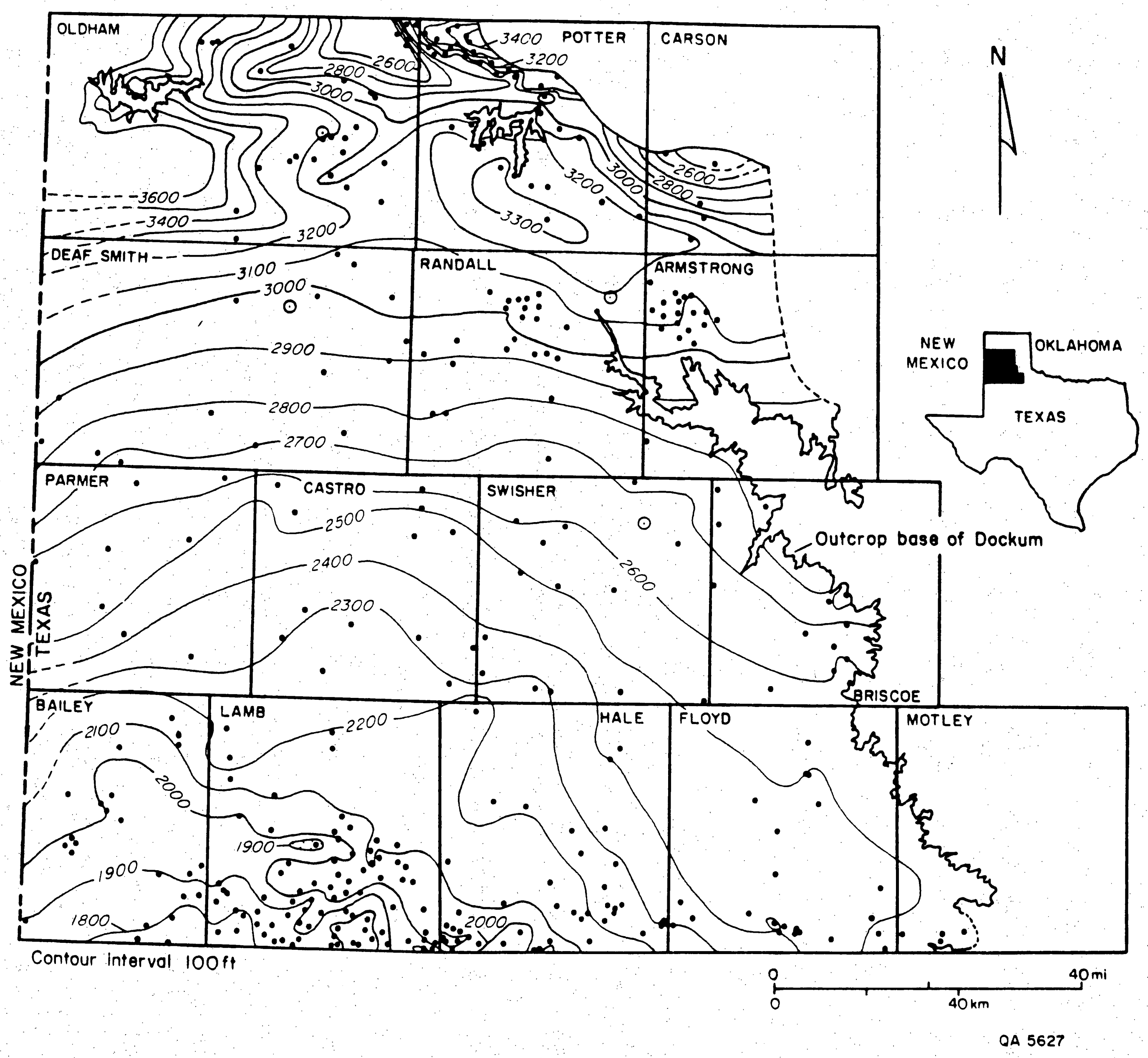

Figure 3. Elevation on the base of the Triassic. Dips are generally less than 1° but are greater in areas of structural complexity.

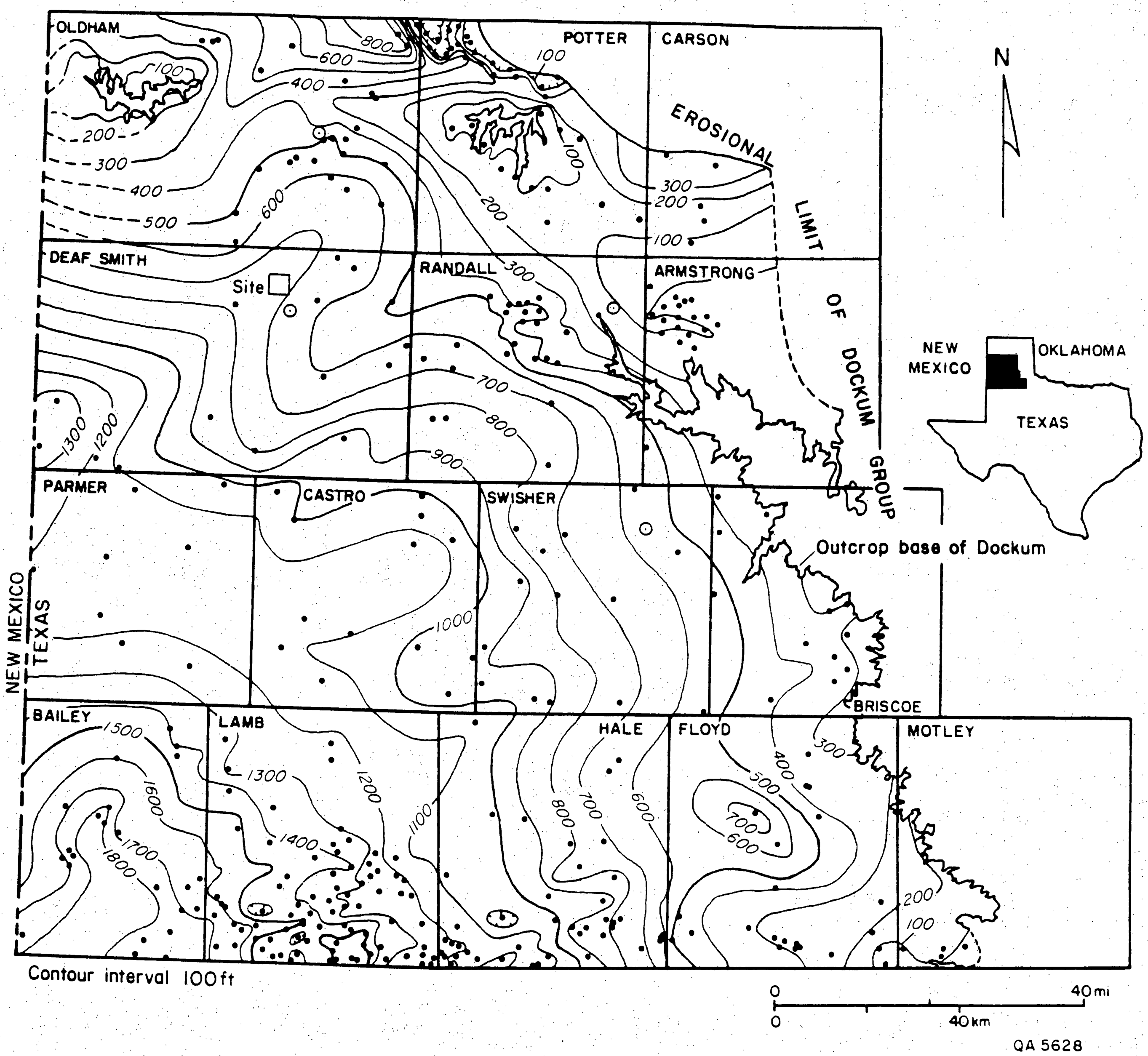

Figure 4. Isopach map of the Dockum Group. The unit thickens to the southwest. Isolated thick areas in Carson, Potter, and Oldham Counties are in fault-bounded structural lows. The faults are not shown. Note the correspondence between base of Dockum structural lows and highs (fig. 3) and isopach thicks and thins.

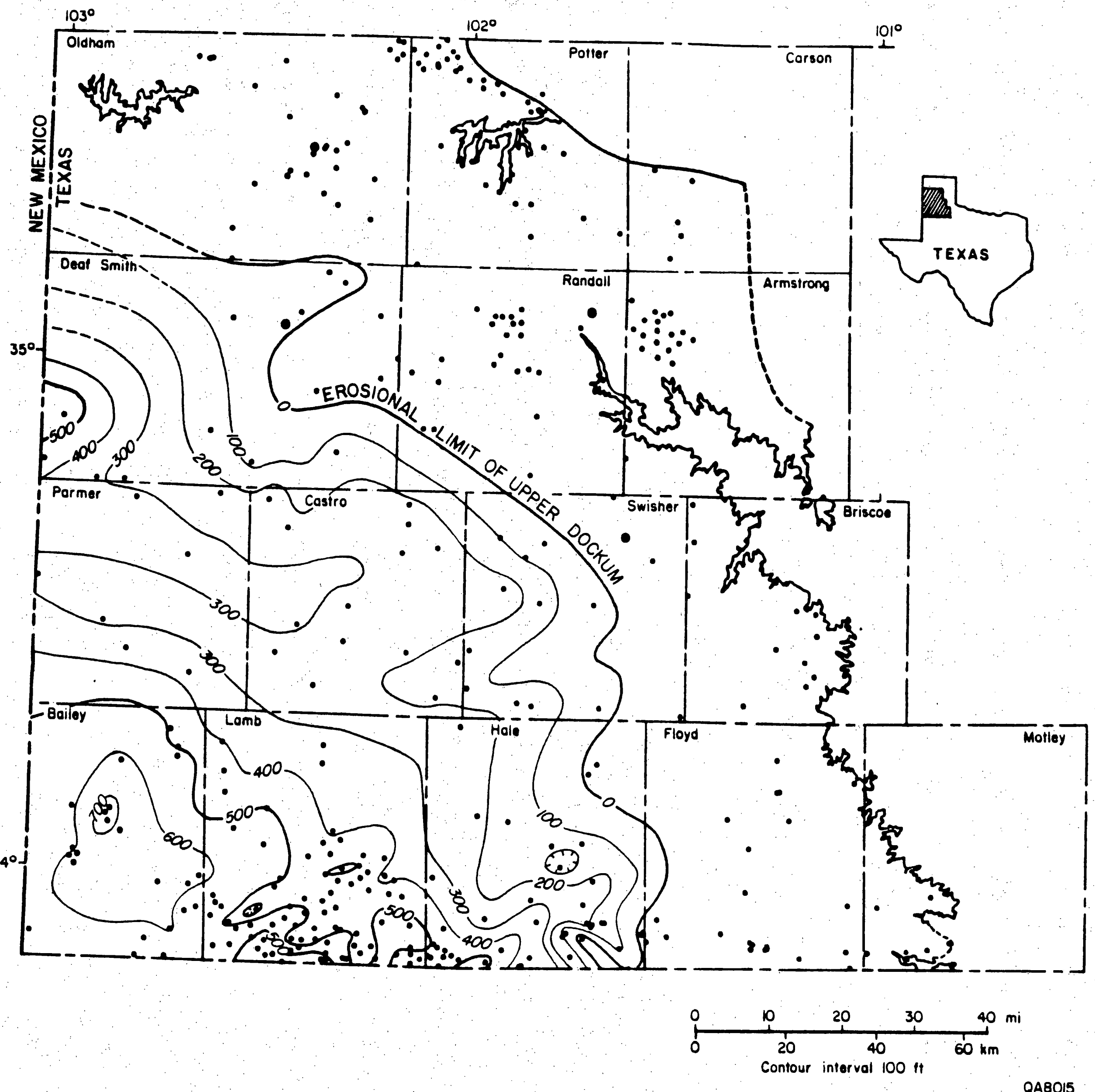

Figure 5. Isopach map of the upper Dockum Group. Thicknesses reflect post-Triassic erosion preceding deposition of Cretaceous and Tertiary units. Note that this informal unit does not crop out in the basin. Its approximate equivalent, the Chinle Formation, crops out over a large area in New Mexico.

erosional remnant left by pre-Ogallala streams to the north and south. A similar thick in Hale County is capped by Cretaceous rocks that protected the underlying rocks from erosion.

The lower Dockum comprises most of the Dockum strata in the Palo Duro Basin. Thickness is greatest, more than 1,200 ft, in Bailey County (fig. 6), and generally decreases to the north and east. Differences in thickness are common. Controls for this variability can be structural, erosional, or both. For example, an isopach thin oriented west-east in Deaf Smith County is the result of channeling by Ogallala stream systems, whereas isopach thicks in Carson and Oldham Counties are in structural lows (fig. 6). In Floyd County an unusual case combines the two. One well contains Cretaceous sediments overlying the Dockum deposits, thus protecting them from post-Cretaceous erosion. However, Dockum thickness is greatest in a well just to the northwest where there is no Cretaceous cover. The isopach thick corresponds to a structural depression on the base of the Triassic as well as in the basement and combines with the protective cover to preserve an anomalously thick Dockum section. The upper Dockum appears to have been eroded prior to deposition of the Cretaceous units, presumably during the Jurassic and Cretaceous (Hobday and others, 1981).

Updated percent-sandstone maps of the upper and lower Dockum were constructed to determine the regional distribution of sandstone and structural influences on their deposition and to detect changes in the trend of depositional systems, and in depositional axes. The great thickness of each percent-sandstone interval (>1,200 ft for the lower and >600 ft for upper Dockum) and the relatively thin (<100 ft) record of individual depositional systems in core and outcrop mean that each map records many separate depositional systems and several depositional cycles. Therefore, the maps do not show a record of individual systems but do show major axes of deposition of superimposed systems.

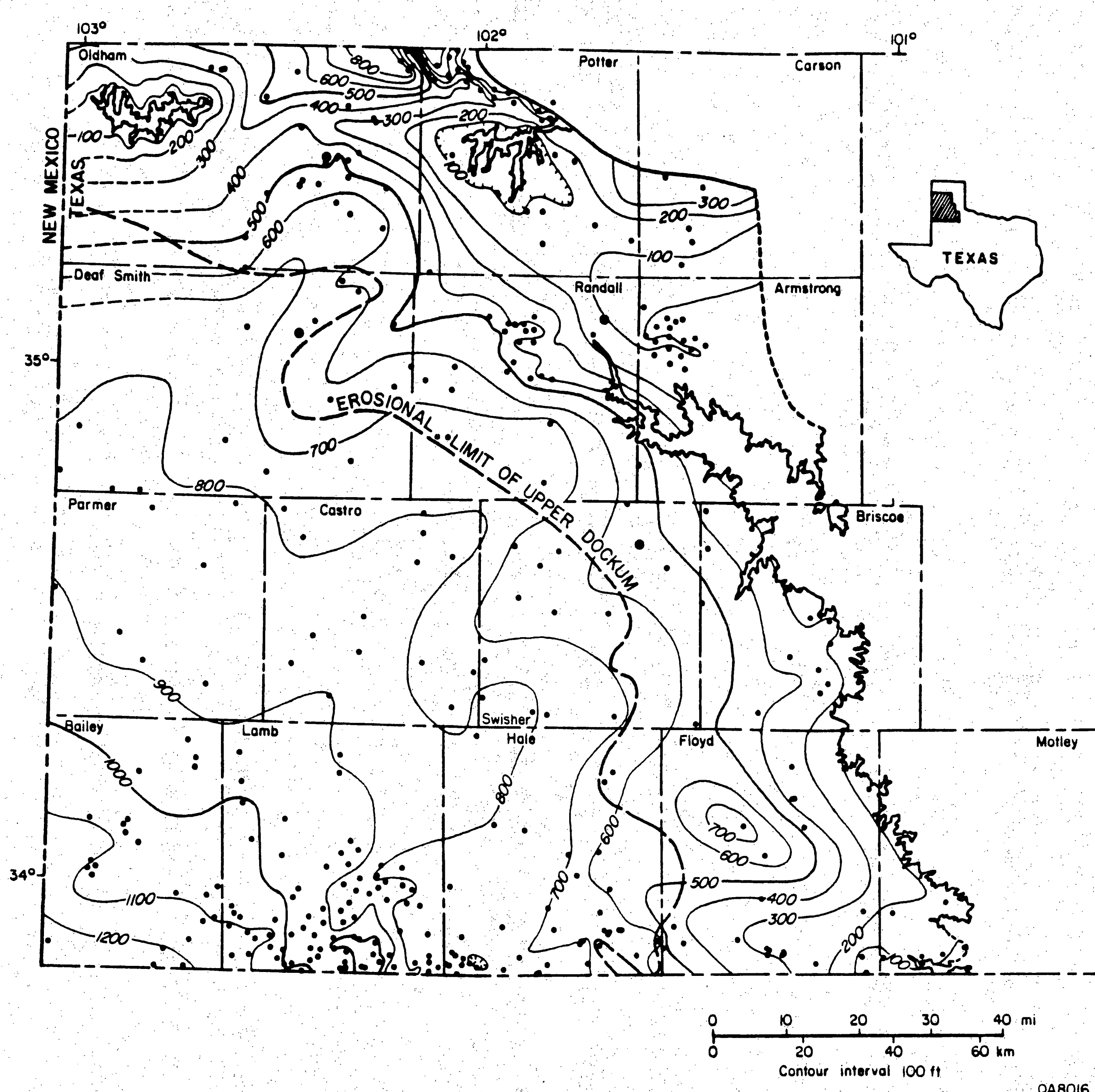

Figure 6. Isopach map of the lower Dockum Group. Thickness generally correlates to elevation on the base of Dockum (fig. 3), thinning on structure highs and thickening in lows. Changes in thickness north and east of the limit of the upper Dockum subcrop are due to post-depositional erosion.

The lower Dockum percent-sandstone map (fig 7) defines several areas of high sandstone concentration. These clearly indicate a predominantly eastern sediment source for the basin and suggest an east-west or northeast-southwest depositional dip direction. A major east-west trend extends from Deaf Smith through Randall and Armstrong Counties. This trend coincides with outcrops in Palo Duro Canyon where Seni (1978) documented an east-to-west transport direction. The patterns also suggest divergence to more southerly transport directions possibly owing to either local basin infilling or regional shifting over time. Percent sandstone generally decreases down structure and paleodip and away from source areas. Percent-sandstone patterns are complex along the northern flank of the Matador Arch, particularly in Lamb County, and they reflect the structure at the base of the Dockum.

Percent-sandstone patterns in the upper Dockum (fig. 8) are similar to those of the lower Dockum in several areas. Two depositional axes occupy almost identical positions in both the upper and the lower Dockum. Complexity of patterns in Lamb County suggests that active structural elements related to the Matador Arch affected deposition. The trends of the depositional axes are generally similar to those of the lower Dockum, although northeast-to-southwest sandstone trends are more pronounced, indicating a continuing dominant eastern sediment source for the upper Dockum. However, broad areas of 10 to 20 percent sandstone in the western part of the basin (fig. 8) may indicate fringes of western depositional systems. Similar upward change of percent-sandstone trends, indicating a shift from eastern to western sources, was noted by Granata (1981) and McGowen and others (1979, 1983). Owing to paucity of data, the source of the sandstones in Deaf Smith County is questionable, although a western source is possible.

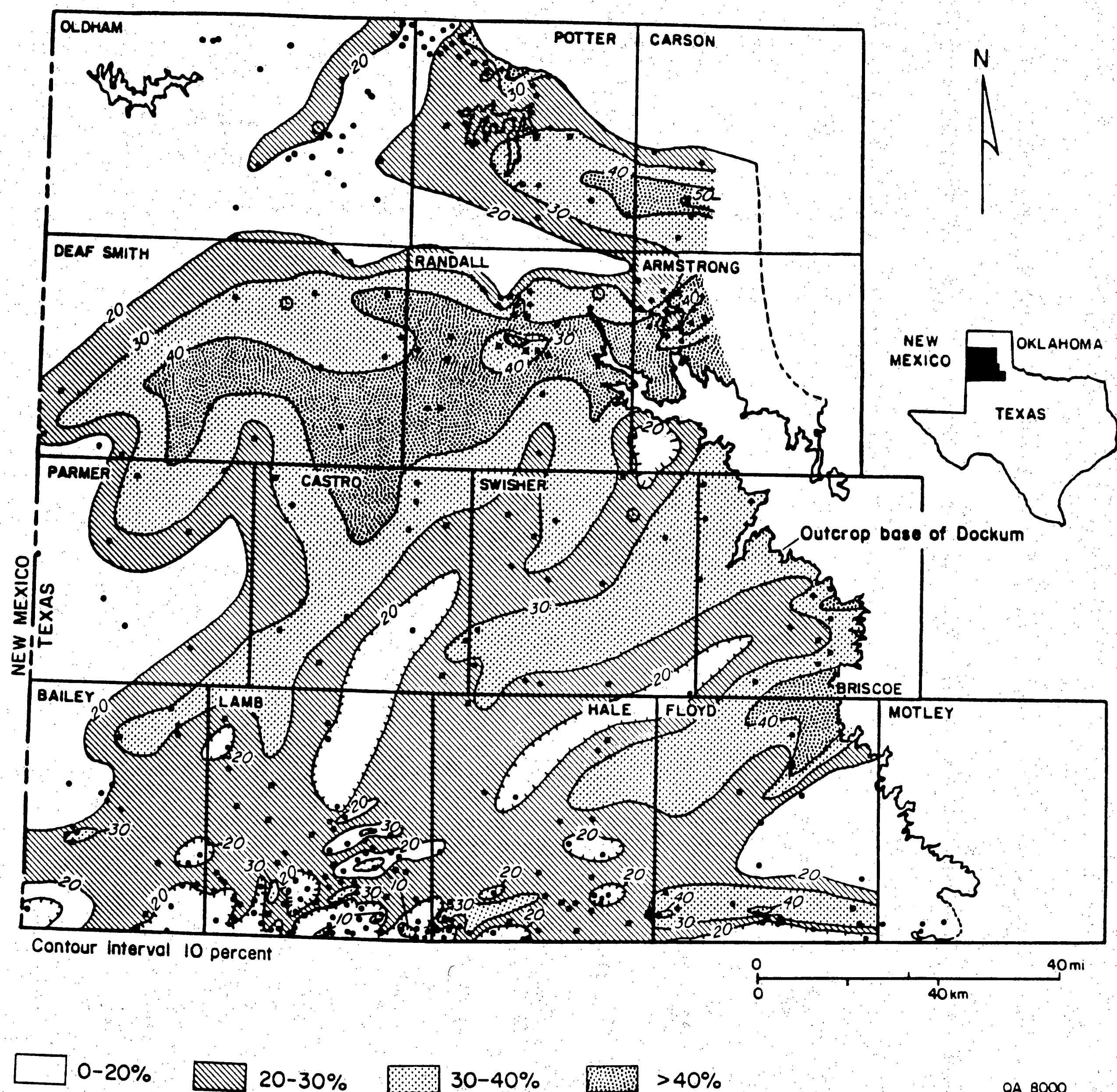

Figure 7. Percent-sandstone map of the lower Dockum Group shows the cumulative result of several progradational events and so highlights only major depositional axes. Primary sediment source direction is from the east with lesser input from the west. Note the general correlation between base of Dockum structure highs and lows (fig. 3) and percent-sandstone thicks and thins.

