Report of Investigations No. 147

STRATIGRAPHY AND PETROLEUM POTENTIAL OF PRE-PENNSYLVANIAN ROCKS, PALO DURO BASIN, TEXAS PANHANDLE

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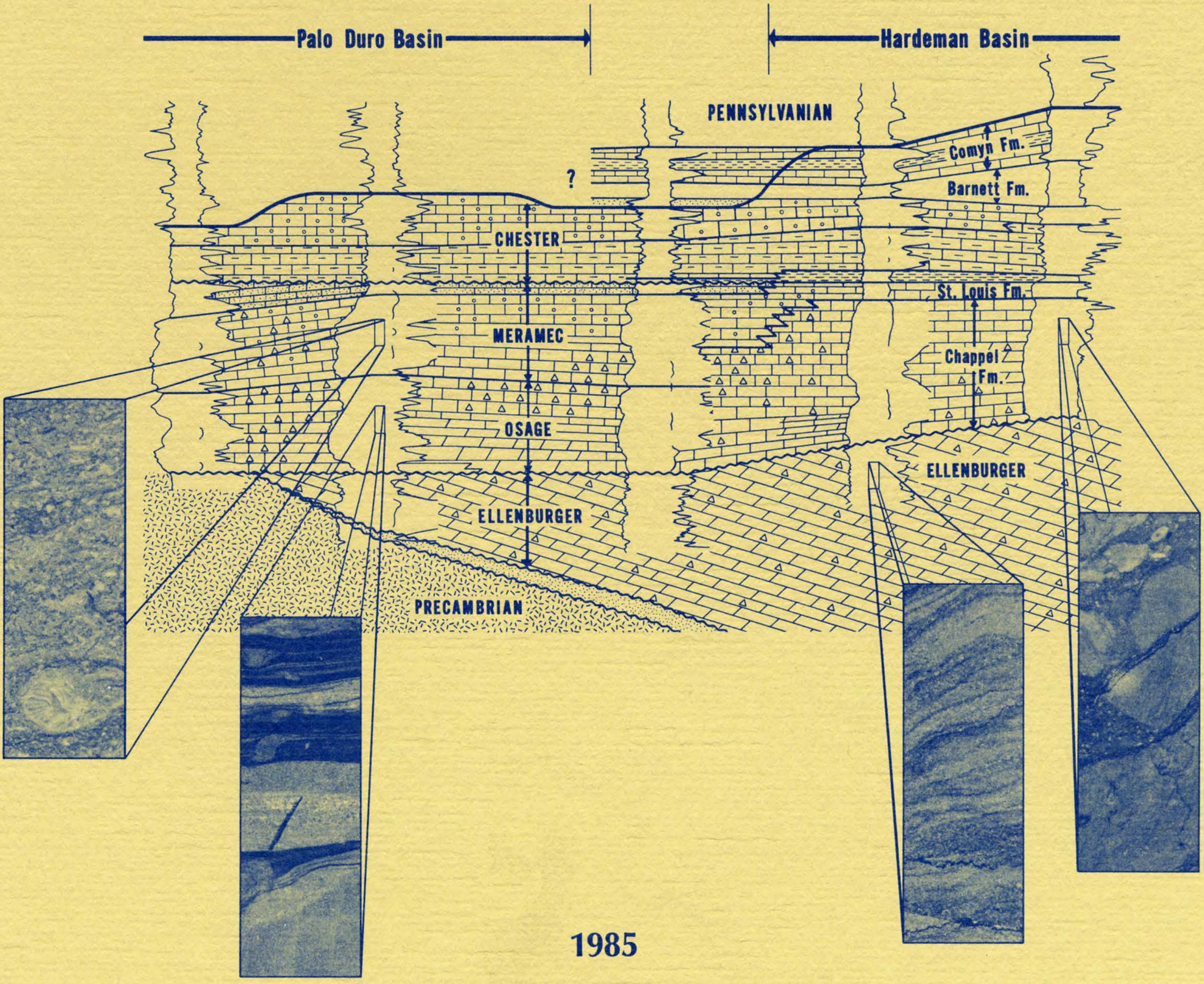

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Bureau of Economic Geology
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STRATIGRAPHY AND PETROLEUM POTENTIAL OF PRE-PENNSYLVANIAN ROCKS, PALO DURO BASIN, TEXAS PANHANDLE

by
Stephen C. Ruppel

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ABSTRACT

Pre-Pennsylvanian rocks in the Palo Duro Basin include (1) basal transgressive marine Cambrian(?) sandstones deposited over Precambrian basement, (2) overlying Lower Ordovician dolomites of the Ellenburger Group that formed when shallow seas covered much of the North American continent, and (3) Mississippian limestones and dolomites deposited when the area was inundated again after middle Paleozoic uplift and erosion. A generally similar stratigraphic sequence exists in the adjacent Dalhart and Hardeman Basins.

Mississippian deposits, the most widespread and best known pre-Pennsylvanian rocks, exhibit considerable facies and paleoenvironmental diversity throughout the Texas Panhandle. The lowermost Mississippian "Osage" contains cherty and shaly dolomites and limestones. In the eastern Palo Duro Basin and in the Hardeman Basin further to the east, these rocks are interbedded carbonate mudstones and limestone turbidites that were deposited below wave base in relatively deep, quiet water. Westward, the "Osage" includes progressively shallower water facies.

"Meramec" limestones are remarkably similar throughout the Texas Panhandle. These coarse-grained, light-colored, skeletal (bryozoan/echinoderm) grainstones record the establishment during the middle to late Meramecian of a widespread, shallow-water, carbonate sand shoal. However, before this shoal developed in the Hardeman Basin, numerous local carbonate buildups formed (Chappel Formation).

The uppermost Mississippian "Chester" contains interbedded ooid grainstones and shales that attest to (1) the maintenance of shallow-water marine conditions and (2) the development of terrigenous clastic source areas associated with early phases of Late Carboniferous tectonic activity. Uppermost "Chester" shales (Barnett Formation) and limestones (Comyn Formation) in the Hardeman Basin to the east are not present in the Palo Duro Basin owing to facies change or erosion or both.

All pre-Pennsylvanian units contain sufficient porosity and permeability, at least locally, to be hydrocarbon reservoirs. Potential structural and stratigraphic traps are plentiful throughout the area. Carbonate buildups are productive in the nearby Hardeman Basin; similar buildups may exist in at least the eastern part of the Palo Duro Basin. However, suitable top seals may be lacking in the Palo Duro Basin.

Although the quality of organic matter contained in the pre-Pennsylvanian deposits in the Palo Duro Basin is good, there is probably too little organic carbon for these rocks to be hydrocarbon sources. The "Osage" of the eastern Palo Duro Basin contains the highest amounts of organic matter. The Barnett Formation, which contains organic-matter-rich shales in the Hardeman Basin to the east, does not extend into the Palo Duro Basin.

Calculations of thermal maturity based on vitrinite reflectance indicate that although pre-Pennsylvanian rocks in the Palo Duro Basin are substantially less mature than those in the Hardeman Basin, most have attained at least the minimum degree of heating necessary to produce hydrocarbons. Thermal maturity in the area generally correlates with the present-day geothermal gradient, which increases toward the east.

Petroleum potential of the pre-Pennsylvanian rocks of the Palo Duro Basin is relatively low. Future exploration in these rocks should concentrate on areas where source rock quality, maturity, and reservoir conditions are optimum. The extreme southern and eastern parts of the basin appear to offer the greatest promise.

Keywords: source rocks, Mississippian, Ordovician, Palo Duro Basin, Hardeman Basin, thermal maturity, stratigraphy, petroleum potential, Ellenburger Group, Chappel Formation.

INTRODUCTION

From the standpoint of oil and gas production, the Palo Duro Basin is an enigma. Except for fields associated with bounding uplifts, there is no current commercial production in the basin, despite the drilling of about 1,000 exploration test wells. This lack of production is surprising in light of abundant hydrocarbon discoveries made throughout the rest of the Texas Panhandle (fig. 1).

Many previous workers (Totten, 1956; Best, 1963; Soderstrom, 1968) ascribed the lack of exploration success in the Palo Duro Basin to the relative sparsity of wells drilled in the area (approximately 7 wells per 100 mi^2; 3 wells per 100 km^2). Dutton (1980a, 1980b; Dutton and others, 1982) concluded that the basin contains all the prerequisites for oil generation and production: source rocks, thermal maturity, reservoir rocks, and traps. Although production was short-lived, the 1982 discovery of oil in Pennsylvanian rocks in Briscoe County, near the center of the basin, seems to support Dutton's analysis.

Pennsylvanian and younger units in the Palo Duro Basin have been adequately characterized (Dutton, 1980a, 1980b); the potential of the pre-Pennsylvanian rocks in the area is less well known. Thermal maturity data (Dutton, 1980b) indicate that Pennsylvanian deposits have reached temperatures necessary to generate significant amounts of hydrocarbons. Mississippian and older rocks should therefore also be thermally mature. Pre-Pennsylvanian rocks contain sufficient porosity to act as hydrocarbon reservoirs (Dutton and others, 1982), but the petroleum potential of these rocks has not been comprehensively studied.

The Palo Duro Basin is being considered by the U.S. Department of Energy as a possible repository for disposal of high-level nuclear waste. Because the integrity of the repository cannot be breached, it is important to know what potential exists for oil and gas accumulation. This report characterizes the potential of pre-Pennsylvanian rocks in the Palo Duro Basin to contain and to produce hydrocarbons.

GENERAL SETTING

The Palo Duro Basin is one of four sedimentary basins that, along with intervening arches and uplifts, make up the Texas Panhandle (fig. 1). This structural configuration was produced by tectonic forces first active during the Late Mississippian or Early Pennsylvanian. The Palo Duro Basin, as it is commonly defined, is bounded on the south by the Matador Arch, on the north by the Amarillo Uplift, and on the west by a slight structural positive that separates the Palo Duro from the Tucumcari Basin in central New Mexico (Budnik and Smith, 1982). To the east, separated from the Palo Duro by another minor structural high, are the Hardeman and Hollis (or Harmon) Basins (Totten, 1956). In the past, some researchers have included the Hardeman and Hollis Basins as part of the Palo Duro. The Dalhart Basin, also considered by some to be part of the Palo Duro, is separated from the latter by the Bravo Dome (fig. 1).

Rocks in the Texas Panhandle range in age from Precambrian to Recent. Except for the northeastern part of the area (Anadarko Basin), however, the pre-Pennsylvanian sequence comprises only Mississippian, Lower Ordovician, and Cambrian(?) rocks (fig. 2); Silurian and Devonian deposits are absent. Total thickness of the pre-Pennsylvanian section is about 1,000 to 1,200 ft (300 to 370 m) in the Palo Duro and Dalhart Basins and 2,000 to 2,500 ft (600 to 730 m) in the Hardeman and Hollis Basins.

