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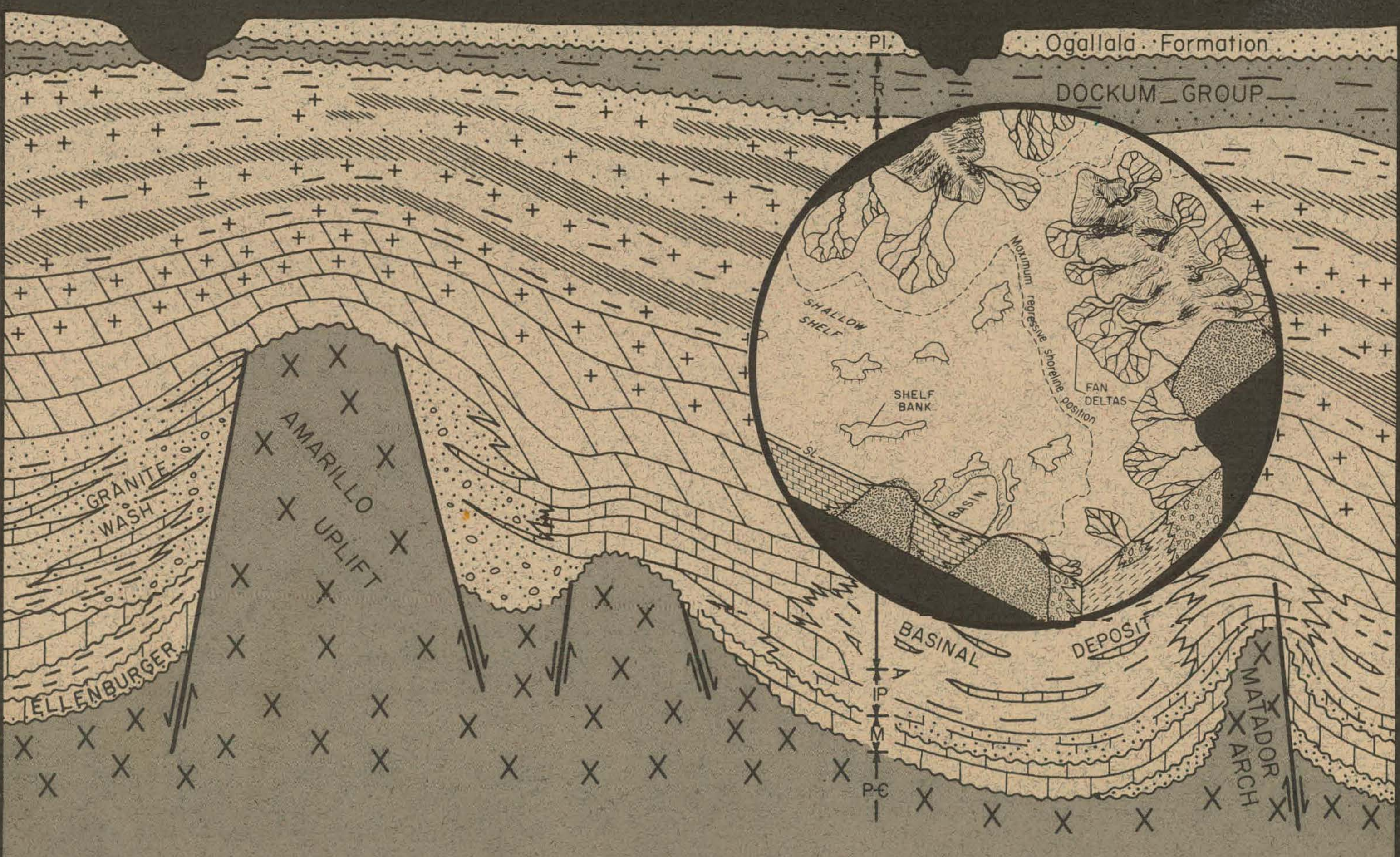
Depositional Systems And Hydrocarbon Resource Potential Of The Pennsylvanian System, Palo Duro And Dalhart Basins, Texas Panhandle

Shirley P. Dutton



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

1980

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DEPOSITIONAL SYSTEMS AND HYDROCARBON RESOURCE POTENTIAL OF THE PENNSYLVANIAN SYSTEM, PALO DURO AND DALHART BASINS, TEXAS PANHANDLE

by

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ABSTRACT

Pennsylvanian clastic and carbonate strata were deposited in a variety of environments within the Palo Duro Basin. Maximum accumulation (totaling 750 m or 2,400 ft) occurred along a northwest-southeast axis. Major facies include fan-delta sandstone and conglomerate, shelf and shelf-margin carbonate, deltaic sandstone and shale, and basinal shale and fine-grained sandstone.

Erosion of Precambrian basement in the adjacent Amarillo and Sierra Grande Uplifts supplied arkosic sand (granite wash) to fan deltas along the northern margin of the basin. Distal fan-delta sandstones grade laterally and basinward into shallow-shelf limestone. Deep basinal shales were deposited only in a small area immediately north of the Matador Arch.

Increased subsidence deepened and enlarged the basin throughout late Pennsylvanian time. Ultimately, the basin axis trended east-west with a narrow northwest extension. A carbonate shelf-margin complex having 60 to 120 m (200 to 400 ft) of depositional relief developed around the basin margin. The eastern shelf margin remained stationary, but the western shelf margin retreated landward throughout late Pennsylvanian time. Porous, dolomitized limestone occurs in a belt 16 to 32 km (10 to 20 mi) wide along the shelf margin. High-constructive elongate deltas prograded into the Palo Duro Basin from the east during late Pennsylvanian time. Prodelta mud and thin turbidite sands entered the basin through breaks in the eastern carbonate shelf margin.

Potential hydrocarbon reservoirs are shelf-margin dolomite, fan-delta sandstone, and high-constructive delta sandstone. Basinal shales are fair to good hydrocarbon source rocks on the basis of total organic carbon content. Kerogen color and vitrinite reflectance data indicate that source beds may have reached the early stages of hydrocarbon maturation.

INTRODUCTION

The Pennsylvanian System of the Palo Duro and Dalhart Basins consists of a subsurface sequence of carbonate and terrigenous clastic rocks. Terrigenous clastics were deposited in fan deltas, alluvial fans, and high-constructive deltas. Carbonates were deposited in shallow marine environments away from centers of clastic deposition. Thick shelf-margin carbonates developed around the margin of a deeper marine environment. Pennsylvanian strata record the initial formation and subsequent subsidence of the Palo Duro Basin and its northern extension, the Dalhart Basin.

Objectives

This study had three major objectives. The first was to identify and map the depositional systems, both terrigenous clastic and carbonate, that compose the Pennsylvanian System. Depositional systems are informal rock-stratigraphic units consisting of an assemblage of process-related facies (Fisher and McGowen, 1967). They are the stratigraphic equivalents of major geomorphic units, such as deltaic, fluvial, or slope systems. Delineation of depositional systems active during the Pennsylvanian Period permits reconstruction of paleogeography and improves capability to predict facies distribution, physical properties, and geometries.

The second objective was to document the development of these shallow cratonic basins. The Palo Duro and Dalhart Basins were formed by the uplift of structural highlands around the area and by crustal downwarping. Distribution of depositional environments was in response to basin evolution during Pennsylvanian time. Reconstruction of the depositional history of the Palo Duro and Dalhart Basins provides a model for interpreting other shallow cratonic basins.

The final objective was to evaluate the resource potential of Pennsylvanian rocks. The Palo Duro Basin is located between two prolific hydrocarbon-producing basins, the Midland and Anadarko Basins, but it has not been as productive as these basins. Detailed stratigraphic analysis delineated potential hydrocarbon reservoir facies in the Palo Duro and Dalhart Basins and located possible stratigraphic trapping configurations. Recognition of the diagenetic history of the sediments helps to predict porosity distribution. These methods were used to delineate areas with the best hydrocarbon potential.

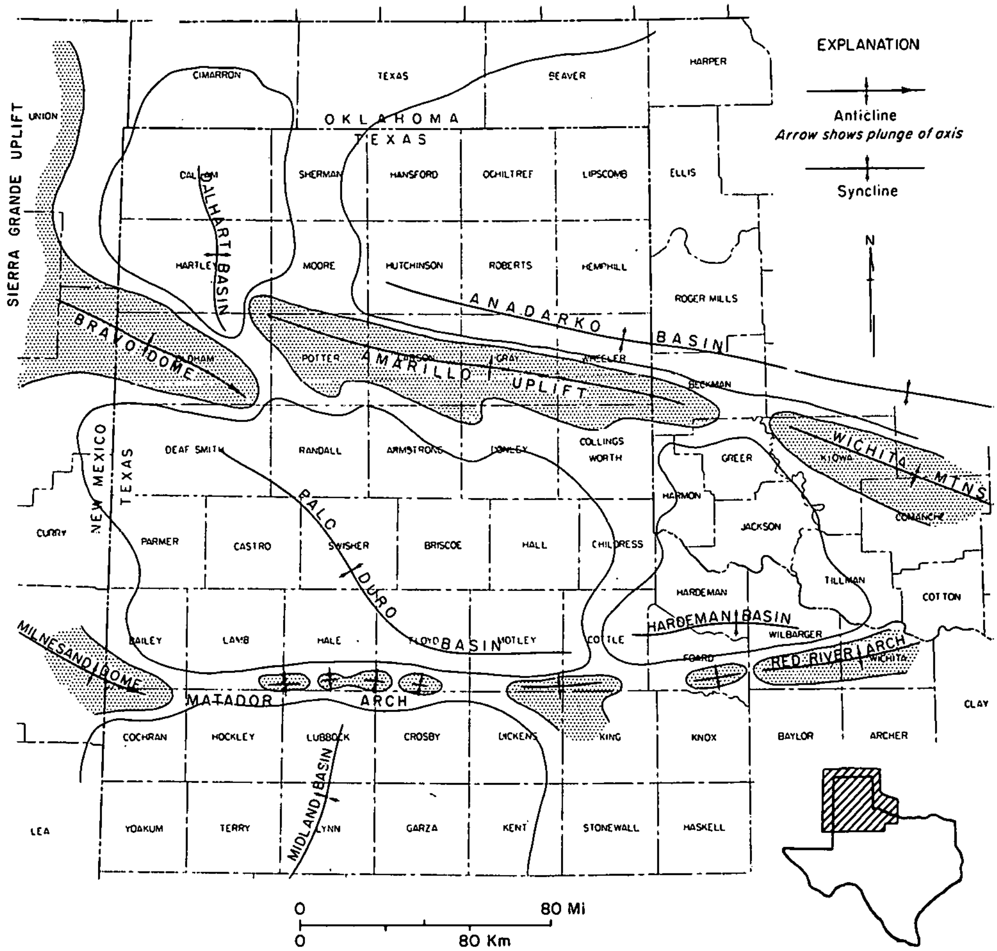


Figure 1. Structural elements of the Texas Panhandle and location of study area (after Nicholson, 1960).

Methods

The area of investigation includes approximately 67,000 km^2 (26,000 mi^2) in all or parts of 32 counties in the Texas Panhandle (fig. 1). Because there are no surface outcrops of Pennsylvanian strata in the area, only subsurface methods were used. In the Palo Duro and Dalhart Basins the data base contains logs from all wells that have been drilled. In those counties over the Matador Arch and Amarillo Uplift where hydrocarbon production is present, data from all wildcat wells and from selected field wells were used. Geophysical logs are available from 520 wells penetrating the top of the Pennsylvanian. Sample logs are available from 247 of the 338 wells penetrating the entire Pennsylvanian section. Electric logs are the most common geophysical logs, but some gamma ray, laterolog, sonic, density, and neutron logs were also used. Cuttings and cores were available from the Bureau of Economic Geology Well Sample and Core Library at the Balcones Research Center in Austin.

Several east-west and north-south stratigraphic cross sections were constructed across the basin (fig. 2). Well names and operators for wells used in cross sections illustrated in this

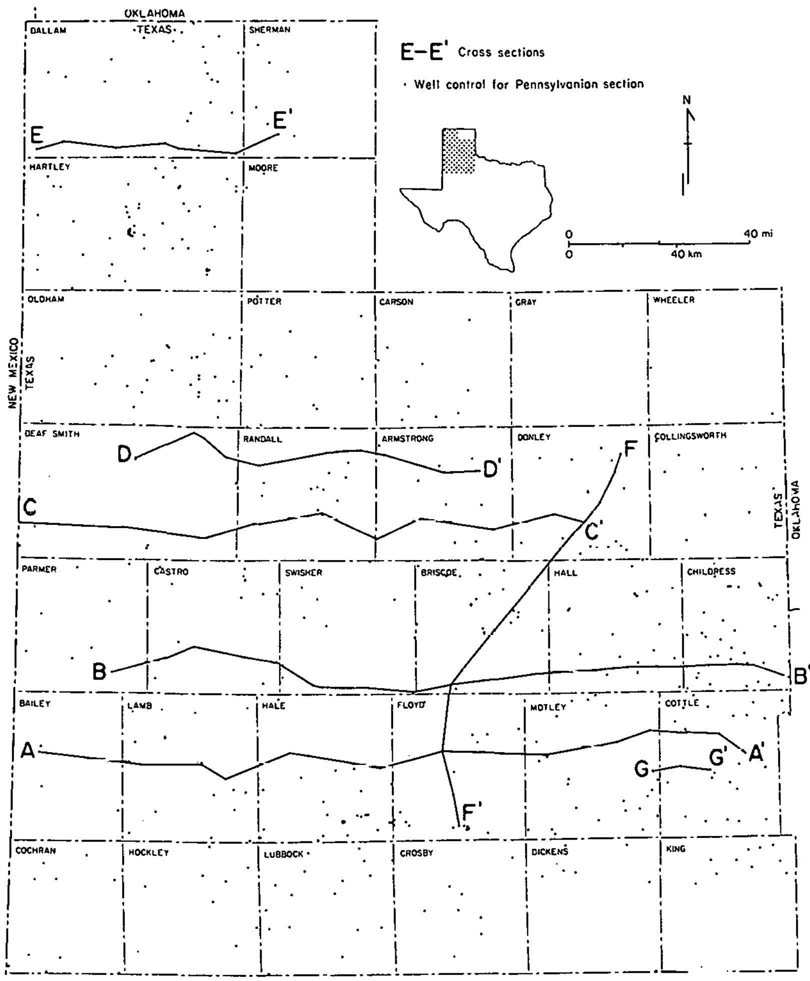


Figure 2. Index map of study area showing well control and locations of cross sections in this report.

report are listed in table 1. Standard subsurface geological methods were employed in the construction of maps and cross sections used in interpreting Pennsylvanian depositional systems, facies, and the structural framework of the basin.

Geochemical analyses were performed by Geo-Strat Inc., Houston, Texas.

Regional Setting

The Palo Duro and Dalhart Basins are located almost entirely within the Texas Panhandle and are surrounded by structural highs (fig. 1). The Amarillo Uplift and Bravo Dome (Oldham Nose) bound the Palo Duro Basin on the north. A narrow trough between these features connects the Dalhart Basin to the Palo Duro Basin. The Sierra Grande Uplift and Milnesand Dome (Roosevelt Positive) form the western basin margin; the Matador Arch is the southern boundary. To the east, the Palo Duro Basin merges with the Hardeman Basin, which bridges Texas and Oklahoma.

The Palo Duro Basin contains rocks from Precambrian to Plio-Pleistocene age (fig. 3). A basal Cambrian (?) sandstone is the oldest stratigraphic unit in the basin. This sandstone is

Table 1. Wells used on cross sections in this report. Well names and operators correspond to the Bureau of Economic Geology numbering system.

County	BEG number	Operator	Well name	County	BEG number	Operator	Well name
Armstrong	3	Pelican Production	#1 Durett	Donley	16	Stanolind	#1 W. J. Lewis
	8	Placid Oil	#1 Matheson		18	Magnolia Petroleum	#1 W. J. Lewis
	10	Stanolind	#1 A. Corbin		26	Underwood & Corsica Oil	#1 V. W. Carpenter
	16	Hassie Hunt Trust	#1 J. A. Cattle		28	Alan Drilling	#1 Sharret Myers
	22	W. V. Harlow	#1 Mattie Hedgecoke		38	J. S. Michael	#1 Thelma Clements
	23	Burdell	#1 McGehee	Floyd	8	Cockrell Corp.	#1 Mize
Bailey	8	Lion Oil	#1 Birdwell		9	Cockrell Corp.	#1 Moss
Briscoe	7	H. L. Hunt	#3 Ritchie		13	Cockrell Corp.	#1 Karstetter
	13	W. J. Weaver	#1 Adair		27	Roy Furr	#1 Battey
	21	Cockrell	#1 Allard	Hale	5	Mason and Walsh	#1 Harrell
	23	Amerada	#1 Hamilton		10	Amerada Petroleum	#1 Kurfees
Castro	11	Sun Oil	#1 Herring	Hall	18	Amerada Petroleum	#1 Lafayette Hughes
	13	Amarillo Oil	#1 L. C. Boothe		22	R. D. Gunn	#1 T-Bar Ranch
	16	Ashmun & Hilliard	#1 J. L. Merritt	Lamb	9	H. L. Hunt	#1 Robertson
	18	Anderson-Prichard	#1 Fowler-McDaniel		15	W. K. Young	#1 F. R. Wilson
Childress	37	Perkins-Prothro	#1 Howard		26	Stanolind	#1 J. W. Hopping
	48	U. H. Griggs	#1 Smith	Motley	6	Humble	#2-C Matador
	49	Sinclair Oil	#1 Willard Mullins		7	Humble	#1-C Matador
	74	British-American	#1 E. V. Perkins		10	Amerada Petroleum	#1 O. E. Birnie
Cottle	17	Great Western	#1 Portwood		16	Humble	#1-H Matador
	22	Sun Oil	#1 Hughes	Parmer	10	Sunray Oil	#1 Kimbrough
	26	Texas Co.	#1 Payne	Randall	1	Frankfort Oil	#1 H. L. Erwin
	37	Humble	#J-1 Matador		5	Frankfort Oil	#1 Rex White
	38	Humble	#J-2 Matador		10	Placid Oil	#1 Greeley
Dallam	40	Sun Oil	#1 Bagot		20	Hassie Hunt Trust	#1 L. B. Carruth
	41	Skelly	#1 Dixon		22	Frankfort Oil	#1-B Stinnett
	42	FWA Drilling	#1 Johnson	Sherman	47	Cities Service	#2-A Buckles
	43	Skelly	#1 Noble	Swisher	10	Consolidated Gas	#1 Patton
	44	Cities Service	#1-A Backus		12	Frankfort Oil	#1 Sweatt
	46	Pure Oil	#1 Cleavenger		13	Sinclair Oil	#1 Savage
Deaf Smith	1	Frankfort Oil	#1 J. F. Coffee				
	3	N. B. Hunt	#1 Overstreet				
	5	Frankfort Oil	#1 Muse				
	7	Humble	#1 R. J. Hyslop				
	12	Honolulu Oil	#1 Ponder				
	15	Ashmun & Hilliard	#1 Oppenheim				

overlain by Lower Ordovician dolomite of the Ellenburger Group. Post-Ellenburger Ordovician, Silurian, and Devonian strata are absent, so that Mississippian carbonates unconformably overlie the Ellenburger Group. An unconformity separates Mississippian and lowest Pennsylvanian strata; Pennsylvanian and Permian rocks are conformable. Post-Paleozoic strata consist of Triassic and Plio-Pleistocene continental sediments, remnants of marine Cretaceous rocks, and Quaternary alluvium (Dutton and others, 1979).

PRE-PENNSYLVANIAN HISTORY

The Palo Duro and Dalhart Basins developed early in the Pennsylvanian Period. Prior to basin subsidence, the area was a stable, shallow shelf periodically covered by epicontinental

Figure 3. Stratigraphic chart and general lithology of the Palo Duro Basin (after Handford and Dutton, 1980).

System	Series	Group	General lithology and depositional setting
Quaternary			Fluvial and lacustrine clastics
Tertiary			
Triassic		Dockum	Fluvial-deltaic and lacustrine clastics
Permian	Ochoa		Sabkha salt, anhydrite, red beds, and peritidal dolomite
	Guadalupe	Artesia	
		Pease River	
	Leonard	Clear Fork	
		Wichita	
	Wolfcamp		Shelf and shelf-margin carbonate, basinal shale, and deltaic sandstone
Pennsylvanian	Virgil	Cisco	
	Missouri	Canyon	
	Des Moines	Strawn	
	Atoka	Bend	
	Morrow		
Mississippian	Chester		Shelf carbonate and chert
	Meramec		
	Osage		
Ordovician		Ellenburger	Shelf dolomite
Cambrian			Shallow marine (?) sandstone
Precambrian			Igneous and metamorphic

seas. To the northeast, in what is now the Anadarko Basin, the Southern Oklahoma Aulacogen was rifted initially in Cambrian time and subsequently subsided from Late Cambrian to Mississippian time (Wickham, 1978). Thick sections of sediment were deposited in the aulacogen, but fewer sediments accumulated on the adjacent shelf in the Palo Duro area. The oldest sediments in the Palo Duro Basin are arkosic and glauconitic sandstones, which probably were deposited in the Late Cambrian (Birsa, 1977). These basal sandstones are restricted to two areas in the eastern and southern parts of the Palo Duro Basin (fig. 4).