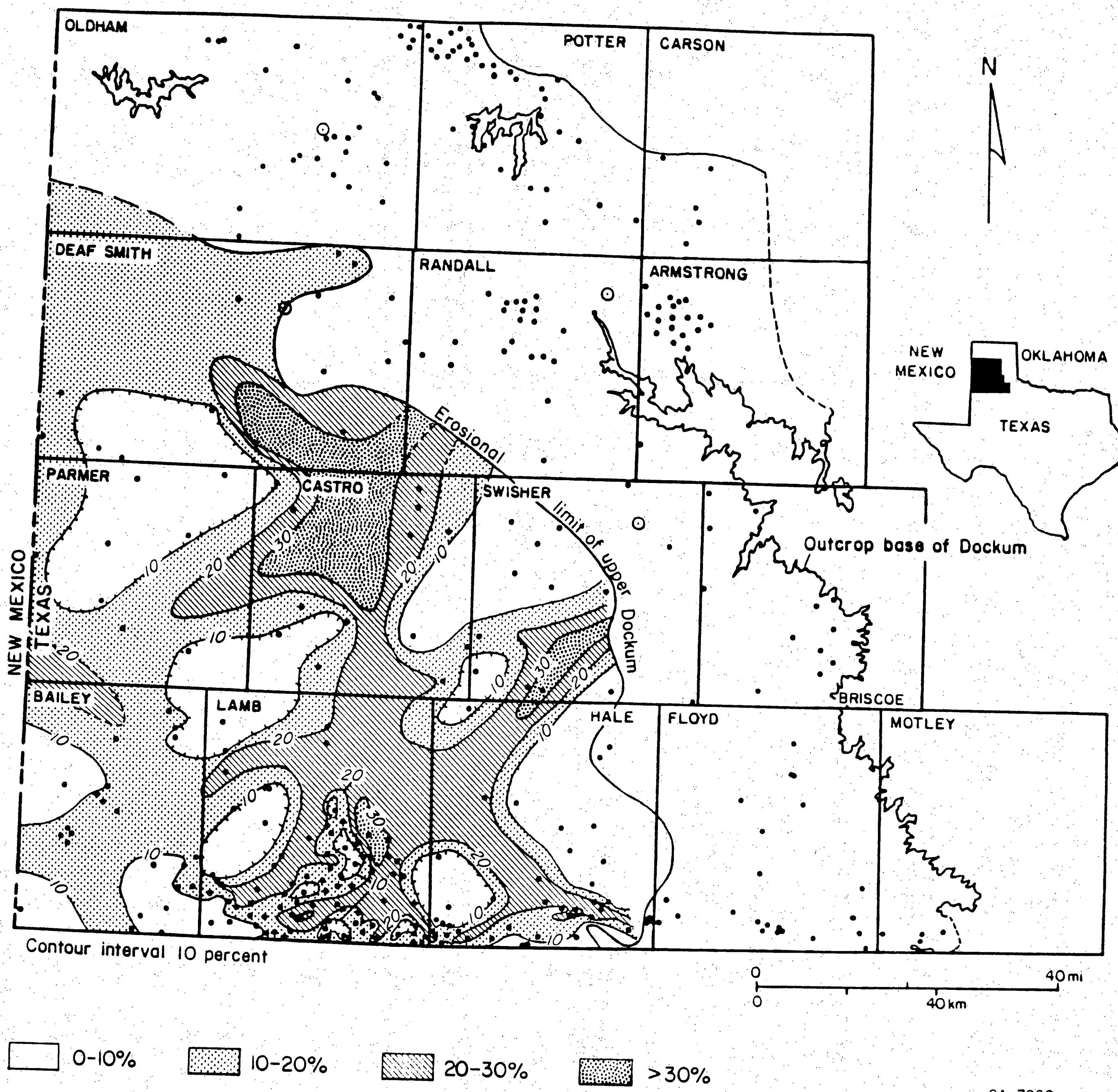

Figure 8. Percent-sandstone map of the upper Dockum Group. Trends combine several progradational events and are generally consistent with those present in the lower Dockum except for a greater proportion of sediment input from western source areas, as indicated by bands of >10% sandstone that project eastward into the basin.

GENETIC DEPOSITIONAL UNITS

Dockum Group strata are composed of interbedded coarse and fine-grained terrigenous clastic rocks resulting from regional and local depositional episodes. Patterns in these depositional events can be recognized in the basin on cross sections compiled from lithologic logs. Lithologic cross sections show several genetic cycles in the Palo Duro Basin. Cycles consist of progradational fine- to coarse-grained clastic sediment separated by silt- and mud-size sediment deposited during lacustrine transgressions. Progradational cycles can be made up of several subcycles of separate progradational events within the overall progradational episode. Therefore, net-sandstone maps do not show a record of an individual depositional cycle but do show the major axes of several superimposed depositional systems. Data collected on these cycles are used to show the areas of thickest sandstone accumulation, spatial orientation of sandstone trends, and temporal changes in the orientation of these trends. Outcrop and core genetic interpretations are heavily relied upon to support interpretations made from geophysical logs.

Methods

Sandstone depositional units were identified using compressed cross sections (abbreviated horizontal distance between wells) composed of lithologic logs interpreted from gamma-ray logs (figs. 9 through 12). A lithologic log highlights only sandstone and mudstone (includes siltstone, mudstone, and claystone on lithologic logs only) lithologies. The Permian Alibates Formation, a regional marker bed, served as the datum for all the cross sections. Reducing the horizontal scale of the cross sections resulted in extreme vertical exaggerations (ranging from 600x to 2300x) and exaggerated the degree of continuity of the sandstone units. Sandstone units are composed of laterally continuous sandstone-rich strata, separated vertically by relatively

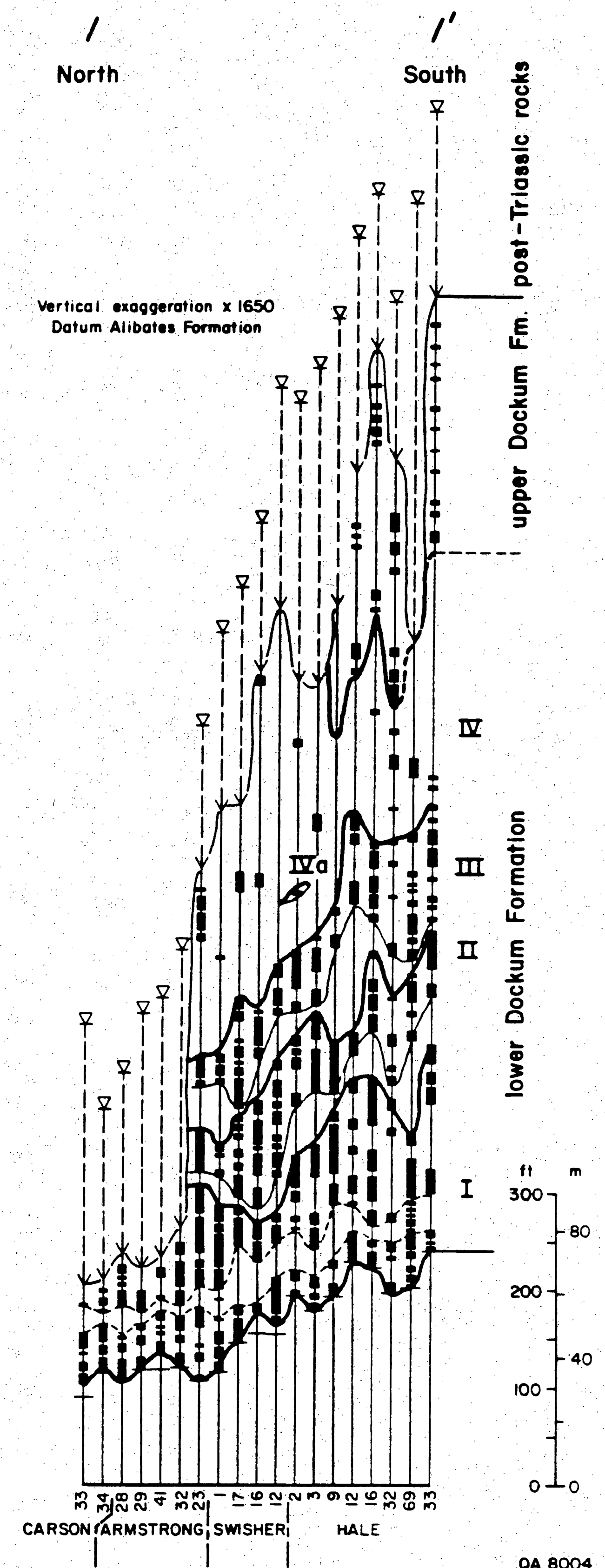

Figure 9. Lithologic cross section 1-1' showing division of lower Dockum sandstones into discrete depositional units. Unit numbers are shown on the side. Sandstone, as interpreted from gamma-ray logs, is indicated by black bars. Note the laterally traceable mudstone interbed in unit 1, highlighted by dashed lines. See figure 1 for line of section.

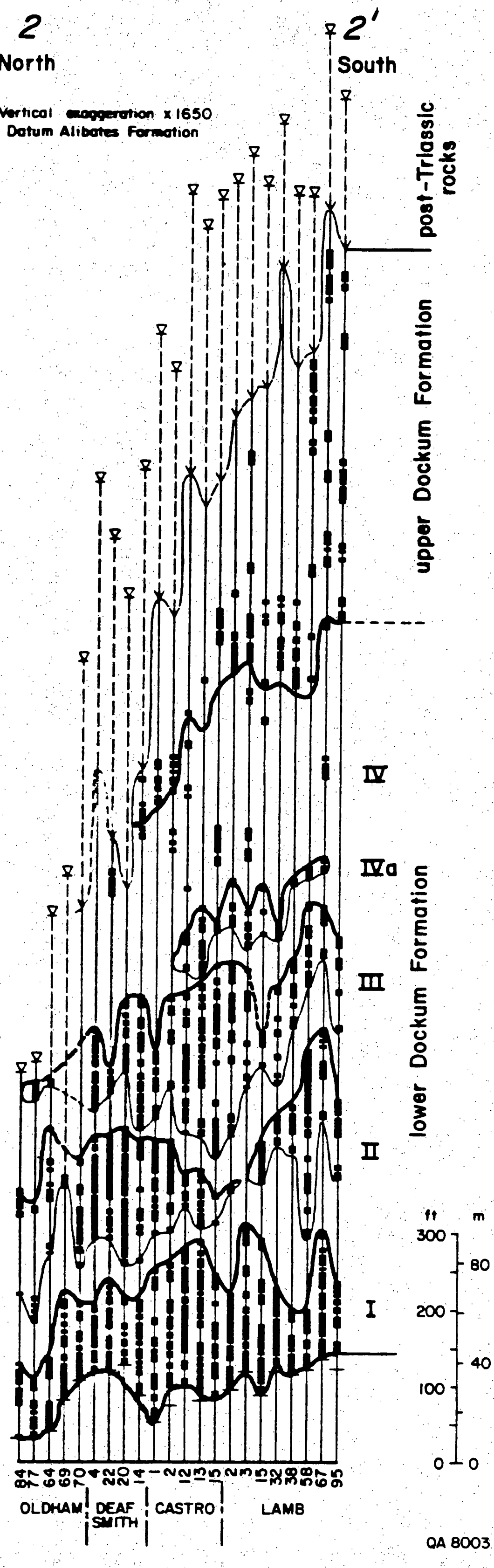

Figure 10. Lithologic cross section 2-2' showing division of lower Dockum sandstones into discrete depositional units. Unit numbers are shown on the side. Sandstone, as interpreted from gamma-ray logs, is indicated by black bars. Note the increase in proportion of mudstone upward in the section. See figure 1 for line of section.

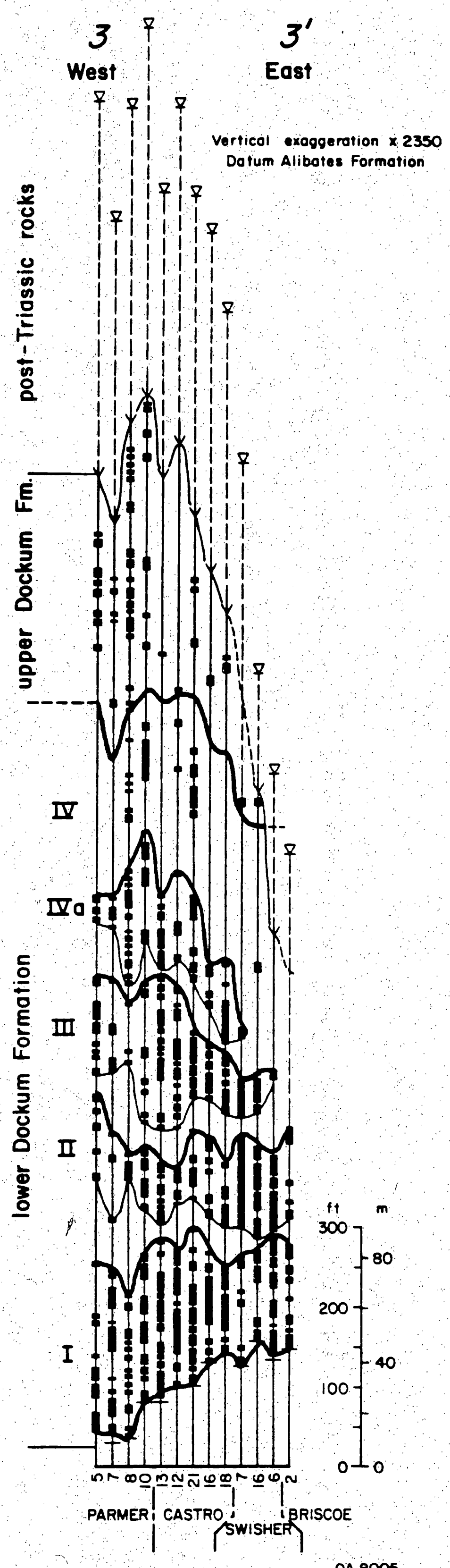

Figure 11. Lithologic cross section 3-3' showing division of lower Dockum sandstones into discrete depositional units. Unit numbers are shown on the side. Sandstone, as interpreted from gamma-ray logs, is indicated by black bars. Note the increase in thickness of mudstone between units 1, 2, and 3 toward the west (down paleodip) and that unit 4a sandstones pinch out toward the east, suggesting a possible western sediment source. See figure 1 for line of section.

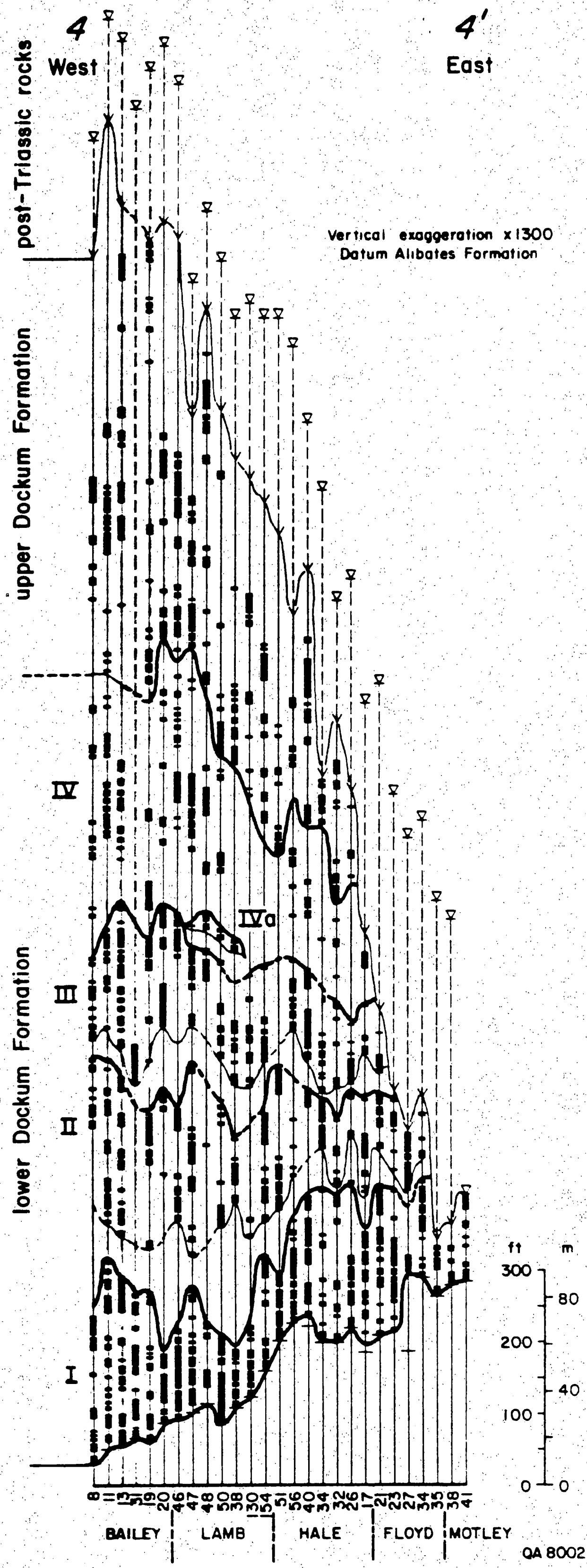

Figure 12. Lithologic cross section 4-4' showing division of lower Dockum sandstones into discrete depositional units. Unit numbers are shown on the side. Sandstone, as interpreted from gamma-ray logs, is indicated by black bars. Note the westward thickness increase in mudstone between units 1 and 2 and truncation of the Dockum section eastward. The greater abundance of sandstone in unit 4 and the upper Dockum compared to section 3-3' suggests that the center of deposition was shifting south through time. See figure 1 for line of section.

thick, widespread, sandstone-poor strata. Unit boundaries are defined as the top of the uppermost sandstone in the unit and the base of the lowermost sandstone in the unit. In areas where the mudstone was thin or absent, owing to either erosion or nondeposition, boundaries were identified by correlating the character of sandstones on gamma-ray logs. In areas where no sandstone is present, the interval is considered to be absent and a value of zero is plotted on the map. Four sandstone units are recognized in the lower Dockum. A fifth unit, unit 4a, has been identified but it is probably a subunit of unit 4, representing a single depositional event within the fourth unit.

Sandstone Unit 1

Unit 1 is at the base of the Dockum Group (fig. 10). Sandstones in this unit are present all across the basin. Individual sandstone beds are usually thicker and contain less mudstone interbeds in paleo-updip areas such as Deaf Smith County, whereas over most of the basin, the unit is thinner and contains less sandstone in thinner beds with more abundant mudstone interbeds.

The aerial distribution of sandstone in unit 1 shows relatively thick net sandstone (>80 ft) covering broad areas (fig. 13). Several primary centers of deposition are present where total sandstone thickness exceeds 100 ft. Sediment transport was from the east, north, and west. In outcrop, the unit 1 sediments are composed of alluvial-fan and fan-delta deposits (Seni, 1978; Boone, 1979; McGowen and others, 1979, 1983; Granata, 1981). Net-sandstone patterns of such systems should show broad areas of moderately thick sandstone with some tongues of thicker sandstone representing entrenched feeder systems. The net-sandstone patterns in figure 13 are consistent with these interpretations. A correlatable mudstone break in the north and east parts of the basin within unit 1 (fig. 9) may mark a shift from alluvial fan to

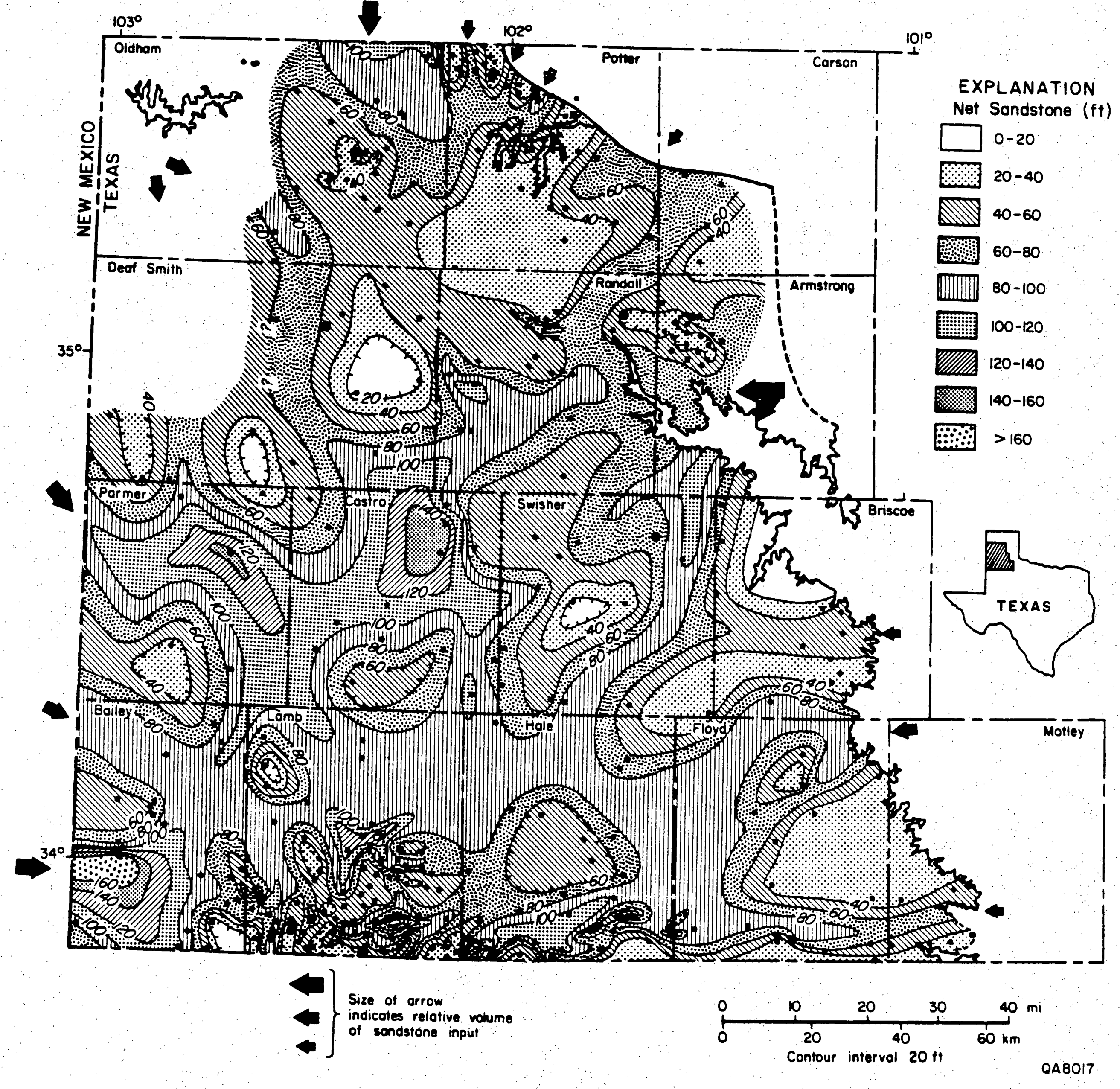

Figure 13. Net-sandstone map of lower Dockum depositional unit 1. Patterns show that sediment sources were in the west, north, and east. Note the relatively broad areas covered by thick sandstone, suggesting alluvial fan and fan-delta environments.

lacustrine deposition. Fan deltas prograded into the local lake. Floodplain deposits are the most common mudstone interbeds; limited lacustrine deposits suggest the presence of small, local lakes.

Sandstones of the basal unit are interpreted to be alluvial-fan and fan-delta deposits (table 1). Sedimentary structures, grain-size trends, bed thickness, and contact relationships are consistent with those observed in outcrop (table 1) (Seni, 1978; Boone, 1979). Fan-delta sandstones are distinguished from alluvial fans by their grain sizes, which are upward-coarsening from mudstone to siltstone to sandstone, and by sedimentary structures that grade upward from ripple cross-stratification to low-angle cross-stratification. The very fine grained sandstone at the base of the Triassic in the Grabbe No. 1 (fig. 14) is interpreted to be an eolian-flat deposit. It was probably derived from reworking channel and overbank sediments of contemporaneous alluvial-fan deposits. Pedogenic dissipation structures (Ahlbrandt and Fryberger, 1981) in the sandstone have obliterated most sedimentary structures diagnostic of its origin.