Studies of pre-Pennsylvanian rocks in the Palo Duro Basin are relatively few. The most comprehensive early study is that by Totten (1956); summaries have been published by Roth (1955), Huffman (1959), Nicholson (1960), Best (1963), and Soderstrom (1968). A stratigraphic analysis of the Dalhart and Anadarko Basins area was prepared by Cunningham (1969). More recently, Mapel and others (1979) characterized the Mississippian of the Southern Mid-Continent region. No detailed study of pre-Pennsylvanian rocks and their hydrocarbon potential has previously been published for the Palo Duro Basin area, however. Such a report is long overdue, considering the continued interest in the area as a possible target for oil and gas exploration.

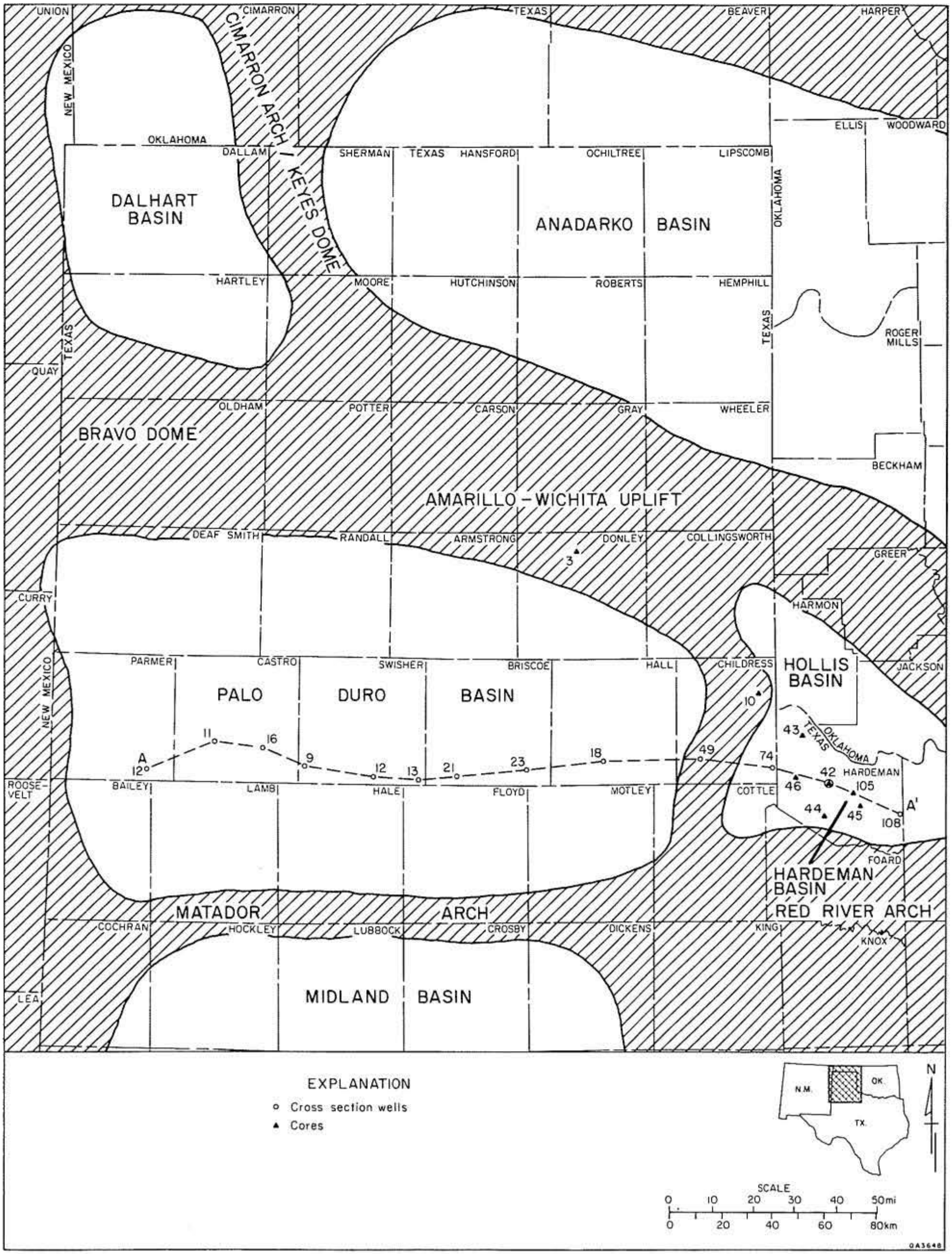

Figure 1. Map of the Texas Panhandle indicating major subsurface features and cored wells. Because the tectonic activity that created the structural differentiation of the area began in the Pennsylvanian, these structures had no effect on most pre-Pennsylvanian deposition. Line of section A-A′ is shown in figure 15. All wells are listed in appendix A.

SYSTEM	SERIES	DALHART / W. ANADARKO BASINS (Cunningham, 1961, 1969)	PALO DURO BASIN (Nicholson, 1960)	HARDEMAN BASIN (Allison, 1979)	MID-CONTINENT REGION (Mapel and others, 1979)
MISSISSIPPIAN	CHESTERIAN			COMYN	D
		CHESTER	CHESTER	BARNETT	
	MERAMECIAN	STE. GENEVIEVE	MERAMEC	STE. GENEVIEVE	C
		ST. LOUIS		ST. LOUIS	
		SPERGEN-WARSAW		CHAPPEL	
	OSAGEAN	OSAGE	OSAGE		B
	KINDERHOOKIAN	KINDERHOOK		OSAGE	A
DEVONIAN					
SILURIAN					
ORDOVICIAN	CINCINNATIAN				
	CHAMPLAINIAN				
	CANADIAN	ELLENBURGER	ELLENBURGER	ELLENBURGER	
CAMBRIAN	UPPER	HICKORY / REAGAN	HICKORY		
PRECAMBRIAN					

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Figure 2. Schemes of stratigraphic nomenclature applied by previous workers to pre-Pennsylvanian rocks in the Texas Panhandle. Some geologists have attempted to subdivide the Meramec of the Palo Duro Basin with formation names used in the Dalhart Basin.

METHODS

Geophysical well logs from more than 7,500 wells in 57 counties of Texas, Oklahoma, and New Mexico were examined for this study. However, only about 250 wells penetrate pre-Pennsylvanian units in the Palo Duro Basin. Commercially prepared sample logs were available for about 175 of these wells. Rock core was described from 2 wells on the periphery of the Palo Duro Basin and 6 wells in the Hardeman Basin (fig. 1); cuttings from 115 wells were examined. Geochemical studies of total organic carbon, kerogen, and vitrinite reflectance were conducted on samples from 58 wells. Most geochemical analyses were performed by Geo-Strat, Inc., Houston, Texas; additional samples were analyzed by GeoChem Laboratories of Houston.

Each well used in this study was assigned a unique county/number designation for reference (for example, Childress 10). A complete list of all wells referred to in this report is given in appendix A.

Although the primary focus of this report is the Palo Duro Basin, the Dalhart and Hardeman Basins are also discussed. The Dalhart, like the Palo Duro, has yet to produce significant quantities of hydrocarbons and thus is also poorly known. The Hardeman Basin, in contrast, has been the site of several significant petroleum discoveries in Mississippian and Ordovician rocks; thus, more information—core, geophysical logs, and reports—is available on the Hardeman Basin than on either Palo Duro or Dalhart Basin.

STRUCTURAL SETTING

Subsurface structure of the Texas Panhandle is indicated by contour maps of the top of the Ellenburger Group (fig. 3) and the top of the Mississippian System (fig. 4). The axis of the Palo Duro Basin generally trends southeast-northwest, the deepest part occurring in southeastern Floyd and southwestern Motley Counties; Mississippian rocks here are more than 7,500 ft (2,286 m) below sea level (fig. 4). Most of the faulting suggested by contour mapping parallels the basin axis. Seismic data from the central and western parts of the basin support this interpretation but also reveal northeast-trending faults (Gustavson and Budnik, 1985). Seismic data also indicate that faulting is much more prevalent than is suggested by structure-contour maps based on well data.

The Matador Arch, which forms the southern boundary of the Palo Duro Basin, is an east-west structural trend composed of isolated high areas commonly bounded by faults (fig. 4). Faulting along this structure is ubiquitous and complex, apparently resulting in numerous small fault blocks. The NRM field (now abandoned), the only pre-Pennsylvanian (Mississippian) hydrocarbon discovery in the Palo Duro Basin, appears to be located on a small fault sliver in one of these structurally complex areas in southeastern Floyd County.

Pre-Pennsylvanian stratal boundaries are poorly understood, but most depictions suggest that they are erosional (Huffman, 1959; Nicholson, 1960), as is certainly true for the Ellenburger Group along the Texas Arch (fig. 3). Available seismic lines, however, indicate that in some areas (for example, in western Deaf Smith County) these boundaries are fault controlled. The somewhat linear nature of many segments of these contacts suggests that contacts elsewhere in the basin may be fault controlled.

A positive area of low relief that extends north-south through Cottle and Childress Counties (fig. 4) separates the Hardeman and Hollis Basins from the Palo Duro Basin. The Hardeman Basin, in turn, is separated from the Hollis Basin by an east-west line of high structures and a similarly trending fault zone. Apparent displacement along this fault zone exceeds 1,000 ft (305 m). Depths in the Hardeman Basin are generally similar to those in the Palo Duro; the Hollis Basin is somewhat shallower (fig. 4).

The Dalhart Basin occupies the northwestern corner of the Texas Panhandle (fig. 1). It is separated from the Anadarko Basin by northwest- and northeast-trending faults and a north-south-trending structural positive (Cimarron Arch/Keyes Dome). Pre-Pennsylvanian units in the Dalhart Basin are shallow (fig. 4); Mississippian rocks reach maximum depths of about 5,000 ft (1,525 m) below sea level.

STRATIGRAPHY

The pre-Pennsylvanian sequence of rocks in the Palo Duro, Dalhart, and Hardeman Basins comprises three parts: (1) a basal thin unit of terrigenous (Cambrian?) siliciclastics, (2) an overlying interval of Lower Ordovician (Ellenburger Group) dolomites, and (3) an uppermost sequence of Mississippian carbonates, predominantly limestones. Although these units are variably developed throughout the area, sections typical for each of the three basins are illustrated in figure 5.

Basal (Cambrian?) Siliciclastics

Thin beds of terrigenous siliciclastics overlie Precambrian basement in several parts of the Texas Panhandle (fig. 6). Although thick sequences of these deposits have been reported from the Hardeman Basin (Montgomery, 1984), thicknesses of more than 50 ft (15 m) are rare. Most of these deposits comprise rounded quartz sandstones, although gray and green shales and clasts of dolomite or limestone or both are locally present. The basal sandstones grade downward into the underlying weathered basement rocks in many places, making precise distinction between the two units locally difficult.