By Ordovician time the entire area had been inundated, and shallow-shelf carbonates were deposited. Rocks of the Lower Ordovician Ellenburger Group are preserved in the eastern and southwestern parts of the Palo Duro Basin and in the Dalhart Basin (fig. 5).

Upper Ordovician, Silurian, and Devonian strata in the Palo Duro Basin either have been eroded or were never deposited. A broad arch, the Texas Peninsula (Adams, 1954), which trended north-northwest through the central part of the present Palo Duro Basin, was uplifted after deposition of the Ellenburger Group. Lower Paleozoic rocks on the arch were eroded, and basement was exposed along the crest of the arch. Isolated remnants of Upper Cambrian basal sandstone and Ellenburger strata occur along the eastern and western flanks of the former arch (figs. 4 and 5).

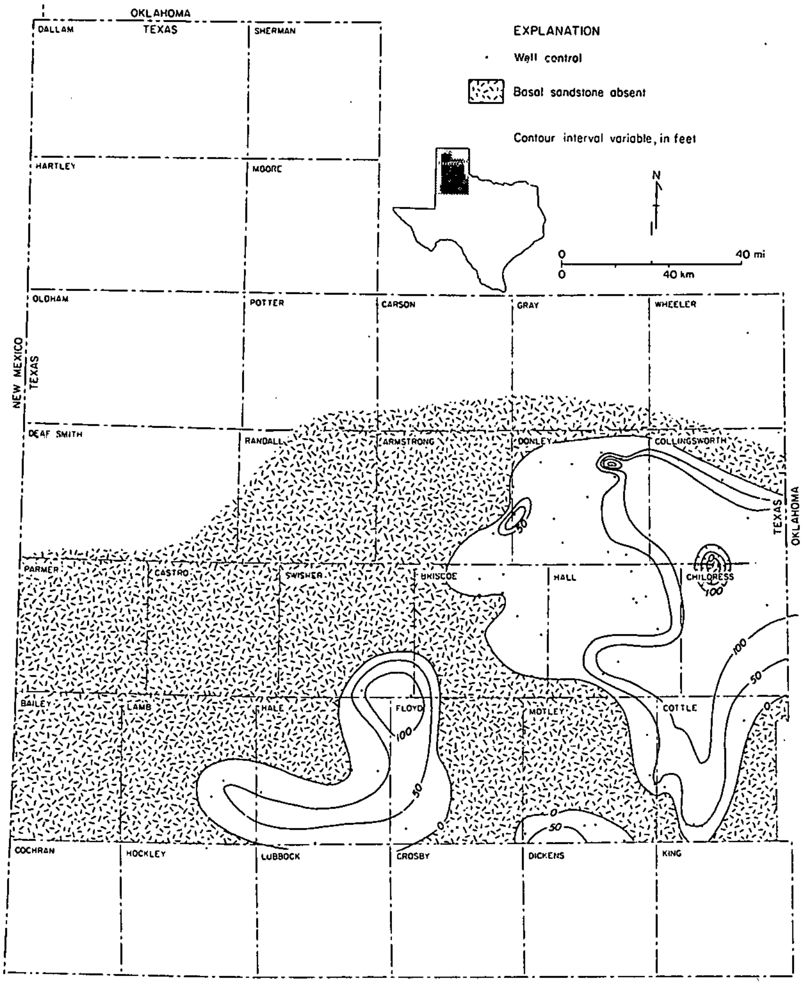


Figure 4. Isopach map of Cambrian (?) sandstone, which directly overlies Precambrian basement. (Map by M. A. Bauer.)

By Mississippian time the Texas Peninsula was no longer a positive element, and marine-shelf carbonates were deposited across the entire region. A maximum thickness of 330 m (1,110 ft) of Mississippian rocks occurs in Childress County (fig. 6). Like those of the Ellenburger Group, Mississippian deposits formed in a shallow marine-shelf environment. Carbonates in the lower part of the Mississippian sequence, mainly in the western and northern parts of the Palo Duro Basin, have been dolomitized.

TECTONIC ACTIVITY

The early Paleozoic was a period of tectonic stability in the Palo Duro region, characterized by alternating shallow marine deposition and subaerial exposure. Tectonic activity was limited to warping of the Texas Peninsula. The major structural elements of the Panhandle developed during late Mississippian and Pennsylvanian time (Nicholson, 1960).

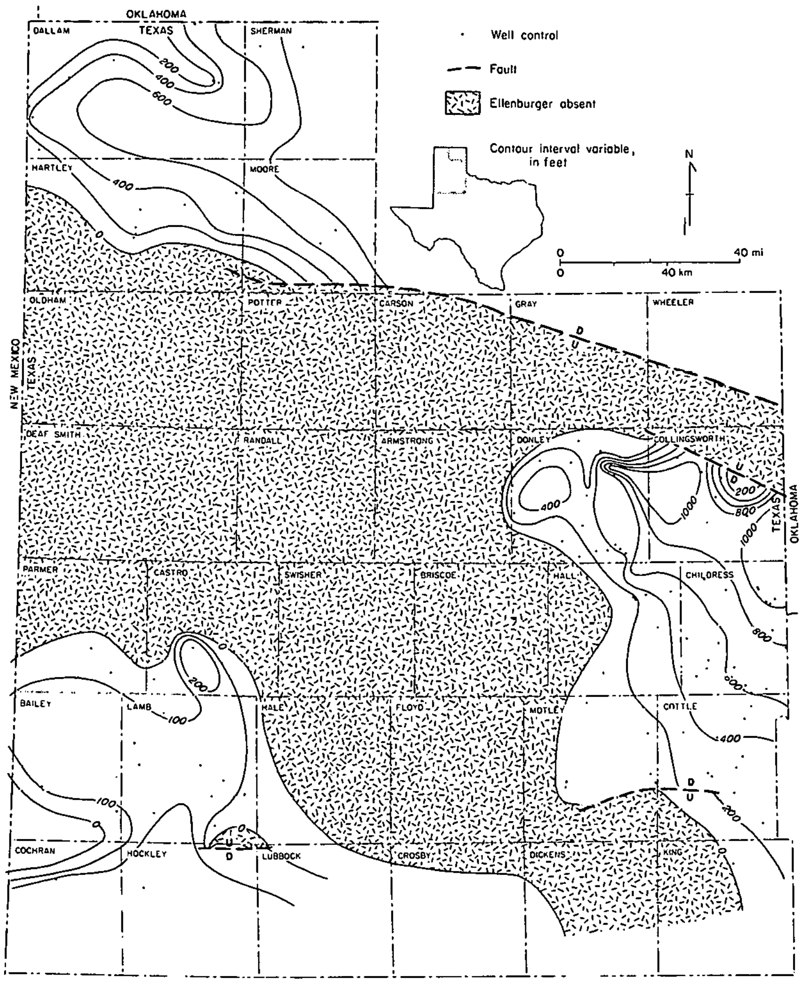


Figure 5. Isopach map of Lower Ordovician Ellenburger Group. (Map by M. A. Bauer.)

The Palo Duro and Dalhart Basins, the Amarillo Uplift, and the Matador Arch are clearly defined by maps showing Precambrian basement structure (fig. 7). The Palo Duro Basin is relatively shallow; Precambrian basement generally occurs less than 3,000 m (10,000 ft) below the surface. The Palo Duro is an asymmetrical basin, its deepest part occurring just north of the Matador Arch.

High-angle faults with large displacements occur along the north side of the Amarillo Uplift. Most fault movement occurred in the early Pennsylvanian (Morrowan), but some displacement continued throughout the Pennsylvanian (Nicholson, 1960). The Matador Arch, which also formed in early Pennsylvanian time, consists of several separate, uplifted blocks trending in an east-west direction. Several smaller northwest- to southeast-trending faults occur just south of the Amarillo Uplift, in the northeastern Palo Duro Basin. Most of the basin lacks evidence of significant faulting.

Faulting in the basin occurred during deformation of the Southern Oklahoma Aulacogen. Deformation of the aulacogen and formation of the Panhandle structural elements coincided

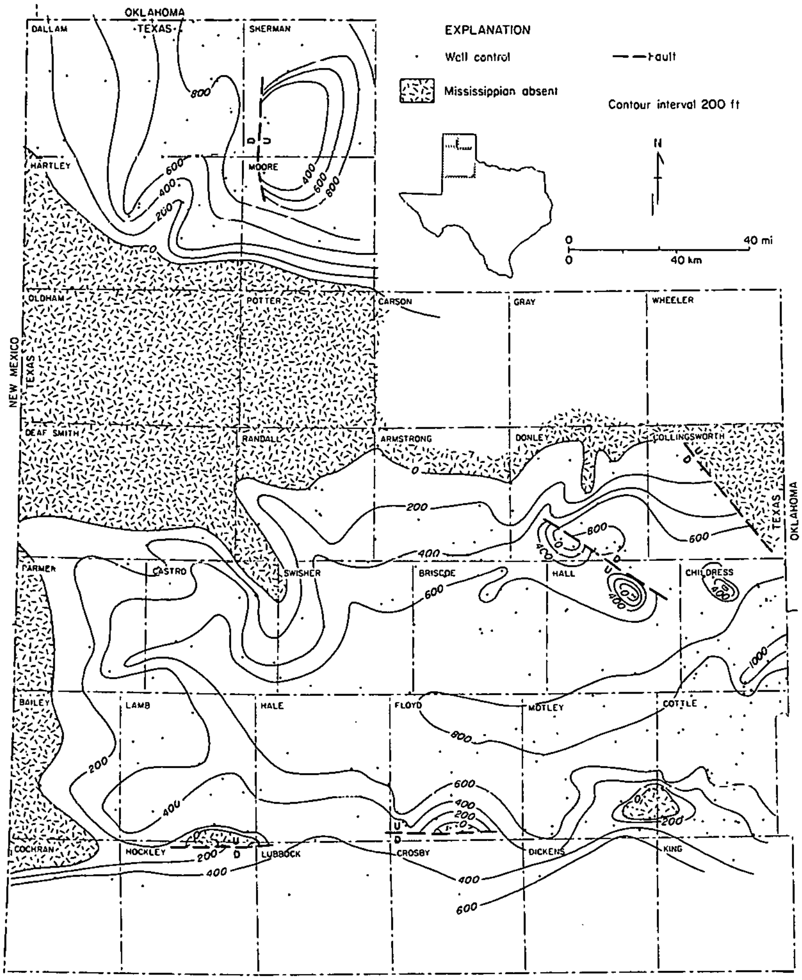


Figure 6. Isopach map of Mississippian System. Mississippian rocks have been eroded from structural uplifts. (Map by M. A. Bauer.)

with the inferred closing of the Paleozoic Gulf of Mexico (Walper, 1976). Major continental collision may have deformed the southern continental margin (Burgess, 1976), including the Ouachita System and the Southern Oklahoma Aulacogen. Compressive stresses caused by the collision may have been transmitted inland along reactivated basement faults (Walper, 1976). Movement along these faults created a system of paired uplifts and fault basins, including the Amarillo-Wichita Mountains and the Anadarko Basin (Walper, 1976).

PENNSYLVANIAN SYSTEM

The Palo Duro and Dalhart Basins formed in the early part of the Pennsylvanian Period. The method of sedimentation in the basins changed throughout Pennsylvanian time in response to changing basin depth and changing source areas. Both facies patterns and total sediment thickness were strongly influenced by regional structural subsidence. Block-faulted Pre-

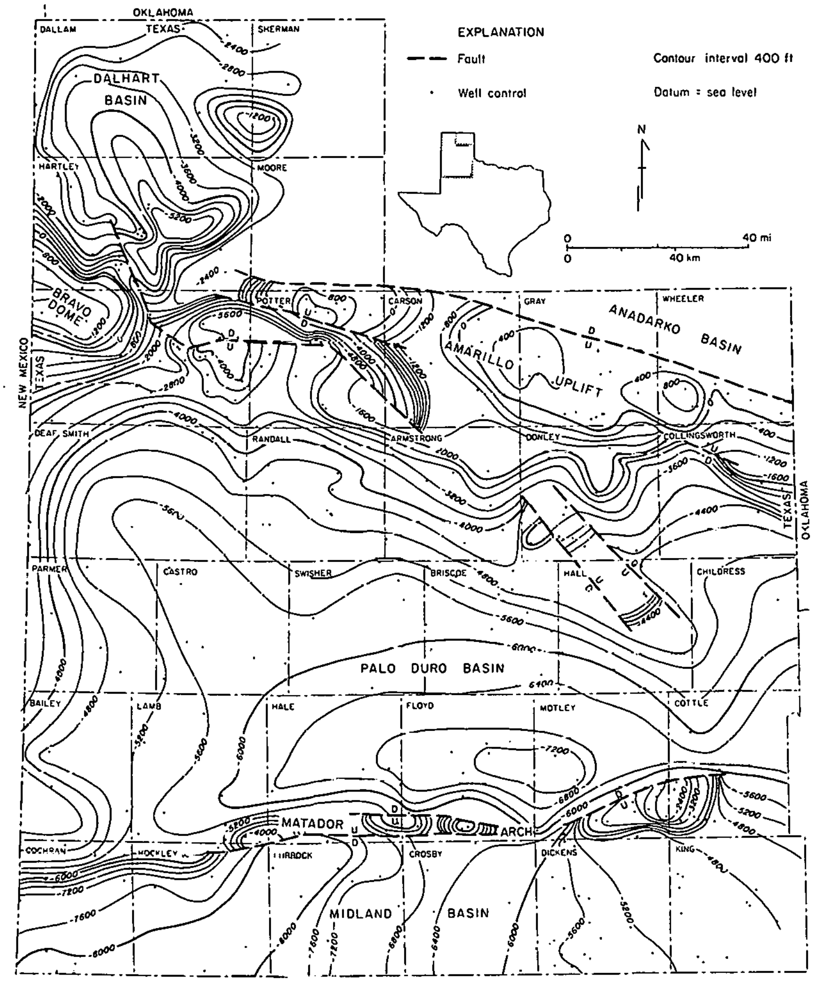


Figure 7. Structure contour map drawn on the top of Precambrian basement. (Map by M. A. Bauer.)

cambrian basement highlands remained exposed throughout the Pennsylvanian. Strata thin onto these positive elements (fig. 8). The area of thickest Pennsylvanian rocks (730 m or 2,400 ft) in the Palo Duro Basin defines the northwest- to southeast-trending basin axis. Present structural relief on the top of Pennsylvanian strata (fig. 9) exhibits a gentle southwest dip over most of the Palo Duro Basin and more complex, faulted structures near the uplifts. The Dalhart Basin was also a Pennsylvanian depocenter. More than 730 m (2,400 ft) of Pennsylvanian sediment was deposited in Dallam and Hartley Counties.

Pennsylvanian rocks in the Palo Duro Basin include, from oldest to youngest, the following groups: Bend (Morrow and Atoka Series), Strawn (Des Moines Series), Canyon (Missouri Series), and Cisco (Virgil Series). Earliest Pennsylvanian Series Springer rocks are absent in the Palo Duro Basin (Nicholson, 1960).

No widespread unconformities or regional marker beds are recognized within the Pennsylvanian System. There is, however, a noticeable vertical change in facies between the lower and upper part of the Pennsylvanian System. Lower Pennsylvanian strata are composed of terrigenous clastics and thin interbedded limestones. Thick upper Pennsylvanian limestone

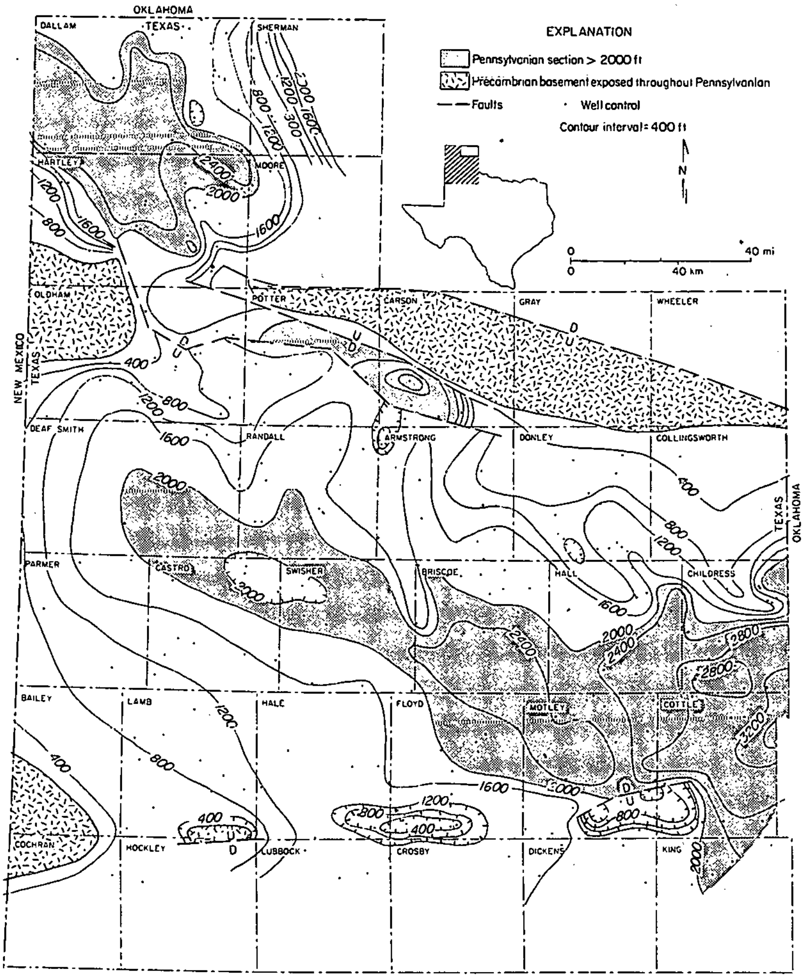


Figure 8. Isopach map of Pennsylvanian System. Sediments thin onto uplifts that were exposed during the Pennsylvanian Period.

buildups are common, and clastics are relatively less important. The approximate stratigraphic level of this vertical lithologic change marks the subdivision of the Pennsylvanian section into a lower sequence (45 percent of the section) and an upper sequence (55 percent). The top of the Strawn Group is the approximate boundary between the two sequences. Consequently, the lower sequence includes the Bend and Strawn Groups, and the upper sequence comprises the Canyon and Cisco Groups. This approximate subdivision was used throughout the basin as a convenient, as well as genetically meaningful, way to divide the Pennsylvanian System.

Lower Pennsylvanian Strata

Lower Pennsylvanian sediments were deposited in three principal depositional systems: fan delta, shallow marine shelf, and deep basin. Thick sequences of sandstone and conglomerate rimming uplifts around the northern Palo Duro Basin are interpreted to be of alluvial-fan and fan-delta origin. Carbonates in the southern part of the basin were deposited

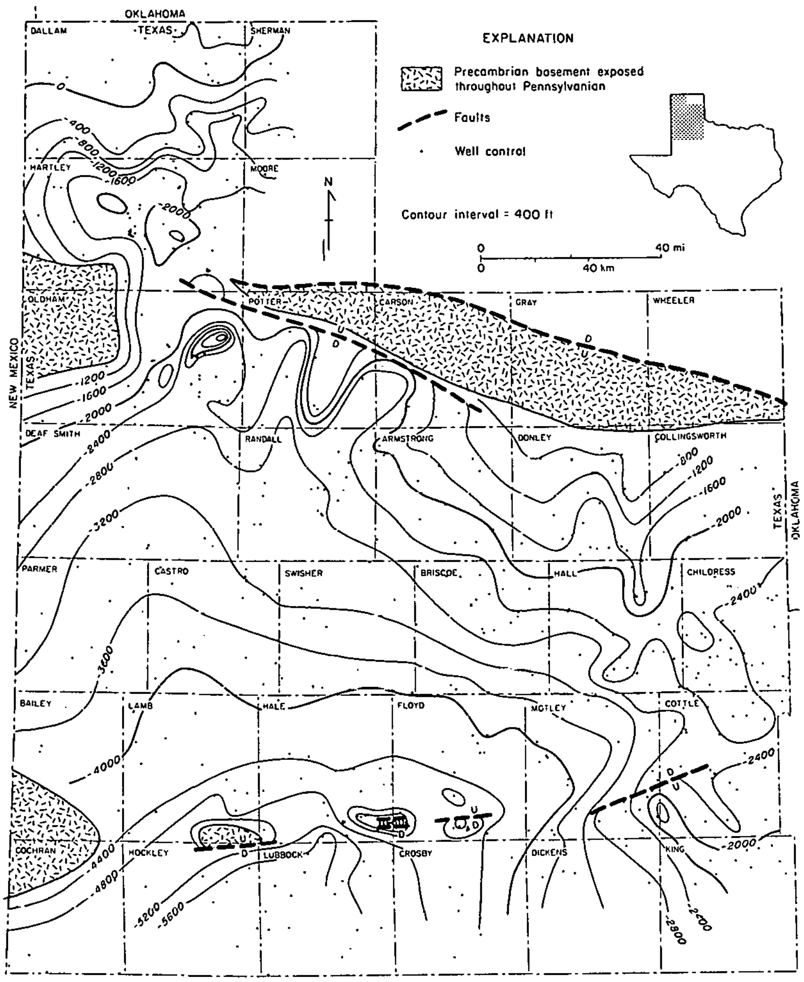


Figure 9. Structure contour map drawn on the top of the Pennsylvanian System.

in shallow marine environments isolated from the influx of clastics. Deep basinal shales accumulated only in a small area immediately north of the Matador Arch.