Sandstone is nearly absent in the Rex White No. 1 well (fig. 15). This area was probably part of a small lacustrine basin throughout deposition of sandstone unit 1.

A soil profile is present at the top of the uppermost sandstone in unit 1 in Mansfield No. 1 (fig. 16). It has a mottled reddish-white color, root traces, and numerous small fractures, some filled with a milky cement (fig. 17). Thin sections show the fractures and cavities to be filled with opal, barite, and analcime. Boone (1979) notes evidence of extensive subaerial weathering in the upper part of the alluvial fan/fan-delta system in Tule Canyon, about 80 mi to the southeast. Present correlations suggest that this episode of subaerial weathering was a widespread event.

Table 1. Description and interpretation of Dockum sandstone units from cored Department of Energy wells.

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 1	S,O,JF - Red-brown to red-orange, low-angle cross-stratified, medium to fine sandstone with thin muddy interbeds; both upward-fining and upward-coarsening grain-size trends present; mudstone and siltstone clasts, as much as several centimeters across, at base of scours, along bedding plains, or in thin conglomeratic interbeds; bases are usually sharp, some are gradational; tops usually gradational; beds are 2 to 20 ft thick.	Alluvial fan and fan delta
	R - Orange-pink, poorly sorted, thin, medium sandstone with scattered well-rounded coarse sand grains and a prominent basal scour.	
Interunit 1-2	S,O,R - Dark-red-brown burrowed mudstone and claystone.	Lake center, lake margin
	JF - Massive (burrowed?) mudstone and claystone.	
Unit 2	JF - Base is massive and normal or inverse graded chert and carbonate pebble conglomerate with sharp erosional base overlain by silty claystone and massive fine sandstone; top of unit consists of basal graded SRF conglomerate and horizontally stratified fine sandstone overlain by about 50 ft of red-brown, upward-fining, low-angle cross-stratified, medium-to-fine sandstone; major lithologic and textural breaks are abrupt; thicknesses of conglomerate beds are 1 to 8 ft; top is gradational into interbedded, soft-sediment-deformed mudstone and siltstone.	Fluvial/distributary channel-fill, proximal deltaic
	S - Numerous beds of SRF conglomerates, as much as 4 ft thick, conglomeratic sandstone, and fine-to-coarse sandstone with siltstone and mudstone interbeds; stylolites may be present in carbonate pebble conglomerate; sandstones have low-angle and trough cross-stratification with less common ripple cross-stratification and abundant organic debris; bed thickness from 1 to 11 ft; sharp basal contacts and gradational upper contacts.	

Table 1 (cont.)

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 2 (cont.)	O - Predominantly siltstone and mudstone with a single sandstone bed at the top of the unit; mudstones are burrowed and usually show signs of weathering and subaerial exposure with fractures and in situ carbonate nodules; one example of a normal and inverse graded mudclast conglomerate, sandstone and siltstone; siltstones can be in thin interbeds in mudstones with faintly recognizable ripple lamination, burrows, fractures, and in situ carbonate nodules; several thick (>20 ft) intervals containing numerous individual sequences of upward-fining, ripple and ripple-drift cross-stratification and soft-sediment-deformed interbedded siltstone and mudstone; upper sandstone has SRF conglomerate at the base and upward-fining ripple-drift and low-angle cross-stratification, fine to very fine sandstone with thin SRF conglomeratic interbeds toward top.	
Interunit 2-3	S, JF, O - Ripple and ripple-drift cross-stratified, soft-sediment-deformed siltstone; interval is thinnest in Grabbe; J. Friemel well contains several 5- to 8-ft upward-coarsening sequences; Mansfield interval is >100 ft thick with a lower section of abundant organic debris and thin sandstone interbeds and an upper part with numerous sequences like those described in unit 2 for Mansfield well.	Distal delta front and swamp
Unit 3	S - SRF conglomerate with stylolites in carbonate pebble zone overlain by ~70 ft of medium to fine sandstone with upward-fining grain sizes and sedimentary structures; contains thin SRF conglomerates and siltstone interbeds; upper two sandstones are fine-grained and very fine grained with mostly ripple-drift cross-stratification; lower sandstone coarsens upward, top sandstone fines upward.	Lower sandstone is fluvial meanderbelt channel-fill and upper two are deltaic
	JF - Several gray-green sandstone beds at bottom, overall upward-coarsening grain size trend from fine to medium sand; sedimentary structures increase in magnitude upward from ripple stratified to cross-stratification inclined 25 degrees; mica and organic flakes are common; middle sandstones are gray-green,	Proximal delta-front and fluvial (or distributary) channel-fill

Table 1 (cont.)

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 3 (cont.)	micaceous, calcareous, low-angle and ripple cross-stratified with organic flakes grading upward into gray-green siltstone and red-brown, calcitic, ripple laminated, silty mudstone with thin interbeds of carbonate granule conglomerate; conglomeratic interbeds are 1 to 3 ft of flattened, grain-supported SRF pebbles; top sandstone erosionally overlies silty mudstone, has thin basal carbonate lag conglomerate grading upward into gray-green, massive low-angle and ripple and ripple-drift cross-stratified, fine sandstone fining upward into ripple-laminated siltstone.	
Interunit 3-4	JF - Gray-green to red-brown, ripple cross-stratified, soft-sediment-deformed, burrowed siltstone with ripples up to 1 inch grading upward into black, low-angle, ripple-stratified mudstone.	Distal delta front and lacustrine
	S - Red-brown brecciated mudstone with in situ carbonate nodules and reworked carbonate-rich mudclasts filling fractures; grades upward into red-brown ripple and low-angle cross-stratified siltstone with thin coarse sand lags in scours.	Lacustrine grading upward into distal delta-front
Unit 4	S - Two beds of red-brown, low-angle to ripple and ripple drift cross-stratified fine sandstone with sandy caliche and SRF basal conglomerates; lower sandstone has sharp base, coarsens up, is mud-rich with soft sediment deformation structures, small-scale faults, load structures, and clastic dikes; upper sandstone has a sharp base and fines upward; in situ carbonate nodules are well developed.	Proximal delta front and distributary channel-fill
	JF - Thin (2 to 4 ft) lower beds of pale green to red-brown, cross-stratified, medium sandstone and massive caliche granule conglomerate with organic fragments; basal contacts are sharp, upper contacts are sharp to gradational; abundant interbeds are generally thick (to 65 ft) consisting of micaceous, ripple and ripple-drift cross-stratified siltstone and mudstone with silty laminae.	Proximal delta front with distal delta front and lacustrine interbeds

Table 1 (cont.)

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 4 (cont.)	Upper interval contains scattered thin, fine sandstone and conglomeratic interbeds with upward-coarsening grain-size trends containing locally abundant organic debris; overlain by yellowish, massive to ripple cross-stratified, micaceous, fine to very fine sandstone with imbricated mudclast base showing complete reduction of clasts at base grading up into partially and nonreduced clasts; some beds appear to be at high angles to core.	Distal and proximal delta front and distributary channel-fill
Post-unit 4	JF - Light brown to pale-red-brown mudstone and siltstone; carbonate content increases upward (possibly due to downward percolation of carbonate-rich waters from superjacent Ogallala Formation); burrows and possible rootlets common in mudstone with carbonate nodules concentrated around burrows. S - Orange-red ripple laminated, carbonate nodule-rich, siltstone and silty mudstone.	Delta front and lacustrine

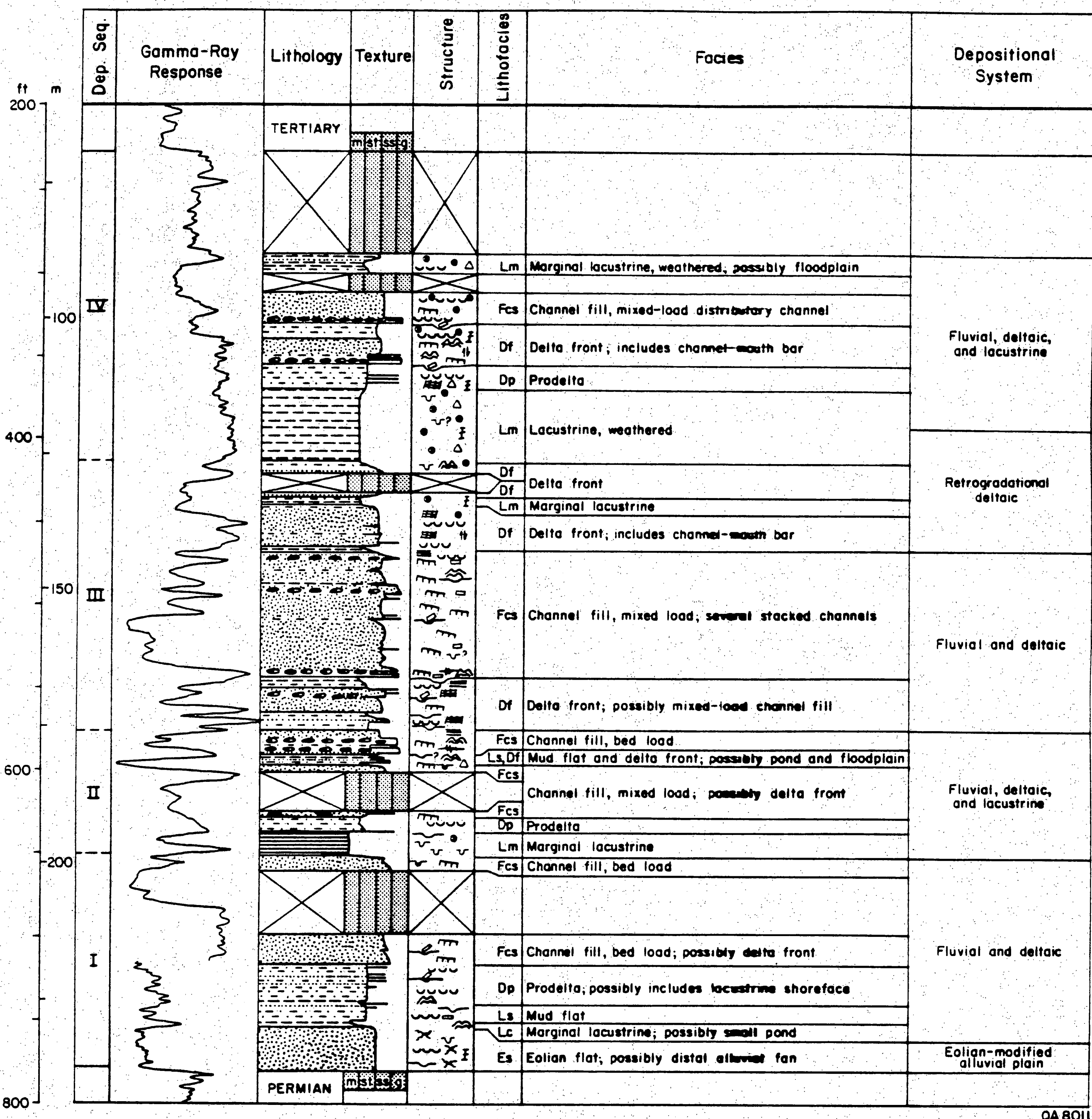

Figure 14. Simplified core log description and interpretation of the Dockum Group, the Department of Energy - Gruy Federal Grabbe No. 1 well, also showing lithofacies, gamma-ray response, and interpretations of genetically related units in the core. Grabbe strata contain abundant sandstone, similar to that in the J. Friemel well, and were proximal to primary sandstone depositional systems. Sandstone unit boundaries are shown on the left; unit 4a is absent in this well. See figure 15 for explanation of symbols.

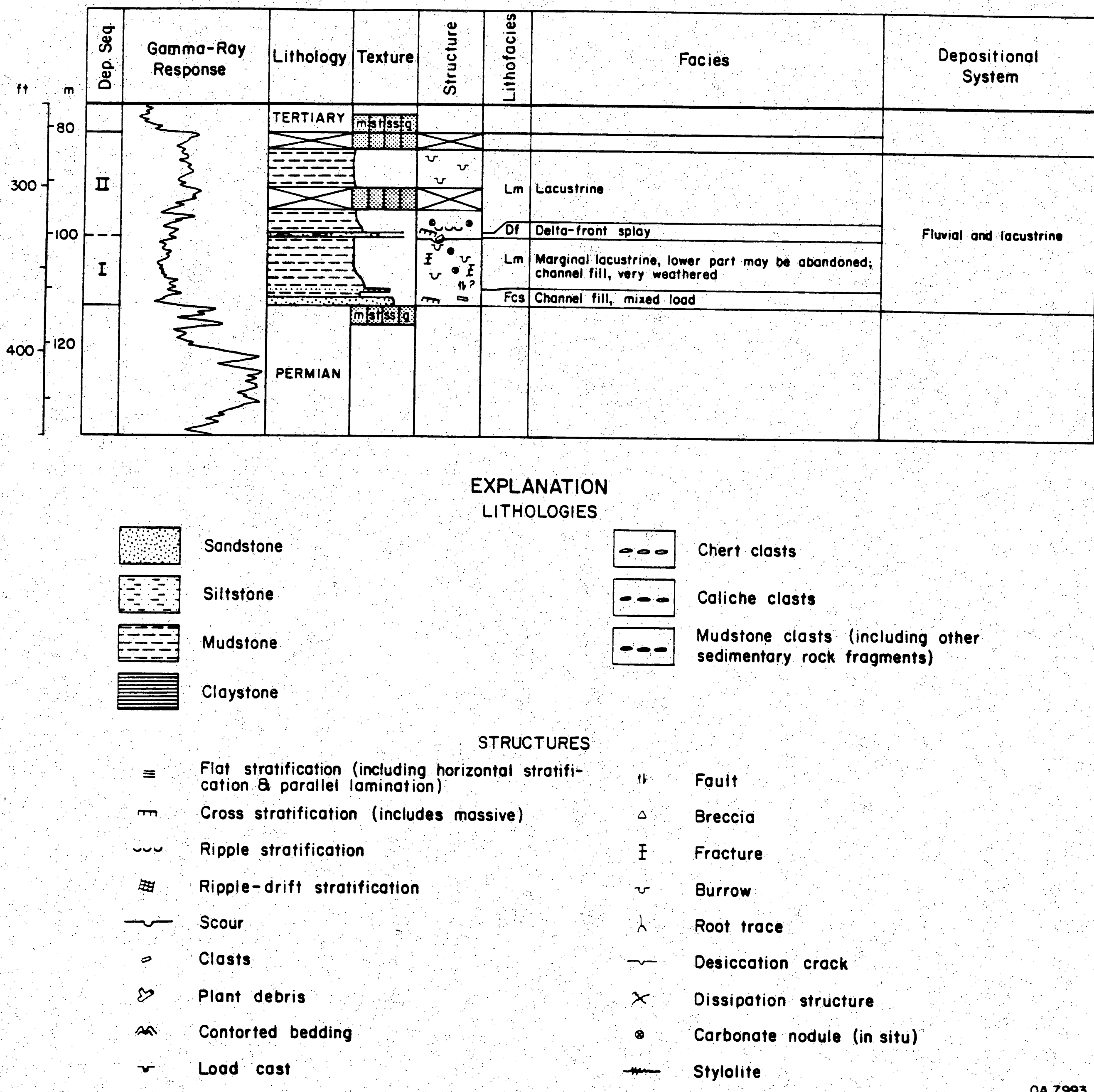

Figure 15. Simplified core log description and interpretation of the Dockum Group, Department of Energy - Gruy Federal Rex White No. 1 well, also showing lithofacies, gamma-ray response, and interpretations of genetically related units in the core. Note the thin, truncated Triassic interval in this well compared with that of the Grabbe, Mansfield, and J. Friemel wells. Sandstone unit boundaries are shown on the left; units 2, 3, 4, and 4a are absent in this well.

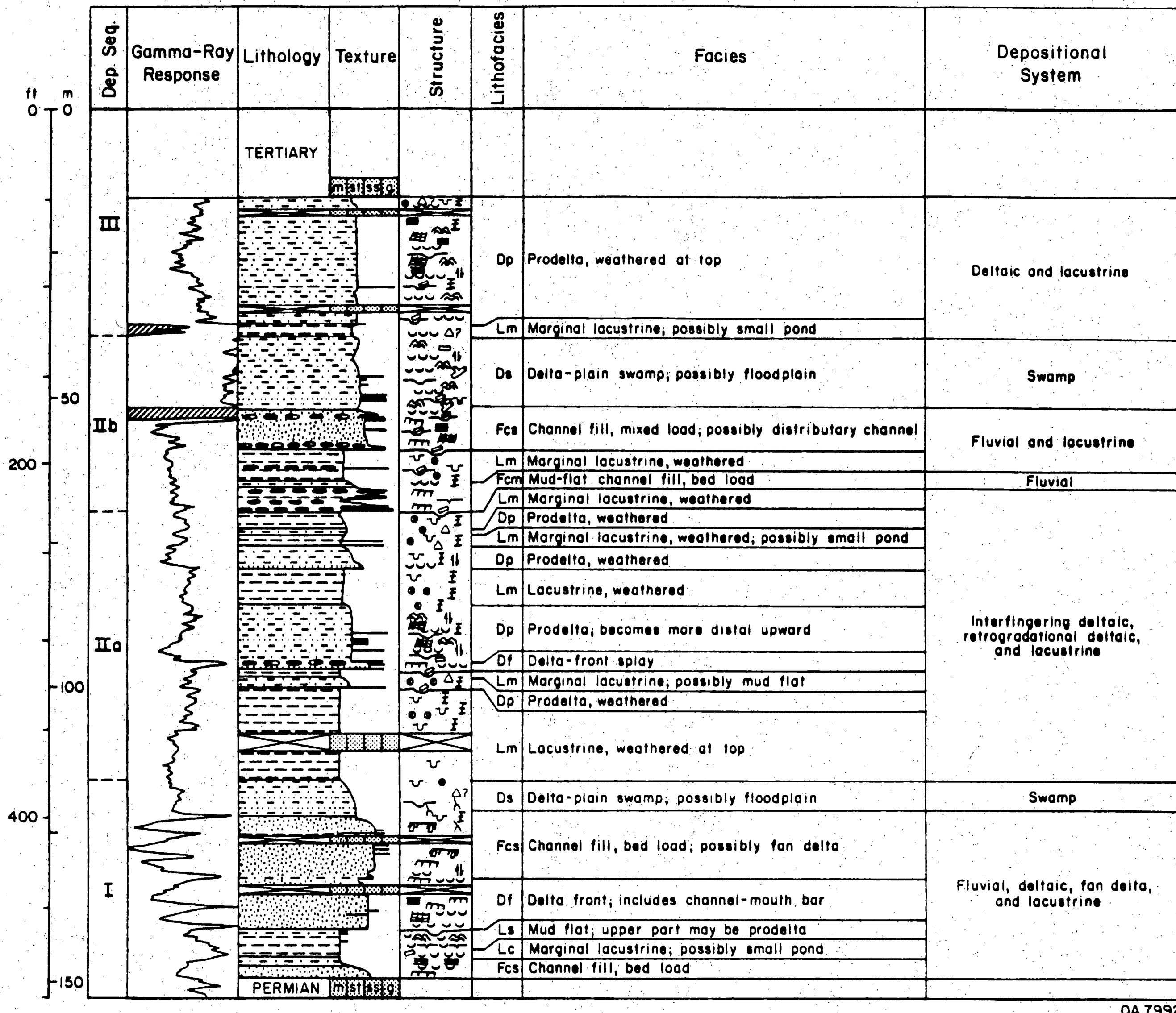

Figure 16. Simplified core log description and interpretation of the Dockum Group, Department of Energy - Stone and Webster Engineering Corporation Mansfield No. 1 well, also showing lithofacies and gamma-ray response and interpretations of genetically related units in the core. Note the overall fine-grained sediments in this well compared with sediments in the J. Friemel and Grabbe wells, indicating a general position more distal to primary sandstone depositional systems. High gamma-ray spikes tend to be associated with sections of high organic content where uranium has fixed upon the reductants. Weathered strata are common, implying frequent periods of subaerial exposure prior to deposition of overlying sediments. Sandstone depositional units are shown on the left; sand-sized sediments from unit 3, as well as from units 4 and 4a, are absent in this well. See figure 15 for explanation of symbols.

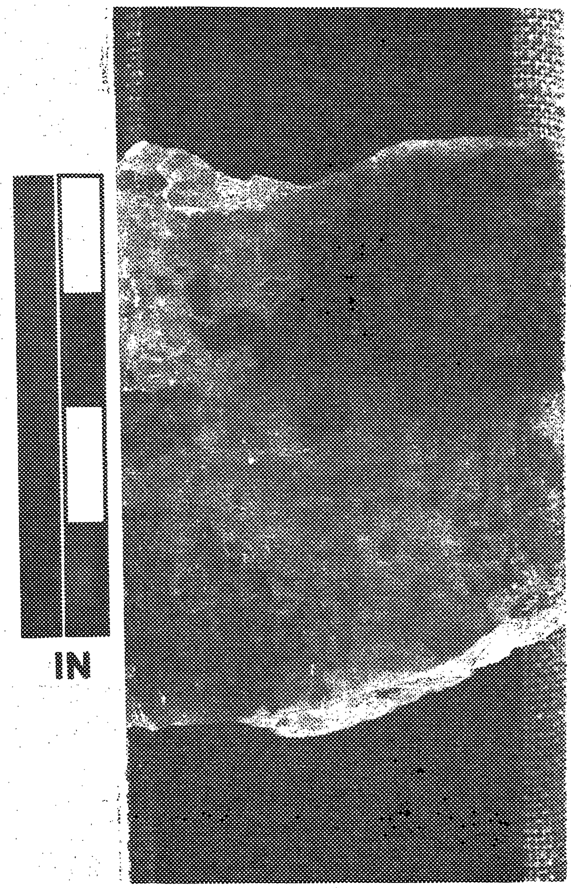

Figure 17. Pedogenic silcrete in distributary-channel sandstone, Mansfield No. 1 well, 400 ft.

In core, the fine-grained siltstone and mudstone interbeds within unit 1 were deposited in a low-energy environment. They may have originated in floodplains or in shallow lacustrine or pond settings that were often subaerially exposed and subjected to brief input of coarser grained material from runoff. In core, it is difficult to distinguish between these two environments. The lack of thick siltstone and mudstone interbeds in J. Friemel No. 1 (fig. 18) suggests that this area did not develop low-energy environments because it was a center for sedimentation with only brief periods of fine-grained deposition.

Vertical grain size trends and lateral relationships suggest that most of the sediments between units 1 and 2 are of lacustrine origin although it is possible that portions are floodplain deposits. Thinning of the interval toward the eastern basin margin, as seen in cross section (fig. 11), is due to both nondeposition and erosion by overlying fluvial depositional systems. Westward thickening suggests that paleodip was roughly east to west.