Distribution of the basal sandstones generally corresponds to that of the overlying Ellenburger Group (fig. 6); this suggests that the sandstones once covered the entire Panhandle in a thin veneer. Middle Paleozoic erosion along the Texas Arch (fig. 3; Adams, 1954) apparently removed most of these deposits, along with the Ellenburger, in the

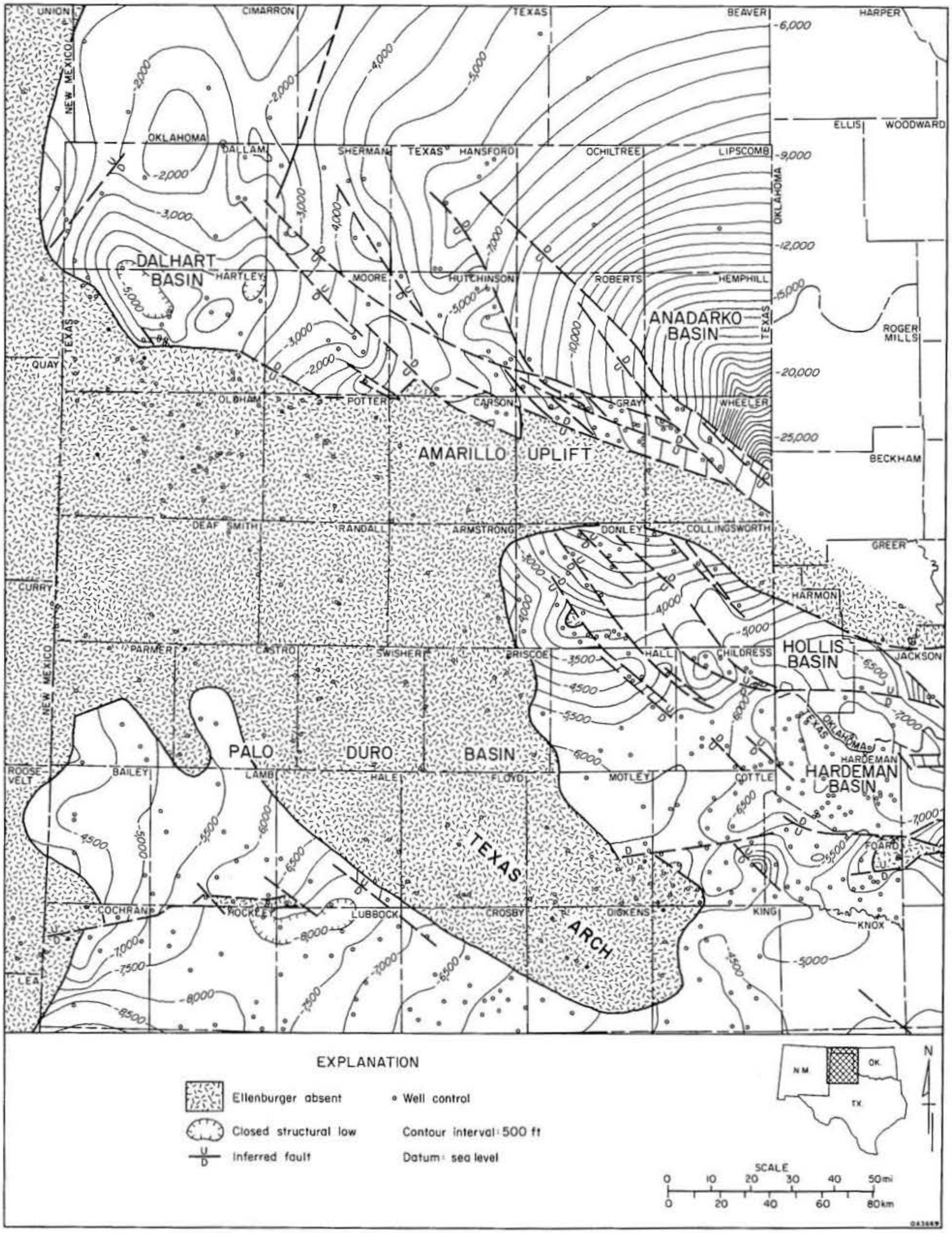


Figure 3. Structure-contour map of the top of the Ellenburger Group (Lower Ordovician). These rocks were removed from much of the Palo Duro Basin by erosion along the Texas Arch. Faults inferred from contour mapping.

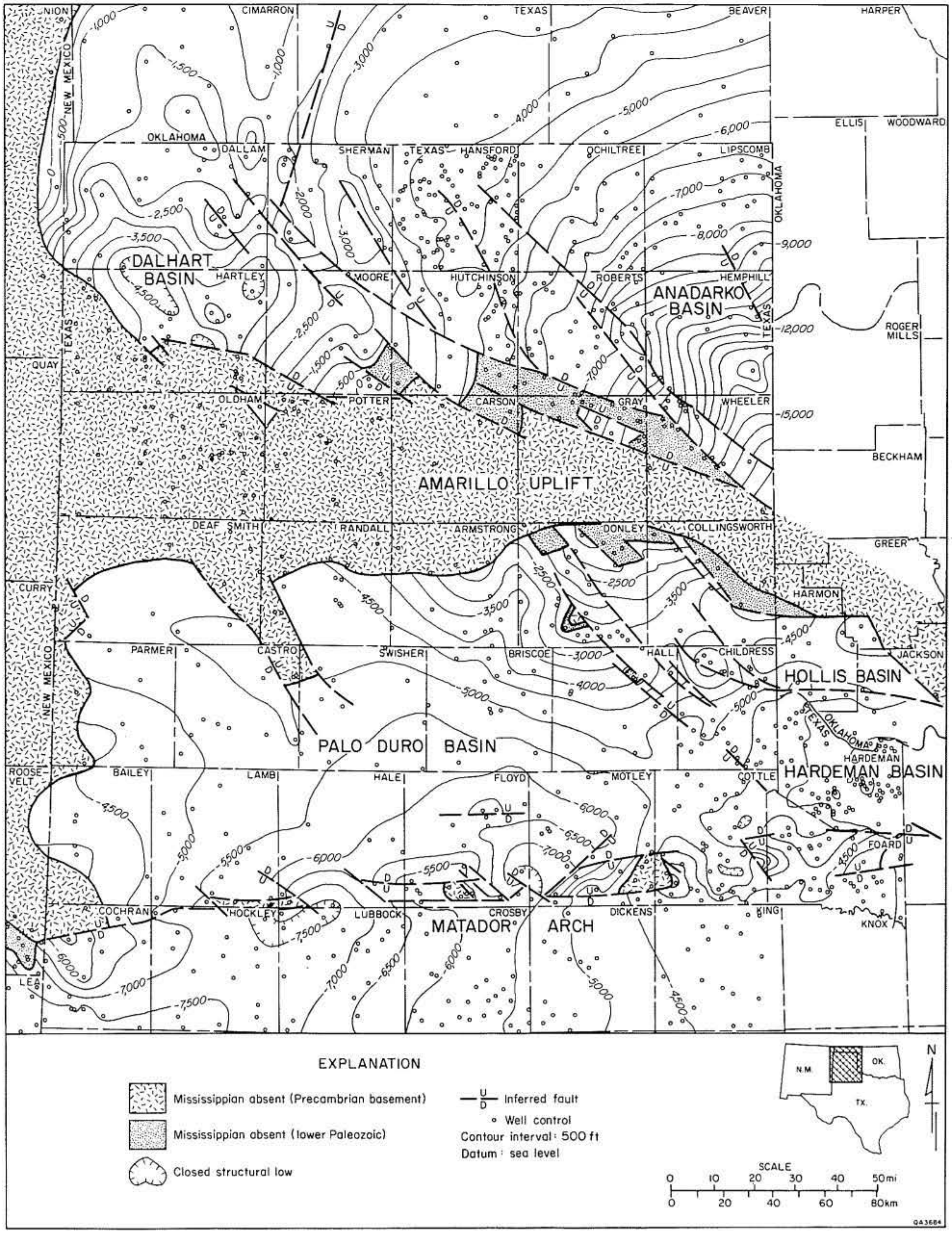


Figure 4. Structure-contour map of the top of the Mississippian System. Faults inferred from contour mapping.