Fan-Delta Systems

Early Pennsylvanian sedimentation was strongly controlled by contemporaneous tectonic activity. Uplifted Precambrian basement surrounding the basin supplied large volumes of terrigenous debris. Major source areas included the Amarillo-Wichita Uplift to the north and east, and the Bravo Dome and Sierra Grande Uplift to the northwest (fig. 1). The Matador Arch fault blocks were smaller, more local sources of clastic sediment. The Precambrian core of the Amarillo Uplift is part of the Wichita igneous province (Flawn, 1956), a complex of granite and gabbro intrusives. Clastic sediments derived from the uplift are referred to as "granite wash" because of the high content of granite fragments and feldspar grains. Samples of granite wash from Cottle County are arkose, lithic arkose, subarkose, and feldspathic litharenite, according to Folk's (1974) sandstone classification (fig. 10).

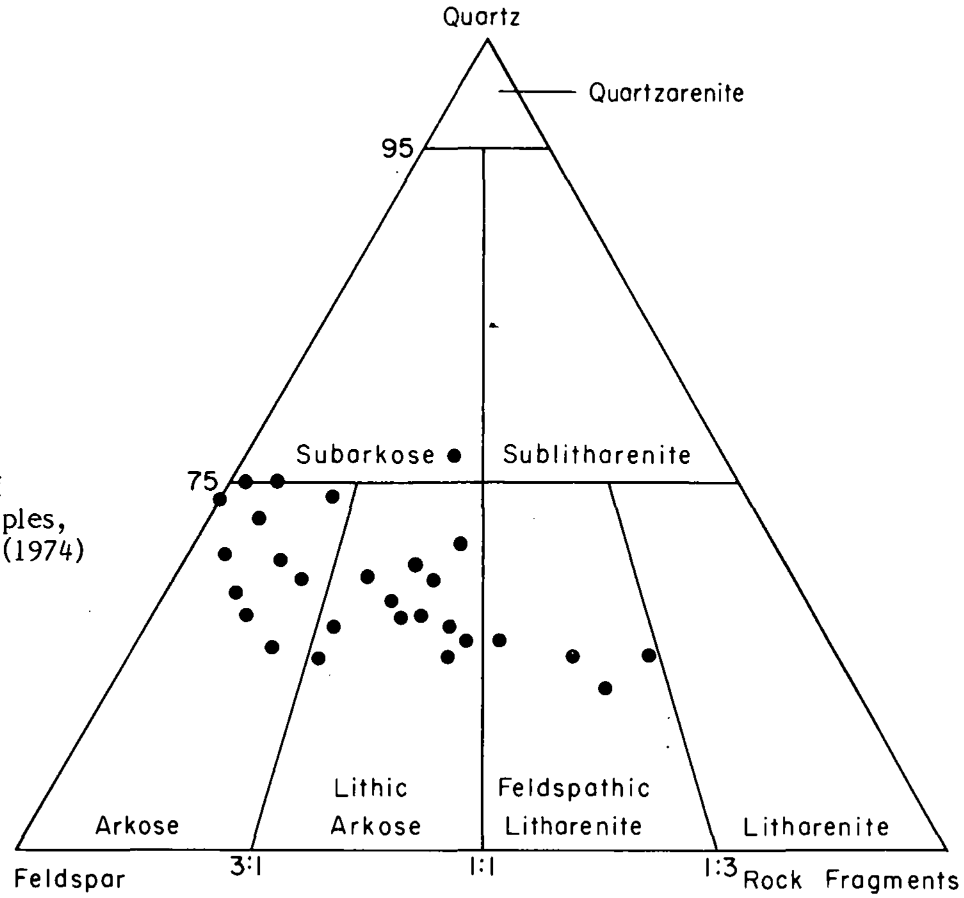


Figure 10. Classification of granite-wash sandstone samples, Cottle County, using Folk's (1974) classification.

In the Palo Duro Basin, thick sequences of Pennsylvanian granite wash are fan-delta deposits. Depositional environments were probably similar to modern fan-delta environments described by McGowen (1970). In most of the basin, fan-delta deposits were identified on the basis of electric log relationships and sample log descriptions. However, granite-wash core was available from two wells in southern Cottle County, Standard Oil #1 Barron, 1,992.8 to 2,000.7 m (6,538 to 6,564 ft) deep, and Standard #2 Tippen, 2,072.0 to 2,080.6 m (6,798 to 6,826 ft) deep (fig. 11).

Modern fan-delta model--A fan delta is an alluvial fan that progrades into a body of water from an adjacent highland (McGowen, 1970). Like alluvial fans, fan deltas have relatively small drainage areas and flashy discharge. A high ratio of coarse-grained to fine-grained sediment is characteristic. During normal sea-level conditions, fan deltas prograde by braided-stream deposition; during periods of high discharge, sheetwash causes aggradation (McGowen, 1970). Braided streams extend essentially the entire length of a fan delta; distributaries are normally short and braided.

McGowen divided the modern Gum Hollow fan delta of the Texas coast into four main depositional environments: fan plain, distal fan, main channels, and prodelta. The fan plain is

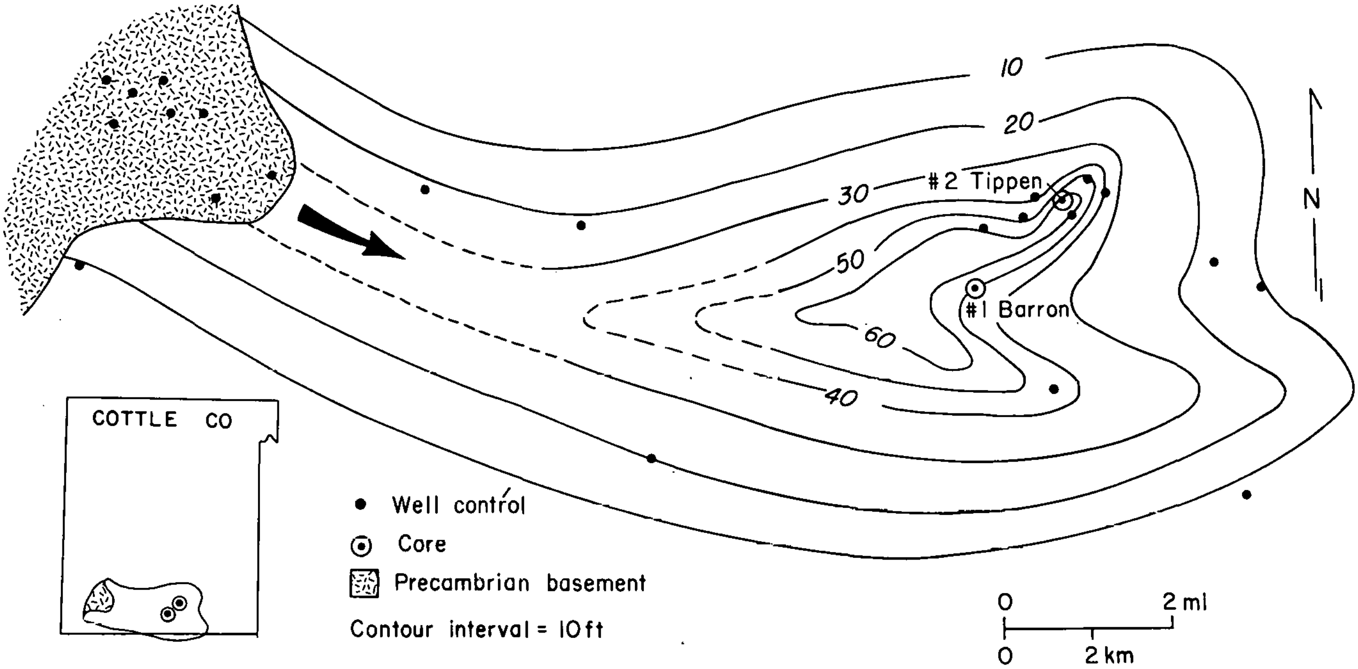


Figure 11. Isopach map of a granite-wash lobe and core locations in Cottle County. Source area was Precambrian basement exposed in Matador Arch fault block.

the subaerially exposed part of the fan delta and is characterized by longitudinal bars and shallow braided channels. Dominant sedimentary structures are trough-fill cross-strata and parallel laminae. The distal fan extends from the fan plain to the open bay; dominant sediment types are parallel-laminated sand, massive, homogeneous sand, and thin mud layers. The prodelta borders the distal fan and is characterized by alternating small trough sets and mud drapes. Braided-stream channels extend from the fan apex and cut across the fan plain and distal fan. Scours, trough-fill cross-strata, and parallel laminae are the main structures. Depositional units deposited in main channels are thicker than those deposited on the delta plain.

According to McGowen (1970), thick wedges of coarse-grained fan-delta deposits typically accumulate along mountain fronts. Faults commonly bound fan sediments, and structural displacement may occur during deposition. Fan-delta deposits typically contain nonresistant grains such as feldspar or rock fragments, which survive because of short transport distances. The Liguanea fan delta at Kingston, Jamaica (fig. 12), is a Pleistocene example of a fan delta adjacent to a mountain front. At Kingston Harbour, coarse-grained clastic sediments prograded onto a carbonate shelf from adjacent coastal mountain ranges. The fan became inactive because of stream capture and abandonment of the Hope River, the major channel feeding it.

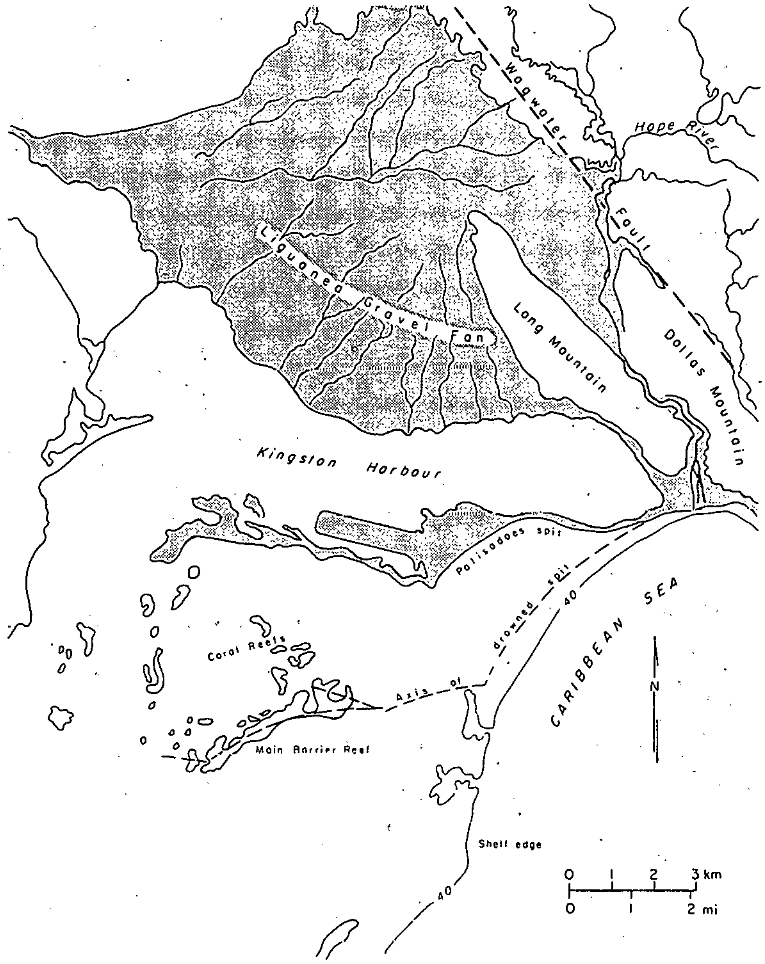


Figure 12. Location map of Liguanea gravel fan delta, Kingston, Jamaica, showing drowned spit and associated reefs (from Goreau and Burke, 1966).

<u>Distribution of granite-wash lobes</u>--Granite-wash sandstones in the Palo Duro and Dalhart Basins exhibit high SP responses characterized by sharp bases and tops and low resistivity (fig. 13); these characteristics can be used to distinguish granite wash from other facies. Granite-wash sandstones are commonly 3 to 15 m (10 to 40 ft) thick. Individual beds are laterally discontinuous and therefore cannot be correlated more than a few tens of kilometers. However, in local areas where granite-wash deposition was concentrated, multistory sandstone bodies were deposited. A granite-wash isolith map (fig. 14) and cross sections of the Pennsylvanian strata (figs. 15, 16, and 17) show thick wedges of granite wash in the northeastern and northwestern parts of the Palo Duro Basin, abutting the Precambrian highlands. Lobes of sandstone extend to the southern margin of the basin. Thin granite-wash sandstones also occur at the eastern end of the Matador Arch in Cottle County. In the Dalhart Basin, granite-wash facies are thickest in the west (fig. 14), adjacent to the Sierra Grande Uplift and Bravo Dome.

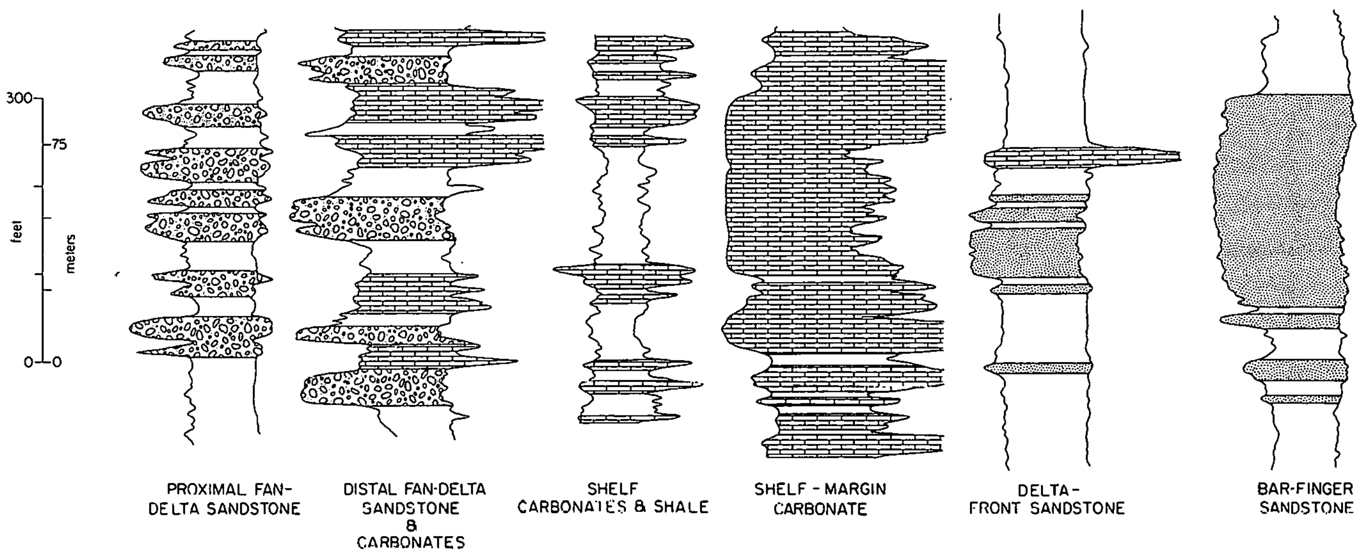


Figure 13. Typical electric log patterns of fan-delta facies, shallow marine shelf and shelf-margin facies, and deltaic facies.

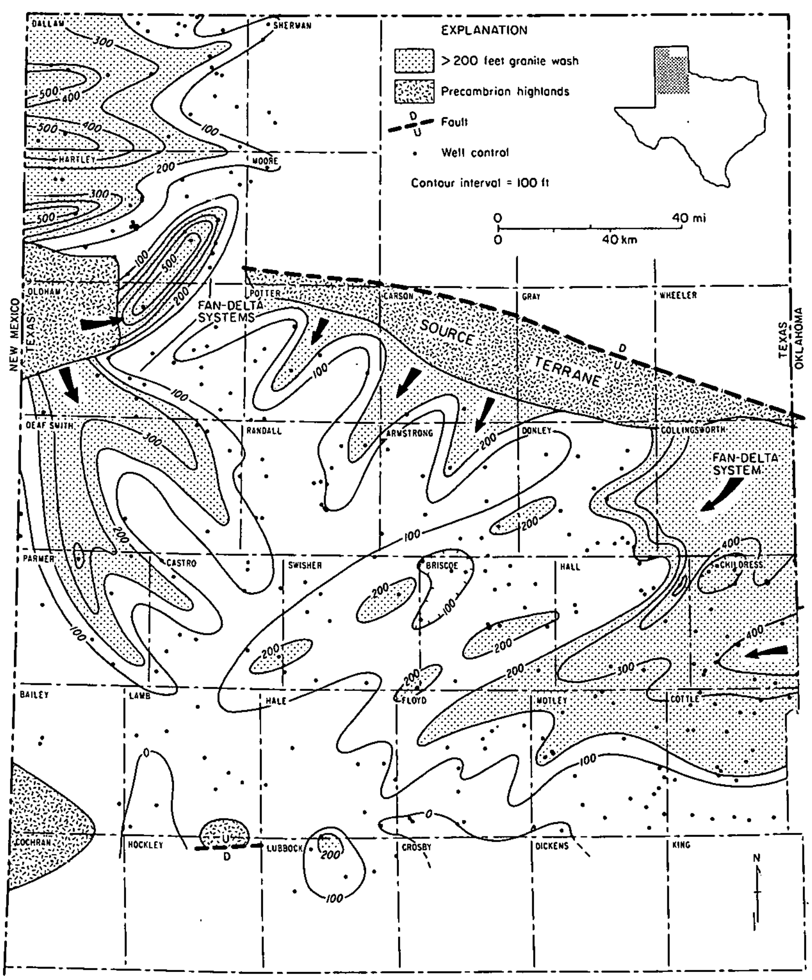


Figure 14. Net granite-wash map of lower Pennsylvanian System.