Sandstone Unit 2

In contrast to unit 1, where sandstone is widely distributed, most sandstone in unit 2 is confined to relatively narrow bands (fig. 19) containing thick sandstones that generally thin and become more diffuse downdip. Two prominent net-sandstone trends appear to originate from mapped valley-fill sections in Palo Duro and Tule Canyons. It is unlikely that the same 1- to 5-km-wide valleys exposed updip in Palo Duro Canyon (Seni, 1978) are actually penetrated by drill holes 50 mi downdip in Deaf Smith County. However, broad topographic lows and shallow valleys probably developed downdip of the relatively steep-walled updip valleys. These physiographic features localized drainage and clastic input. As lake level rose these valleys accumulated thick deposits of sandstone, the thickest present within the Dockum in

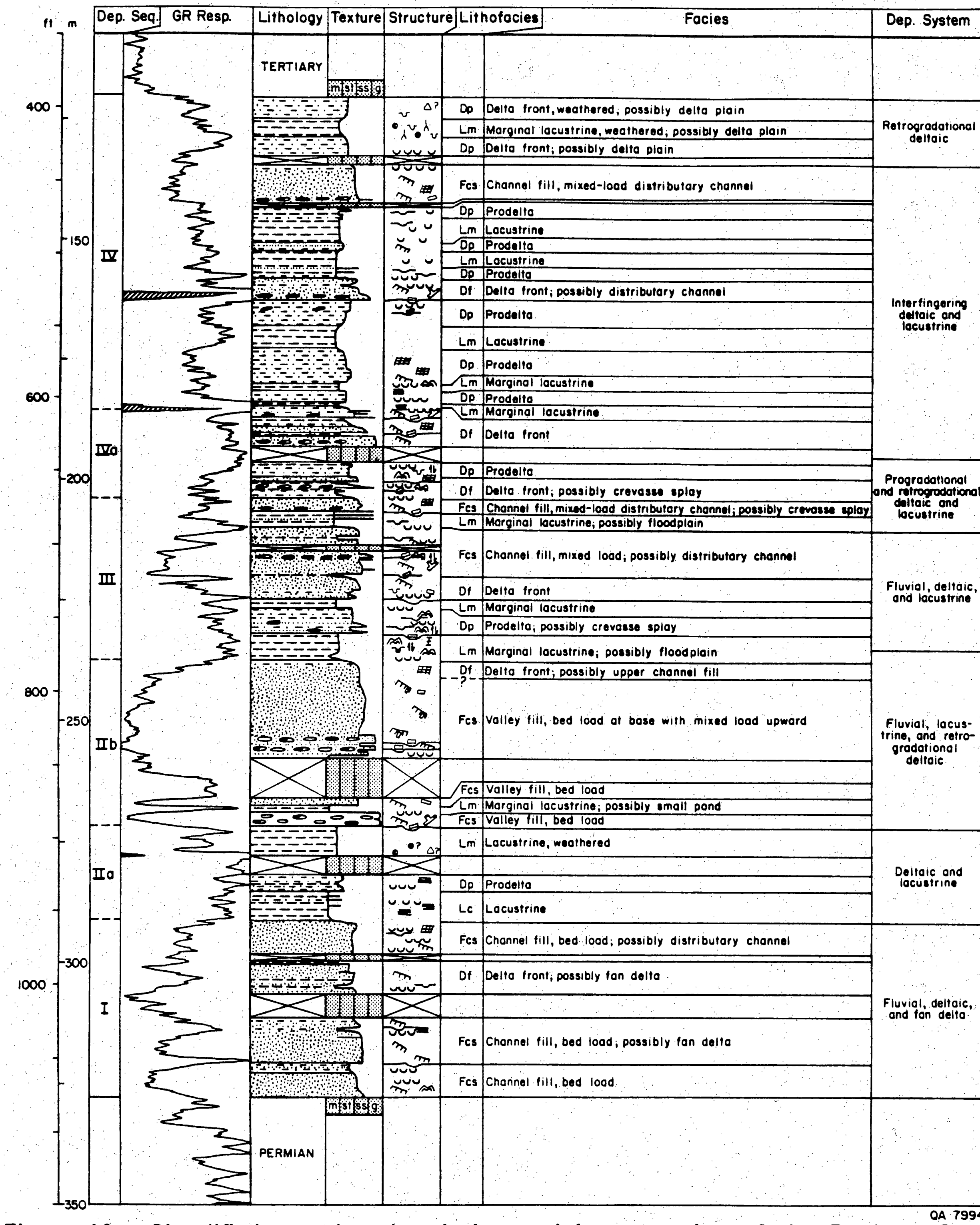

Figure 18. Simplified core log description and interpretation of the Dockum Group, Department of Energy - Stone and Webster Engineering Corporation J. Friemel No. 1 well, also showing lithofacies, gamma-ray response, and interpretations of genetically related units in the core. This core contains the thickest cored Triassic interval illustrating a range of depositional environments. High gamma-ray spikes, due to uranium compounds precipitating around reductants, tend to be associated with beds containing plant debris. Sandstone unit boundaries are shown on the left; unit 4a is absent in this well. See figure 15 for explanation of symbols.

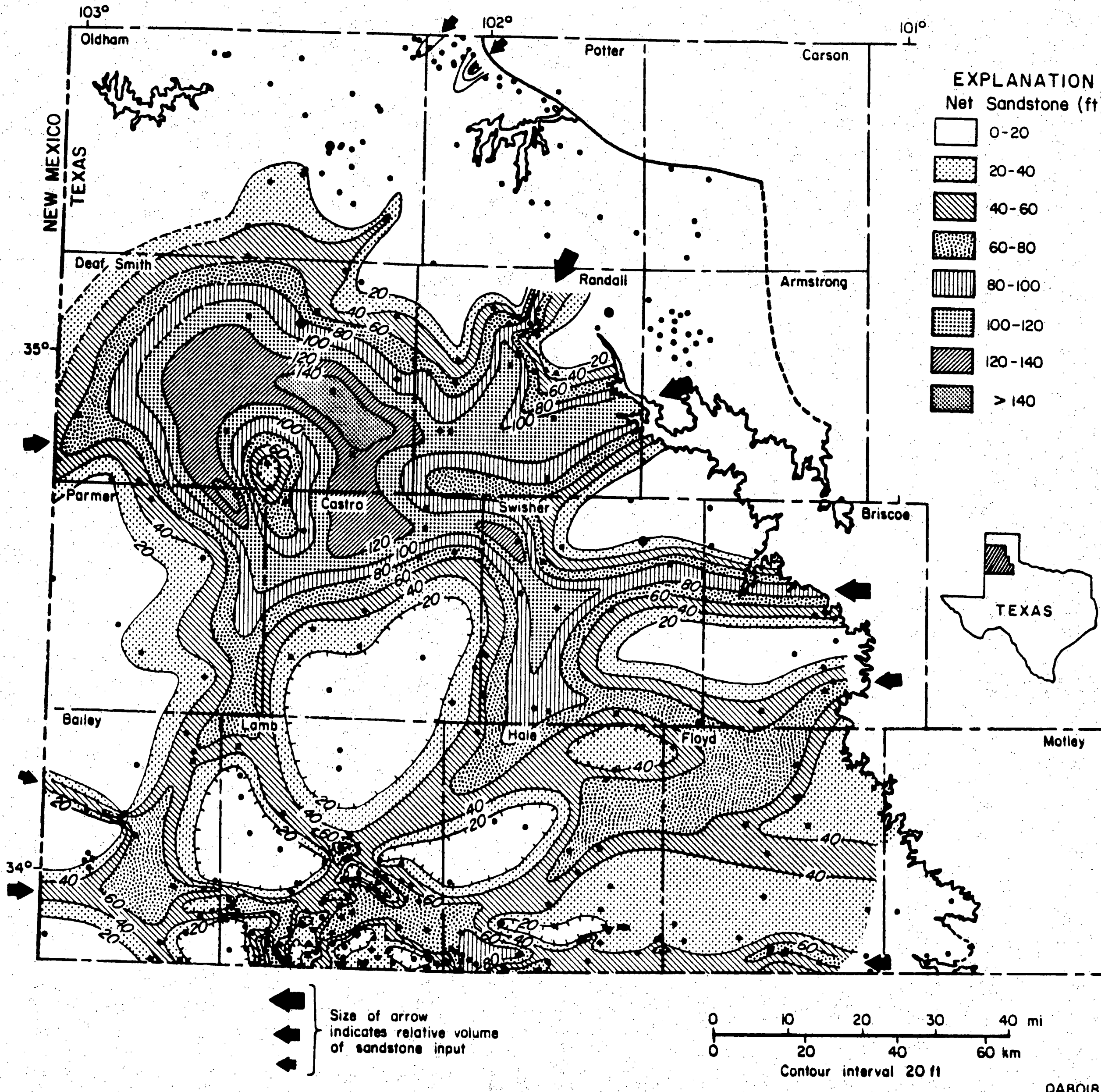

Figure 19. Net-sandstone map of lower Dockum depositional unit 2. Primary sediment source was from the east. East-west trends of thick sandstone in Deaf Smith and Swisher Counties correspond to valleys filled by retreating fluvial-deltaic systems during a rise in lake level.

the Palo Duro Basin. This would account for the high concentrations of sandstone in narrow bands as well as their massive appearance on well logs. Sandstone sedimentation appears to have been more diffused to the south, resulting in thinner sandstone beds and abundant mudstone interbeds. These probably are the result of deltaic sedimentation prior to valley incision, as noted in outcrop. Apparently valleys were not well developed in the southern part of the basin.

Depositional environments interpreted for core intervals of unit 2 (table 1) are similar to those interpreted from outcrop (table 2). The J. Friemel No. 1 and Grabbe No. 1 wells appear to intersect sediment deposited in downdip extensions of valleys mapped in outcrop. Bed-load streams deposited conglomerates, conglomeratic sandstone, and sandstone. As lake level rose, transgressive fan deltas backfilled the valleys with thick sandstone deposits. These grade upward into delta-front siltstones and mudstones in the J. Friemel No. 1, whereas in the Grabbe No. 1, further up paleodip, they grade into another phase of deltaic sedimentation. The base of unit 2 in Grabbe No. 1 (fig. 14) records an episode of deltaic sedimentation not preserved in Tule Canyon or in J. Friemel No. 1.

Unit 2 sandstones in J. Friemel No. 1 make up part of the informally named Santa Rosa aquifer system in the Palo Duro Basin. Location of the aquifer generally correlates with location of thick, coarse-grained, extensive valley-fill sediments.

Mansfield No. 1 well exhibits sediments deposited in lower energy, lacustrine-influenced environments (fig. 16). Thick, soft-sediment-deformed siltstone with thin interbeds of mudstone are interpreted as distal delta-front deposits; burrowed mudstones are lacustrine deposits. A graded mudstone-clast conglomerate, about 10 ft thick, was formed by braided-stream processes on a mudflat exposed by a drop in lake level. It may correspond to the period of valley development, but because of its

Table 2. Description and interpretation of Dockum sandstone units from outcrop. (From Seni [1978] and Boone [1979]).

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 1	Interbedded sandstone and mudstone with conglomeratic lenses in lenticular, relatively thin bodies; large trough and foreset cross-stratification dominate sandstone, and ripple lamination is most abundant in siltstone and mudstone; Scoyenia burrows and calichified zones are common in mudstone in Palo Duro Canyon; mudstone beds are thinner and less extensive in Tule Canyon; thickness of unit is as much as 160 ft.	Fluvial braided stream, alluvial fan and fan delta
Unit 2	Characterized by abundance of sandstone and conglomerate in complex assemblage of lobate sandstone sheets, incised by deep valleys that are filled with thick interbedded conglomerate and sandstone. In Palo Duro Canyon, the lobate sandstone section is from 100 to 170 ft thick and consists of broad sheets of trough cross-stratified sandstone and granule to pebble conglomerate; valley-fill sandstones consist of trough cross-stratified, conglomeratic medium sandstone, and chert and quartz pebble conglomerate, which grade upward into trough cross-stratified and parallel-laminated fine to medium sandstone; unit grades upward into ripple cross-laminated and horizontal laminated, interbedded mudstone, siltstone, and fine sandstone.	Fluvial braided stream and deltaic; valleyfill deposited by aggradational braided streams in fluvial, delta-platform and delta-front environments
	In Tule Canyon, unit is about 200 ft thick, consisting of predominantly conglomerate and conglomeratic sandstone containing large-scale trough and foreset cross-stratification, overlain by finer grained sandstone displaying upward-fining texture and an upward decrease in scale of sedimentary structures; conglomerates consist of granule- to boulder-size clasts of chert, vein quartz, and sedimentary rock fragments, a compositional suite of lithoclasts essentially identical to the conglomerates in Palo Duro Canyon.	Fluvial braided and meandering stream
Unit 3	Characterized by lobate and lenticular sandstone and conglomeratic sandstone bodies. In Palo Duro Canyon ripple and trough-fill cross-stratification are most common in upward-coarsening sequences with foresets to 50 ft high.	Delta front and delta platform

Table 2 (cont.)

DEPOSITIONAL UNIT	UNIT DESCRIPTION	DEPOSITIONAL ENVIRONMENT
Unit 3 (cont.)	In Tule Canyon trough and foreset stratification dominate in upward-fining sequences overlain by upward-coarsening sequences; unit thickness is as much as 200 ft with individual sandstone sequences to 65 ft.	Fluvial meandering stream overlain by deltaic

Unit 4 is not exposed.

downdip location, it did not develop the deep valleys common along the eastern part of the basin. The uppermost sandstone/conglomerate was deposited by braided streams that probably scoured through their own deltaic deposits as they prograded into the shallow lake. These deposits may represent a more advanced stage of progradation and channel development than that found in the mudstone conglomerate previously described. All of the mudstones and some of the siltstones in Mansfield No. 1 display evidence of subaerial exposure, some possibly for prolonged periods, again supporting a frequently exposed shallow lake setting.

Sediments between units 2 and 3 are markedly different from those separating units 1 and 2 (table 1). In Grabbe No. 1 the section is thin, suggesting a brief interval between periods of deltaic deposition (fig. 14). In J. Friemel No. 1, several 5- to 6-ft upward-coarsening sequences are present (fig. 18). In Mansfield No. 1, the interval is more than 110 ft thick (fig. 16), consisting mostly of ripple and ripple-drift cross-stratified siltstone overlying interbedded, soft-sediment-deformed, organic-rich siltstone and mudstone. Thickness of the organic-rich interval (28 ft) suggests that it is not a muddy channel plug; it is thicker than most channels in the Dockum. The abundance and size of organic debris, lignitic leaves, twigs, and small sticks indicate short transportation distances and a prolific source. Proximity to the underlying distributary sandstone and the abrupt nature of the contact suggest a rapid change in environment. For these reasons, this interval is interpreted to represent swamp sediments deposited on a foundering delta. Swamp development may be due either to avulsion of the fluvial feeder channel and subsequent foundering of the delta or to rise in lake level. Overall, the interval in Mansfield No. 1 represents a transgressive episode from the underlying distributary channel sandstone, to a swamp environment, upward into distal delta-front siltstones Seni (1978) reported similar deposits in an interdeltaic embayment in Palo Duro Canyon. Part of the Mansfield unit 2 interval may be the distal equivalent of the deltaic deposits characteristic of unit 3.

Sandstone Unit 3

Sandstone unit 3 is characterized by numerous, relatively thin sandstones with abundant interbedded mudstone (figs. 9, 10, and 12). Sandstones tend to be less laterally continuous than in underlying units. The north-central and western parts of the basin contain the highest sandstone concentration and the thickest sandstone beds; these are presumably along the main axes of sediment transport. Sandstone beds distal to depositional axes are generally thinner and are scattered over a greater vertical range.

Net sandstone trends for unit 3 show relatively narrow bands of moderate thickness (>40 ft) leading to broad areas of high sandstone thickness (>80 ft) (fig. 20). These patterns suggest fluvial trunk streams leading to lacustrine deltas. Studies of the outcrop equivalents of unit 3 indicate that the sediments are fluvial-deltaic (table 2), containing at least two separate progradational events in both Palo Duro and Tule Canyons (Seni, 1978; Boone, 1979). Sandstone contour patterns and orientation of the net-sandstone trends of the subsurface systems are identical to those measured in Palo Duro Canyon (Seni, 1978).

In the subsurface, sandstones generally reflect characteristics seen in outcrop (table 1). The fluvial meanderbelt sandstones mapped by Boone (1979) in Tule Canyon are represented in unit 3 of the Grabbe No. 1 core by several stacked, upward-fining, channel-fill sandstones (fig. 14). Sandstones in the lower part of the unit have conglomeratic bases with thinner conglomeratic lenses upward in the sandstone. These represent channel-lag and channel-bar deposits similar to modern

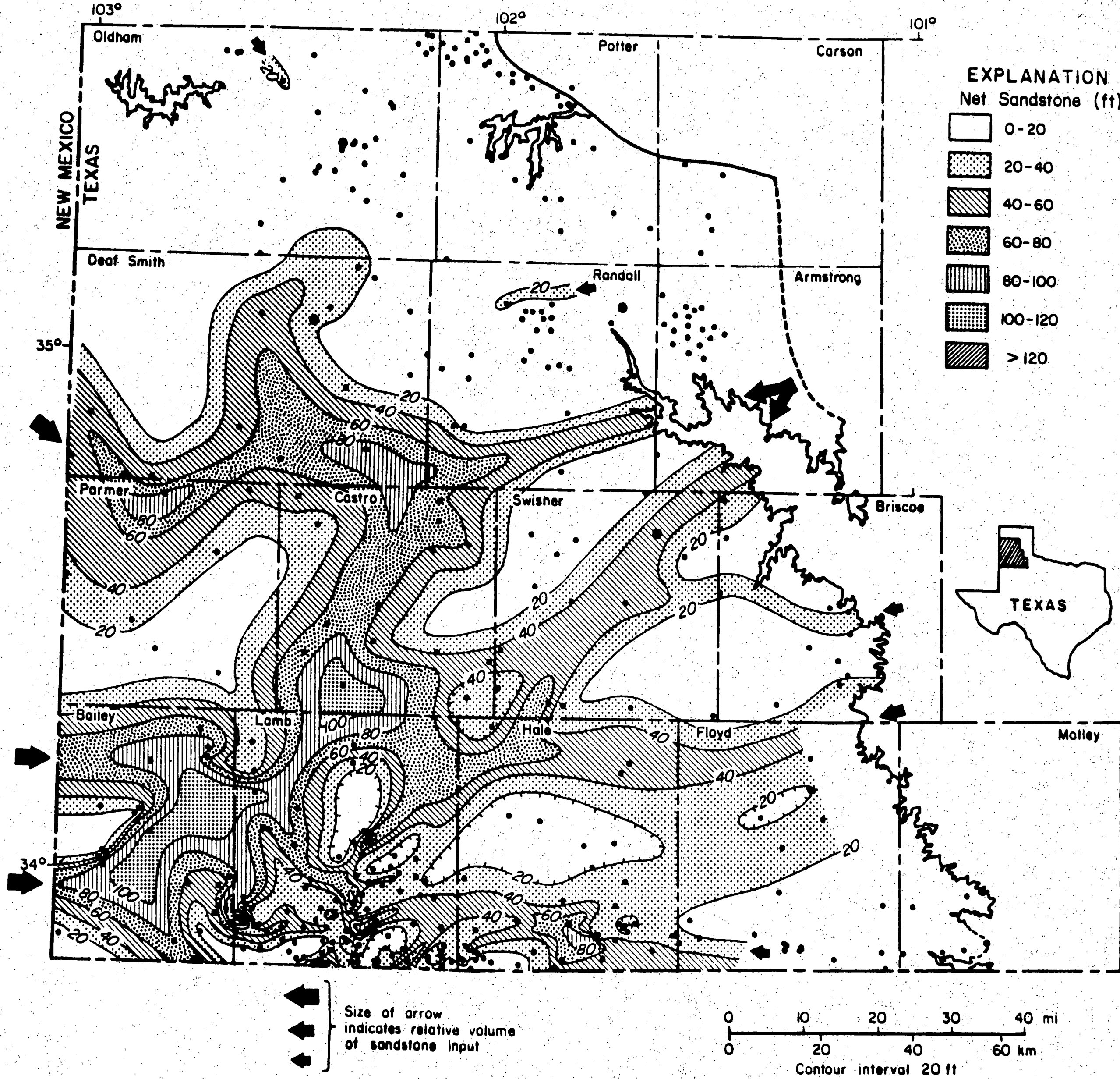

Figure 20. Net-sandstone map of lower Dockum depositional unit 3. Primary sediment sources were from the east, but significant contributions were from the west. Only thin, scattered sandstones from unit 3 are present in Oldham, Potter, Carson, and Armstrong Counties.

and ancient coarse-grained point bars described by McGowen and Garner (1975). The upper sandstones of unit 3 have two possible origins. Because they overlie fluvial sandstones, consisting of thinner sandstone beds (from 6 to 13 ft thick) with mainly ripple-drift cross-stratification, suggestive of lower energy environments, the upper sandstones could be crevasse splay deposits. Alternatively, this unit is overlain by lacustrine mudstone and lobate lacustrine deltaic deposits in outcrop (Boone, 1979), suggesting that a shift to lacustrine-influenced deposition occurs somewhere in or above unit 3. No levee deposits are apparent, upper sandstone beds are thin, gradational bases are common, and only ripple, ripple drift, and parallel lamination are present. They are interpreted to be deltaic sediments, probably small distributary channel-fill and proximal channel-mouth bar, deposited over the fluvial sandstone beds as the delta facies retreated from the basin center in response to an expansion of the lacustrine environment.

Unit 3 in J. Friemel No. 1 consists of two sequences of upward-coarsening then upward-fining sandstone trends that are interpreted to have been deposited in a deltaic environment (fig. 18). At the base are burrowed, fine-grained, delta-front sandstone beds overlain by distributary channel-fill sandstone and conglomerate. The overlying siltstone appears to be delta-front sediment with thin, granule conglomerates representing delta-front splays. The upper sandstone is a distributary channel-fill that scoured into the delta-front sediments.

The sediments between units 3 and 4 are interpreted as delta-front and lacustrine deposits (table 1). In Grabbe No. 1, these sediments have been extensively weathered and are interpreted to be subaerially exposed lacustrine mudstones overlain by delta-front siltstones. In J. Friemel No. 1 they are similar to delta-front sediments previously described in unit 2 in the Mansfield No. 1 well.

Sandstone Unit 4

Sandstone in unit 4 is concentrated in the western and southwestern parts of the basin (fig. 21). Net-sandstone contour patterns indicate a dominant western sediment source with subordinate eastern sources. Sandstone beds are generally thin and scattered over a large vertical thickness, but a few thicker sandstones are present (<40 ft) (figs. 10 and 13). Separation of this unit from unit 3 is questionable in some areas, suggesting that portions of unit 4 may be laterally equivalent to some unit 3 sandstones.

Lithologic cross sections (figs. 10 and 11) show that unit 4 is encompassed by abundant mudstone. Sandstone horizons tend to have little lateral continuity. Outcrop equivalents may be the many lobate deltas in the upper portion of the lower Dockum noted by Boone (1979) in Tule Canyon, in which sandstones represent channel deposits and thinner sandstones probably proximal delta and delta-front deposits.

Unit 4 in J. Friemel No. 1 appears to be the result of deltaic sedimentation alone (table 1), thus supporting outcrop and cross section interpretations. Thin beds, scoured bases, intraformational scour surfaces, primarily ripple and low-angle cross-stratification, and spatial relationships to the mudstone section suggest that the sandstone and conglomerate beds are distal delta-front splays (fig. 18). However, because of their proximity to underlying fluvial distributary channel deposits as previously described, an alternate explanation is that the unit 4 sandstones are overbank fluvial splays, possibly prograding into a pond. Subsequent lake expansion would then account for delta facies overlying the overbank deposits.