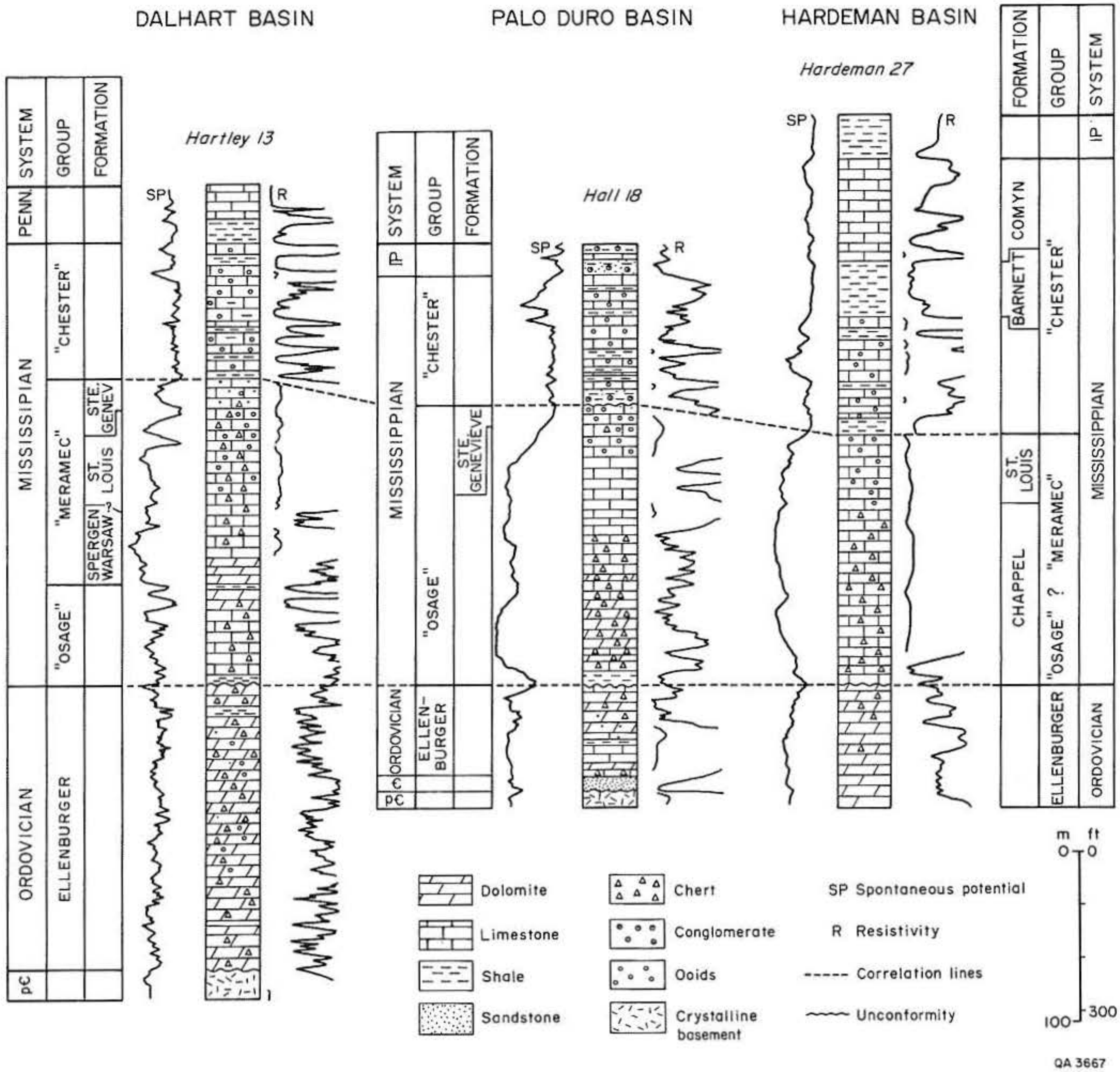


Figure 5. Typical pre-Pennsylvanian sections in the Dalhart, Palo Duro, and Hardeman Basins. The interval above the St. Louis Formation in the Hardeman Basin had previously been assigned to the Ste. Genevieve Formation (Allison, 1979; Asquith, 1979; Ross, 1981; Ahr and Ross, 1982). This study, however, indicates that this interval is equivalent to the "Chester," as recognized elsewhere in the Panhandle. The Ste. Genevieve does not appear to be present in the Hardeman Basin. The uppermost Mississippian (upper "Chester") has been assumed to be absent from the Palo Duro and Dalhart Basins because of erosion. Correlations in this study suggest that at least some parts of these areas may contain uppermost Mississippian rocks (Comyn equivalents) erroneously assigned to the Lower Pennsylvanian. Well names given in appendix A.

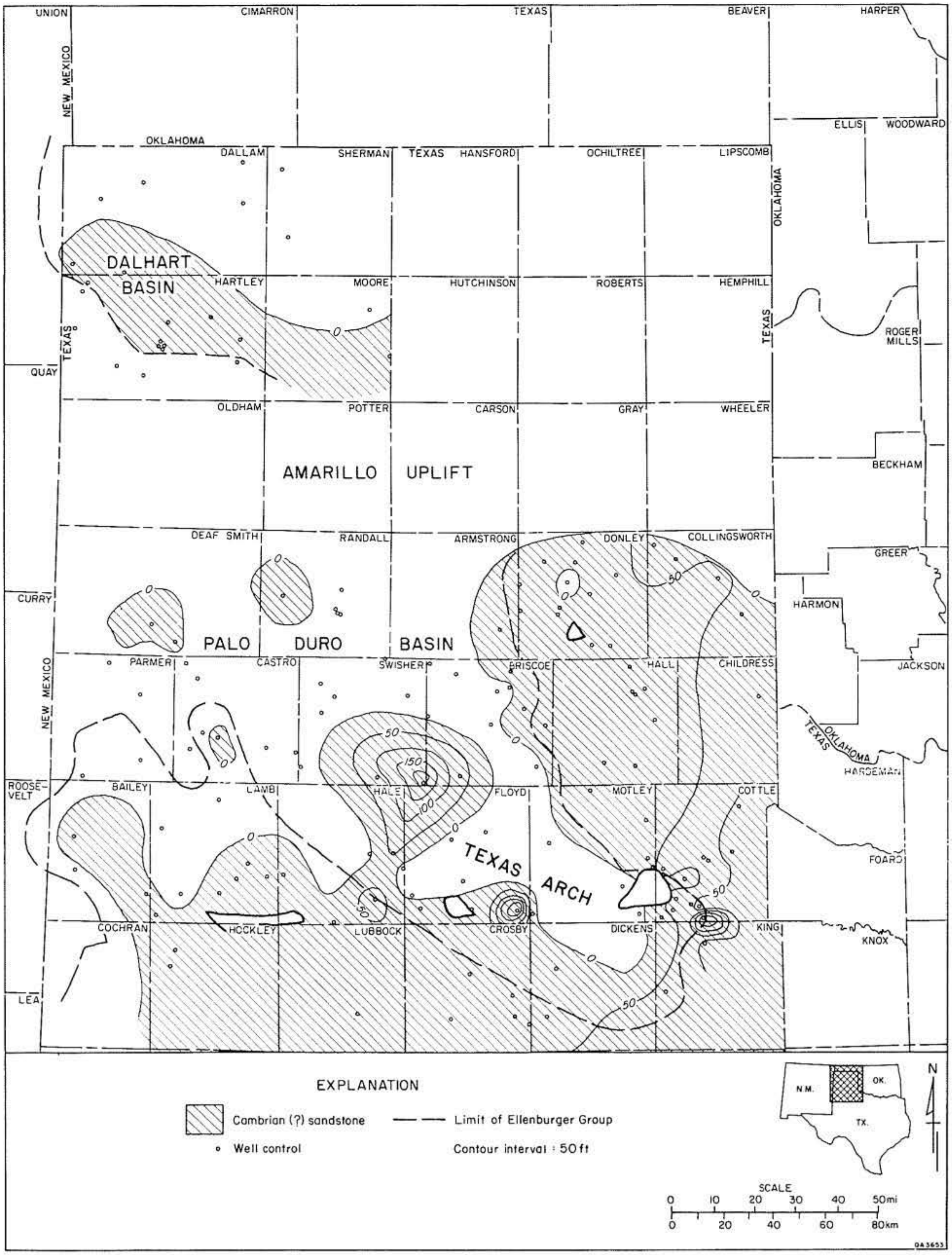


Figure 6. Thickness map, basal Cambrian(?) siliciclastic deposits. Note similarity of distribution to that of the overlying Ellenburger Group (Lower Ordovician).

central Palo Duro Basin. In at least two areas in the Palo Duro Basin, however, substantial thicknesses of basal, rounded quartz sandstones are present where the Ellenburger is absent. In southeastern Swisher and southeastern Floyd Counties (fig. 6), more than 200 ft (61 m) of such deposits have been reported on sample logs; these sandstones are overlain by Mississippian carbonates.

The exact age of the basal siliciclastics in the Texas Panhandle is unknown; however, some have been correlated with the Hickory Sandstone (member of the Cambrian Riley Formation), which crops out in Central Texas. Other deposits of similar lithology are known, however, from younger Cambrian and Ordovician units (Wilberns Formation) that crop out in Central Texas. Barnes and others (1959) assigned basal clastics in north Texas to the Wilberns Formation, which suggests that the basal clastics of the Panhandle should also be regarded as Wilberns rather than Riley (Hickory) equivalents. In the absence of more complete data, however, precise correlation of the Panhandle basal sandstones cannot be established. Because of their stratigraphic position below the Ellenburger Group, most of these basal sandstone deposits are probably Cambrian, having been formed during the general marine transgression of the area at the beginning of the Paleozoic.

The origin and age of the thick deposits of sandstone in Swisher and Floyd Counties are more enigmatic. Because they are overlain by Mississippian rocks, these sandstones may be (1) basal deposits formed during the transgression of the area in the Late Devonian-Early Mississippian, (2) Precambrian sandstones that were not removed during middle Paleozoic erosion along the Texas Arch, or (3) thick deposits of Cambrian basal clastics deposited in structural depressions. Coarse terrigenous clastics of possible Devonian/Mississippian age (those that overlie Lower Ordovician rocks but underlie known Mississippian deposits) are unknown in the Palo Duro Basin. If these thick sandstone deposits are associated with this transgressive event, they are anomalous. Although a Precambrian age cannot be ruled out for these deposits, there is no basis for separating them from the Cambrian(?) sandstones described above. Thus meager evidence favors the third interpretation. The thick accumulation in Floyd County coincides with a structural low between uplifted blocks along the Matador Arch. This suggests that the accumulation of these basal sandstones was controlled by structural features that have been intermittently active throughout much of the Paleozoic.

Lower Ordovician Ellenburger Group

The Ellenburger Group was defined by Barnes and others (1959) to contain all Lower Ordovician deposits in the subsurface of north and West Texas and southeast New Mexico. Partly equivalent rocks in Oklahoma and the northern Texas Panhandle are included in the Arbuckle Group. Although lithologically similar, the Arbuckle differs from the Ellenburger in that the former contains Upper Cambrian as well as Lower Ordovician rocks (Cloud and Barnes, 1946). In this report, the term Ellenburger is used because it is more common in Texas usage, although the exact age of these deposits is unknown.

The Ellenburger is present throughout the Texas Panhandle except where it has been removed by erosion along the Amarillo Uplift and the Texas Arch (fig. 7). In the Palo Duro Basin and in the Dalhart Basin to the north, the Ellenburger generally reaches maximum thicknesses of only about 500 ft (152 m). Although thicknesses as great as 2,000 ft (610 m) have been indicated in the Hardeman and Hollis Basins (Bartram and others, 1950; Barnes and others, 1959; Huffman, 1959), such values are not supported by available well data. It is clear, however, that the Ellenburger thickens markedly east and northeast of the Palo Duro Basin into the area immediately south of the Amarillo-Wichita Uplift (Collingsworth, Childress, and Hardeman Counties, Texas, and Harmon County, Oklahoma).