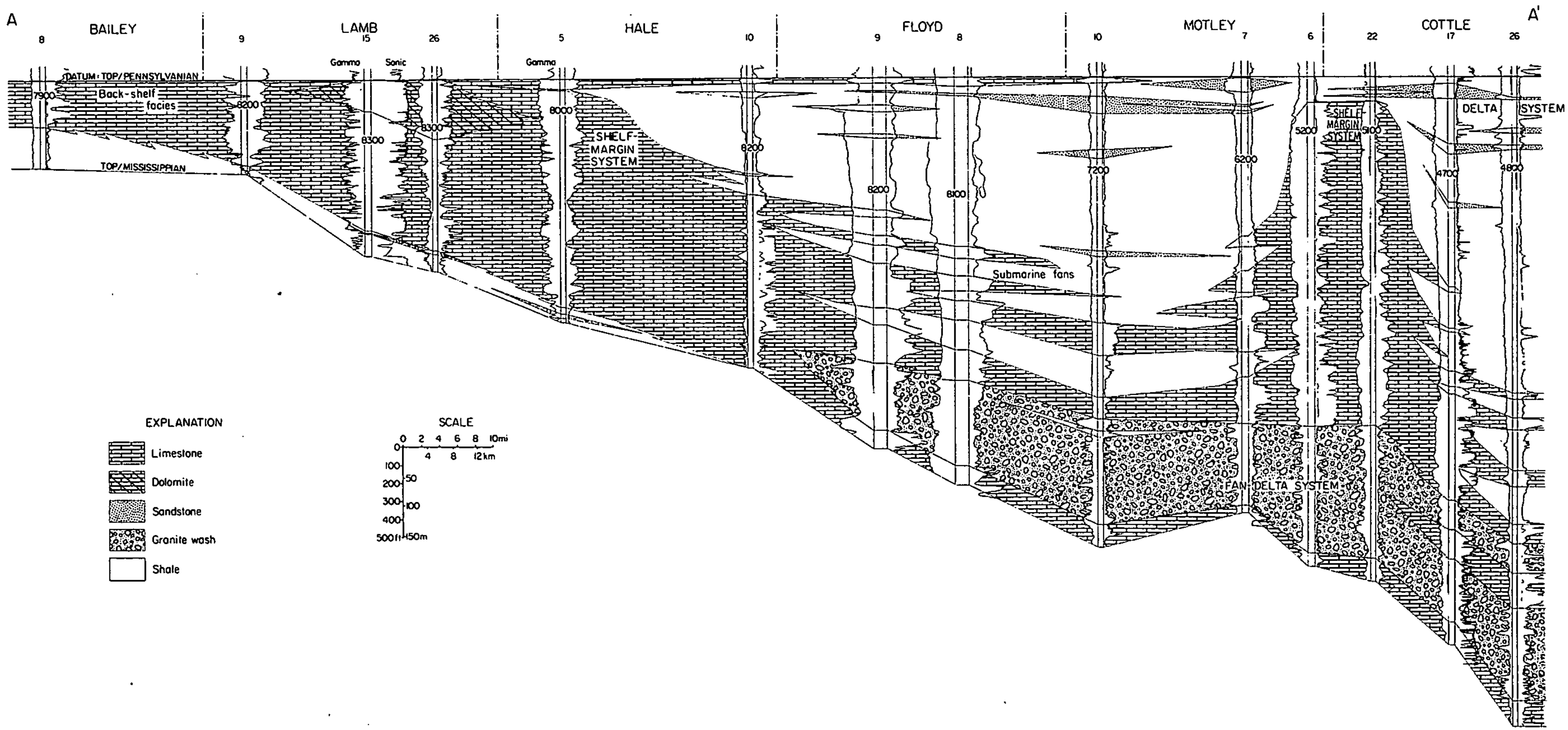


Figure 15. East-west Pennsylvanian cross section A-A', from Bailey to Cottle Counties. Line of section shown in figure 2.

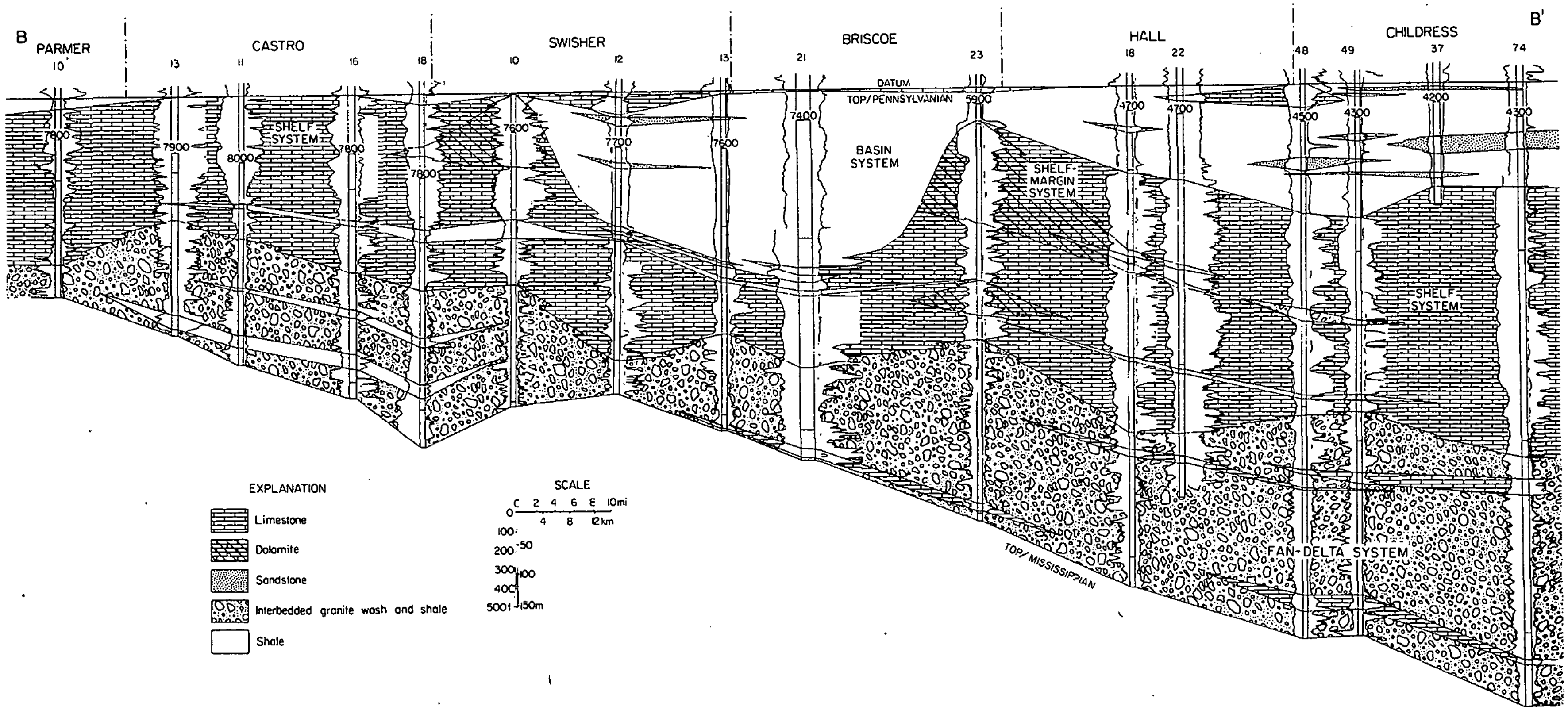


Figure 16. East-west Pennsylvanian cross section B-B', from Parmer to Childress Counties.

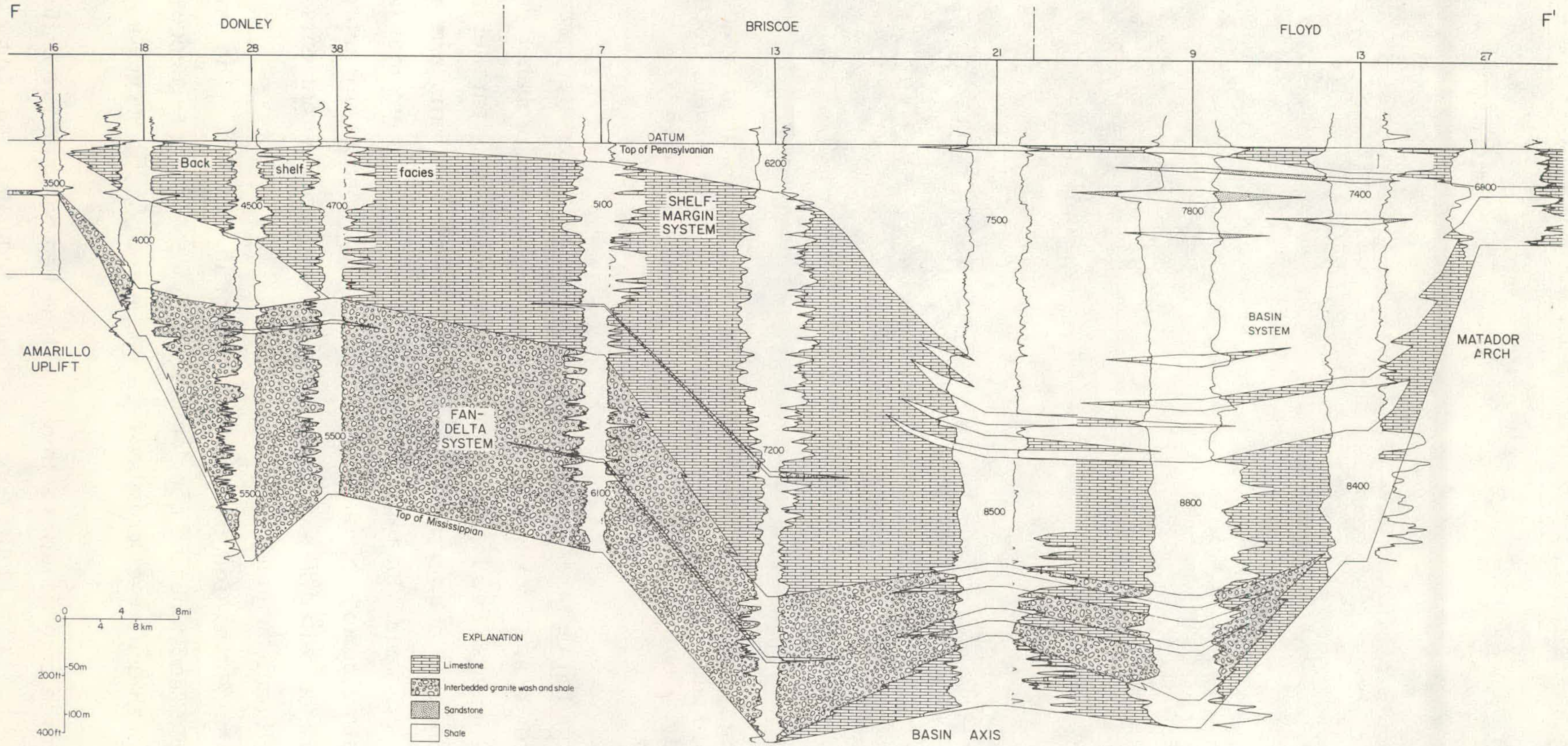


Figure 17. North-south Pennsylvanian cross section F-F', from Donley to Floyd Counties.

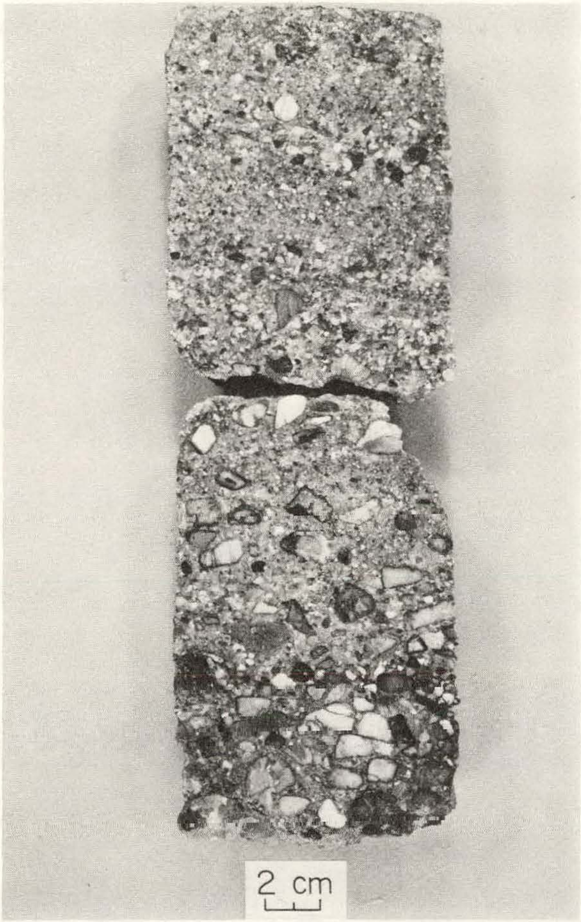


Figure 18a. Upward-fining sequence in granite wash from Standard and Robinson #2 Tippen well, Cottle County. Depth is 2,080.6 m (6,826 ft).

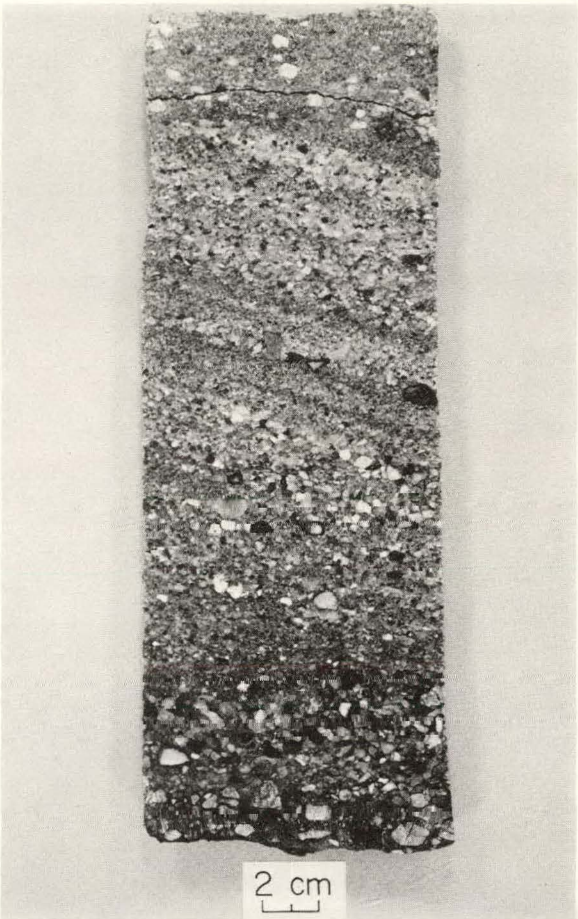


Figure 18b. Crossbedding in granite wash, Standard Oil #1 Barron well, Cottle County. Depth is 1,995.2 m (6,546 ft).

Lower Pennsylvanian fan-delta facies--A typical fan-delta facies tract can be interpreted from log and core data. Proximal terrigenous clastics were probably deposited in subaerial fan-plain environments (fig. 13). Sandstones commonly display parallel laminae and crossbedding. Coals deposited in interchannel marsh/swamp environments are interbedded with fan-plain sandstone and shale. In some places thin limestone beds are interbedded with fan-plain deposits, indicating periods of marine inundation. Carbonates are more abundant downdip, where they were deposited in subaqueous, distal fan-delta environments undergoing alternating clastic and carbonate sedimentation (fig. 13).

The two cores from Cottle County represent fan-plain deposits. The granite wash consists of medium-grained sandstone and conglomerate. Upward-fining sequences exhibiting scours and large-scale trough or foreset crossbeds are common (fig. 18), suggesting deposition in braided streams.

The Standard #1 Barron core contains a thin limestone bed between two braided-channel sandstones. The lower 4.3 m (14 ft) of the core is a channel sandstone that fines upward into

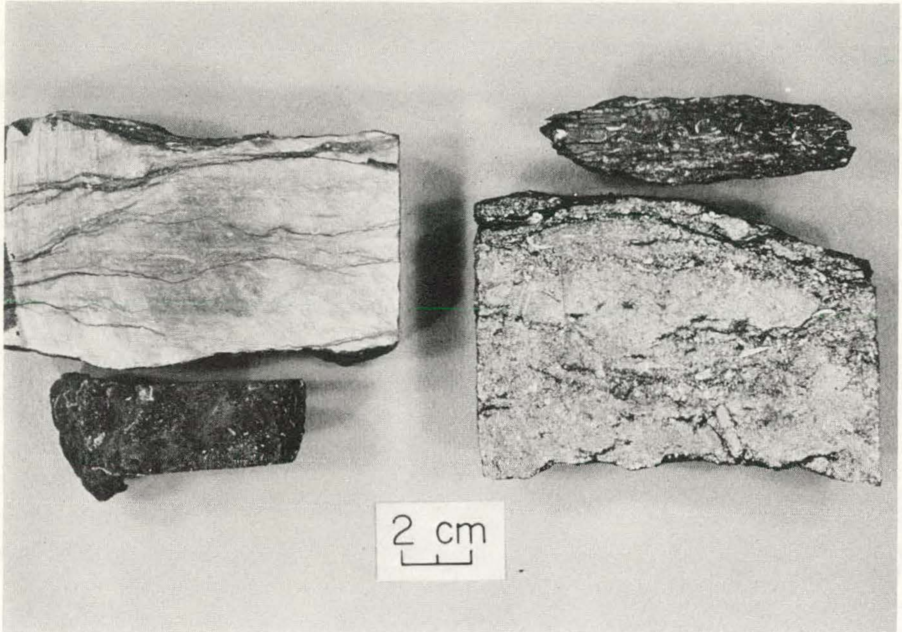


Figure 19. Brachiopod wackestone from Standard Oil # 1 Barron well, Cottle County. Depth is 1,996.1 m (6,549 ft). This comes from a marine unit capping an upward-fining deltaic sequence.

organic, channel-fill black shale. This is capped by a black lime mudstone and a 0.3 m (1 ft) thickness of shaly brachiopod wackestone (fig. 19). Limestone deposition probably began following shifting or abandonment of the braided-stream channel and subsidence of the fan plain. Low species diversity in this core may be related to turbid, low-salinity water conditions resulting from continued suspension-load, clastic sedimentation. Well cuttings of other limestones interbedded with granite wash are relatively pure carbonates, suggesting deposition in nonturbid waters in some areas. In the Standard #1 Barron well core, an overlying 2.7 m (9 ft) thickness of channel sandstone is in sharp contact with the wackestone. This pulse of clastic deposition was caused by reestablishment of a braided-stream channel. Renewed clastic deposition resulting in multiple, stacked channel-fill units was probably caused by fan-delta lobe shifting. Major clastic cycles in the Palo Duro Basin may have been initiated by tectonic activity in the faulted highlands.

Alternation of clastic and carbonate deposition was the dominant type of sedimentation over most of the northern Palo Duro Basin during early Pennsylvanian time. A similar depositional style was described by Becker (1977) for Pennsylvanian granite wash in the Anadarko Basin in Wheeler County, immediately north of the Amarillo Uplift (fig. 1). In the Anadarko Basin, carbonate sediment production ceased or was greatly reduced during periods of clastic sedimentation. Clastic-filled channels flowed across low areas in underlying carbonate units and deposited sediment basinward of the carbonate buildups. When each episode of terrigenous sedimentation ended, carbonate deposition was reestablished. Bioherms developed preferentially on platforms supported by clastics of the previous depositional cycle.

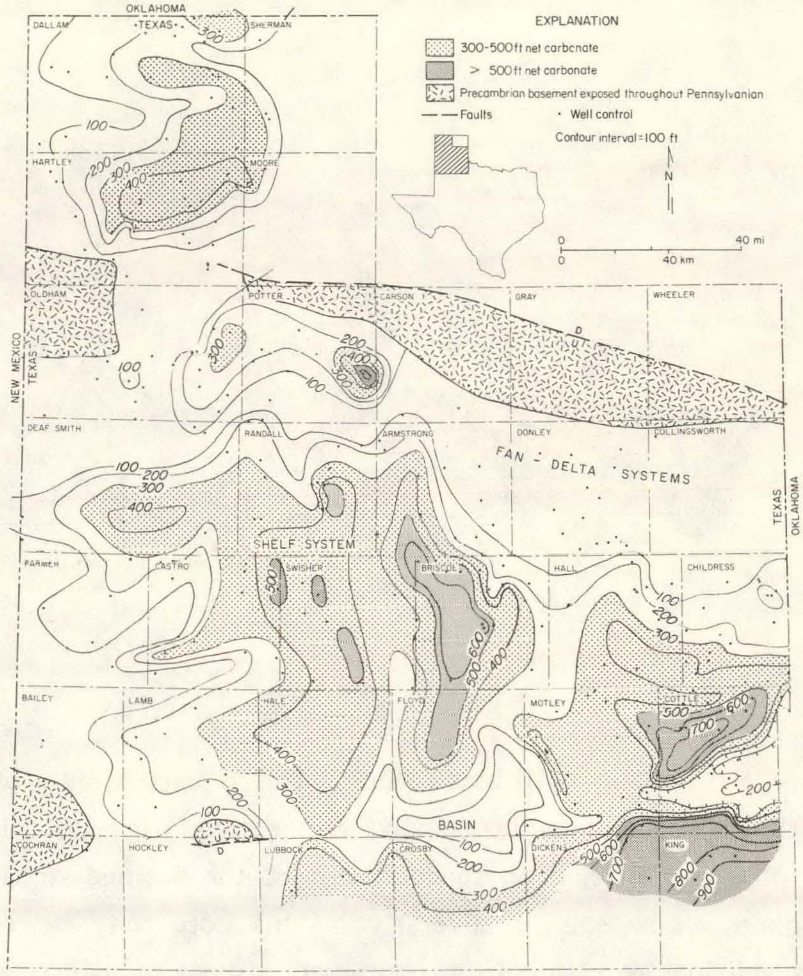


Figure 20. Net limestone map of lower part of the Pennsylvanian System.