In Grabbe No. 1, unit 4 appears to be of delta-front and distributary-channel origin (table 1). The unit coarsens upward from lacustrine mudstone into a soft-sediment-deformed delta-front siltstone and sandstone (fig. 14). These sediments are

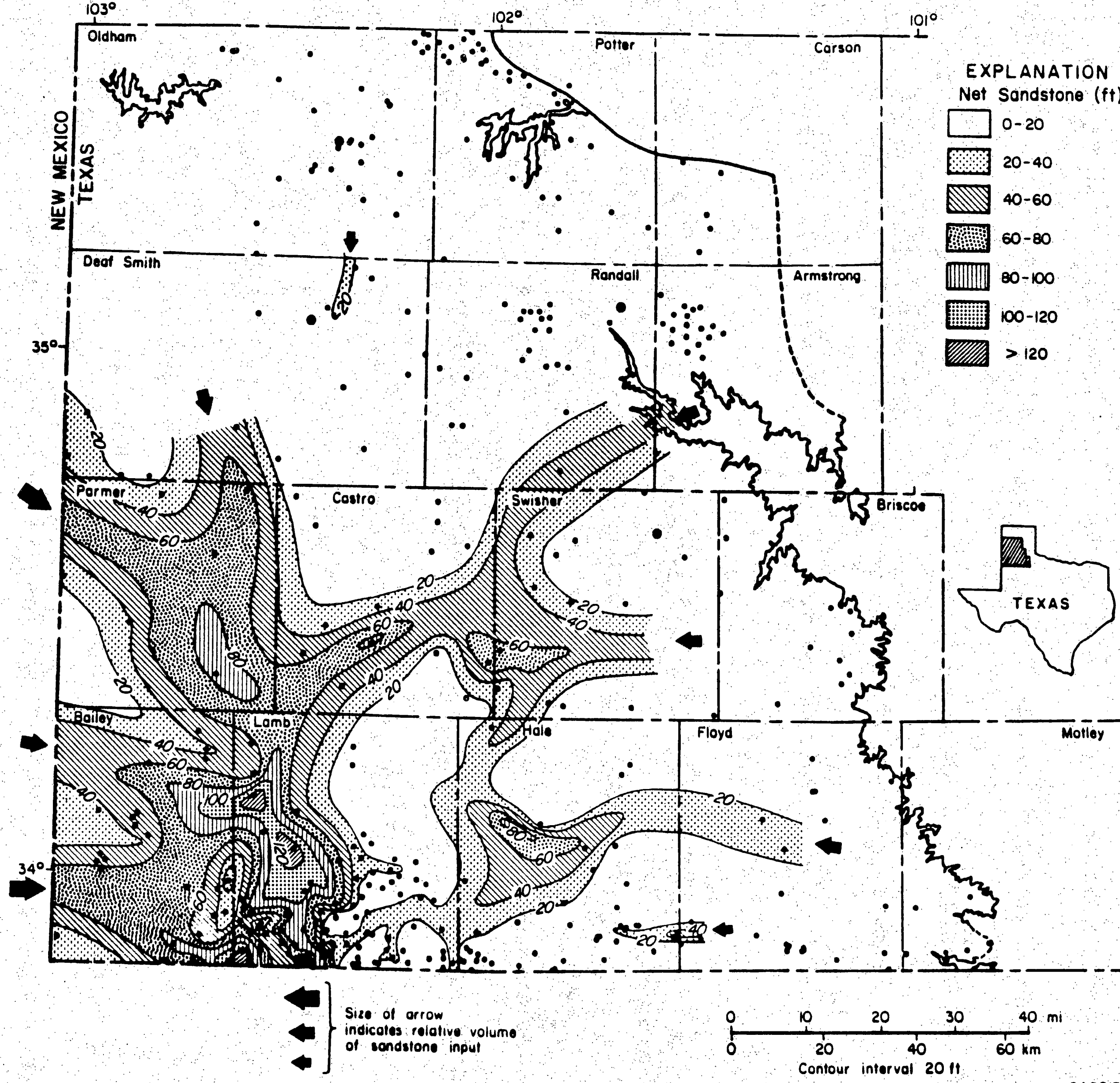

Figure 21. Net-sandstone map of lower Dockum depositional unit 4 showing all remaining sandstone up to the base of the upper Dockum. Major sediment contributions come from western sources. Erosion has removed these sediments in the northern and northeastern parts of the basin.

erosionally overlain by distributary channel-fill conglomeratic sandstone with an upward decrease in scale of sedimentary structures.

Subunit 4a

Subunit 4a represents the only attempt to recognize and divide apparently individual, single-event, genetically related sandstones. Net-sandstone patterns strongly indicate a deltaic origin and a source in the northwest (fig. 22). The southernmost delta lobe appears to abut against and terminate along a topographic feature overlying the Littlefield basement structure in south-central Lamb County.

WELL LOG LITHOFACIES

Lithofacies were identified in the subsurface at two levels of investigation. At the first level, lithologies were identified on gamma-ray well logs, and general facies interpretations were made of each lithology. The second and more detailed level was based on four Dockum cores and included identifying specific lithologies with sedimentary characteristics that collectively define unique depositional facies.

Three sedimentary lithofacies, sandstone, sandstone-mudstone, and mudstone, are recognized in the Palo Duro Basin from gamma-ray well logs. The sandstone facies is dominantly sandstone, including conglomerate, in beds at least 15 ft thick. These also may contain thin interbeds of mudstone and siltstone, but such interbeds cannot be detected on the logs. The sandstone-mudstone facies consists of roughly equal amounts of interbedded sandstone and mudstone with individual sandstone and conglomerate beds less than 15 ft thick. The mudstone facies contains dominantly siltstone and mudstone. Thin interbeds of sandstone and conglomerate, less than 5 ft

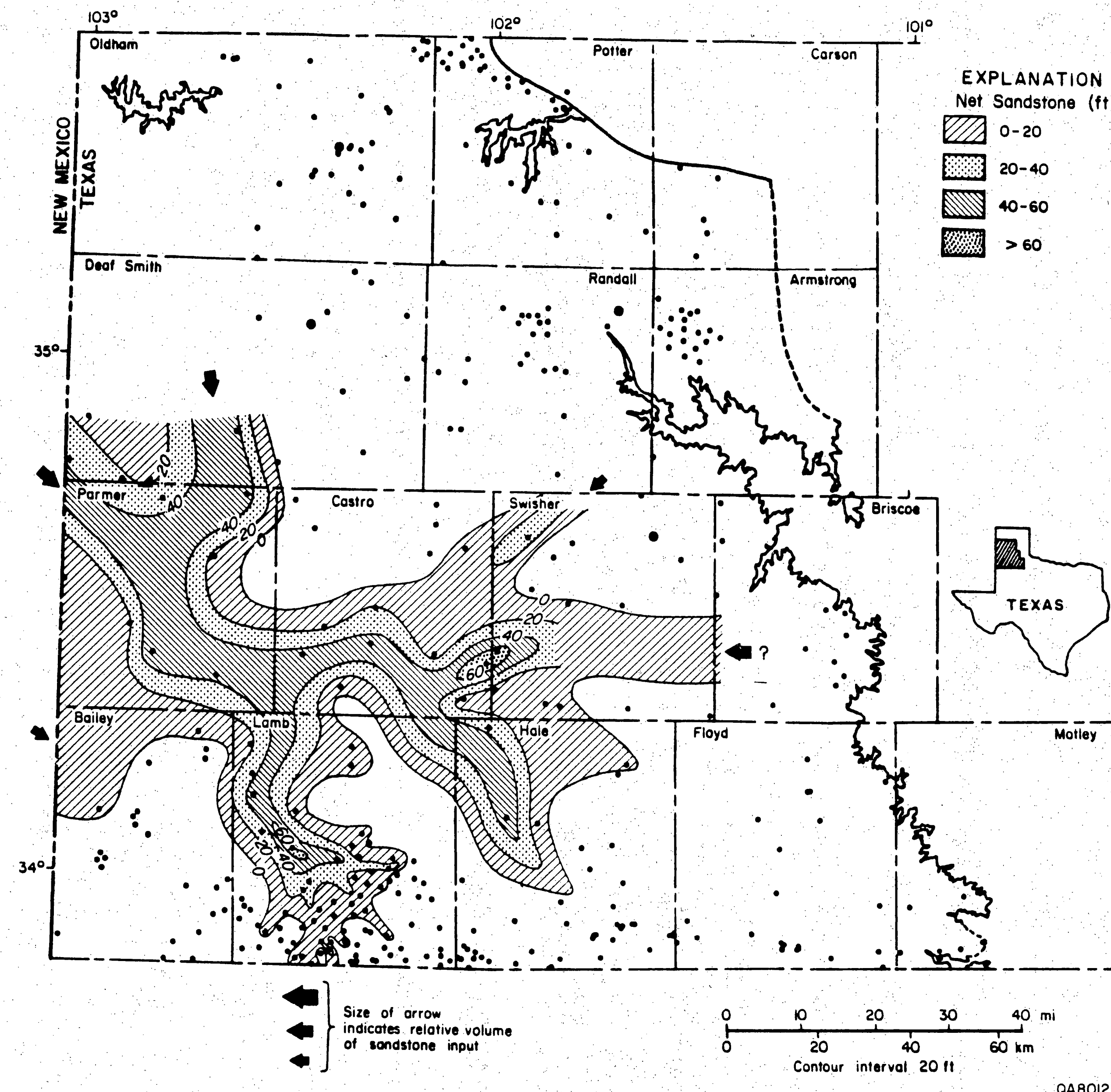

Figure 22. Net-sandstone map of lower Dockum depositional unit 4a. Sediment sources were in the west and possibly east. Correlations of the unit are questionable to the east where the unit thins and merges with laterally equivalent sandstones. Erosion has removed these sediments in the northern part of the basin.

thick, are known from core examination to occur in this lithofacies. Although the best gamma-ray logs are used in each well, the character and sensitivity of the gamma response vary between logs. Variable gamma response may have caused some of the apparent lateral lithofacies changes on the cross sections.

The sandstone lithofacies occurs in beds from 15 ft to greater than 100 ft thick. The thickest beds are located in Deaf Smith and Swisher Counties in depositional unit 2 (figs. 23 through 26). This lithofacies is unequally distributed in the basin both aerially and stratigraphically. Aerially, it is more common along the north and east margins of the present extent of the Dockum. Figures 23 through 26 show that the sandstone lithofacies is less common in the deeper parts of the basin. Stratigraphically, the sandstone lithofacies is dominant in the first and second depositional units but occurs scattered throughout the remaining section.

The sandstone-mudstone lithofacies is more common in the deeper parts of the basin and higher in the section than is the sandstone lithofacies. It grades laterally into the sandstone or the mudstone lithofacies and can overlie or underlie either lithofacies. This lithofacies occurs in laterally continuous horizons in the lower part of the Dockum, except in Bailey, Lamb, and Hale Counties (fig. 26) where this lithofacies is more laterally restricted than elsewhere in the basin. Occurrence of this lithofacies becomes patchy upward (figs. 23 and 26).

The mudstone lithofacies dominates the Dockum Group sediments. It is thickest in the upper part of the section and may thicken laterally downdip (for example, the mudstone between unit 1 and 2 in figure 25). It is the most laterally continuous lithofacies present.

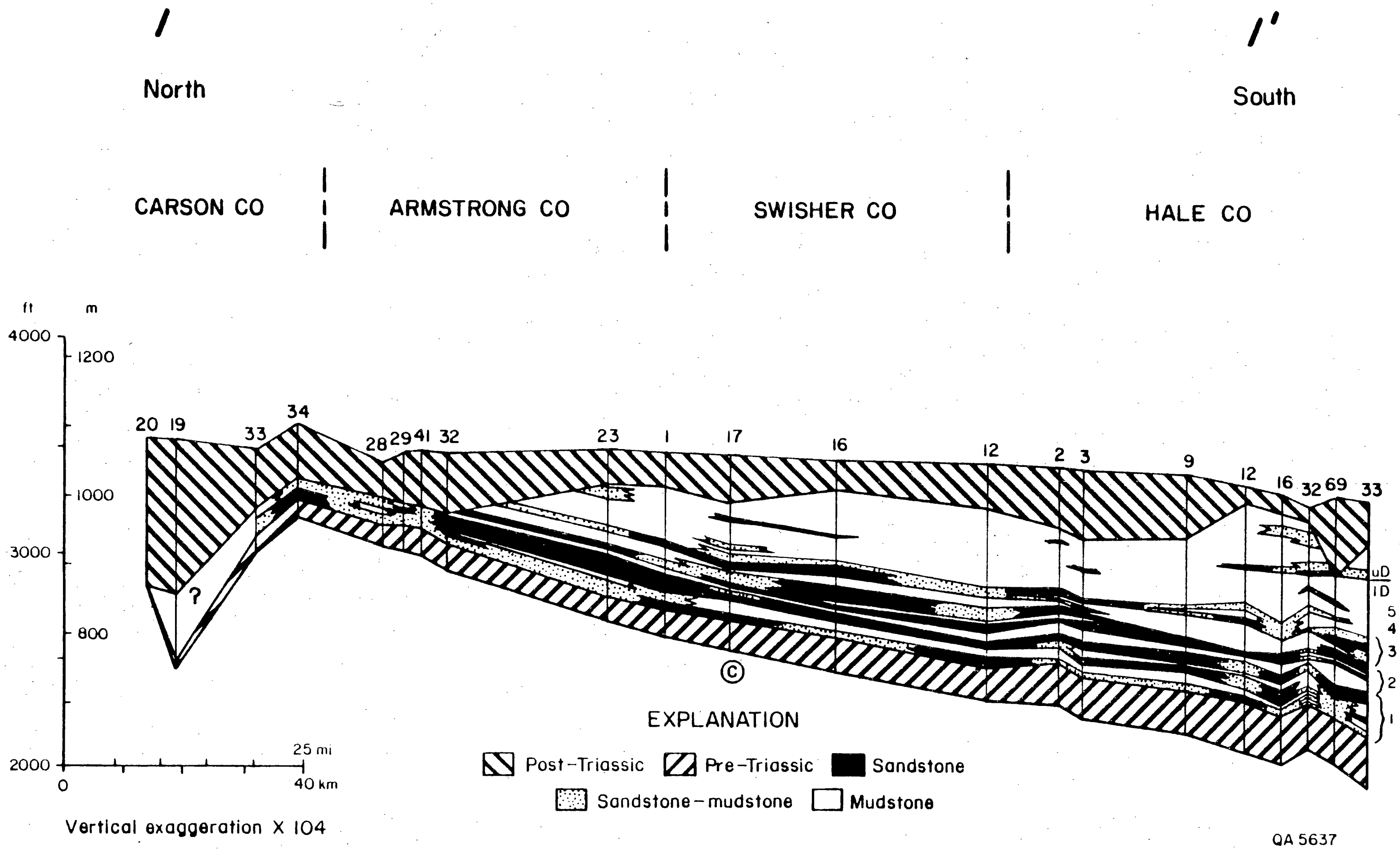

Figure 23. Lithofacies cross section 1-1'. This section illustrates the greater abundance of the sandstone lithofacies in the updip areas of the basin. See text for lithofacies definitions and figure 1 for line of section.

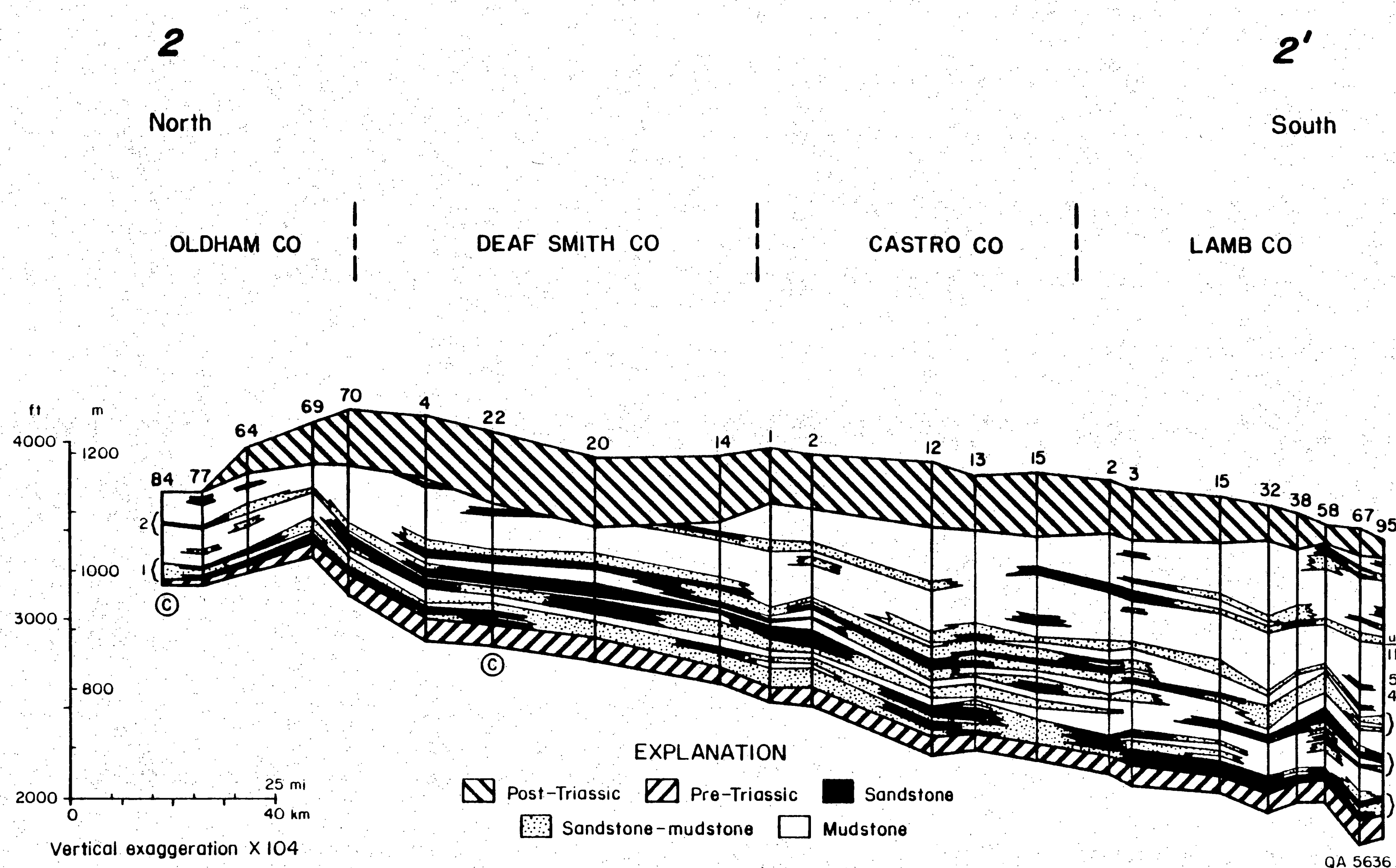

Figure 24. Lithofacies cross section 2-2'. The greater relative abundance of the sandstone lithofacies in Deaf Smith County is a result of the presence of the valley-fill system. The widespread occurrence of the sandstone-mudstone lithofacies in Castro and Lamb Counties is primarily caused by deltaic deposition. See text for lithofacies definitions and figure 1 for line of section.

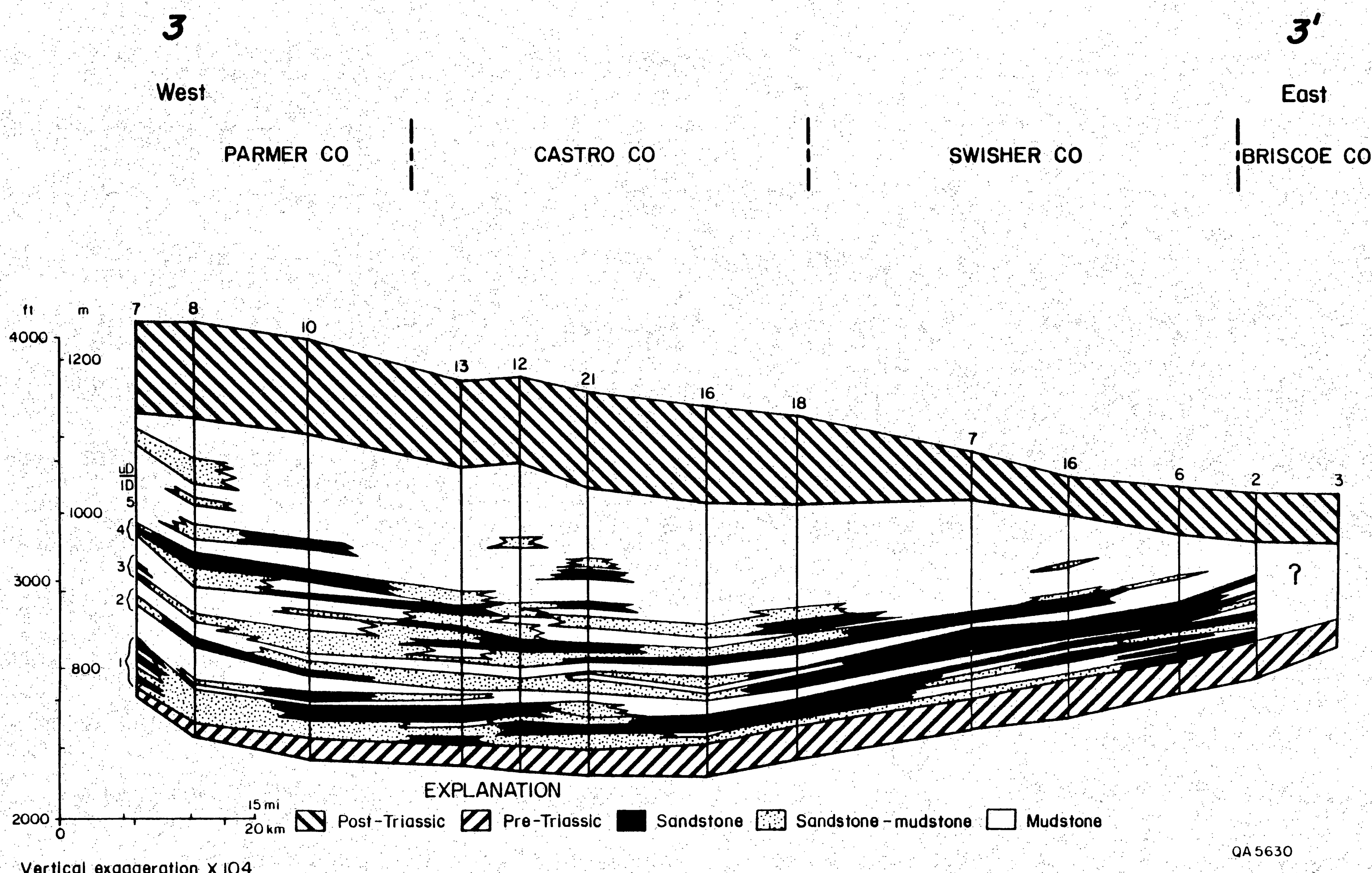

Figure 25. Lithofacies cross section 3-3'. Note greater concentration of sandstone lithofacies in the east, up paleodip, and more mixed sandstone-mudstone in the west, down paleodip. See text for lithofacies definitions and figure 1 for line of section.