Sample logs indicate that the Ellenburger Group consists primarily of fine- to coarse-grained, sucrosic to rhombic dolomite; limestone is rare. Shale and medium- to coarse-grained, rounded quartz sandstone are locally common; chert is common throughout the Ellenburger and in many places it is oolitic. Glauconite and pyrite are minor accessory minerals; glauconite is especially common at the base and the top. Color in the Ellenburger is variable. Dolomite is usually gray to brown, but white, cream, pink, and yellow are also reported. These rocks do not, however, show a progressive southwest to northeast darkening of color as suggested by Barnes and others (1959). Most shales in the Ellenburger are waxy and gray-green; red-brown shales are less common. Chert is

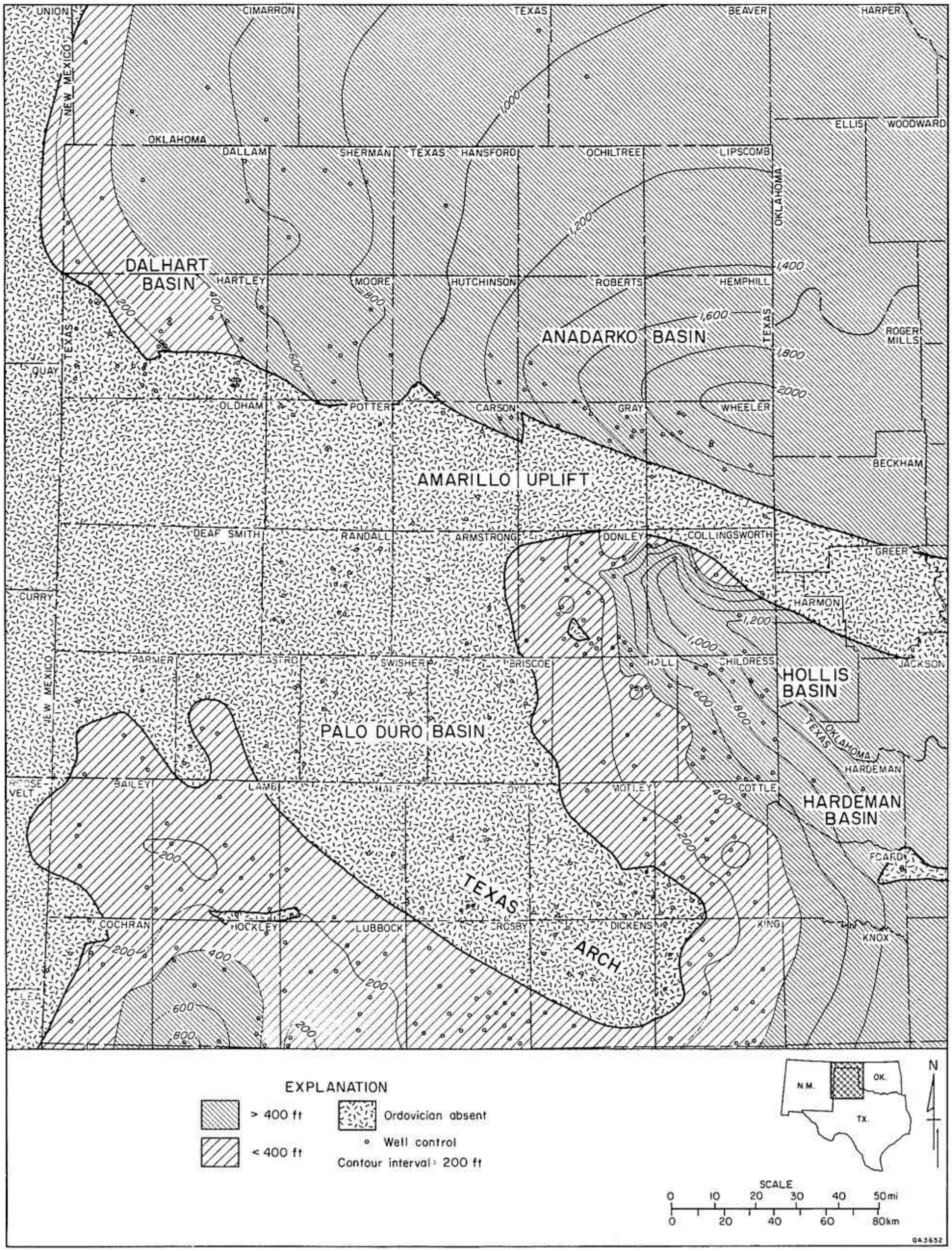


Figure 7. Thickness map, Ellenburger Group (Lower Ordovician).

most commonly white to pink, although shades of blue are also reported.

Examination of cores from Hardeman County shows the Ellenburger to be composed nearly entirely of crystalline dolomite. Although dolomitization has obscured most textures in the Ellenburger, sedimentary structures are recognizable in some zones. Most common are fine, parallel, planar laminations (fig. 8); some intervals are cryptalgally laminated (fig. 9). Burrowed aphanitic dolomite is also present (fig. 10). Much of the Ellenburger, however, is massive dolomite; allochems are rarely preserved. The uppermost Ellenburger is commonly brecciated (fig. 11); these breccias contain dolomite clasts, rounded quartz sand, and glauconite. The lithology of the Ellenburger in the study area is similar to that described by Folk (1959) in Central Texas and by Cardwell (1977) in the Arbuckle Group of Oklahoma.

Sedimentary structures observed in Hardeman County cores are consistent with previous interpretations that the Ellenburger was deposited in a quiet, shallow-water sea that covered large parts of the North American continent during the Early Ordovician (Cloud and Barnes, 1946). There is no evidence that any major environmental diversity existed anywhere in the Panhandle. Even in the Anadarko Basin, where thicknesses exceed 2,000 ft (610 m), the Ellenburger (Arbuckle) appears to record shallow-water subtidal to supratidal deposition. Because the unit grades from predominantly dolomite in West Texas and the Panhandle to limestone in Central Texas and southern Oklahoma (Barnes and others, 1959), a slight west-to-east freshening (decrease in salinity) of water may have existed during deposition. Folk (1959), however, pointed out that there is no evidence to suggest that this salinity change is related to any major change in bathymetry. Breccias commonly found at the top of the Ellenburger are probably due in part to karstification produced during subsequent periods of exposure.

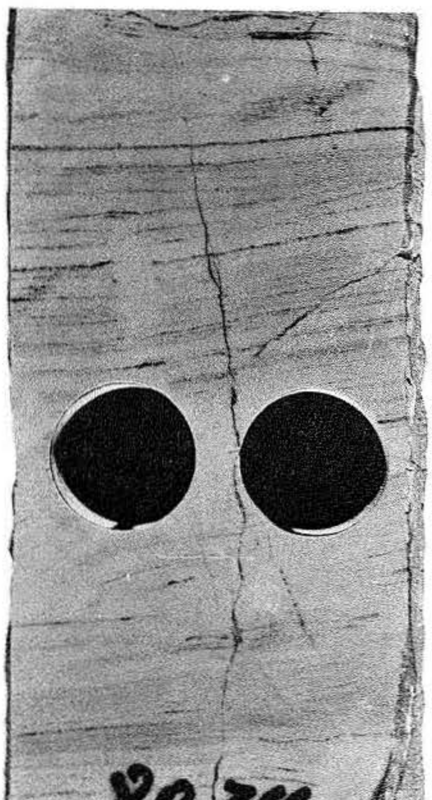


Figure 8. Aphanitic dolomite containing parallel planar laminations, Ellenburger Group, Hardeman Basin. Note that a vertical burrow has disrupted laminations above core plug borings. Hardeman 45 well, 8,074 ft (2,461 m). Core is 8 cm wide.

Figure 9. Burrowed aphanitic dolomite, Ellenburger Group, Hardeman Basin. Minor porosity developed in burrow fill and along fractures. Hardeman 45 well, 8,082 ft (2,463 m). Core is 8 cm wide.

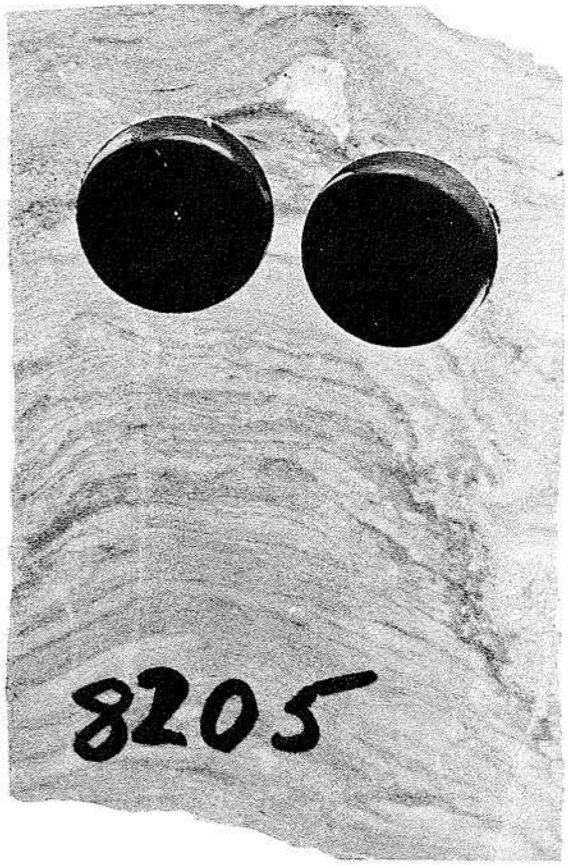


Figure 10. Cryptalgally laminated aphanocrystalline dolomite, Ellenburger Group, Hardeman Basin. Hardeman 45 well, 8,205 ft (2,501 m). Core is 8 cm wide.

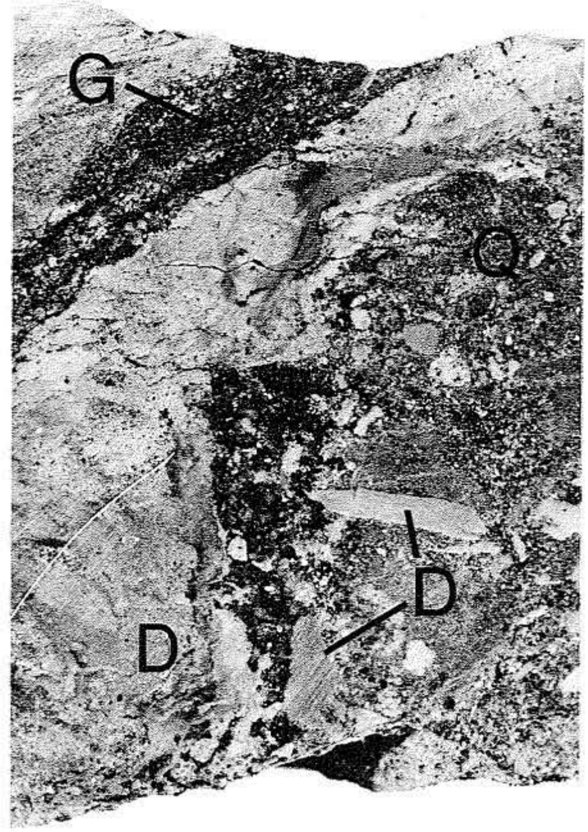


Figure 11. Breccia horizon developed at the top of the Ellenburger Group. Breccia contains glauconite sand (G), dolomite clasts (D), and quartz sand (Q). Hardeman 105 well, 8,113 ft (2,473 m). Core is 8 cm wide.

The Mississippian System

Deposits of apparent Mississippian age are present throughout much of the Texas Panhandle (fig. 4). In the Palo Duro Basin, these rocks overlie the Ellenburger or rest directly on Cambrian(?) sandstones or Precambrian basement (fig. 12); in the Dalhart and Hardeman Basins they overlie the Ellenburger. Middle and Upper Ordovician, Silurian, and Devonian rocks are, for the most part, present only in the Anadarko Basin (fig. 12); these middle Paleozoic deposits were apparently removed from much of the Panhandle by erosion during the Middle Devonian (Huffman, 1959; Amsden and others, 1967). Middle and Upper Ordovician rocks are present in the northern fringes of the Dalhart Basin and in the extreme eastern part of the Hollis Basin (fig. 12).