Each pulse of clastic deposition initiated a new cycle. These interbedded carbonate and clastic units display reciprocity, as each unit helped control the distribution of the next. Clastic and carbonate sedimentation in the Palo Duro and Dalhart Basins may have also exhibited such reciprocity.

Marine Shelf and Basinal Systems

Subsidence of the Palo Duro Basin began to produce a broad, shallow basin during early Pennsylvanian time. The southern part of the basin was far enough from the mountains so that only a limited amount of fan-delta sand reached it (fig. 14); sedimentation consisted of deposition of thin shelf carbonates and terrigenous mud. A net limestone map outlines broad areas of carbonate deposition (fig. 20). Thickest accumulations of lower Pennsylvanian limestone in Cottle, King, Briscoe, Floyd, Randall, and Swisher Counties coincide with areas where upper Pennsylvanian shelf margins later developed. In the Dalhart Basin, carbonate production was restricted to the eastern side, away from the thick wedge of granite wash

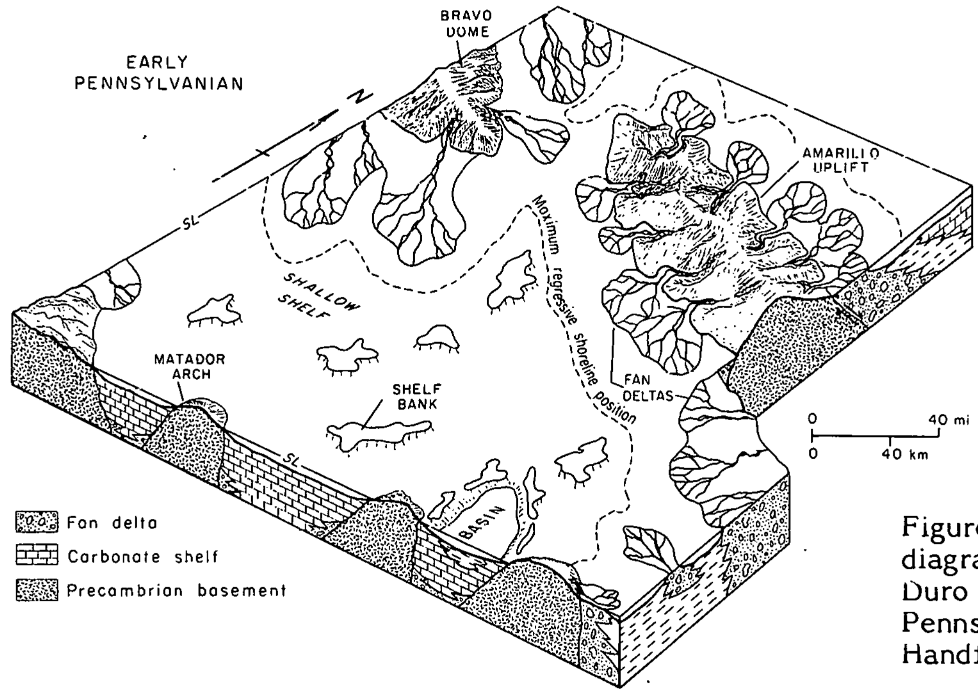


Figure 21. Schematic block diagram depicting the Palo Duro and Dalhart Basins in early Pennsylvanian time (from Handford and Dutton, 1980).

(fig. 14). In a small basinal area north of the Matador Arch in Floyd and Motley Counties, shale deposition began in early Pennsylvanian time and continued throughout the period in which water depth precluded carbonate sedimentation. A schematic paleogeographic map (fig. 21) summarizes early Pennsylvanian depositional environments.

Upper Pennsylvanian Strata

Fan-delta, shallow marine-shelf, and deep-basin environments existed through late Pennsylvanian time, but their relative importance changed. Movement along fault systems in the uplifts essentially ended in late Pennsylvanian. Highland areas had been eroded extensively and no longer supplied significant amounts of clastic sediment to the basin. Fan-delta systems still active were much smaller and confined to flanks of the uplifts (fig. 22). Many coastal areas that had been subaerially exposed in early Pennsylvanian time were transgressed as the late Pennsylvanian basin subsided.

Late Pennsylvanian paleogeography was characterized by a large, well-defined, deep basin surrounded by carbonate shelf margins (figs. 13 and 23). Subsidence enlarged and modified the basin to an east-west-trending basin having a narrow northwest extension. Late Pennsylvanian basin fill is composed mainly of shale and thin sandstone beds.

Shelf-Margin Systems

Carbonate shelves rimmed the late Pennsylvanian basin, and shelf edges probably stood a few hundred meters above the basin floor (figs. 15, 16, 17, 24, and 25). The shelf margin is

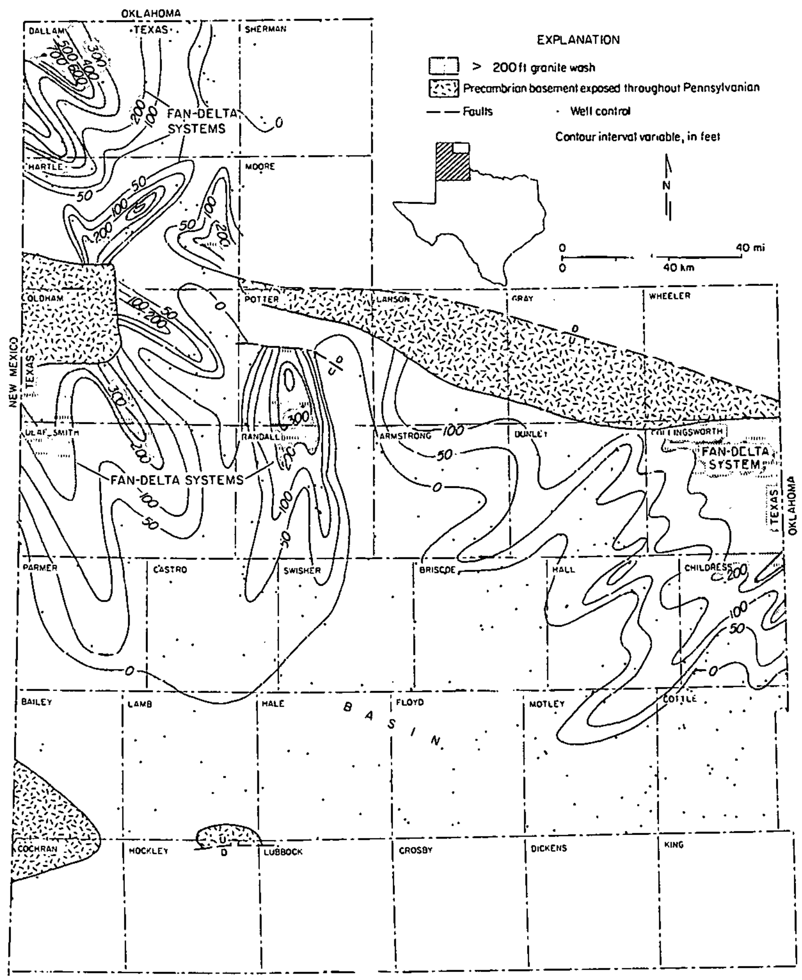


Figure 22. Net granite-wash map of upper part of the Pennsylvanian System.

best defined along the eastern and western sides of the basin (fig. 23). The northern extension of the shelf margin ended near the Amarillo Uplift. To the south, the Palo Duro Basin merged with the Midland Basin, but the passage was partly blocked by carbonate buildups on fault blocks of the Matador Arch. A late Pennsylvanian block diagram shows the position of these features (fig. 26).

More than 300 m (1,000 ft) of carbonate aggraded at the shelf margins (fig. 23). Shelf-margin limestones obtained from well cuttings contain crinoids and fusulinids, and chert is commonly present. A core from the Furr #1 Battey well in Floyd County taken at depths from 2,079.7 to 2,087.3 m (6,823 to 6,848 ft) contained shelf limestone. The limestone, which was deposited on one of the Matador fault blocks in Floyd County, is a shaly lime mudstone to wackestone. Scattered crinoids and brachiopods indicate low diversity because of turbid water. Along most of the late Pennsylvanian shelf margins, the water was probably cleaner and thus able to support a more diverse fauna.

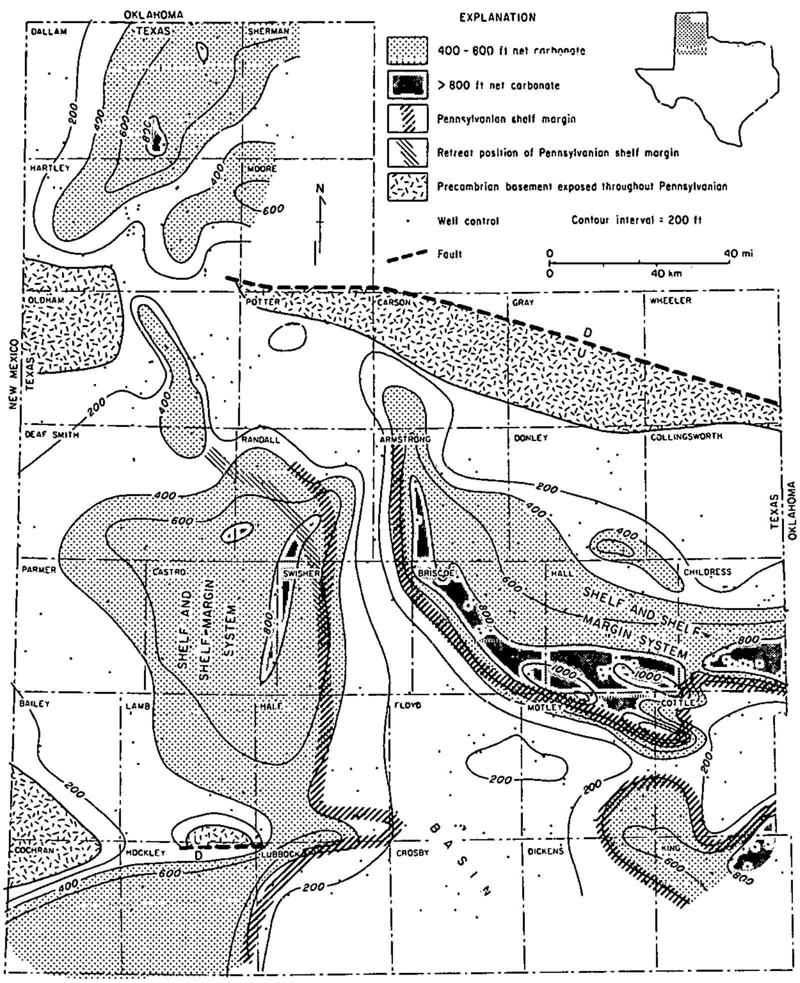


Figure 23. Net carbonate map of upper part of the Pennsylvanian System. Position of older shelf margin is shown by dark hachured lines, and younger (retreated) position is shown by lighter hachures.

Pennsylvanian cratonic basins commonly exhibit thick shelf-margin limestone facies (Wilson, 1975) that were formed by encrusting and sediment-baffling organisms. Phylloid algae, the most important Pennsylvanian mound-builder, formed mounds by trapping carbonate mud and skeletal debris. Crinoids, bryozoans, fusulinids, echinoids, sponges, and brachiopods existed alongside the algae and contributed to mound development (Erxleben, 1975). Algae lived only where water was clean and shallow; crinoids and brachiopods were the dominant species in turbid water (such as in the environments interpreted from the Furr #1 Battey well cores). By analogy with other Pennsylvanian shelf-edge deposits, Palo Duro shelf margins were probably composed of phylloid algae.

Shelf-Margin Retreat

Galloway and others (1977) suggested that clastics can control progradation of carbonate shelf margins. The history of the Palo Duro shelf margins indicates that clastics may influence

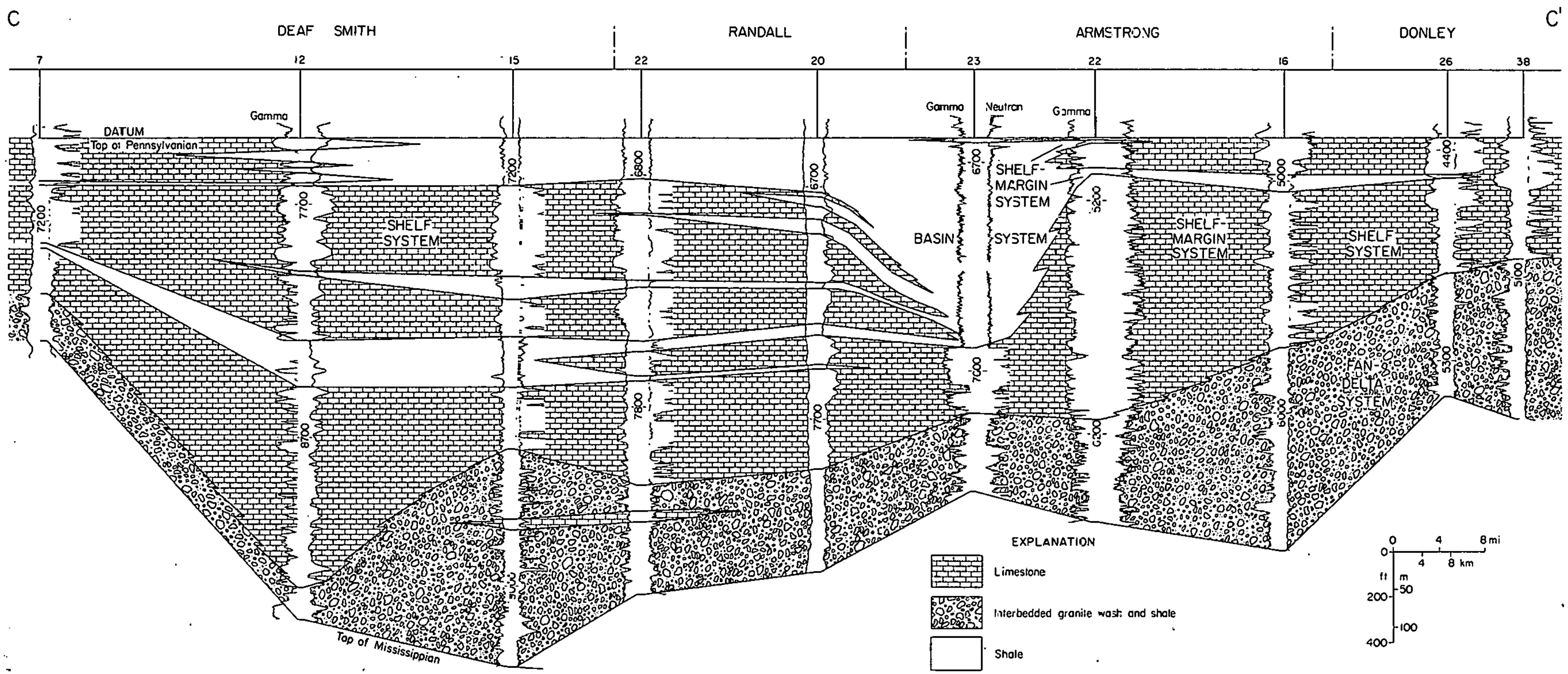


Figure 24. East-west Pennsylvanian cross section C-C', from Deaf Smith to Donley Counties.

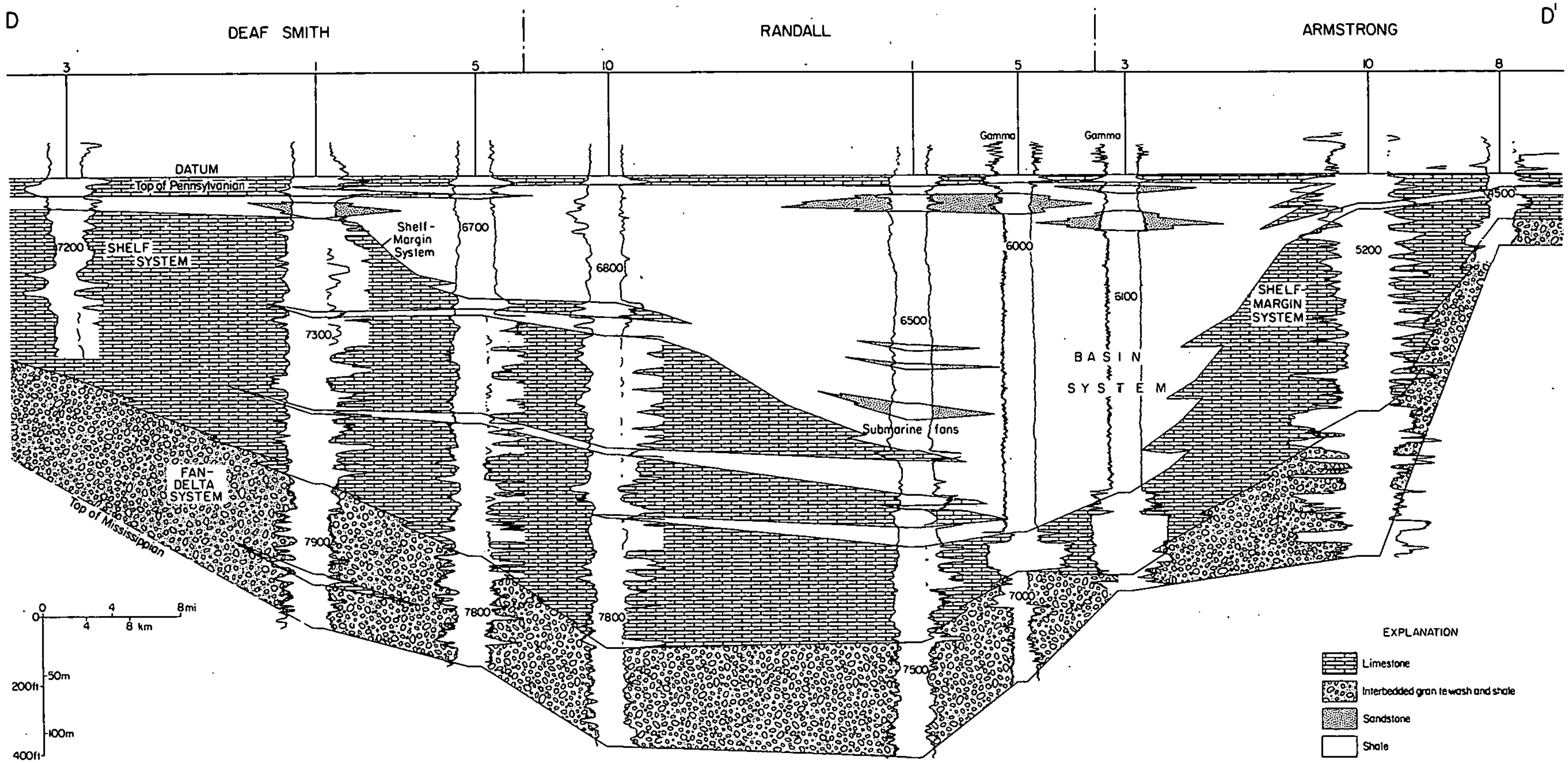
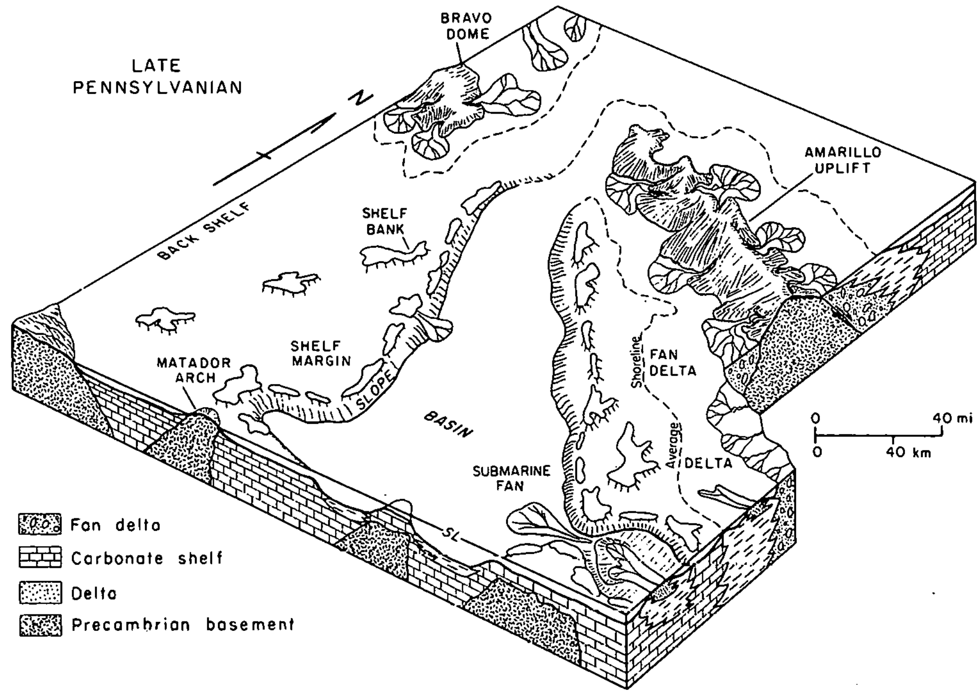


Figure 25. East-west Pennsylvanian cross section D-D', from Deaf Smith to Armstrong Counties. Younger shelf edge is located landward (west) of the older position.