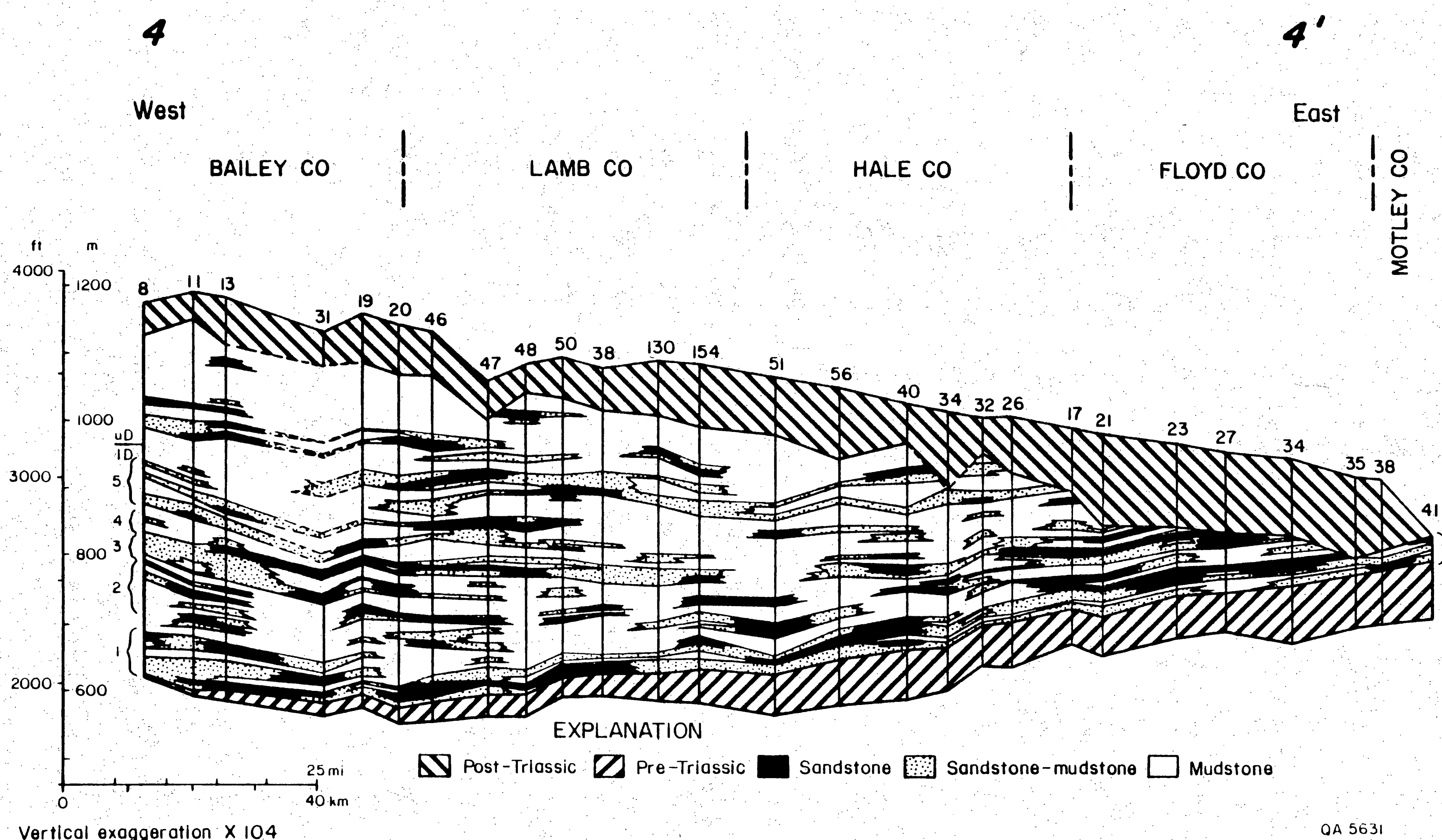

Figure 26. Lithofacies cross section 4-4'. This section shows the abundance of laterally discontinuous mixed sandstone-mudstone lithofacies, which is due to more distal deltaic deposition, in Lamb and Hale Counties, down paleodip. See text for lithofacies definitions and figure 1 for line of section.

Lithofacies Relationships and Depositional Environments

Vertical and lateral associations between the lithofacies provide clues to their genetic relationships. Overall, the most common vertical lithofacies relationship is sandstone-mudstone overlying mudstone, closely followed by mudstone overlying sandstone, mudstone overlying sandstone-mudstone, and sandstone overlying mudstone. The two possible relationships between sandstone and sandstone-mudstone have a very low frequency of occurrence. The most common lateral relationship between facies is sandstone grading into sandstone-mudstone; sandstone grading laterally into mudstone is the least common. Spatial relationships between lithofacies suggest that vertical changes in the depositional environment tend to be more abrupt than lateral changes. Abrupt lateral lithofacies changes are probably less common because they are a product of base-level fluctuations in a low-relief basin, making gradual changes less likely.

Comparisons between updip and downdip cross sections show some changes in lithofacies relationships that are due to changes in depositional environment. For example, lithofacies cross section 1-1' (fig. 23) represents an updip section whereas 2-2' (fig. 24) is a downdip section. The most significant vertical difference seen in the cross sections is the downdip decrease in the abrupt association of sandstone over- and underlying mudstone and an increase in mudstone overlying sandstone-mudstone and sandstone-mudstone overlying sandstone. A possible explanation of the former situation may simply be the overall decrease in the downdip abundance of the sandstone facies. Alternatively, downcutting by the systems depositing the sandstone lithofacies may have removed the sandstone-mudstone lithofacies in updip areas, whereas this process was not as common downdip, where the depositional systems were closer to base level. Downdip decrease in abundance of sandstone lithofacies is the most likely cause of the decrease in the mudstone-over-sandstone facies relationship. Better development and preservation of deltaic facies in downdip areas would account for the increase in mudstone-under-sandstone-mudstone and sandstone-mudstone-under-sandstone associations.

Paleodip cross sections 5-5' and 6-6' (figs. 25 and 26) also display the expected downdip lateral facies changes. Sandstone lithofacies generally give way to the mixed sandstone-mudstone lithofacies, grading from fluvial to deltaic depositional systems.

Although making specific environmental interpretations of these three lithofacies is difficult, general interpretations are possible using outcrop and core data. That the sandstone lithofacies is generally found in the updip areas and is thickest in unit 2, previously described as being composed of dominantly fluvial valley-fill deposits, indicates that this lithofacies represents fluvial-channel environments. This lithofacies thus marks the location of the primary fluvial transport routes in the Dockum. However, there are undoubtedly deltaic sediments included within this lithofacies that cannot be distinguished using available well control or technology.

The sandstone-mudstone lithofacies represents a variety of environments. In general, this lithofacies represents distal clastic deposits; they are either thin fluvial sandstones off the main channel axes or thin deltaic sandstones associated with prograding stream systems. Mudstone interbeds of this facies are both lacustrine and fluvial floodplain mudstones and siltstones. The presence of this lithofacies is more common higher in the section reflects the dominance of deltaic sedimentation, and therefore of laterally discontinuous sandstone beds, in the upper part of the section. These deep-water lacustrine deltas higher in the Dockum section (Seni, 1978; Boone, 1979) probably did not prograde far enough into the basin for the fluvial facies to be preserved. Thinner genetic sequences, resulting from rapidly changing environmental conditions during shallow-water lacustrine sedimentation in the lower part of the

Dockum, account for the abundance of this lithofacies in the basal unit.

The mudstone lithofacies represent two primary depositional environments, marginal and deep lacustrine, and distal delta front. Undoubtedly some floodplain and possibly even abandoned channel plugs also are present. Dominance of this lithofacies reflects the progressive shift to a deeper, and probably more extensive, lacustrine setting. As core from the upper section contains some very weathered lacustrine mudstones, an alternative explanation may be that lacustrine conditions were not much different from previous conditions but are the result of reduced clastic sediment influx.

CORE LOG LITHOFACIES

Analysis of GF and SWEC core from the Dockum Group allows more refined lithofacies recognition on geophysical well logs. Ten lithofacies are identified in core representing four depositional environments; lacustrine, deltaic, fluvial-deltaic, and eolian (table 3). Lithofacies included in the combined fluvial-deltaic environment are those in which sedimentary structures and vertical lithologic relationships in core are not definitive enough to allow more precise environmental delineation.

Lacustrine System Lithofacies

Two lithofacies are recognized as originating in lacustrine environments (table 3). In lithofacies Lm, burrowing is the primary identifying characteristic. It is commonly very intense, destroying all original sedimentary structures (fig. 27). Scoyenia is the most abundant burrow type (Häntzschel, 1962) seen in core, but Teichichnus is also present. McGowen and others (1979) and Seni (1978) also note these burrow types occurring in mudstone intervals in outcrop. A warm lacustrine environment is

TABLE 3. Description and interpretation of core lithofacies.

LITHOFACIES	ENVIRONMENT	DESCRIPTION	THICKNESS
Lm Burrowed, brecciated, and massive mudstone and claystone	Lacustrine Lake center, lake margin	Dark red to pale red, may be finely laminated or massive; burrows up to 9 mm across; reduction spots common and may have thin reduced zone in contact with reduced siltstones or sandstones; may include fine interbeds of siltstone and silty starved ripples; carbonate nodules common; bleached can be associated with fractures. Brecciated intervals are dark to pale red-brown with abundant fractures, locally filled with reworked clasts; carbonate nodules are common.	3-44 ft
Lc Finely laminated mudstone and clay-stone	Lake center	Moderate reddish-orange to grayish-purple, finely laminated with scattered silty interbeds and starved ripples.	1-19ft
Ls Ripple laminated, interbedded mudstone and siltstone	Lake shore and mudflat	Red-brown to gray-green, finely interbedded ripple and parallel stratified; some scouring at bases of siltstone beds; common disturbed bedding, ripup clasts, and filled desiccation cracks; rare burrows.	3-18 ft
Dp Ripple and ripple drift, cross-stratified siltstone	Deltaic Distal delta front	Moderate orangish-red to red-brown; typically has scoured silt base with upward-fining grain sizes and sedimentary structures into deformed, interbedded siltstone and mudstone; very micaceous; some burrowing.	3-75 ft Genetic units 1-14 ft
Df Interbedded siltstone and sandstone	Proximal delta front	Red-brown to gray-green, very micaceous with fine organics and mudclasts common along bedding planes; sandstone may be muddy; beds may show normal or inverse grading of grain sizes and sedimentary structures; sandstones tend to have scoured bases and siltstones gradational; common burrows, soft-sediment deformation structures, and carbonate nodules; rare fractures.	20-30 ft Genetic units 1-11 ft

TABLE 3 (cont.)

LITHOFACIES	ENVIRONMENT	DESCRIPTION	THICKNESS
Ds Organic-rich, finely interbedded, mudstone, siltstone, and sandstone	Delta-plain swamp	Grayish-red purple to reddish-brown to gray-green; abundant organic plant fragments; ripple lamination dominates; common disturbed bedding and intraclasts, generally associated with coarser interbeds; limonitic stains along root traces; variable calcitic cement.	26-43 ft
Fcs Interbedded sandstone and conglomerate	<u>Fluvial/deltaic</u> Channel-fill	Red-brown to gray-green, very micaceous and calcitic with scoured bases and reactivation structures; grain sizes and scale of sedimentary structures decreases upward; common interbeds of siltstone and mudstone and soft sediment deformation structures; conglomerates are reworked carbonate nodules, SRF's, rarely chert and quartz clasts, and commonly large plant fragments.	8-72 ft Genetic units 4-32 ft
Fcm Mudclast siltstone, sandstone, and conglomerate	Mudflat channel-fill	Red-brown to light brown; low-angle cross-stratification normal and inverse grading; thin mudstone interbeds with filled desiccation cracks.	10 ft Genetic units 2 inches to 1 ft
Es Bimodal sandstone with clay illuviation	<u>Eolian</u> Eolian flat	Red-brown; faint ripple forms and burrows; scattered ripup clasts, heavy mineral placers, and coarse-grained, well-rounded sand grains; clay illuviation (pedogenic) structures dominate.	27 ft

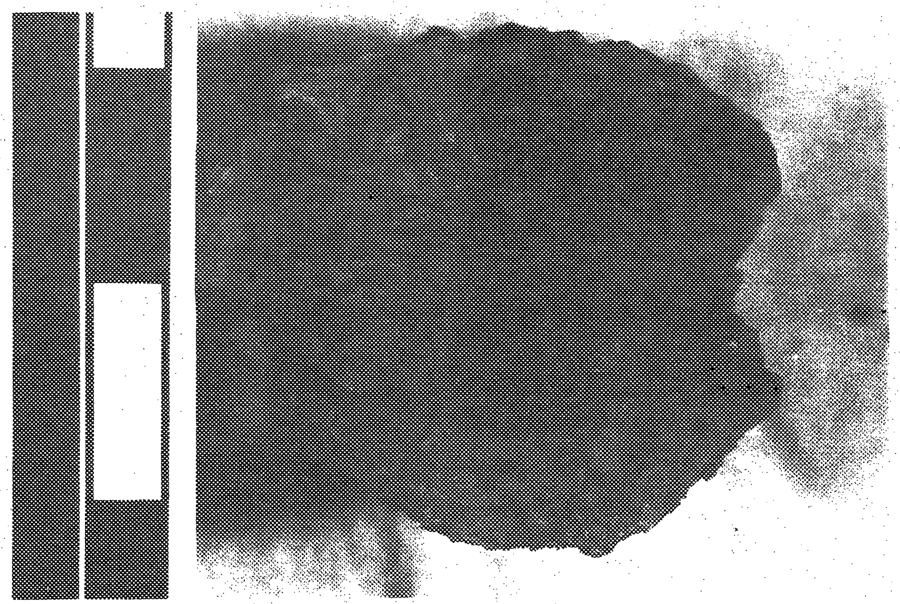

Figure 27. Intensely burrowed claystone, Rex White No. 1 well, Randall County, 291 ft. Burrows of Scoyenia have a maximum diameter of 9 mm. See figure 1 for well location.

suggested as a habitat for Scoyenia by Frey and others (1984). Vertical relationships in core usually show lithofacies Lm alternating between and transitional with delta-front lithofacies (lithofacies Dp and Df). However, abrupt overlying associations with genetically unrelated lithofacies Fcs and Fcm are present. These are presumably the result of local channelization by overlying fluvial systems, although some may be the result of more widespread entrenchment by fluvial systems related to drops in lake level. Lithofacies Lm may also overlie fluvial-deltaic lithofacies Fcs as a result of delta avulsion or rapid lacustrine expansion. In two examples from the Mansfield No. 1 well, swamp lithofacies Ds underlies lithofacies Lm. These probably result from gradual foundering of an abandoned delta lobe or a very gradual rise in lake level.

Brecciated mudstone in lithofacies Lm is less common than the burrowed mudstone and also differs from it in that weathering has almost completely masked all depositional and biogenic structures (fig. 28). An example of this style of lithofacies Lm is in the Grabbe No. 1 well (fig. 14). Delta-front siltstone of lithofacies Df is above and below this interval. The occurrence of delta-front sediments directly on the weathered horizon suggests very rapid progradation following re-establishment of the lacustrine setting, thus preventing accumulation of additional lacustrine mudstone. Some thin horizons similar to this lithofacies occur in the Mansfield No. 1 well, but the brecciation is not as intense, and primary and secondary structures are still visible.

The brecciated mudstone of lithofacies Lm strongly resembles dolomitic mudstones in the Eocene Green River Formation of Wyoming (Smoot, 1983). Smoot interpreted the Green River mudstones to have been deposited by sheetfloods on a subaerially exposed mudflat with varying degrees of reworking by floodwaters. In the Dockum, locally abundant dolomite has been identified with the scanning electron microscope

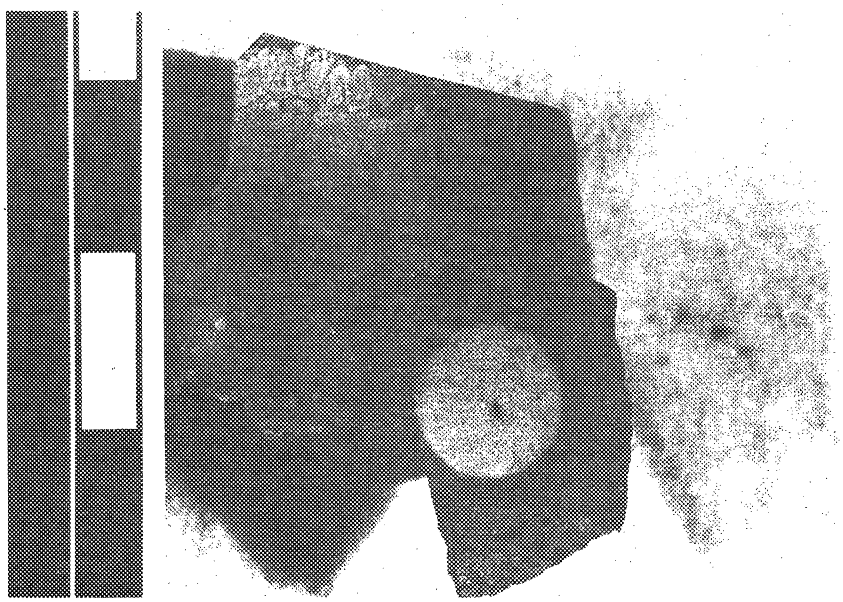

Figure 28. Pervasively brecciated mudstone paleosol, Grabbe No. 1 well, Swisher County, 372 ft, showing reworked calcified mudclasts deposited in fractures. See figure 1 for well location.

(SEM) in core chips of some weathered mudstones from lithofacies Lm, but it is not clear whether the dolomite formed during subaerial weathering or by later diagenetic processes. Subaerial exposure of the Dockum mudstone is suggested by calcification of the mudstone, mudcracks, and the desiccation breccia at the top of the lithofacies. Local reworking by floodwaters or lake waters is indicated by angular and rounded calcitic mud intraclasts deposited in fractures.

Lithofacies Lc is found in the J. Friemel No. 1 well (fig. 18). It consists of massive claystone with 0.5 to 1.0 mm planar laminations of micaceous siltstone. This lithofacies represents lake-center deposits that accumulated away from coarse clastic input. The lack of burrowing may indicate anaerobic bottom conditions. It is overlain by lithofacies 3. Lithofacies 7 underlies this section, suggesting a very rapid increase in lake depth.

Lithofacies Ls, uncommon in core, is characterized by ripple cross-laminated, finely interbedded mudstone and siltstone (table 3). Desiccation cracks suggest at least periodic subaerial exposure, whereas disturbed bedding and load structures indicate periods of rapid deposition of water-saturated sediments. Lithofacies Ls is interpreted to represent sediments deposited either on a lake shore mudflat of a foundering delta or on lacustrine sediments following a drop in lake level and preceding lacustrine transgression. Lithofacies Ls is most commonly underlain by lithofacies Lc, suggesting that lithofacies Lc may be a shallow pond deposit. In one case, lithofacies Ls overlies lithofacies Lc, which overlies lithofacies Fcs. This association suggests that lithofacies Lc may be an abandoned fluvial channel-fill or floodplain deposit. Where lithofacies Df or Dp overlies lithofacies Ls, it suggests a rapid return to high lake levels during which progradation was locally active. Similar rock descriptions and interpretations are reported by Smoot (1983) for the Wilkins Peak Member of the Green River Formation in Wyoming.

Deltaic System Lithofacies

Four deltaic system lithofacies are recognized in core. Lithofacies Dp is characterized by interbedded, cross-stratified, ripple, and ripple-drift cross-stratified siltstone and sandstone (table 3) containing thin beds of conglomerate and mudstone. Mansfield No. 1 and J. Friemel No. 1 wells contain the best examples of this facies (figs. 16 and 18). Individual beds are as much as 75 ft thick and contain many discrete depositional sequences from less than 1 ft to almost 14 ft thick (figs. 29 and 30). Each sequence represents sediment deposited in the delta-front environment during a single depositional event of unknown duration. Lithofacies Lm commonly overlies or underlies lithofacies Dp, although overlying associations with lithofacies Df and Fcs are common in the J. Friemel No. 1.

Lithofacies Df is characterized by interbedded, cross-stratified, ripple, and ripple-drift cross-stratified siltstone and sandstone with thin beds of conglomerate and mudstone (table 3). A well-preserved sequence, for example between 310 ft and 370 ft in Grabbe No. 1 (fig. 14), consists of conglomerate or conglomeratic sandstone of lithofacies Df abruptly overlying lithofacies Dp and grading upward into cross-stratified, soft-sediment-deformed, muddy sandstone with abundant organic fragments and clay intraclasts on bedding planes in lithofacies Df. These are in turn overlain by distributary-channel sediments of lithofacies Fcs. Lithofacies Df is interpreted to have been deposited in proximal delta-front and distributary-channel-mouth-bar environments.

Examples of lithofacies Ds occur in two locations in the Mansfield No. 1 well (fig. 16). In both occurrences these sediments overlie lithofacies Fcs and underlie

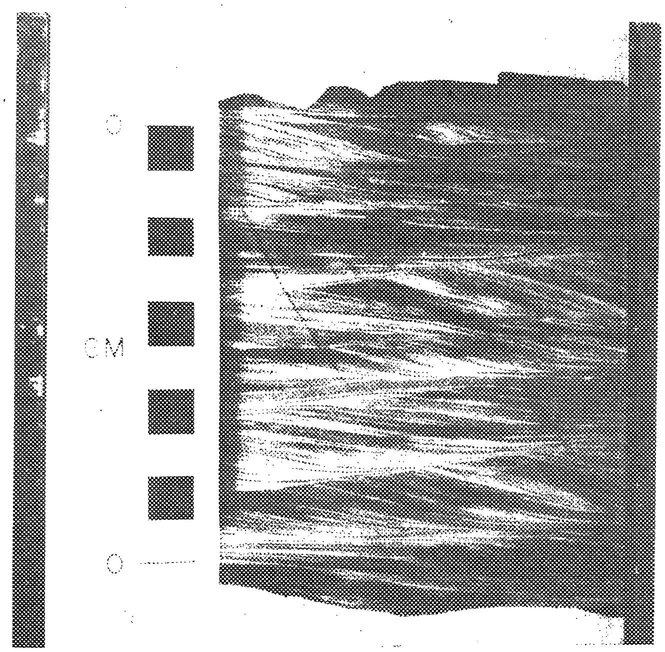

Figure 29. Ripple and ripple-drift cross-stratified siltstone lithofacies 4, Mansfield No. 1 well, Oldham County, 107 ft. Ripples are as much as 2.0 cm high. See figure 1 for well location.

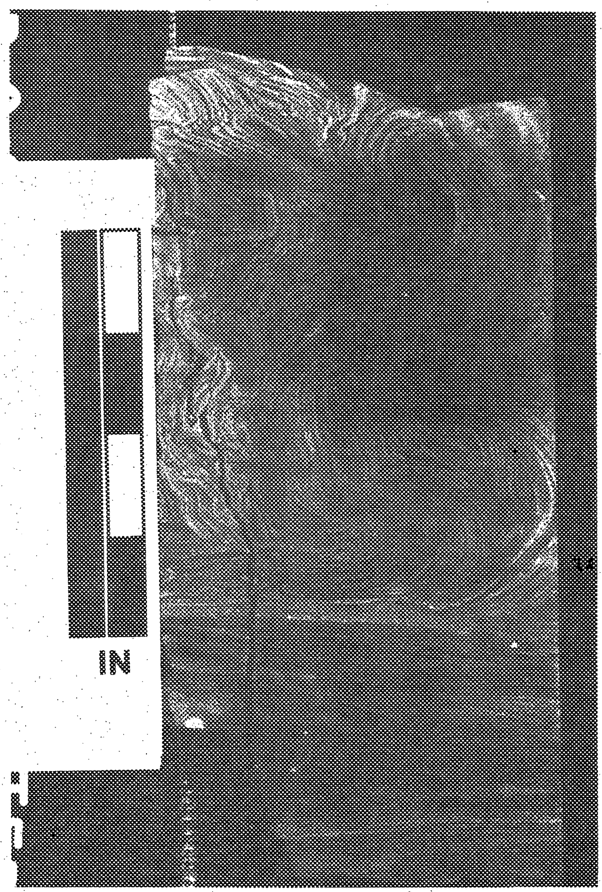

Figure 30. Soft-sediment-deformed interbedded siltstone and mudstone that typically caps lithofacies 4, Mansfield No. 1 well, Oldham County, 302 ft. See figure 1 for well location.

lithofacies Lm. Lithofacies Ds is interpreted to represent marsh or swamp sediments (table 3). Associated lithofacies suggest that lithofacies Ds developed on a foundering delta during or preceding lacustrine transgression. Thickness of this lithofacies indicates that foundering or transgression was slow, allowing sedimentation to keep pace with the relative rise in base level. Delta foundering could be due to abandonment by stream avulsion, decrease in sediment supply, or increase in lake level. In one case, there is a hiatus between deposition of underlying lithofacies Fcs and deposition of lithofacies Ds, during which a silcrete soil horizon developed in lithofacies Fcs sediments. The depositional hiatus could represent prolonged subaerial exposure caused by sediment bypass due to a drop in lake level.