Mississippian rocks are as much as 4,000 ft (1,220 m) thick in the Anadarko Basin north of the Amarillo Uplift (fig. 13). South of the uplift area, greatest thicknesses are in the Hollis and Hardeman Basins, where 1,400 ft (427 m) of Mississippian rocks have been reported (fig. 13). The Palo Duro and Dalhart Basins contain maximum thicknesses of about 900 ft (274 m).

The Mississippian System of North America comprises four series: Kinderhookian, Osagean, Meramecian, and Chesterian (Dott, 1941; Cheney and others, 1945). These series have been used to subdivide the Mississippian in the Texas Panhandle (fig. 2). However, owing to the scarcity of biostratigraphic control, recognition of these units in the subsurface of the Panhandle is based on lithostratigraphic rather than chronostratigraphic correlation. Recently recovered biostratigraphic evidence underscores this fact; the "Osage" has been found to be, at least in part, Meramecian in age (Ruppel, 1983, 1984, this paper). Recognizing the inconsistencies of Mississippian stratigraphic usage in the Texas Panhandle and elsewhere, the U.S. Geological Survey (Mapel and others, 1979) used

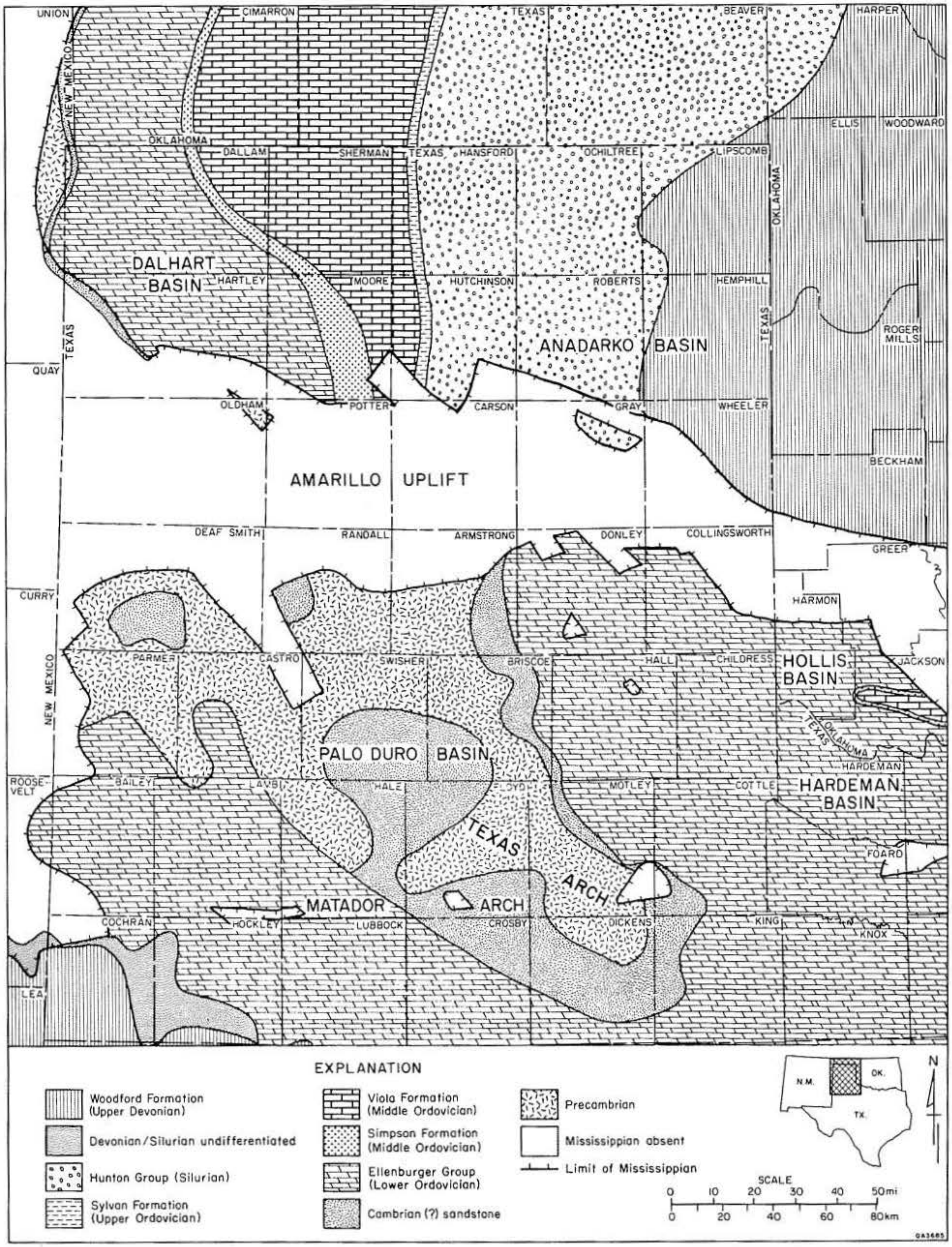


Figure 12. Mississippian subcrop. Post-Ellenburger, pre-Mississippian strata are largely confined to the Anadarko and Midland Basins.

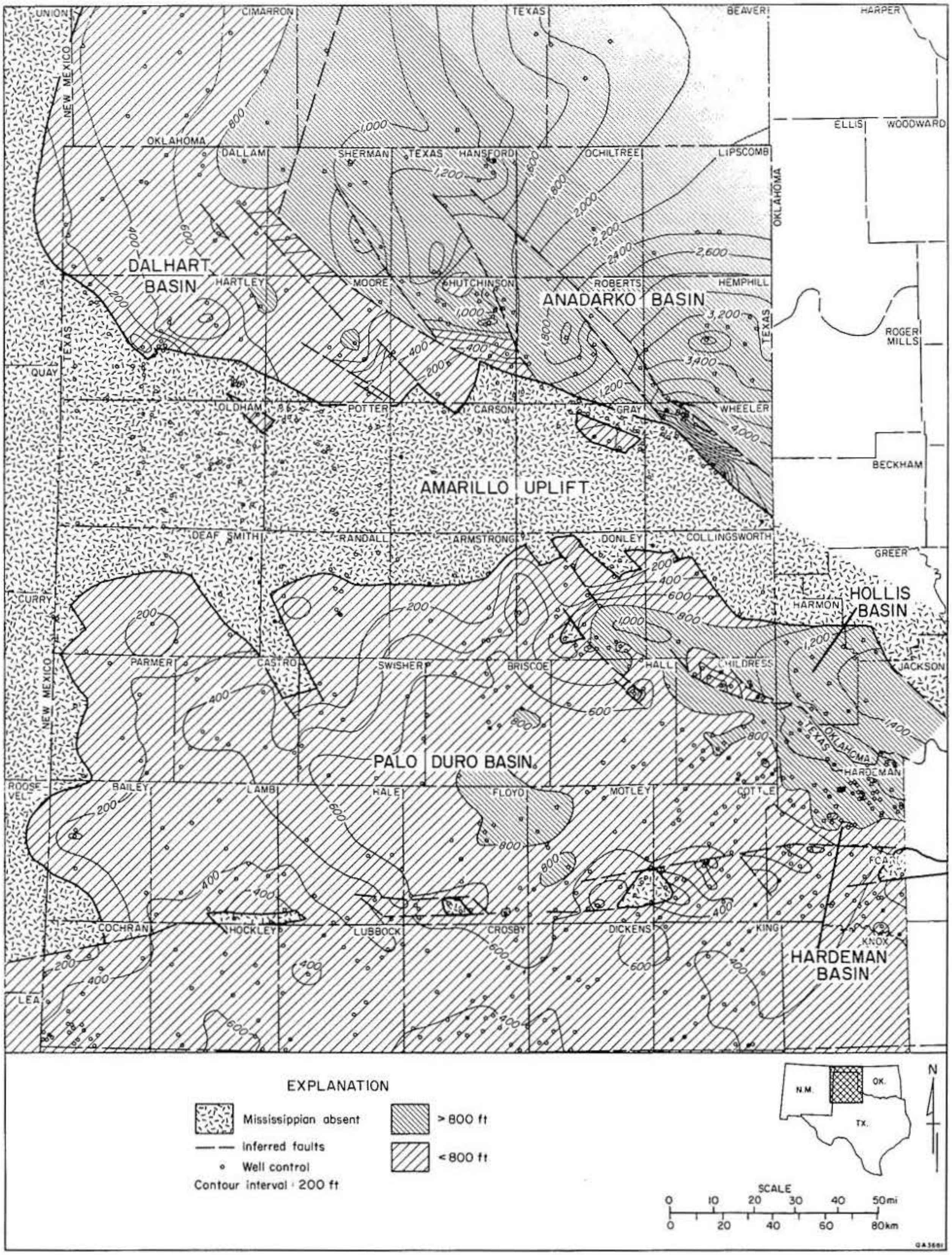


Figure 13. Thickness map, Mississippian System. Maximum thickness in the Palo Duro Basin is about 900 ft (275 m). Faults inferred from contour mapping.

letter designations to subdivide the system into informal intervals (fig. 2). This scheme has not received any measure of acceptance, however. The appropriate solution to these nomenclatorial problems is to assign rock stratigraphic names (for example, groups) to intervals currently referred to as series. This is not practical at present, however, owing to our imprecise understanding of these rocks. Since the present terminology has become ingrained by constant use, it should be retained until a proper rock stratigraphic sequence can be defined; to introduce new unit names now would only add to the confusion.

Accordingly, in this report, existing series names are retained as they have been conventionally applied. It must be kept in mind that in the Texas Panhandle these terms refer to groups (rock stratigraphic units), not to proper series (time stratigraphic units). To emphasize this point, these names are shown in quotation marks (for example, "Meramec") wherever they have been used in a rock stratigraphic sense. Where the same term is used in its proper sense as a series, an "-ian" ending is employed (for example, Meramecian).