Figure 26. Schematic block diagram depicting Palo Duro and Dalhart Basins in late Pennsylvanian time (from Handford and Dutton, 1980).



margin retreat as well. The shelf margin was stationary along the eastern and southwestern sides of the basin through late Pennsylvanian time. Carbonate deposition kept pace with basin subsidence, enabling the shelf margin to aggrade. Along the northern part of the western shelf in Deaf Smith, Randall, and Swisher Counties, however, at least two different shelf margins can be recognized (figs. 23, 24, and 25). The younger shelf margin is located 29 km (18 mi) west, or landward, of the older shelf margin in northeastern Deaf Smith County. The two shelf margins merge in central Swisher County. Retreat of this part of the shelf margin probably resulted from the combined effects of clastic sedimentation and subsidence. A net sandstone isolith map of upper Pennsylvanian strata shows a major fan-delta lobe prograding southward into the basin between the northeastern and northwestern shelf margins (fig. 27). Progradation of this fan-delta lobe probably decreased carbonate productivity significantly at the shelf margin. Shelf-margin development diminished enough so that it could not keep pace with continuing basin subsidence. Shelf-margin carbonates were reestablished 29 km (18 mi) to the west in shallow, clear water, isolated from the terrigenous influx. The northeastern margin, which was also near the prograding fan-delta lobe, overlay a basement high (fig. 7 and 25) and did not subside as rapidly as the western margin. The position of the northeastern shelf margin remained constant because the lower rate of carbonate production kept pace with the lower rate of subsidence.

The position of the shelf margin did not shift elsewhere in the basin. Aggradation rather than progradation occurred because carbonate productivity was insufficient to support the lateral accretion of the shelf margin (Galloway and others, 1977). In the Palo Duro Basin

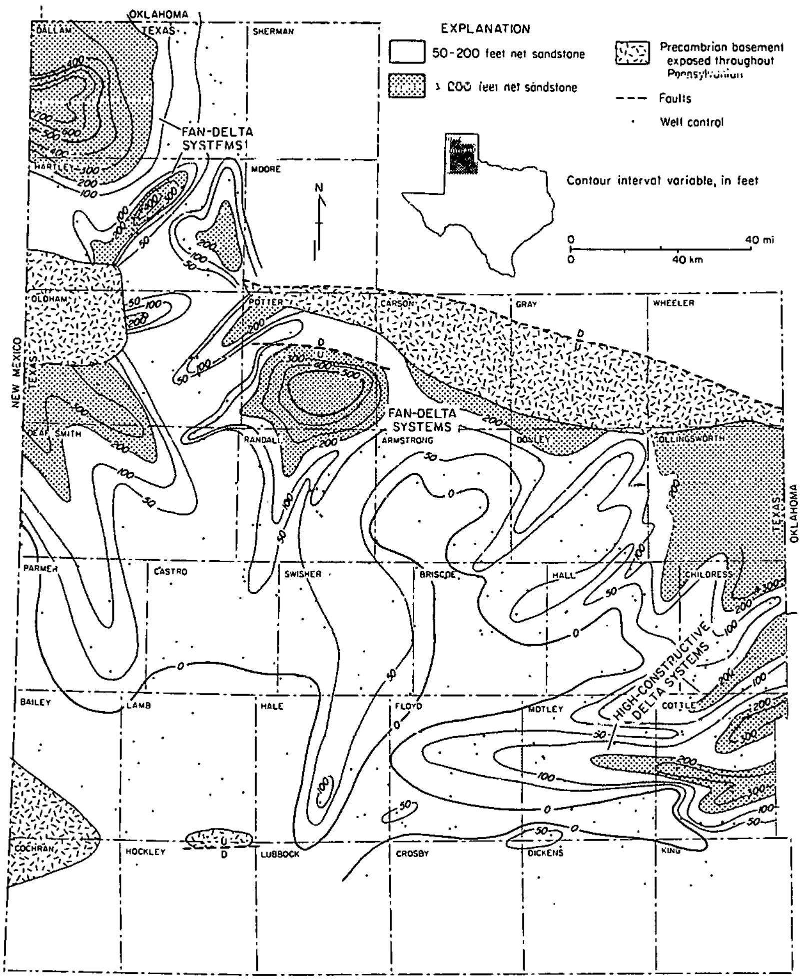


Figure 27. Net sandstone map of the upper Pennsylvanian System, including both granite wash and nonarkosic sandstone.

during Wolfcampian time, shelf-margin progradation took place in areas near major clastic sources and between periods of clastic influx (Handford and Dutton, 1980). Shelf-margin aggradation occurred in areas that received less clastic sediment.

Well defined shelf margins did not develop in the Dalhart Basin. Carbonates were deposited around a fan-delta lobe that extended northeast from the Bravo Dome (figs. 21 and 28). Prodelta mud was deposited downdip as far as southeastern Dallam County; this inhibited carbonate production. By the end of Pennsylvanian time there was no longer a clastic supply from the dome, and shallow, shelf limestone covered the area.

Deltaic and Basinal Systems

In the deepest part of the basin, water was too deep for carbonate production. Timing of basin filling with respect to aggradation of the carbonate shelf margins is difficult to determine. Terrigenous sediment probably entered the basin by delta progradation through breaches and low areas in the shelf-margin carbonates (fig. 23). Carbonate production

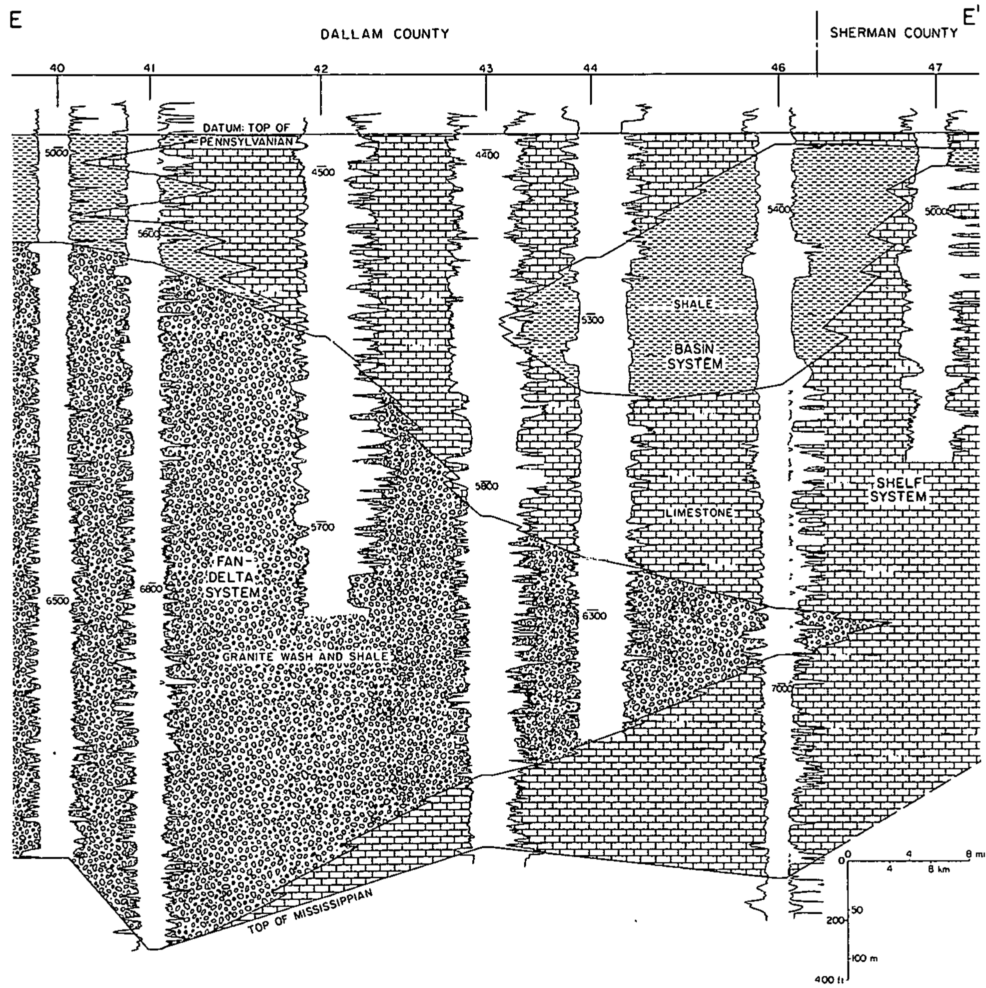


Figure 28. East-west Pennsylvanian cross section E-E' through the Dalhart Basin from Dallam to Sherman Counties.

stopped in areas of clastic input, but it probably continued in places that were not affected by the terrigenous influx.

Deltaic clastics entered the basin in pulses; between these episodes the basin was essentially starved. Centers of clastic deposition shifted through time. A section of deltaic sand thicker than 90 m (300 ft) was deposited in an east-west trend across central Cottle County (fig. 27) in the late Pennsylvanian. Deltaic deposition then shifted to northern Cottle and southern Childress Counties, and the older sands were covered by several hundred meters of interbedded shelf limestone and shale. Most of the clastics were derived from the Wichita Mountains to the east. By late Pennsylvanian time the Hardeman Basin was filled with deltaic sediment as far west as Cottle County (Frezon and Dixon, 1975). Clastics entering the Palo Duro Basin generally remained confined to the shelf, but in a few areas they were transported through the shelf margin into the basin, probably as turbidites. Most of the basin fill was mud or silt, but some sand was deposited locally.

The geometry of some of the sand bodies on the shelf indicates they were deposited by high-constructive elongate deltas. An elongate sandstone body 60 m (200 ft) thick in western Cottle County (fig. 29) resembles bar-finger sands described by Fisk (1961) and Frazier (1967).

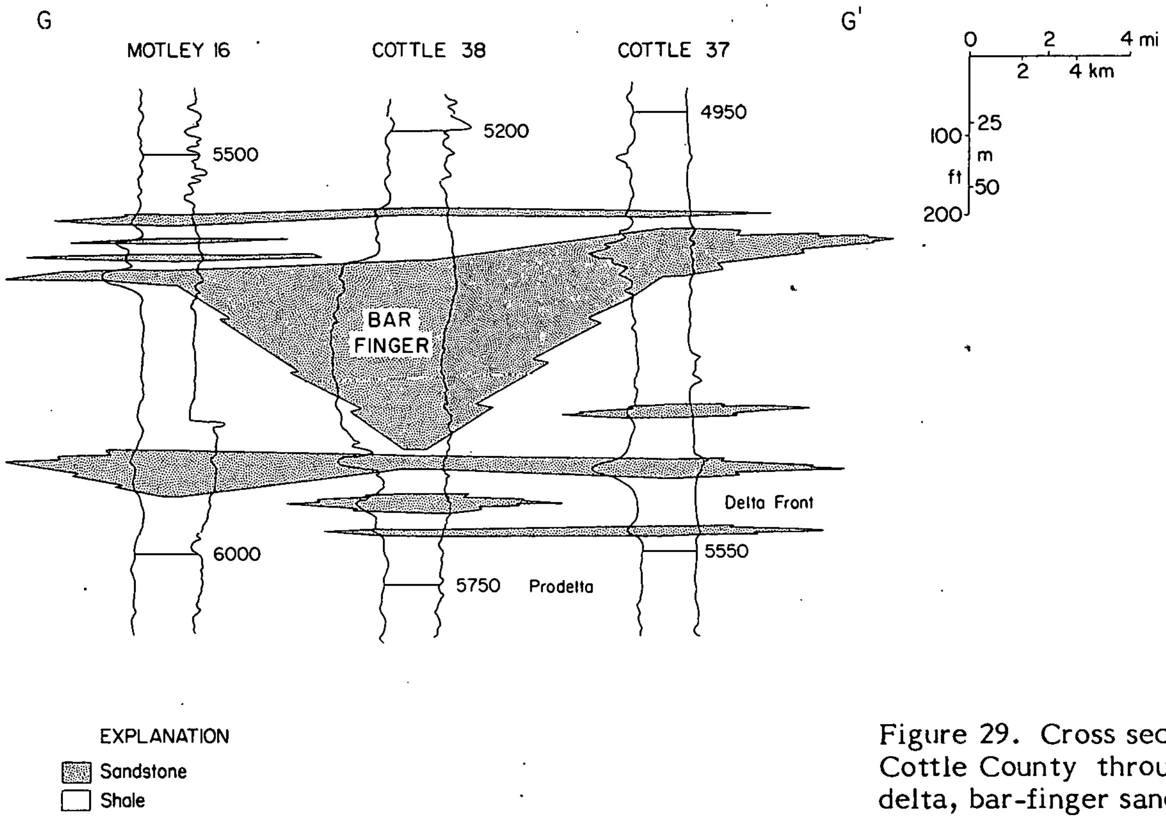


Figure 29. Cross section G-G' in Cottle County through elongate-delta, bar-finger sandstone.

The sandstone is approximately 3 km (2 mi) wide, and overlies a thick sequence of shale (fig. 13). Net sandstone patterns in Cottle County outline other narrow, elongate sandstone trends characteristic of bar-finger deposits (fig. 27).

There are a few thin sandstones in the basin (figs. 15, 16, and 17) separated by thick shale sequences. The shales may be prodelta muds punctuated by occasional deposition of distal delta-front sands. Some of the basin fill may be submarine fan deposits.

The modern Indonesian Mahakam Delta and adjacent shelf-margin carbonates (fig. 30) provide an analog for the eastern Palo Duro Basin during late Pennsylvanian time. The Mahakam Delta progrades onto the shelf of the Makassar Strait (Gerard and Oesterle, 1973). Normal marine-shelf and clastic slope deposits accumulate beyond the zone of deltaic sedimentation. Carbonate reefs grow at the shelf margin bordering the Makassar Trough. Deltaic sediments do not prograde as far as the shelf margin because of tidal and longshore currents. However, an increase in deltaic sedimentation or a decrease in marine processes would result in deposition of deltaic and slope clastics in shelf-margin and slope environments, respectively. Carbonate sedimentation would continue on the shelf margin isolated from the delta.

During the late Pennsylvanian and early Wolfcampian, the Palo Duro Basin in Cottle and Childress Counties had a configuration similar to that of the modern Mahakam Delta region. The Paleozoic deltas prograded from the east. Most of the deltaic sediment was deposited

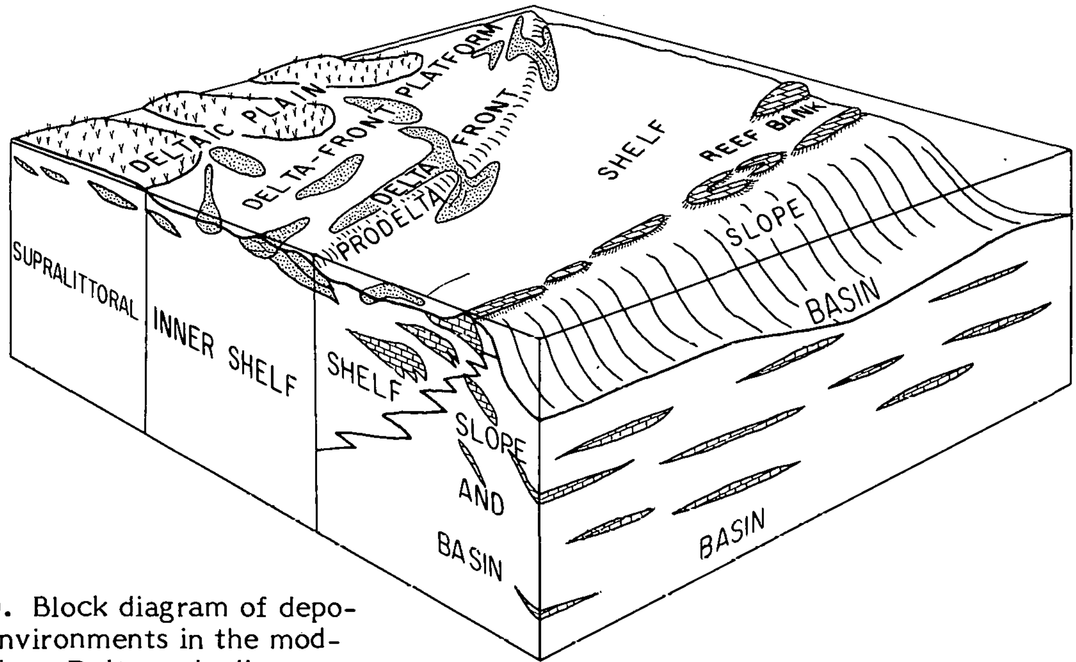


Figure 30. Block diagram of depositional environments in the modern Mahakam Delta and adjacent shelf, Indonesia (from Gerard and Oesterle, 1973).

landward of the shelf margin, but some sediment passed through breaches and was carried into the basin by turbidity flows. The narrow break in the shelf margin in western Cottle County (figs. 23 and 26) was probably the passageway into the basin for most of the eastern clastics. Carbonate and clastic deposition occurred simultaneously in different areas. Clastic sediment bypassed the shelf-margin carbonate environments and allowed turbidite deposition in the deep basin without a drop in sea level.

The Amarillo Uplift was an important northern source of terrigenous clastics deposited in the Palo Duro Basin. Fan deltas in Potter and Carson Counties introduced distal fan sand and mud directly into the narrow northern arm of the basin (fig. 27).

Shelf margins also supplied carbonate debris carried into the basin by submarine feeder channels. Carbonate sediments originating in shallow shelf-edge environments were carried downslope in debris flows, forming aprons around the toes of slopes and extending into the basin floor as submarine fans (figs. 16 and 24). A well in northeastern Swisher County, the Standard #1 Johnson, penetrated one of these carbonate submarine aprons. Core from the carbonate interval occurring 2,384.8 to 2,386.3 m (7,824 to 7,829 ft) down contains both matrix-supported conglomerate and skeletal grainstone (fig. 31). The conglomerate is a carbonate mudstone to wackestone containing mudstone clasts. The sediment probably moved downslope as a matrix-supported debris flow and was deposited in an upper fan or feeder channel (Walker, 1978). The grainstone was probably deposited in a braided channel of a suprafan lobe.

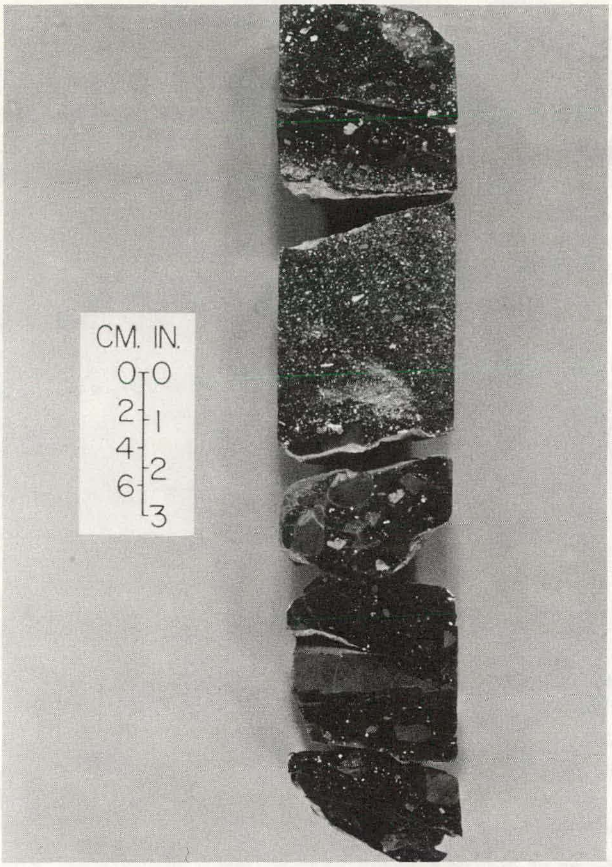


Figure 31. Matrix-supported, debris-flow conglomerate deposited in an upper submarine fan or feeder channel.

Pennsylvanian-Permian Transition

Carbonate deposition characterized the Palo Duro Basin during most of late Pennsylvanian time. Clastic sedimentation dominated the eastern portion of the basin near the end of the period (figs. 15 and 16) while carbonate deposition continued uninterrupted around the rest of the basin. Subsidence and basin expansion continued into early Permian; consequently, lower Wolfcampian shelf margins (fig. 32) are located landward of those established in the upper Pennsylvanian (fig. 23).