Examples of progradational (regressive) associations seen in core show lithofacies Df overlying lithofacies Lm, Lc, and Dp and underlying lithofacies Fcs (figs. 14, 16, and 18). Other regressive associations show lithofacies Ls underlain by lithofacies Lc and overlain by lithofacies Dp and Df. Regressive associations occur under normal sedimentary conditions where lake levels are fairly constant. Transgressive associations are exhibited by lithofacies Fcs underlying lithofacies Df, Dp, and Lm. Other examples show lithofacies Ds overlying lithofacies Fcs and underlying lithofacies Lm. Transgressive associations occur where lacustrine expansion shifted deltaic facies shoreward, over fluvial facies.

Fluvial-Deltaic System Lithofacies

Lithofacies Fcs, generally equivalent to the sandstone lithofacies in the well log lithofacies, defines the sandstone-rich depositional systems. It is characterized by thick, interbedded sandstone and conglomerate with sharp bases and gradational tops (table 3). This lithofacies is primarily of fluvial origin, but the sedimentologic characteristics are not sufficiently diagnostic to classify it as either fluvial channel or delta distributary channel, and it is rare that distinctions can be made between the two. Outcrop data indicate that equivalents of lithofacies Fcs in sandstone unit 1 and possibly unit 2 intervals of the lower Dockum are bed-load stream deposits, whereas those above (units 3 and 4) are mixed-load stream deposits. The geometry of these sediments, which helps distinguish stream types in outcrop (Seni, 1978), is not discernable in the subsurface. Lithofacies Fcs has characteristics similar to those found in modern fluvial-channel environments (Harms and Fahnestock, 1965; Bernard and others, 1970; McGowen and Garner, 1975).

Lithofacies Fcs most commonly overlies deltaic lithofacies Dp and Df, which suggests that many occurrences of lithofacies Fcs are delta distributary channels. Several examples of lacustrine lithofacies Lm and Lc underlying lithofacies Fcs indicate that fluvial downcutting was a common process during Dockum deposition. Even if in some cases lithofacies Fcs consists of proximal deltaic sediments, these deposits eroded the previously deposited distal delta front siltstone. A variety of lithofacies occur above lithofacies Fcs; deltaic lithofacies Dp and Df are especially common, but lacustrine lithofacies Lm and Lc also regularly occur above lithofacies Fcs. The presence of delta lithofacies overlying fluvial lithofacies indicates that slow lacustrine expansion was common. Lacustrine lithofacies directly over fluvial lithofacies shows that rapid expansion was also a regular occurrence. Some of the overlying muddy lithofacies may be abandoned channel plugs.

One occurrence of lithofacies Fcm is known in core (fig. 16). This lithofacies is interpreted to have formed by bed-load streams moving across a mudflat exposed by a drop in lake level (table 3). It is underlain by a very weathered zone of lithofacies Lm and overlain by relatively unweathered lithofacies Lm. The mudclasts in lithofacies Fcm are derived from the underlying mudstone (fig. 31). Seni (1978) identified a similar deposit in an interdeltaic embayment setting in Palo Duro Canyon. The core example occurs within the sandstone unit (2) correlated with valley-fill sediments in J. Friemel No. 1 core in Deaf Smith County and updip in Palo Duro Canyon. The exposed weathered mudflat may be temporally correlative with the valley incision event.

Eolian System Lithofacies

Lithofacies Es occurs only at the base of the Dockum in the Grabbe No. 1 well (fig. 14). This lithofacies is interpreted to be the result of eolian reworking of distal alluvial fan sediments (table 3). Pettijohn and others (1973) and Folk (1974) characterized eolian sediments as (1) being well sorted, (2) showing an absence of micaceous minerals, (3) having a dull appearance or frosted surface on quartz grains, and (4) having bimodal grain sizes. No distinct eolian ripple forms (Kocurek and Dott, 1981) were identified in core, but a homogeneous fine grain size, the presence of bimodal lags containing well rounded, frosted grains, and the pervasive presence of pedogenic structures suggest that eolian processes were important in the formation of this lithofacies (fig. 32). Small, thin mudstone ripup clasts suggest some sedimentation or reworking by fluvial processes. Sheet-sand flow in desert environments can produce ripple-laminated sand covered by a veneer of mud, later reworked into mud clasts (Smoot, 1983; Sneh, 1983). Similar features also were found by Hubert and Hyde (1982) in semiarid sheet-flow deposits in the Upper Triassic red beds in Nova Scotia. About 2 ft of finely laminated claystone, lithofacies 2, overlies the sandstone. Here, lithofacies 2 possibly represents pond deposits. No core was recovered below this sandstone.

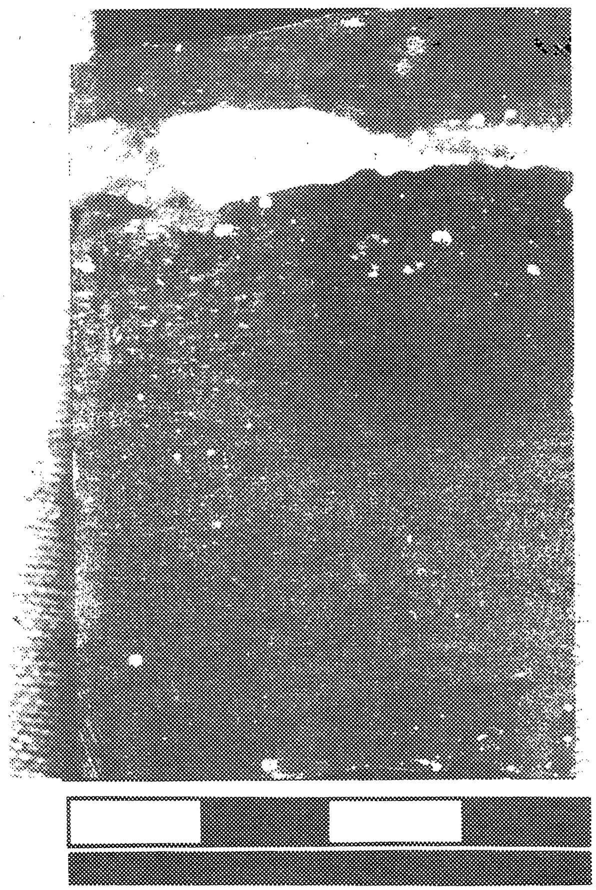

Figure 31. Interbedded silt- to pebble-sized mudclast conglomerate showing normal and inverse grading and filling of desiccation cracks by sand-size mudclasts in Mansfield No. 1 well, Oldham County, 219 ft. See figure 1 for well location.

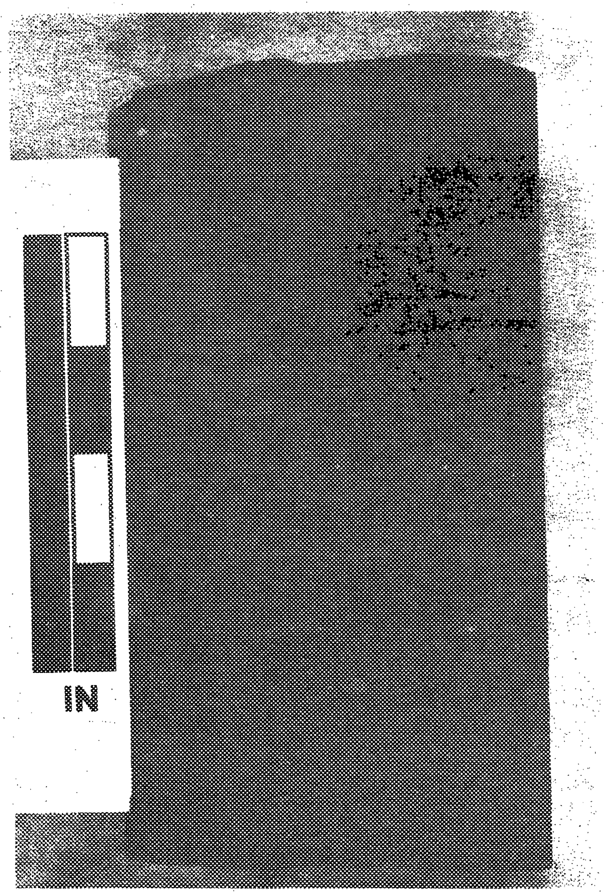

Figure 32. Pedogenic clay illuviation structures in bimodal sandstone from the base of the Triassic, Grabbe No. 1, Swisher County, 771 ft. See figure 1 for well location.

COMPOSITION

Compositional analysis of the Dockum sandstones is still in an early stage. Eighty-six thin sections from the Grabbe No. 1 well have been examined and described. Rock chips from Grabbe No. 1 are currently being examined on the SEM, and some compositional data are being acquired with the SEM by the energy-dispersive spectrometer (EDS) and the electron microprobe.

Dockum sediments are generally texturally and compositionally distinct from sediments lower in the section. They have an overall composition that places them in the litharenite and arkosic litharenite range, their quartz: feldspar: rock fragment (Q:F:R) ratios averaging 55:10:35. This differs from Permian samples, which cluster around a lithic arkose composition with average Q:F:R ratios of 65:22:13. In the Dockum, medium and coarse sand is common, and most grains are angular or subangular. Both potassium- and sodium-rich feldspars are also present. The ratio of feldspar to quartz is significantly higher in Permian rocks than in Dockum rocks. Feldspar is slightly more weathered in Dockum sandstones than in Permian sandstones, but few grains have been entirely removed. Dissolution textures on feldspar grains were found with the SEM. Composite quartz-mica rock fragments are common in the Permian, but show little or no foliation, while Dockum quartz-mica rock fragments have well-developed foliation and are clearly derived from schist, gneiss, and phyllite. Stretched composite quartz and large, fresh flakes of muscovite, chlorite, and biotite are common, also suggesting a metamorphic source.

The basal Dockum sandstone in Grabbe No. 1 is both compositionally and texturally different from the overlying Dockum sediments and is more similar to the underlying Upper Permian rocks. The sandstone is bimodal, with well-rounded supermature, medium-grained sand in a finer, angular sand matrix. The sandstone plots with Permian samples in or near the lithic arkose area of a Q:F:R diagram. Although it can be questioned whether this sandstone is indeed Triassic, its similarity to Permian rocks may be the result of having Permian source beds. Similar observations were made by Page and Adams (1940) and Seni (1978).

Diagenesis of Dockum rocks is the result of post-depositional compaction and mineral reactions with formation waters. Mica flakes and clay chips were deformed by compaction. Coarse, pore-filling sparry calcite is the most common cement, on average filling half of the available pore space. Porosity before cementation averaged 18 percent. Scattered quartz overgrowths are noted from SEM analysis, and kaolinite books are common in zones that correlate with skeletalized plagioclase grains. Dissolution of plagioclase must have occurred after deposition and compaction of the sandstone because the skeletal grains would have been crushed by transportation or overburden pressure. The correspondence in location and amount of skeletal feldspar and kaolinite suggests that dissolution of plagioclase feldspars was the source of the kaolinite. Most Dockum feldspar grains are fresh or slightly sericitized or vacuolized. Authigenic sericite and illite are found coating grains in rock chips. The timing of and relationships among the various diagenetic events are unclear at this time.

STRUCTURE AND TECTONICS

In the Palo Duro Basin, structural features are found to have locally influenced the thickness of total sediment packages, orientation of sandstone trends, and thickness of sandstone units. Analysis of the effects of known basement structures on the Dockum strata has provided guidelines with which to identify areas that may overlie additional basement structures that cannot be positively identified with current well control. By considering individual sandstone depositional units, it is possible to detect the location and timing of structures that localized sandstone accumulation.

Structural Influence on Deposition

Recent studies in the Palo Duro Basin have shown that basinwide sediment thickness trends have shifted through time in response to episodic structural adjustments to regional stresses (Budnik, 1984). Budnik (1983) previously showed the influence of structure on the distribution and facies of strata overlying the Castro Trough and Arney Block in the central Palo Duro Basin. A basement structure map, simplified from Budnik (1984), defines major basin structural elements (fig. 33), not all of which influenced sediment distribution during Dockum time. Intrabasinal structures of particular interest are those well defined in basement and having persistent influence on Dockum deposition, which include the Castro Trough system and adjacent highs, the Arney Block and the south Castro high, and the Littlefield structure, a low-expression, positive feature flanked by structural lows. The consistent local control on deposition exerted by these structures can be used to infer the presence of other basement structures that are not as well defined and yet still apparently affected deposition during the Triassic. The effects of basin-bordering structures such as the Amarillo Uplift are thought to have been minor and at most had slight positive topographic expression and acted as a barrier to fluvial transport systems. The Wichita and Arbuckle Uplifts of the Wichita Mountain system in Oklahoma probably attained greater relief and were an important sediment source for the Dockum in the Palo Duro Basin.

Net-thickness maps of thick intervals of Dockum strata tend to exaggerate structural control of deposition by showing the cumulative effects produced over long periods of time. The total Dockum isopach shows good correspondence with

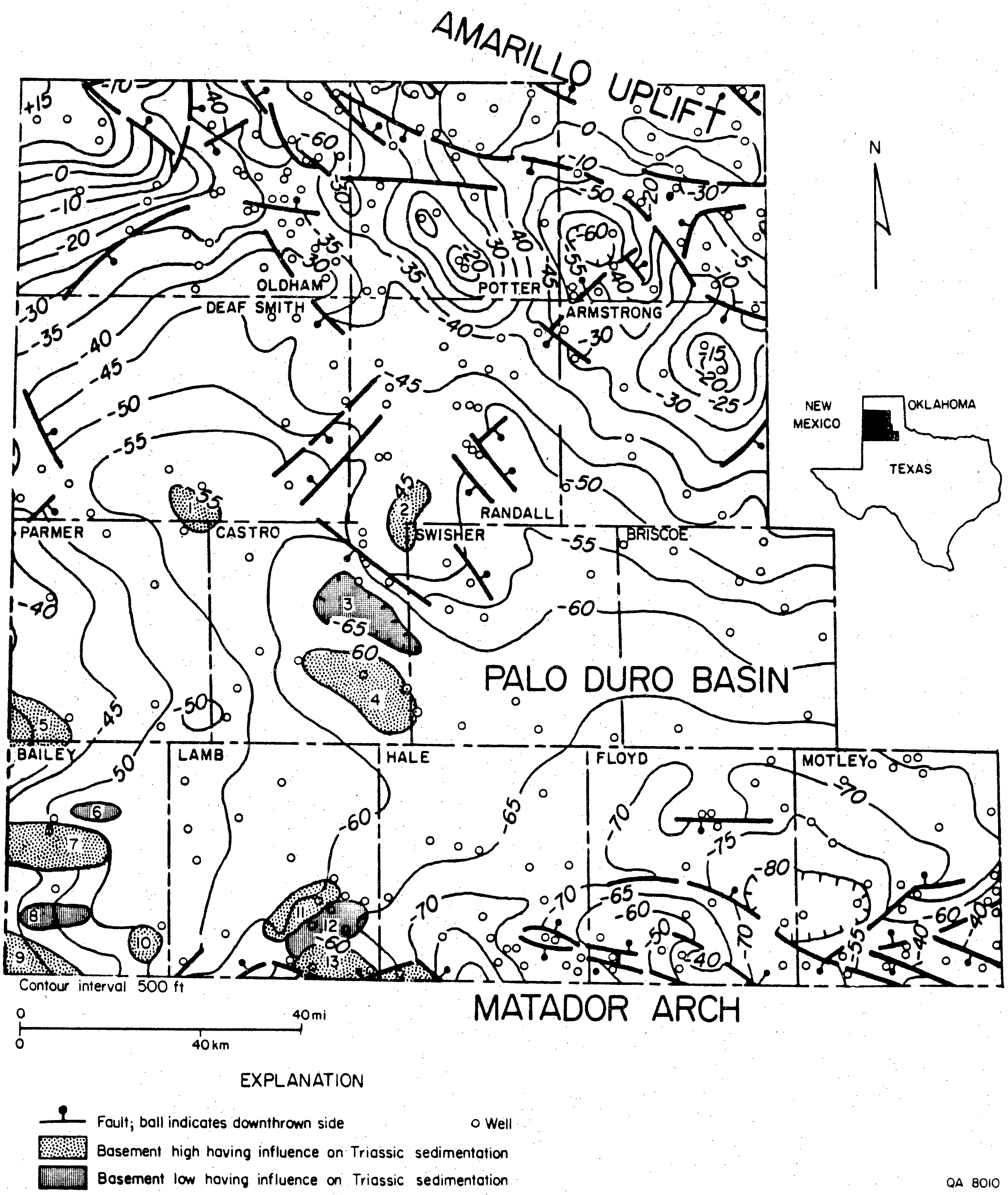

Figure 33. Simplified map of basement elevation (modified from Budnik, 1984). Structure names are mostly informal and intended only to identify structures referred to in the text. Structures are (1) South Deaf Smith high, (2) Arney Block, (3) Castro Trough, (4) South Castro high, (5) Northwest Bailey high, (6) Northwest Bailey low, (7) West Bailey high, (8) Southwest Bailey low, (9) Southwest Bailey high, (10) Southest Bailey high, (11) Littlefield Structure, (12) South Littlefield low, (13) Anton-Irish high.

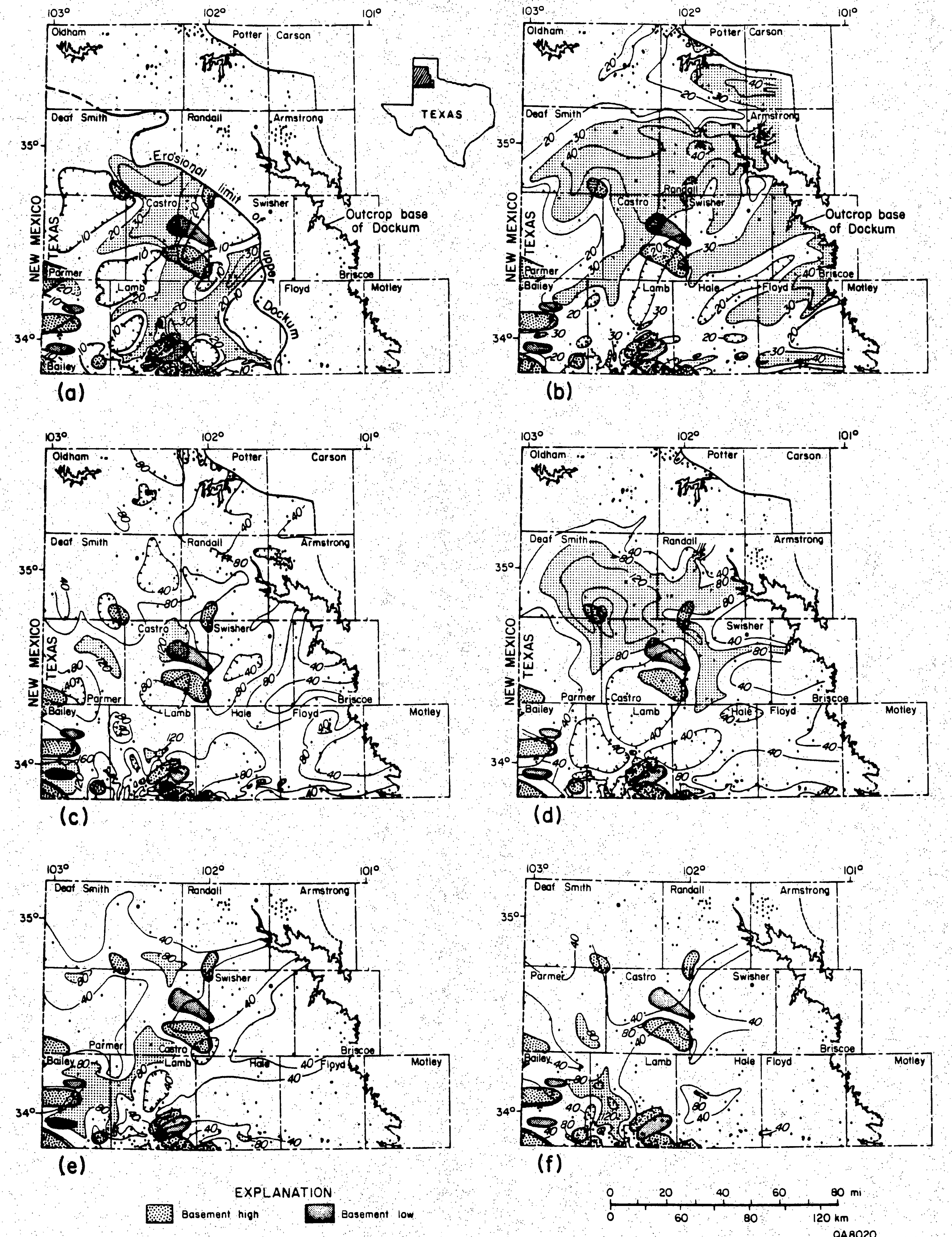

Figure 34. Simplified percent-sandstone and net-sandstone maps with highlighted basement structures. Note the correspondence between basement lows and highs and net-sandstone thicks and thins.

basement structure in the Castro Trough system (fig. 4), even though post-depositional erosion has modified the isopach in southern Castro County. In addition, the Littlefield structural high in Lamb County has a thin cover of Triassic sediments (about 1,300 ft) whereas the structurally lower flanks have thicker deposits (about 1,400 ft). Isopach maps of both the upper and lower Dockum reflect the correlations seen in the total isopach map (figs. 5 and 6). Percent-sandstone maps of both the upper and lower Dockum indicate the role of the Castro Trough system and the Littlefield structure in localizing sandstone accumulation (fig. 34a and b). Localization is achieved in structurally low areas by (1) producing preferred paths for fluvial channels and delta development, and (2) preserving more sandstone by locally increased subsidence.

Net-sandstone maps of the four sandstone units in the lower Dockum display specific examples of the correspondence between structure and sandstone accumulation (fig. 34c-f). Of particular note is the continued role of the Castro Trough system in capturing and funneling sediment through the basin, best illustrated during deposition of sandstone unit 1 (fig. 34a) Graphic examples of greater sandstone thicknesses in the Castro Trough versus the adjacent highs are shown in figures 35 and 36. The Littlefield structure is also a persistent influence in Lamb County, where net sandstone thickens in structural lows on the flanks of the structure and thins across the top (fig. 37). Apparent breaches in the structure, implied by relative sandstone thicks across the top of the structure (fig. 34c), may occupy minor structural lows but are more likely because of the dense well control revealing the complex nature of sandstone distribution.