Hardeman Basin

Because of numerous recent hydrocarbon discoveries, the Mississippian sequence has been more extensively studied in the Hardeman Basin than elsewhere in the Panhandle. Basic Mississip-

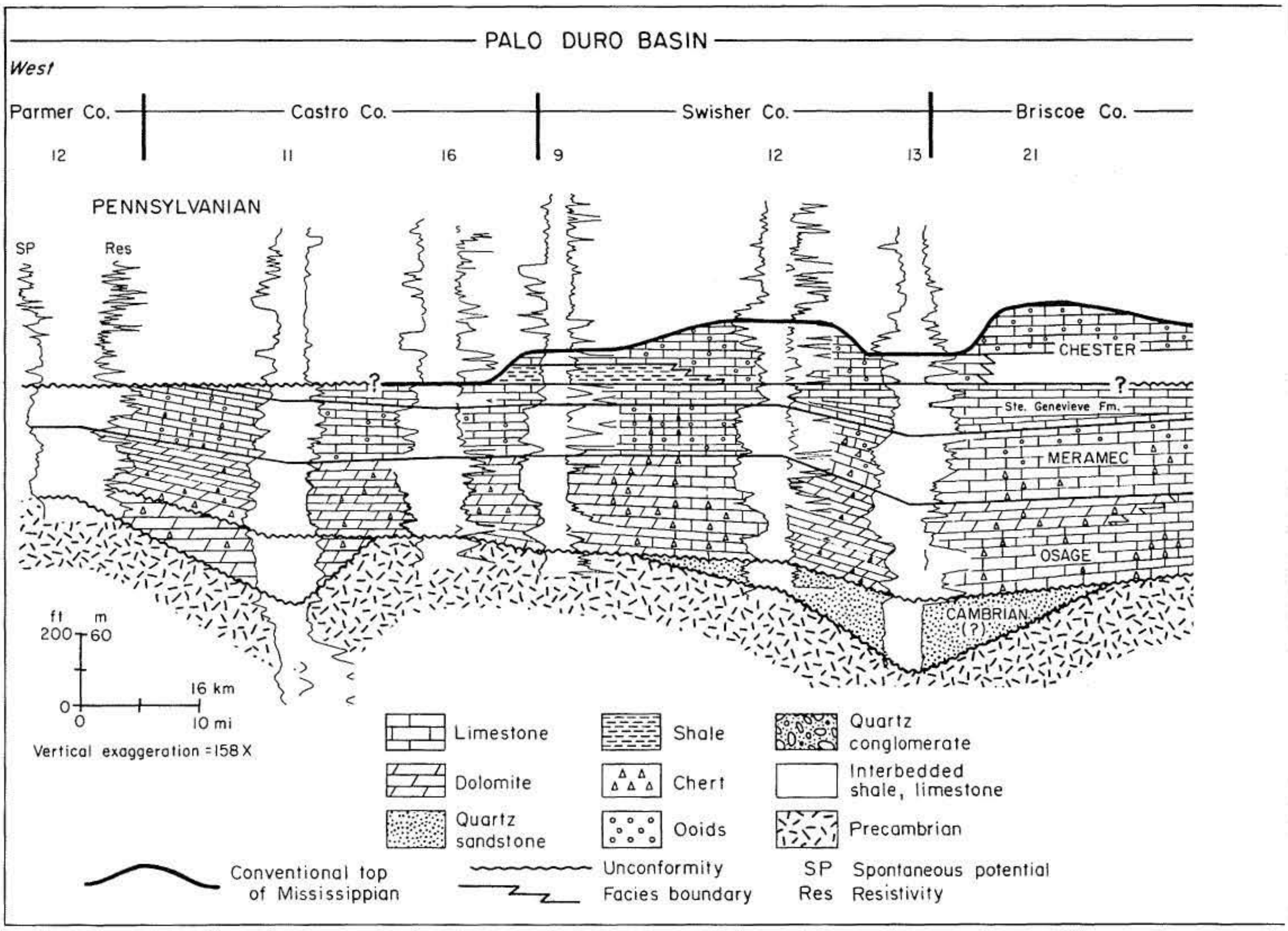
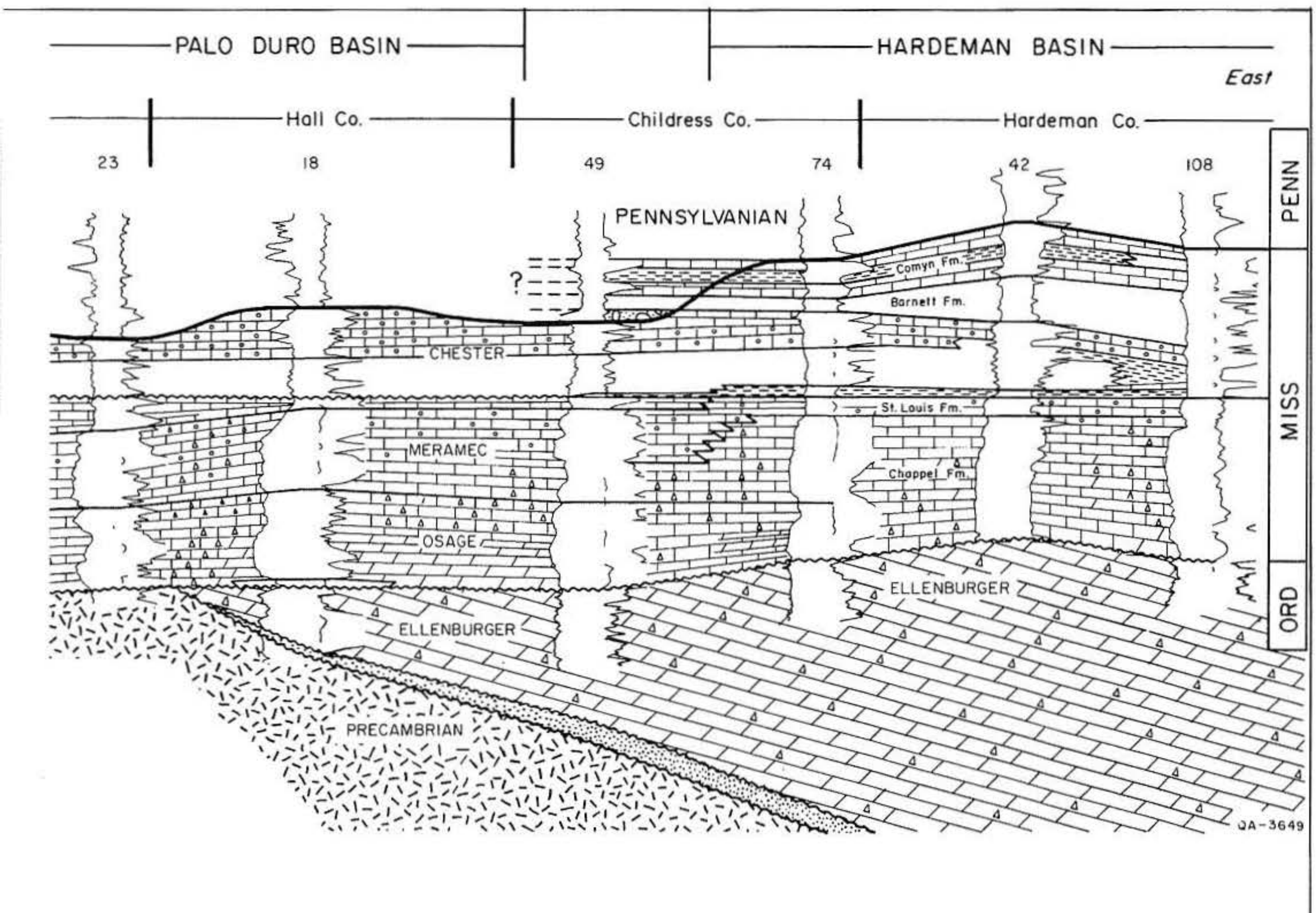


Figure 14. West-east cross section of pre-Pennsylvanian strata through the Palo Duro and Hardeman Basins. Location of line of section is indicated in figure 1. Note that facies changes take place between the two basins, in Childress County, in the upper "Meramec." The Ste. Genevieve Formation, which forms the top of the "Meramec" throughout the rest of the Texas Panhandle, cannot be recognized in the Hardeman Basin; it grades eastward into the St. Louis Formation. The apparent westward thinning of the "Chester" in Childress County, which is usually assumed to be the result of erosion of

pian stratigraphy is uniform throughout the Hardeman and Hollis Basins. The Chappel Formation forms the base of the sequence, resting directly on Ellenburger Group dolomites (fig. 5). Commonly, the Chappel, which comprises diverse carbonate lithologies discussed later in this report, is subdivided into an upper, "Meramec," part and a lower, "Osage," part and is overlain by oolitic limestone (grainstone/packstone) generally referred to as the St. Louis Formation (fig. 5). Although placement of the upper boundary of the St. Louis is variable, most place the top of the formation at the base of a prominent shale bed that overlies the highly resistive carbonates that compose the St. Louis and Chappel Formations.

Overlying the St. Louis Formation is an interval composed of oolitic limestone and shale that has been referred to as the Ste. Genevieve Formation (Allison, 1979; Asquith, 1979; Ross, 1981; Ahr and Ross, 1982). This usage is unfortunate because the lithology of this interval is unlike that of the Ste. Genevieve as defined elsewhere in the Mid-Continent (Totten, 1956; Worden, 1960; Cunningham, 1969). In addition, the "Ste. Genevieve" of the Hardeman Basin, which is included in the "Meramec," is correlative with rocks assigned elsewhere to the "Chester" (fig. 14). Thus, the miscorrelation of the Ste. Genevieve in the Hardeman Basin has resulted in stratigraphic inconsistencies at both the formation and the group levels. The term



the uppermost Mississippian in the Palo Duro Basin, may also be due to facies changes. Upper Chester deposits in Childress 74 are directly correlative with rocks conventionally considered to be Pennsylvanian. Similar thickness variations in the "Chester," as it is conventionally mapped, in the Palo Duro Basin may also represent facies change rather than differential erosion of the uppermost Mississippian. Well names given in appendix A.

Ste. Genevieve Formation is therefore deleted from the stratigraphic section for the Hardeman Basin in this report (fig. 14). The interval overlying the St. Louis Formation is considered to be an unnamed lower part of the "Chester." The Ste. Genevieve Formation of the Mid-Continent is apparently absent from the Hardeman Basin owing to facies change.

The upper part of the "Chester" in the Hardeman Basin contains rocks assigned to the Comyn and Barnett Formations (figs. 2 and 5). The generally highly radioactive, highly resistive, brown to black shales and dark limestones of the Barnett Formation form a persistent marker throughout much of north Texas. Distribution of the Barnett in the Texas Panhandle is, however, limited almost entirely to Hardeman County (fig. 15), where the unit reaches a maximum thickness of about 150 ft (46 m). Although generally correlative into Oklahoma (Hollis Basin), the Barnett undergoes a gradual northward facies change to lighter colored shales (fig. 15). The Barnett Formation appears to grade westward in the Palo Duro Basin into shales previously assigned to the Pennsylvanian (fig. 14). The overlying Comyn Formation, which is predominantly carbonate, forms the top of the Mississippian section in the Hardeman Basin (fig. 5). Most consider the contact of the Comyn with the overlying Pennsylvanian to be gradational (Montgomery, 1984). However, because biostratigraphic control is lacking, placement of the Mississippian/Pennsylvanian boundary at this point is arbitrary.