Deposition was continuous from the Pennsylvanian to the Permian Periods. Combined paleontological (fusulinid) and lithological data were used to estimate the top of the Pennsylvanian System. A thin, widespread limestone unit was deposited over much of what had formerly been the deep basin (figs. 15, 16, and 17) near the end of the Pennsylvanian. The top of this limestone serves as an operational marker for the top of the Pennsylvanian. Where the limestone does not occur, the boundary is conventionally placed at the top of a widespread shale (fig. 17). In places where shelf-margin limestone deposition continued without a break into the Permian, as in the western part of the basin (fig. 16), the systemic boundary is projected into the thick carbonate sequence from the nearest wells where it can be recognized.

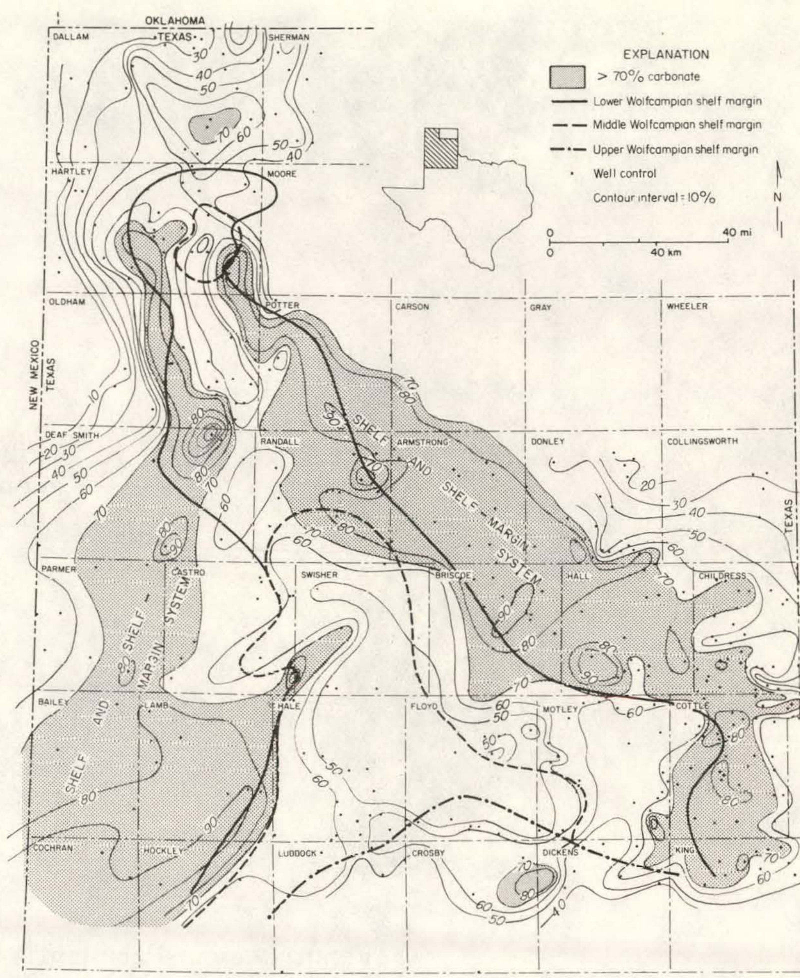


Figure 32. Percent carbonate map of Wolfcampian strata showing position of Wolfcampian shelf margins (from Handford and Dutton, 1980).

DIAGENESIS AND POROSITY DISTRIBUTION

Several diagenetic changes, particularly compaction and cementation, have altered the Pennsylvanian sediments. Distribution of porosity in the Palo Duro and Dalhart Basins is controlled by original depositional environments and postdepositional changes. Determining diagenetic history helps predict porosity trends in the Palo Duro and Dalhart Basins and thus potential hydrocarbon reservoirs.

Shelf-margin limestones were dolomitized. The dolomite is buff-brown and medium to coarsely crystalline; it exhibits vuggy porosity and contains chert. Most of the dolomite occurs within a zone 16 to 32 km (10 to 20 mi) wide just landward of the shelf edge (fig. 33). Dolomitization of the shelf-margin limestones increased their porosity. A porosity map based on qualitative sample log descriptions coincides closely with dolomite distribution and is confined to a narrow band along the shelf edge (figs. 33 and 34). Density, sonic, and neutron logs indicate that dolomite porosity averages 8 to 10 percent, and ranges between 5 and 25

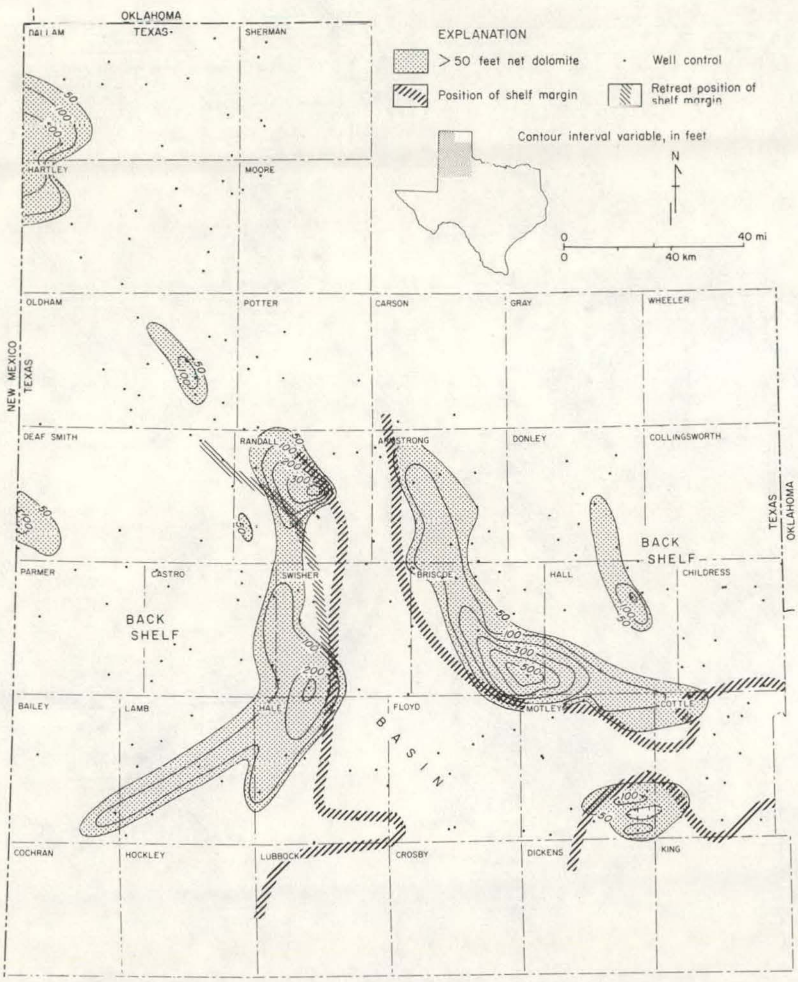


Figure 33. Isopach map of upper Pennsylvanian dolomite based on sample log information.

percent. An insufficient number of logs were available to construct a quantitative map, but available values coincide with porosity trends delineated by examination of sample logs. Undolomitized limestone has lower porosity, ranging between 3 and 8 percent and averaging about 4 percent.

Granite-wash porosity calculated from porosity logs ranges between 3 and 21 percent and averages about 14 percent. Precementation porosity (or minus-cement porosity) in granite-wash facies was higher, but it has been reduced by precipitation of quartz overgrowths (fig. 35), calcite, and ferroan dolomite (ankerite?) cement (fig. 36). Original depositional porosity has been enhanced by secondary porosity resulting from leaching of feldspar grains (fig. 37). Distribution of porous granite wash ($\phi \geq 10$ percent) closely resembles total granite-wash distribution, indicating that original porosity distribution, cementation, and leaching occurred uniformly throughout the facies. Deltaic sandstones contain from 0 to 20 percent porosity. Average porosity in nonshaly sandstones is about 12 to 14 percent.

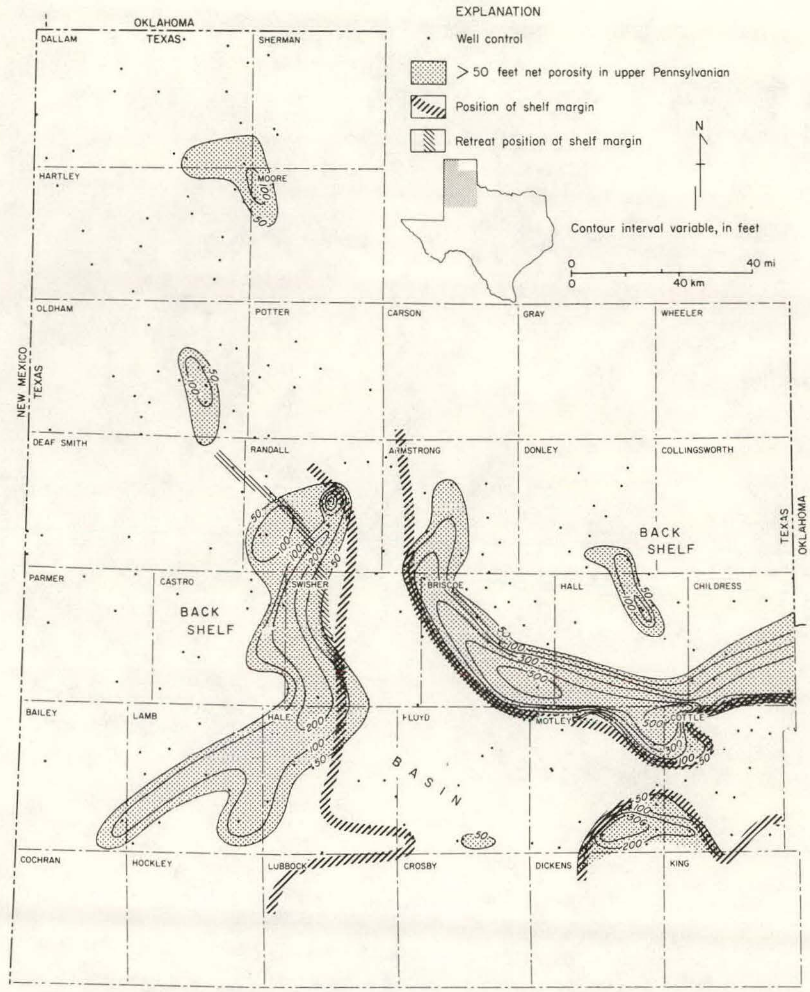


Figure 34. Isopach map of porous upper Pennsylvanian carbonate. Determination of porosity was based on qualitative sample log descriptions. Excellent correlation exists between porosity and dolomite occurrence (fig. 33).

PETROLEUM POTENTIAL

The Palo Duro Basin has not been a successful area for hydrocarbon exploration. Oil and gas have been produced from the Matador Arch and Amarillo Uplift and in Cottle, Childress, and Oldham Counties, but these areas are on the fringes of the Palo Duro Basin. However, hydrocarbon shows in drill-stem tests have been observed in several Pennsylvanian facies of the Palo Duro Basin, including shelf-margin carbonate, fan-delta granite wash, and deltaic sandstone (fig. 38). In the Dalhart Basin there is already some hydrocarbon production from Pennsylvanian granite wash. Because of these shows and the fact that many areas have not been well tested, both basins will probably be sites of future exploration.

Four things are necessary for hydrocarbon accumulation: source rocks, appropriate thermal history, reservoir facies, and traps. The Palo Duro Basin has abundant potential reservoirs; it probably contains source rocks and traps as well. However, the thermal history of the basin may not have been sufficient to generate hydrocarbons. The main zone of oil

Figure 35. Euhedral quartz overgrowths (Q) in Standard and Robinson #2 Tippen well, Cottle County; depth 2,074.5 m (6,806 ft).

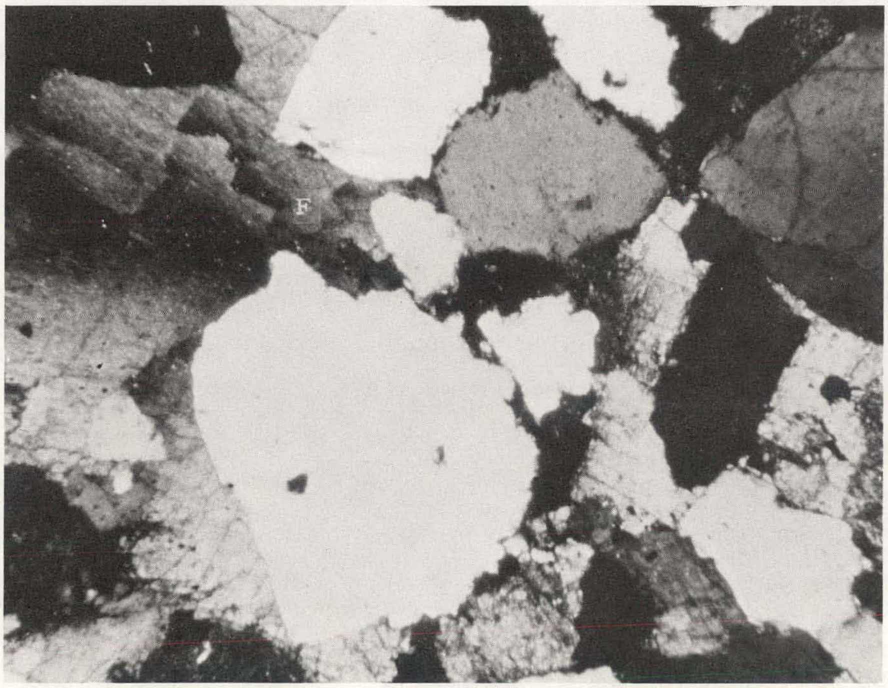


Figure 36. Ferroan-dolomite (ankerite?) cement (F) with undulose extinction in Standard and Robinson #2 Tippen well, Cottle County; depth 2,076.6 m (6,813 ft).

generation occurs at temperatures between 66° and 150° C (150° and 300° F) (Pusey, 1973). The current average geothermal gradient in the basin is 20°C per km (1.1°F per 100 ft) (fig. 39). Given this low gradient, Palo Duro sediments may not have been buried deeply enough to reach temperatures necessary for hydrocarbon generation. However, time as well as temperature is a factor in hydrocarbon maturation, and hydrocarbons may form at lower temperatures, given sufficient time (Dow, 1978).

Figure 37. Secondary porosity (P) in Standard and Robinson #2 Tippen well, Cottle County; depth is 2,074.5 m (6,806 ft).

Source Rocks

Total organic carbon (TOC) content is a measure of a rock's potential as a hydrocarbon source bed. To determine whether sediments in the Palo Duro Basin contained sufficient organic matter to generate hydrocarbons, well-cutting samples were collected from 20 geographically scattered wells (table 2 and fig. 38) and analyzed for TOC. A total of 341 samples were taken from a range of depths. Sampling was concentrated in the most likely source beds, such as Pennsylvanian and Lower Permian basinal shales and prodelta facies. Eleven wells contained Pennsylvanian samples with greater than 0.5 percent TOC, which is considered the boundary between poor and fair source rocks (Dow, 1978). Pennsylvanian rocks from five wells had TOC values greater than 1.0 percent (fig. 40) and should be good quality source rocks. The highest values of organic carbon were found in basinal shales near the Pennsylvanian-Permian boundary. Samples from the basin facies contained statistically significantly more organic carbon than samples from fan-delta, shelf, or delta deposits. Total-organic-carbon values from the entire Pennsylvanian section were averaged for each well (fig. 41). Distribution of organic carbon generally follows the outline of the earliest Wolfcampian shelf margin (fig. 32)--the high TOC values occur in the basin. The 0.5-percent-TOC contour line outlines the area containing fair to good potential source rocks.

Thermal Maturity

Pennsylvanian source rocks had to reach sufficiently high temperatures in order for hydrocarbons to be generated from disseminated organic matter. Physical characteristics of

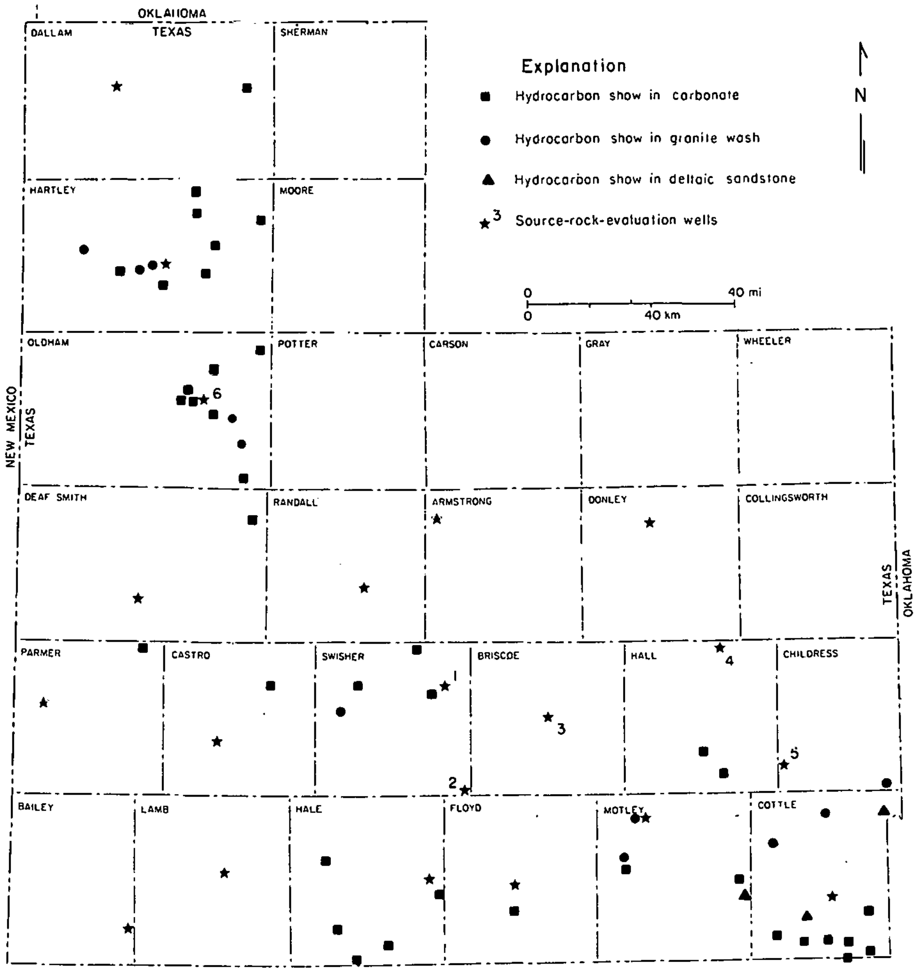


Figure 38. Hydrocarbon shows from drill-stem tests and cuttings in Pennsylvanian carbonate, granite wash, and sandstone. Total organic carbon values for numbered, source-rock-evaluation wells are plotted in figure 40.

the remaining organic material, especially color and reflectance, indicate maximum paleotemperatures. Kerogen color and vitrinite reflectance were determined for all samples having greater than 0.5 percent total organic carbon.

Kerogen, insoluble organic matter having high molecular weight, occurs in shales and other sediments (Barker, 1979). It consists mainly of plant material, including amorphous sapropel and algal debris; spores, pollen, and plant cuticle; woody tissue (vitrinite); and inert coaly material. Amorphous sapropel and algal debris are rich in lipids and are the most important source of hydrocarbons. Spores, pollen, plant cuticle, vitrinite, and coaly debris are of lesser importance in the generation of hydrocarbons. Higher temperatures are necessary to generate oil from these plant tissues than from lipid-rich amorphous material (Tissot and Welte, 1978).