Several additional poorly defined basement structures are implied by isopach, percent-sandstone, and net-sandstone patterns in the Dockum. Cumulative maps, both isopach and percent-sandstone, show inferred basement structural lows in southwestern

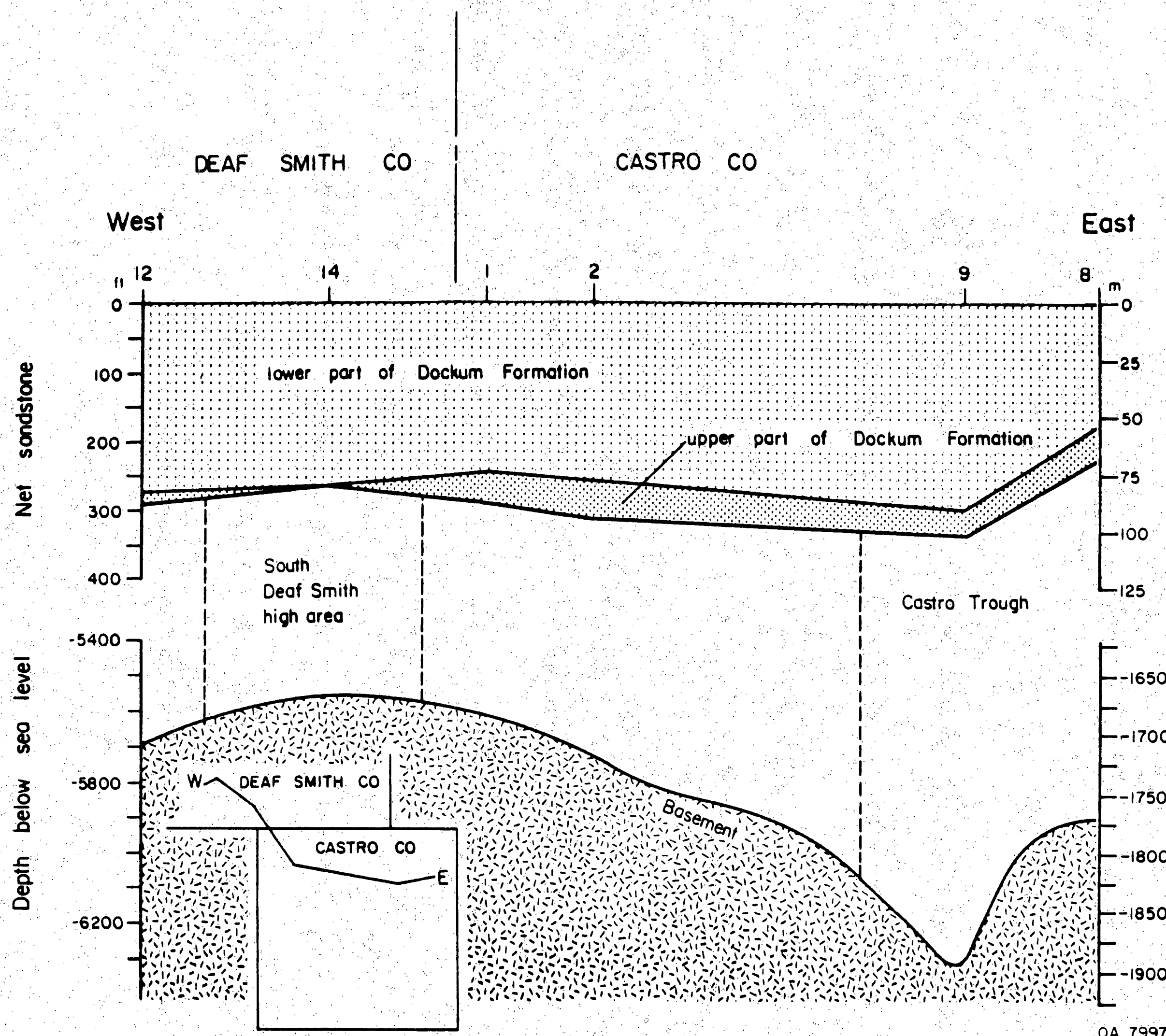

Figure 35. Basement structural profile and net sandstone, Deaf Smith and Castro Counties. Net-sandstone values show good positive correlation with basement highs and lows, particularly with the Castro Trough system.

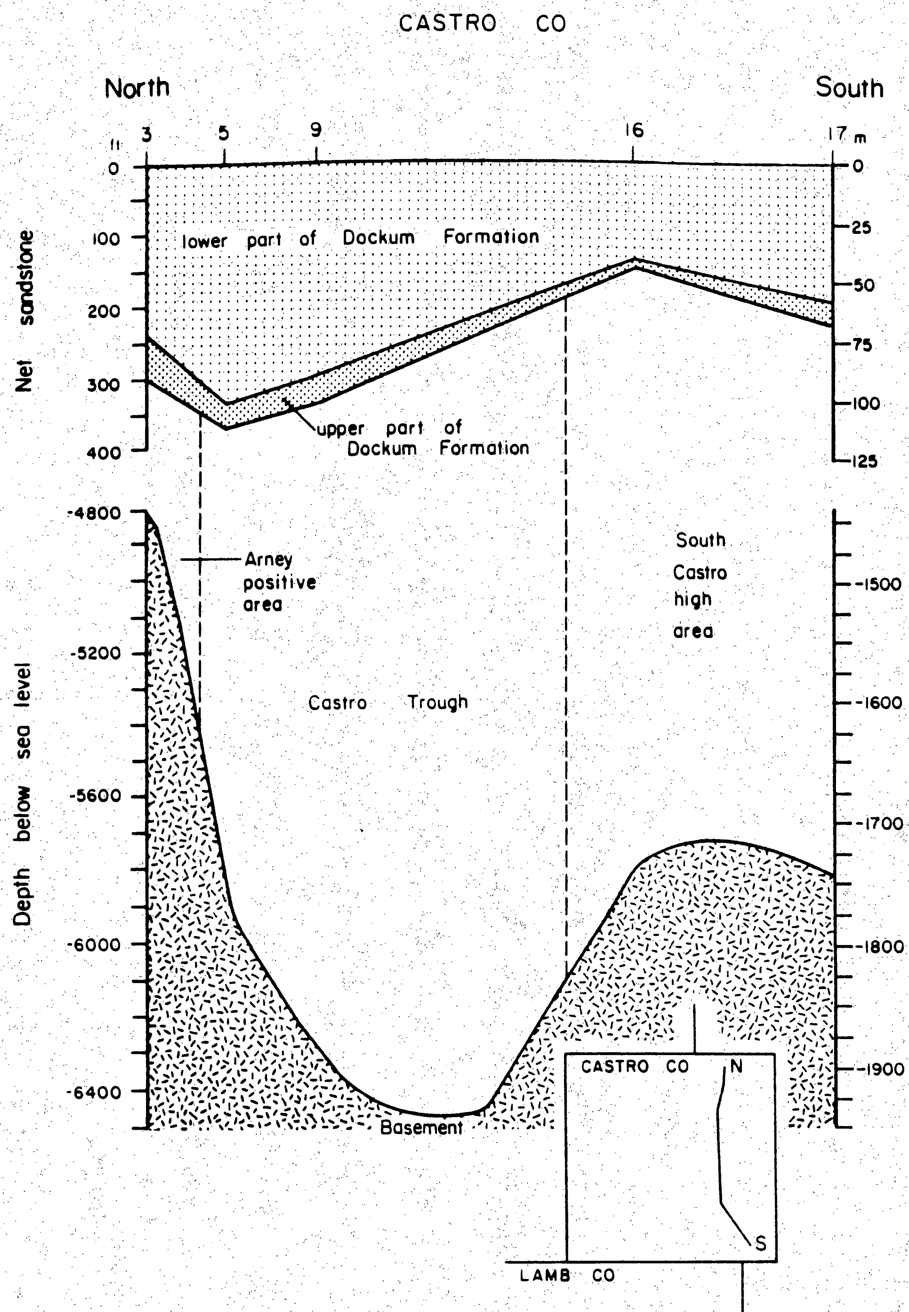

Figure 36. Basement structural profile and net sandstone, Castro County. Net-sandstone values show good positive correlation with the Castro Trough and the adjacent structural highs.

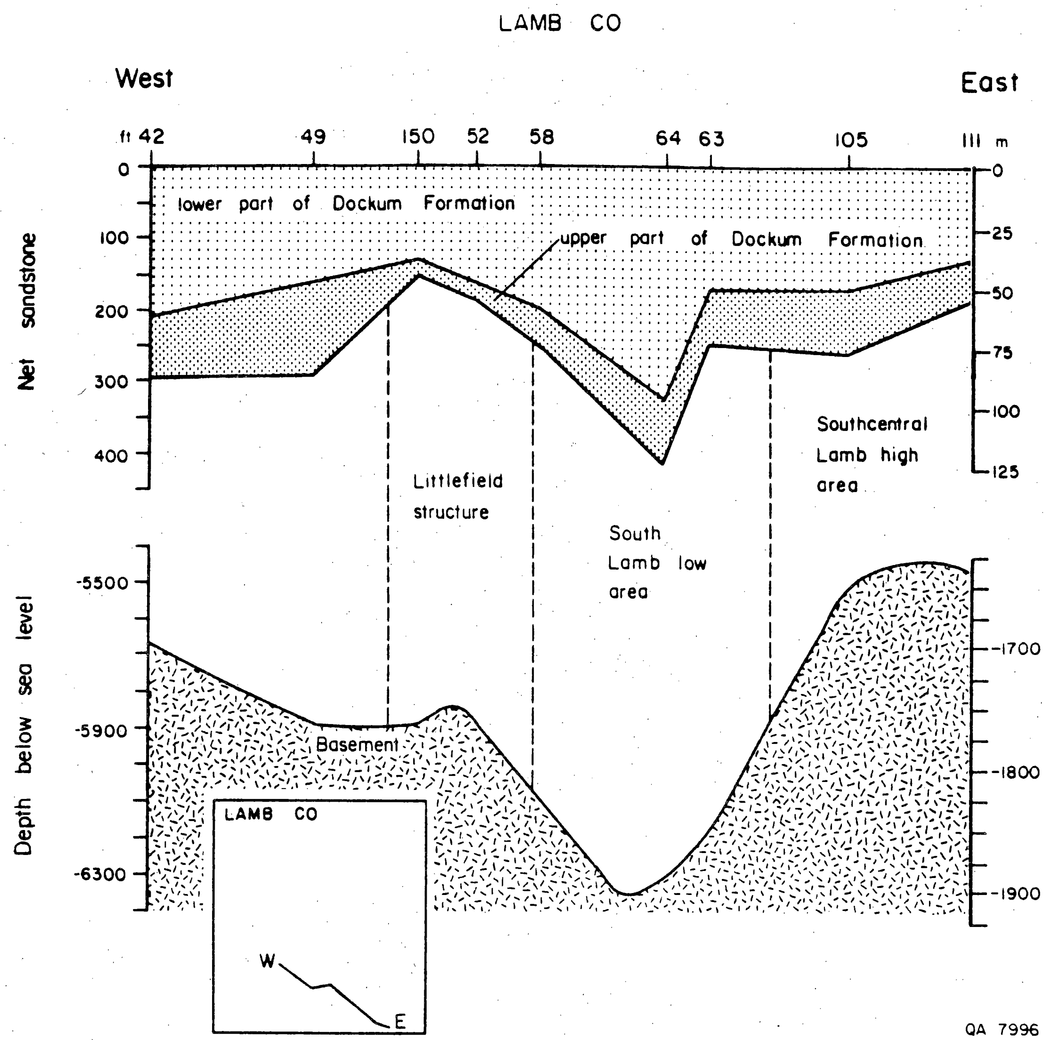

Figure 37. Basement structural profile and net sandstone, Lamb County. Basement highs and lows associated with the Littlefield structure show good correlation with net sandstone values.

and northwestern Bailey County. Structural highs are inferred in western, southwestern, and southeastern Bailey, south-central Deaf Smith, south-central and far southeastern Lamb Counties (possibly part of the Anton-Irish structure). Of these inferred structures, only the northwest low and west high in Bailey and possibly the south Deaf Smith high are discernable on the isopach maps.

The inferred structural highs and lows in Bailey County are reflected in all the net-sandstone maps of the lower Dockum except the northwest low (not showing in unit 2) and the southeast high (not showing in unit 4) (fig. 34c-f). The fact that one basement well shows a low in the vicinity of the inferred northwest low suggests that the structure would be defined if additional well control existed.

The south Deaf Smith high inferred from the Dockum is also present in more detailed maps of the basement (Budnik, 1984), although it has only about 200 ft of relief. Net-sandstone maps of units 1, 2 and possibly 3 show sandstone thinning in the area of the structure (fig. 34c-e). The influence is also hinted at in a profile across the structure showing net sandstone thickness (fig. 35) and in the total isopach map (fig. 4).

The defined basement high in south-central Lamb County shows partial to total correlation with net-sandstone maps. However, several negative correlations with other maps exist. For instance, the basement high shows as a low on structure maps of the base of the Triassic (fig. 3) and on top of the Permian Alibates Formation. It is also a thick on the total isopach map (fig. 4). The inverse relationship over this structure is due to solution of underlying Permian salts following deposition of Dockum units, previously discussed by Johns (1985). Removal of salts would drop and preserve the strata in this area and thus explains why the structure appears as a high with respect to Dockum sandstone distribution and as a low with respect to basal Triassic and upper Permian structure.

Another possible example of inverse relationships occurs in the Anton-Irish area. Net-sandstone maps of all the lower Dockum sandstone units indicate the presence of a structure in the Anton-Irish area (fig. 34c-f). However, in each of these maps the basement high also contains a sandstone thick. These thicks are not in the same wells that reach basement, but the relatively dense Triassic well control may be revealing the complex nature of local sandstone distribution, like that shown for the Littlefield structure.

Reoccurrence of thick, elongate, net-sandstone trends along basement structure lows implies structural control on the location of depositional axes. On the Eastern Shelf of the Midland Basin, Brown (1969) noted that sandstone bodies were vertically offset because of compaction of muddy floodplain and interdeltaic sediments. However, in areas of stacked or multistory sandstone channels, Brown found anomalous deepening of structural gradients into the basin. He inferred that in these areas structure controlled the geometry of the sandstones by locally accelerating the rate of subsidence, thereby creating preferred paths for sediment transport. Similar processes may have caused localization of many of the Dockum sandstone trends.

Source Directions

Previous studies have shown that the Dockum depositional basin was filled from sediment sources to the east, south, west, and north (McKee and others, 1959; McGowen and others, 1979). The Ouachita Tectonic Belt was a proximal source at the southern end of the basin, supplying sediment to adjacent alluvial-fan and fan-delta deposits, and a distal source in the east, supplying braided and meandering stream systems (McGowen and others, 1979). East of the basin, the Wichita and Arbuckle Uplifts contributed large quantities of clastic debris, as did the area of the Sangre de Cristo uplift to the west and northwest.

Rock sources for initial Dockum deposits are thought to be Upper Permian red beds. This view is supported by the presence of well-rounded, coarse sand grains, identical to those found in the Permian, and a bimodal distribution of grain sizes in some lowermost Dockum sandstones (Page and Adams, 1940; Johns and Hovorka, 1984). These rocks plot as subarkose-to-litharenite-to-feldspathic litharenite on Q:F:R diagrams. Permian rocks have similar distribution ratios.

Depositional trends in unit 1, the basal sandstone interval, indicate sediment sources from the east, northeast, northwest, and west (fig. 13). The net sandstone thickness suggests that input was highest from the east and west. In unit 2, trends exhibit the dominance of eastern source areas (fig. 19). These trends are primarily due to incision and backfilling of fluvial valleys in the northeastern part of the basin. Unit 2 may contain the first sediment from the Wichita, Arbuckle, and possibly Ouachita source areas finally reaching the basin and overwhelming locally derived Permian source rocks. Implied sediment sources of unit 3 are also primarily from the east (fig. 20). However, thick accumulations of sandstone in the western part of the basin suggest a significant sediment component from that direction. The sandstone in units 4 and 4a apparently had almost exclusively western sediment sources (figs. 21 and 22). The possible causes of this change in sediment source direction are (1) expansion of the lacustrine basin in the upper part of the lower Dockum, which enabled the relatively close, western-derived systems to prograde into the Palo Duro Basin before the more distant eastern-derived systems, or (2) greater uplift of western sources.

Post-Depositional Structure

Tectonic events following deposition of the Dockum Group have resulted in uplift, tilting, and faulting of the strata. Structure contours on the top of the Triassic trend roughly northeast (fig. 38), approximately parallel to the present topographic surface. This contrasts with the basinal geometry of the structure contours on the base of the Triassic (fig. 3). The trend of the contours on top of the Triassic is generally the same whether the Dockum is overlain by the Miocene Ogallala Formation or the Cretaceous Edwards Limestone, implying that the northwest to southeast slope was present at least by Early Cretaceous time. Hobday and others (1981) report that Dockum sediments were source beds for clasts in the Lower Cretaceous Antlers Formation in North Texas. Cross sections (figs. 25 and 26) show the post-Triassic-pre-Cretaceous erosion surface cutting deepest into Dockum strata in the eastern part of the basin. Gradual subsidence of the rifted margins of the Gulf of Mexico probably caused the initial development of this slope, possibly in combination with uplift of western areas.

In the northern part of the Palo Duro Basin, structure contours on the base of the Dockum strata trend east to west. This cannot be the original configuration of the contours. Analysis of core and outcrops indicates that the sediments were deposited from dip-oriented fluvial-deltaic systems in an east-to-west direction. Reorientation of the contours must have occurred following Triassic deposition. Budnik (1984) reports that the Late Cretaceous to Early Tertiary Laramide Orogeny affected the Palo Duro Basin area. Among the probable effects was uplift along the Amarillo Uplift trend that modified the attitude of the surrounding strata.

CONCLUSIONS

The Triassic Dockum Group is composed of many interbedded sequences of sandstone, siltstone, and mudstone deposited under progradational and transgressive conditions by fluvial, deltaic, and lacustrine systems. These systems deposited

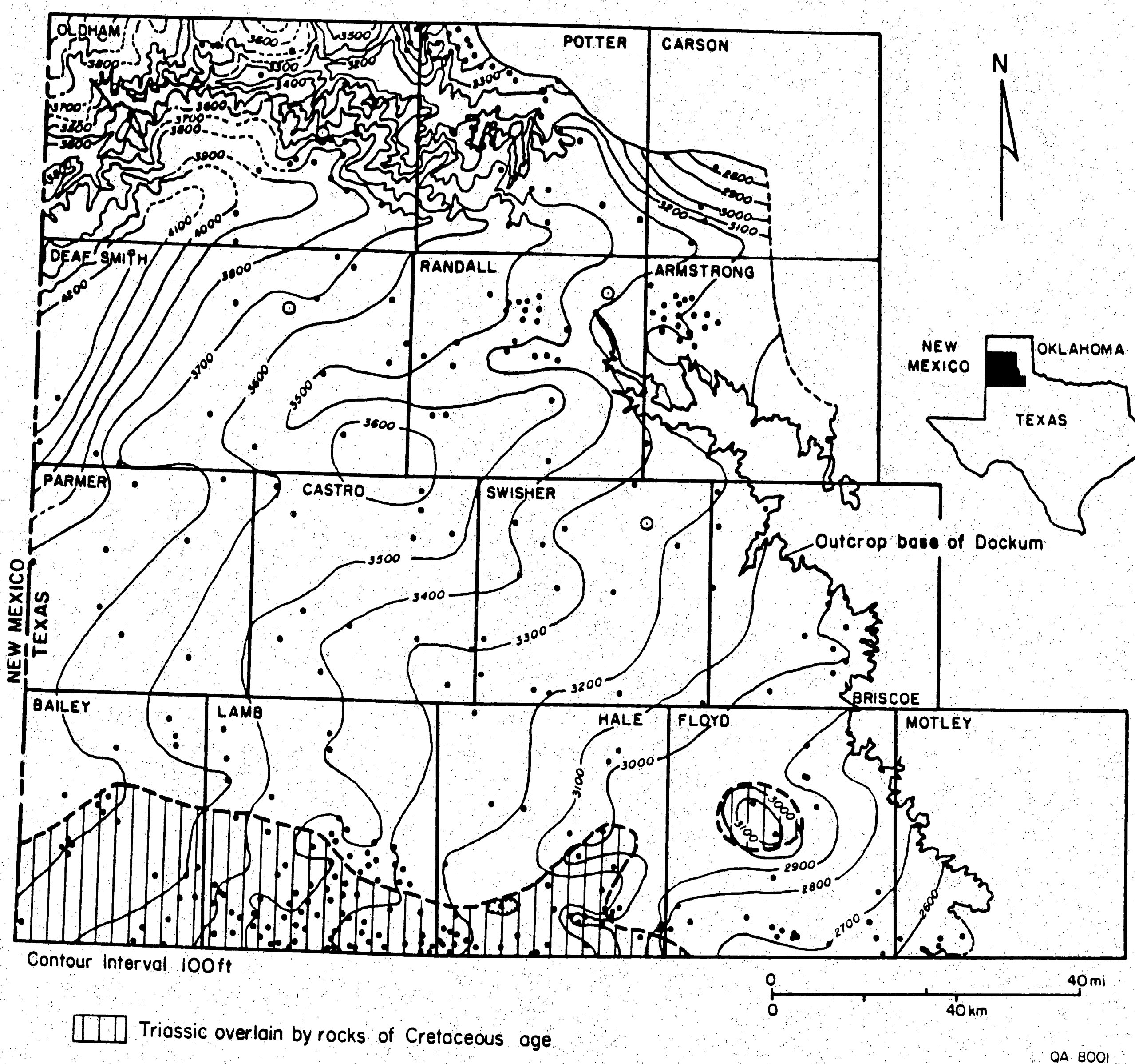

Figure 38. Elevation at top of Dockum Group showing the extent of overlying Cretaceous units. One example of the effect of post-Triassic erosion is the east-west-trending low through Deaf Smith County, which was scoured by pre-Ogallala streams.

sediment in a relatively shallow lacustrine basin under variable climatic conditions. Changes in the amount of rainfall caused lake levels to fluctuate dramatically, giving rise to rapid and abrupt vertical and lateral facies changes and modifying the types of stream systems discharging into the lake.

At least four major progradational events occurred in the lower Dockum of the Palo Duro Basin. The basal unit represents initial Triassic sedimentation in the basin. Net-sandstone maps indicate that sediment sources were from the west, north, and east. Core and outcrop equivalents of this unit suggest that deposition was by alluvial-fan and fan-delta systems on alluvial plains and in a shallow lake basin or in several discontinuous shallow lakes. A widespread siltstone and mudstone between units 1 and 2 thickens to the west and southwest, suggesting an expansion and deepening of the lake system to the west in what is now Bailey and Parmer Counties. Deltaic sedimentation from an eastern source during the second sequence was interrupted by a major fall in lake level, during which entrenched streams carved deep valleys into the underlying strata in updip areas. Cannibalized sediment was redeposited downdip as large areas of lacustrine mudstone were exposed to erosion and subaerial weathering. Subsequent rise in lake level allowed streams to fill the valleys with aggradational bed-load fluvial and transgressive deltaic sandstone deposits.

The upper two sandstone units in the lower Dockum record progradational deltaic sedimentation. Unit 3 is a basinwide progradational event in which sediment emanated from both eastern and western source areas. Core and outcrop equivalents exhibit classic delta-front, delta, and fluvial progradational sequences. Data suggest deposition in deeper lake settings than for previous units. Discontinuous sandstones of units 4 and 4a are derived from mixed western and eastern source areas. Lack of lateral continuity may be partly due to delta abandonment by stream avulsion.

Lithofacies trends suggest, generally, more proximal depositional environments in the eastern and northeastern areas of the basin and distal conditions to the west and southwest. Sandstone lithofacies represent major fluvial channel systems and proximal deltaic environments. These are more common lower in the Dockum and in the east. Mixed sandstone-mudstone lithofacies represent deposition by smaller stream systems, distal deltaic sedimentation. It also may represent deposition during which rapid lake-level fluctuations are common. This lithofacies dominates the upper part of the section and western basinal areas. Mudstone lithofacies represent deposition in very distal deltaic and lacustrine environments. This lithofacies is most common in the upper part of the Dockum section.

Nine lithofacies are recognized in core from the Dockum Group. Claystone, mudstone, and siltstone lithologies are present in the two lacustrine system lithofacies. Dominant sedimentary structures include burrowing, fine lamination, and ripple cross-stratification. Most lacustrine intervals exhibit evidence of varying degrees of subaerial exposure and weathering, ranging from mudstone desiccation cracks to pervasive brecciation, calcification, and reworking of ripup clasts. Four deltaic lithofacies are identified, representing the endpoints of delta evolution. Sequences of ripple and ripple-drift cross-stratified siltstone and soft sediment deformed, interbedded, siltstone and fine- to coarse-grained sandstone represent distal and proximal delta-front lithofacies. Delta abandonment is recorded in mudflat lithofacies of finely interbedded mudstone, siltstone, and sandstone and in marsh or swamp deposits that accumulated on abandoned distributary channel deposits. Two fluvial lithofacies, including delta distributary channels, are thick, interbedded, fine-to-coarse sandstone and conglomerate with upward-fining grain-size trends and sedimentary structures. A single occurrence of a graded mudclast conglomerate suggests deposition by bed-load streams on an exposed mudflat during a period of low lake level. A single eolian lithofacies developed on the distal end of an alluvial-fan deposit.

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