With increasing temperature, kerogen color undergoes progressive darkening, from colorless to dark brown and black. Kerogen color can be used as an indication of thermal metamorphism and can be quantified as a "thermal alteration index" (Staplin, 1969). In this system kerogen color is described on a scale of light yellow to black, corresponding to thermal

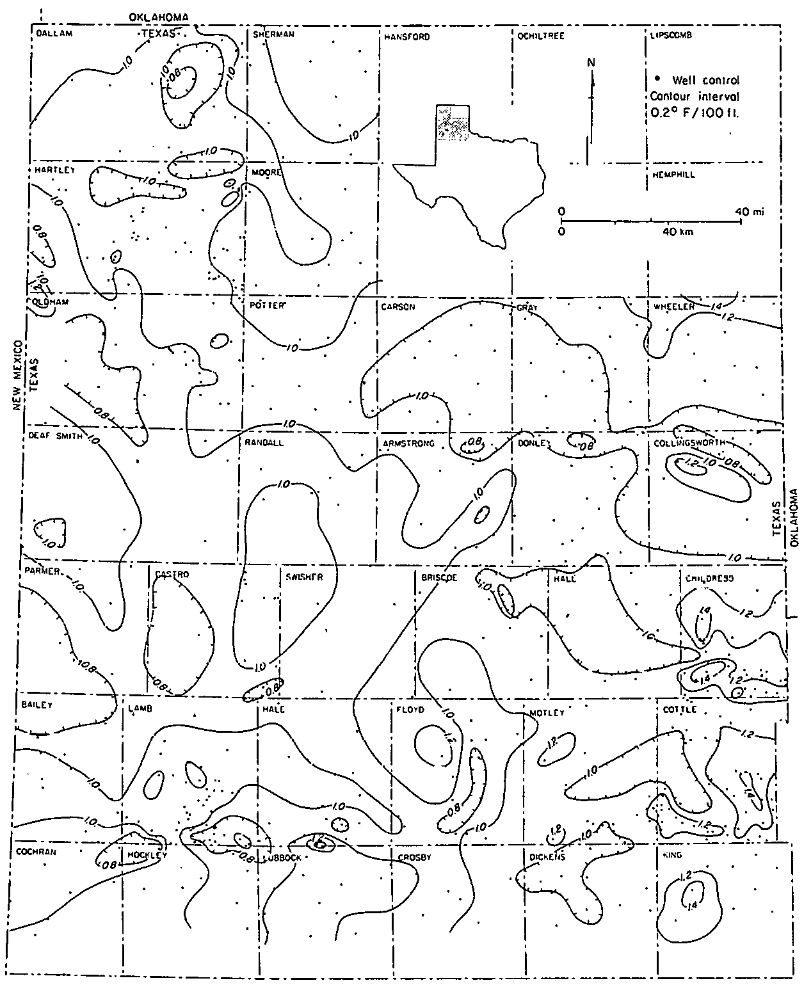


Figure 39. Geothermal gradient map of Palo Duro and Dalhart Basins.

alteration from 1 (no alteration) to 5 (severe alteration). All the Pennsylvanian kerogen samples from the Palo Duro Basin were yellow orange to orange, which indicates slight alteration, or a thermal alteration index of 2 in Staplin's system and 3 in the Geo-Strat system (Schwab, 1977).

Amorphous sapropel is the most abundant type of kerogen in the majority of samples. Herbaceous material, such as spores, pollen, and plant cuticle, is generally second in abundance. Vitrinite and coaly inerts are least common. At a thermal alteration index of 3 (Geo-Strat system), temperatures were probably high enough to begin generation of hydrocarbons from lipid-rich amorphous material (fig. 42). Temperatures were probably too low to generate oil from the other types of kerogen.

The amount of light reflected by vitrinite particles is another paleothermometer for source rocks. Pennsylvanian samples had a broad range of vitrinite reflectance values (Ro). Vitrinite populations showing the lowest reflectance probably indicate the temperatures that were reached in the Palo Duro Basin. Vitrinite with higher reflectance may have been reworked from older sediments (Tissot and Welte, 1978).

Table 2. Wells sampled for geochemical source-rock analyses.

County	BEG number	Operator	Well name	County	BEG number	Operator	Well name
Armstrong	1	Standard of Texas	#1A Palm	Hale	10	Amerada	#1 Kurfees
Bailey	20	Shell	#1 Nichols	Hall	1	Amarillo	#1 Cochran
Briscoe	13	Weaver	#1 Adair	Hartley	25	Phillips	#1A Cattle
Castro	11	Sun	#1 Herring	Lamb	26	Stanolind	#1 Hopping
Childress	48	Griggs	#1 Smith	Motley	1	Central	#1 Ross
Cottle	41	Baria & Werner	#1 Mayes	Oldham	52	Stanolind	#1 Herring
Dallam	22	Harrington	#1 Brown & Tovra	Parmer	4	Stanolind	#1 Jarrell
Deaf Smith	12	Honolulu	#1 Ponder	Randall	18	Slessman	#1 Nance
Donley	20	Doswell	#1 McMurty	Swisher	6	Standard	#1 Johnson
Floyd	10	Sinclair	#1 Massie	Swisher	13	Sinclair	#1 Savage

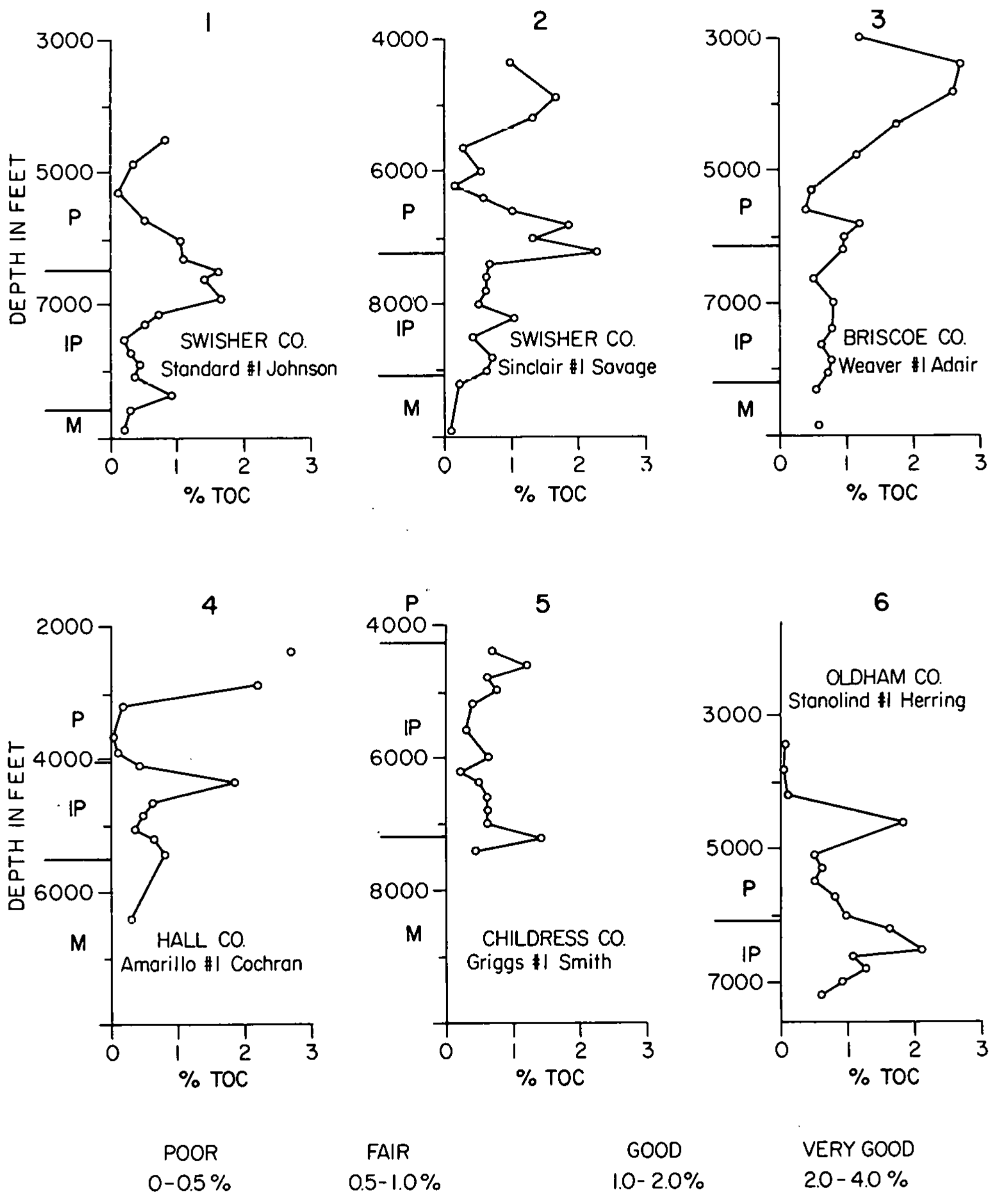


Figure 40. Plot of total organic carbon (TOC) against depth for six wells having highest TOC values of Pennsylvanian samples. Location of wells shown in figure 38.

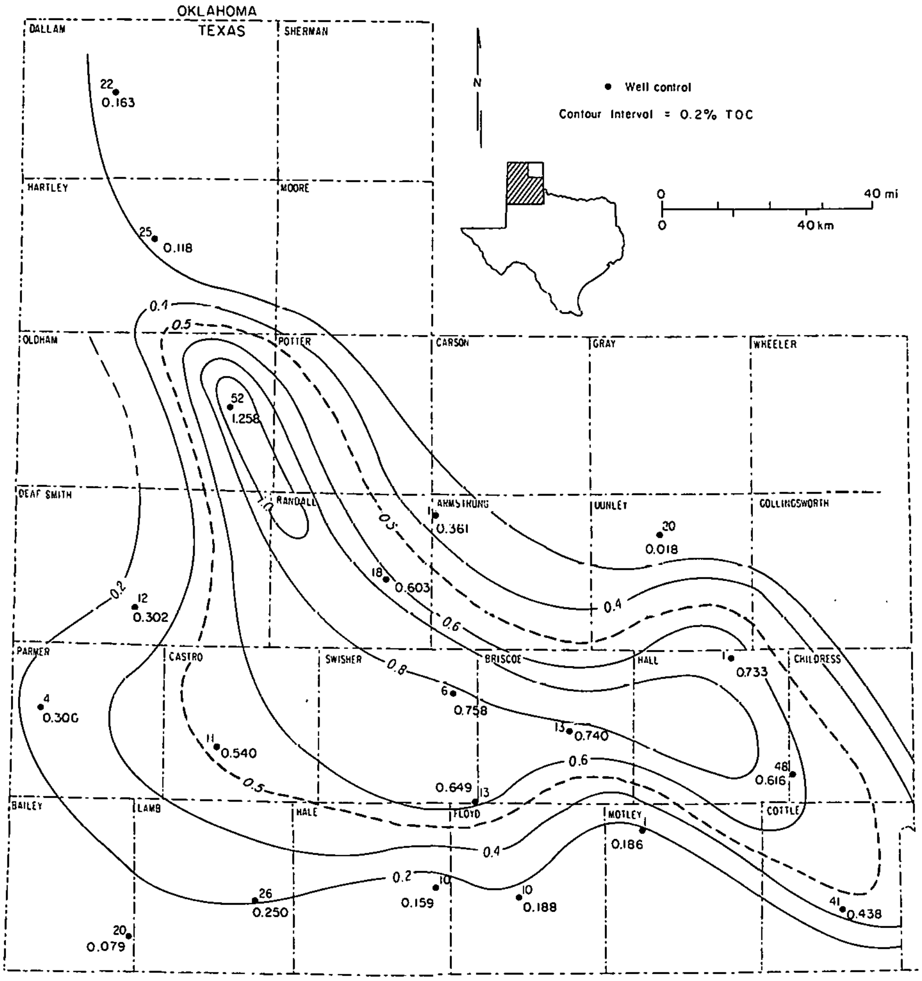


Figure 41. Distribution of total organic carbon in Pennsylvanian rocks of the Palo Duro Basin.

The average reflectance in representative Pennsylvanian vitrinite was 0.52 percent (fig. 42). According to Tissot and Welte (1978), vitrinite reflectance less than 0.5 to 0.7 percent indicates immature source rocks, while reflectance between 0.5 to 0.7 and 1.3 percent indicates that source rocks reached the main zone of oil generation. There is no sharp boundary between maturity and immaturity because organic matter having different compositions responds at different rates to temperature increases. Vitrinite reflectance of 0.52 percent suggests that the source rocks in the Palo Duro Basin were borderline between immaturity and hydrocarbon generation.

Determinations of kerogen color and vitrinite reflectance tests yield results that are consistent with each other and suggest that hydrocarbon generation may have begun in Pennsylvanian source rocks in the Palo Duro Basin. The principal temperature zone of oil generation was probably not reached for any kerogen types. However, the presence of amorphous, lipid-rich sapropel in the kerogen makes it likely that some oil could have formed at the temperatures indicated by the source rocks. Temperatures were probably not high enough to generate oil from the lipid-poor kerogen types.

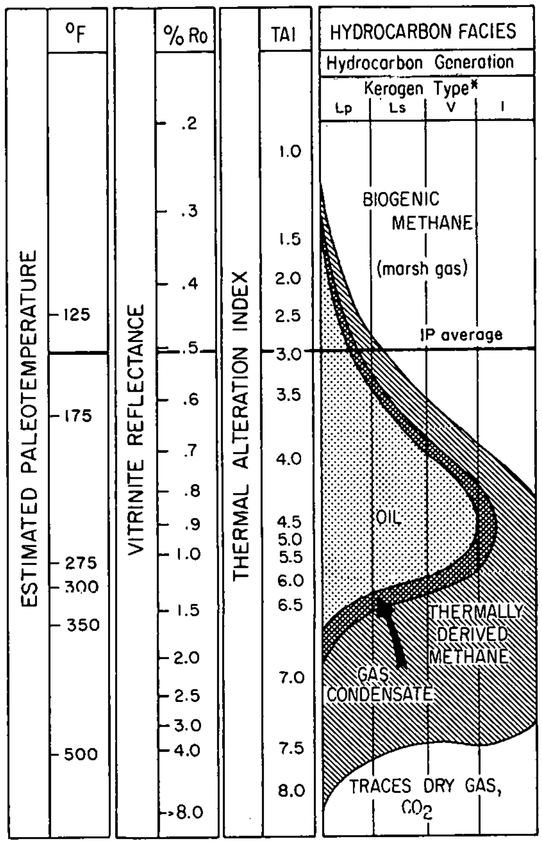


Figure 42. Relation of kerogen color (thermal alteration index) and vitrinite reflectance values in Pennsylvanian source rocks to hydrocarbon facies (from Schwab, 1977).

Reservoirs and Traps

After generation, oil may migrate from the source rocks through permeable units until it accumulates in a trap or disperses at the surface. For economically recoverable deposits to form, reservoir rocks and trapping mechanisms must be available at the time of hydrocarbon migration. Several possible reservoir facies exist in the Pennsylvanian strata of the Palo Duro Basin (table 3). Shelf-margin dolomite, fan-delta granite wash, and deltaic bar-finger sandstones are porous, potential reservoirs. Traps could be structural, stratigraphic, or a combination of the two.

Shelf margins consist of dolomitized limestone (fig. 33), having an average porosity of 8 to 10 percent. The Pennsylvanian dolomites, which in many areas are capped by tens of meters of shale, pinch out laterally into basinal shale and less porous shelf limestone. This potential stratigraphic trap configuration is illustrated on cross section B-B' (fig. 15).

The Empire Abo Field in the Delaware Basin in Eddy County, New Mexico, produces oil from a similar stratigraphic trap (LeMay, 1972). Porous shelf-margin dolomite of the Permian (Leonard) Abo Formation interfingers landward and along strike with tight, shelf, anhydritic dolomite and shale. On the basinward side, the producing dolomite is flanked by dark, argillaceous carbonates interbedded with fine-grained sandstones. Tight basinal deposits also overlie the porous dolomite so that it is completely enclosed in impermeable facies.

Table 3. Reservoir potential of Pennsylvanian facies.

Reservoir	Porosity	Traps	Producing analog
Shelf-margin dolomite	8-10%	1. Stratigraphic 2. Combination 3. Structural	Empire Abo Field, Eddy County, New Mexico, Leonardian dolomite
Fan-delta granite wash	13-15%	1. Structural 2. Combination 3. Stratigraphic	Mobeetie Field, Wheeler County, Texas, Missourian fan-delta granite wash
High-constructive delta sandstone	12-14%	1. Stratigraphic 2. Combination 3. Structural	Morris Buie - Blaco Fields, Shackelford County, Texas, Virgilian deltaic sandstone

Several factors could limit the reservoir potential of the shelf-margin dolomite facies in the Palo Duro Basin. The landward, shelf facies is a normal marine limestone rather than the tight, anhydritic dolomite found in the Empire Abo Field. Log-computed porosity of the limestone averages 3 to 5 percent, but locally occurring, more porous limestones may have allowed migrating hydrocarbons to escape. Another potential problem concerns the timing of dolomitization with respect to hydrocarbon migration. If dolomitization occurred after migration, no reservoir facies would have been present to host accumulations of hydrocarbons. Dolomite has been tested in the Consolidated Gas #1 Patton well, Swisher County, and no hydrocarbons were recovered. Drill-stem tests at two levels within the dolomite recovered only "salty sulfur water."

A second possible Pennsylvanian reservoir facies in the Palo Duro Basin is the granite-wash facies (table 3). Oil stains and shows in granite wash have been noted in cuttings and drill-stem tests (fig. 38), and there is oil production from granite-wash sandstones in Lambert Field, eastern Oldham County. Granite wash generally has good porosity (13 to 15 percent), and individual sandstone bodies are surrounded and sealed by shale or tight limestone. An example of such a stratigraphic trap is displayed on cross section B-B' in Childress County wells #48 and #49 (fig. 16). The lower half of section B-B' is depicted as almost all granite wash, but, as the electric logs show, it consists of multiple sandstones 6 to 12 m (20 to 40 ft) thick, interbedded with shale and limestone. Each of the sandstones is a possible reservoir.

The lack of updip seals for these sandstones may be the limiting factor in their reservoir potential. To the north, the sandstones abut the buried Amarillo Uplift, which is impermeable, but they are overlain by porous Permian granite wash and carbonate. Hydrocarbons may have migrated updip into Permian reservoirs or crossed the Amarillo Uplift into the Anadarko Basin.

Granite-wash deposits make good reservoirs in other areas where appropriate traps are present. Several fields producing from granite wash are located on the northern flank of the Amarillo Uplift, including the Mobeetie Field in Wheeler County. The hydrocarbons in these Missourian rocks are trapped in an anticlinal structure (Sahl, 1970), but the trap may be partly stratigraphic. Oil is also produced from Pennsylvanian granite-wash fan-delta lobes in Wichita and Archer Counties, south of the Wichita and Arbuckle Mountains of Oklahoma (Erxleben, 1975).

The third possible reservoir facies in the Pennsylvanian of the Palo Duro Basin is the deltaic sandstone located in the eastern part of the basin. Bar-finger sandstones are enclosed by prodelta and delta-flank shale and may be sealed updip by mud plugs deposited after distributary channels were abandoned. Where these sandstones have porosity up to 12 to 14 percent, as in Cottle #38 (fig. 29), they are possible reservoirs. Bar-finger-sandstone reservoirs occur in upper Pennsylvanian Cisco Group strata of the Eastern Shelf of the Midland Basin. The Morris Buie - Blaco Field in Shackelford County produces from a 15 m (50 ft) thick bar-finger sandstone. The trap is primarily stratigraphic, combined with a subtle structural hinge (Galloway and Brown, 1972).

CONCLUSIONS

1. The Palo Duro and Dalhart Basins formed during the early Pennsylvanian Period by uplift of surrounding structural highlands. Thick wedges of coarse-grained clastics were deposited by alluvial fans and fan deltas adjacent to uplifted areas. Alternating clastic and carbonate sedimentation was common in distal fan-delta environments. Extensive carbonate deposits formed on a shallow shelf in the southern portion of the Palo Duro Basin, isolated from the influx of clastics.

2. By late Pennsylvanian time, substantial subsidence of the Palo Duro Basin had occurred. A deep-basin shale environment developed, flanked by thick shelf-margin carbonates. The western shelf margin retreated landward in response to continued subsidence and fan-delta clastic sedimentation. Highlands were considerably eroded, and fan-delta systems were smaller and confined closer to source areas. High-constructive deltas prograded into the southeastern portion of the basin.

3. Shelf-margin carbonates were dolomitized to form a zone 16 to 32 km (10 to 20 mi) wide. Dolomite porosity averages 8 to 10 percent. Porosity in granite-wash sandstone has been reduced to 13 to 15 percent by quartz, calcite, and ferroan-dolomite cements. Deltaic sandstones average 12 to 14 percent porosity.

4. Geochemical analyses indicate that Pennsylvanian basinal shales are fair to good potential source rocks, containing greater than 0.5 percent total organic carbon. Kerogen color and vitrinite reflectance values suggest that organic matter is borderline between immaturity and hydrocarbon generation. Amorphous, lipid-rich sapropel in particular may have reached the early stages of hydrocarbon maturation.

5. The Pennsylvanian System contains three potential reservoir facies: shelf-margin dolomite, fan-delta granite wash, and deltaic sandstone. Hydrocarbon shows in cuttings and drill-stem tests have been observed in each of the three facies. Exploration in the Palo Duro Basin has not been very successful, but there is production in areas on the fringes of the basin and in the nearby Dalhart Basin.

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