In the Hardeman Basin the Chappel Formation has been extensively studied because of the discovery of numerous hydrocarbon reservoirs. The Chappel is characterized by common lateral variations in lithology. Three basic depositional settings have been recognized, comprising at least six lithofacies (Allison, 1979; Ahr and Ross, 1982; Ross, 1982): (1) relatively deep water, open-marine (interbuildup) deposits composed of laminated, cherty, spicular wackestone (Allison, 1979; Asquith, 1979), (2) carbonate buildups comprising both core (mudstone and wackestone) and flank (skeletal grainstone and packstone) facies, and (3) ooid sand shoals composed of ooid/skeletal grainstone (Ahr and Ross, 1982). As indicated previously, many assign the ooid facies to the St. Louis Formation. Recent study of Chappel cores in the Hardeman Basin generally supports these interpretations. The Chappel Formation records the local development of carbonate buildups in a generally deeper water, open-platform marine setting that eventually shallowed into ooid sand shoals.

Palo Duro Basin

The Mississippian section in the Palo Duro Basin differs from that in the Hardeman Basin (fig. 14). Typically, Mississippian rocks in the Palo Duro Basin include subequal thicknesses of "Osage," "Meramec," and "Chester" rocks; the "Chester," as it is conventionally defined, is much thinner than in the Hardeman Basin, however (fig. 14). Questionable "Kinderhook" rocks are locally present in the Palo Duro Basin.

"Kinderhook"

The "Kinderhook" is largely restricted in the Texas Panhandle to the Anadarko Basin (fig. 16), where it is composed of light-colored, mostly fine-grained, angular to subrounded, quartz sandstone that is locally glauconitic and commonly interbedded with green to gray shale. Interbeds of light-colored limestone or dolomite are also present, particularly near the periphery of its extent. Although "Kinderhook" deposits have been reported in several wells in the Palo Duro Basin and in the Dalhart Basin to the north, the distribution of basal Mississippian sandstones similar to those in the Anadarko Basin is extremely limited in these areas (fig. 16). Such deposits are present in a few wells on the northern edge of the Palo Duro Basin immediately south of the Amarillo Uplift (Donley and Collingsworth Counties) and along the western, southern, and eastern margins of the Dalhart Basin (fig. 16). The distribution of these sandstones suggests that they may have been derived from the same source as "Kinderhook" sandstones in the Anadarko Basin and that these deposits may have originally extended over much of the uplift area before being removed by erosion.

Although basal Mississippian sandstones are rare in the rest of the Palo Duro Basin, shales that may be temporally equivalent are present at the base of the section in many wells. These shales are common in all parts of the basin except near the Texas Arch (fig. 17). The equivalence of these shales to "Kinderhook" sandstones cannot be established; however, they are grouped with "Osage" rocks.

Totten (1956) and Allison (1979) reported "Kinderhook"-like deposits of sandstone (Misener

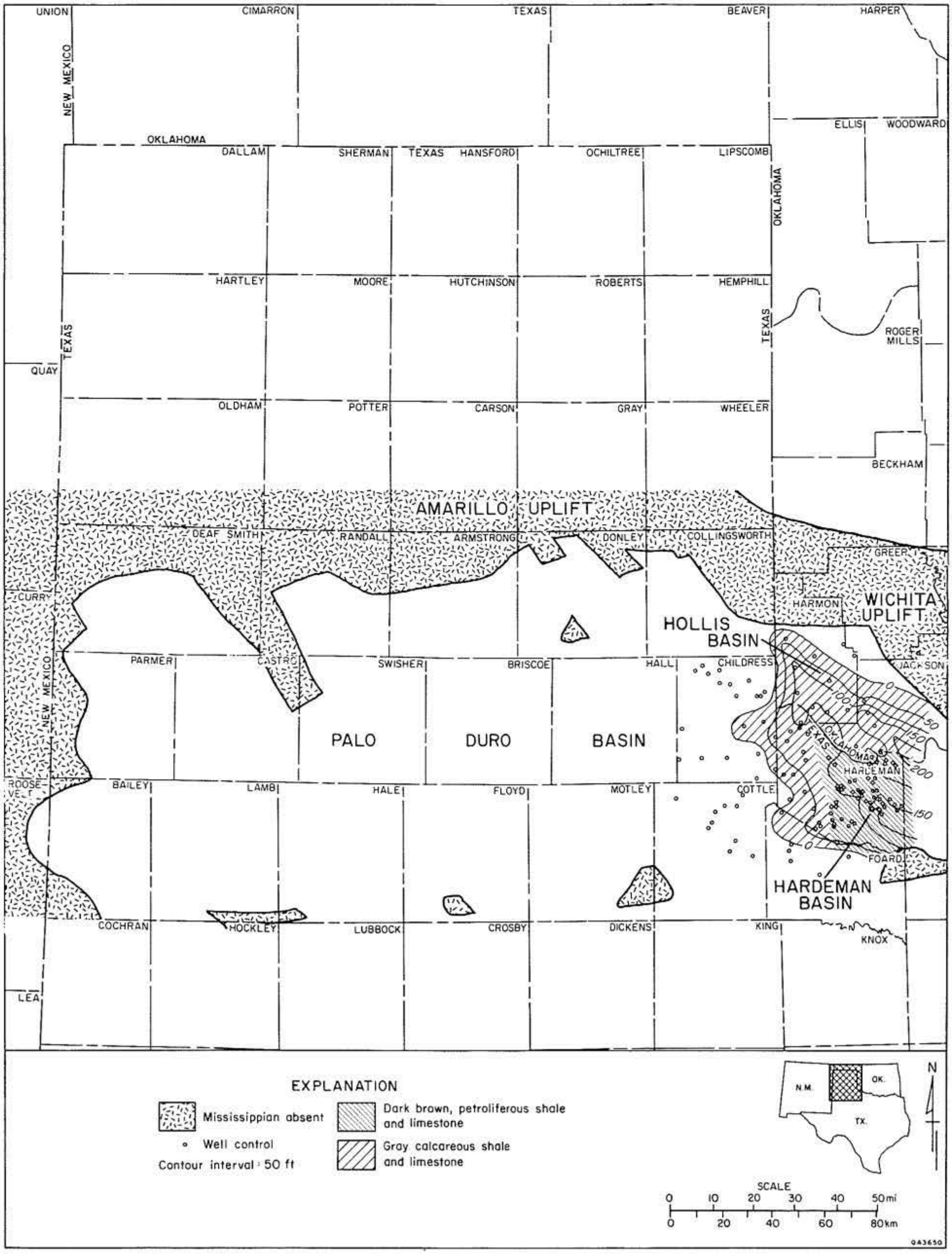


Figure 15. Map showing thickness and distribution of the Barnett Formation in the Texas Panhandle. The unit thickens to greater than 1,000 ft (305 m) eastward in the northern Fort Worth Basin (Montague County, Texas) (Henry, 1982). Although the unit can be traced throughout the area indicated, two distinct facies can be recognized. In eastern Hardeman County, the Barnett is composed of dark-brown to black shale and limestone; to the west and north the unit grades into gray calcareous shale and limestone locally interbedded with sandstone.

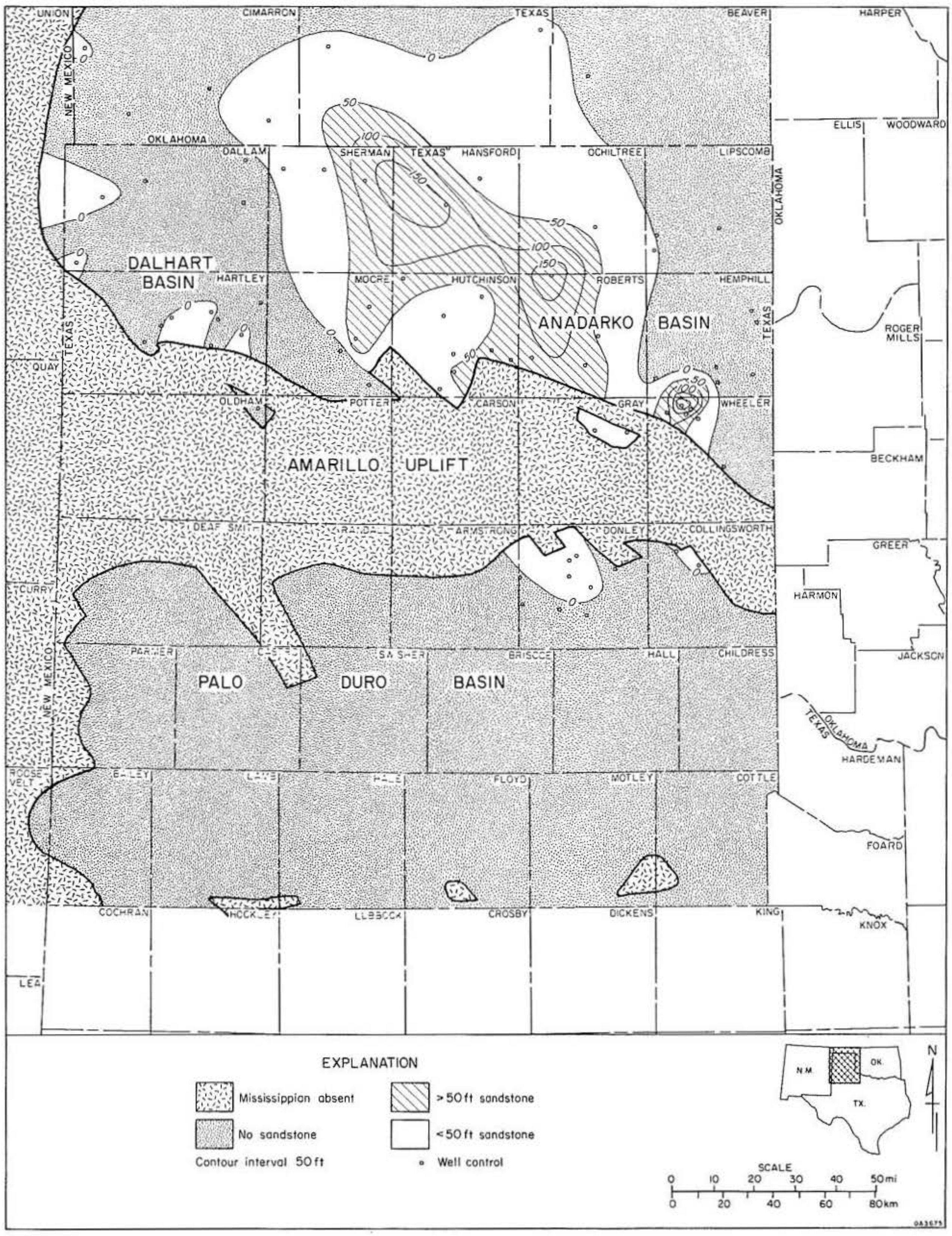


Figure 16. Map showing thickness of basal Mississippian sandstones ("Kinderhook") in the Texas Panhandle. Distribution patterns suggest a possible source along the Amarillo Uplift in Carson, Gray, and Wheeler Counties. These sandstones are absent in the Palo Duro and Dalhart Basins.

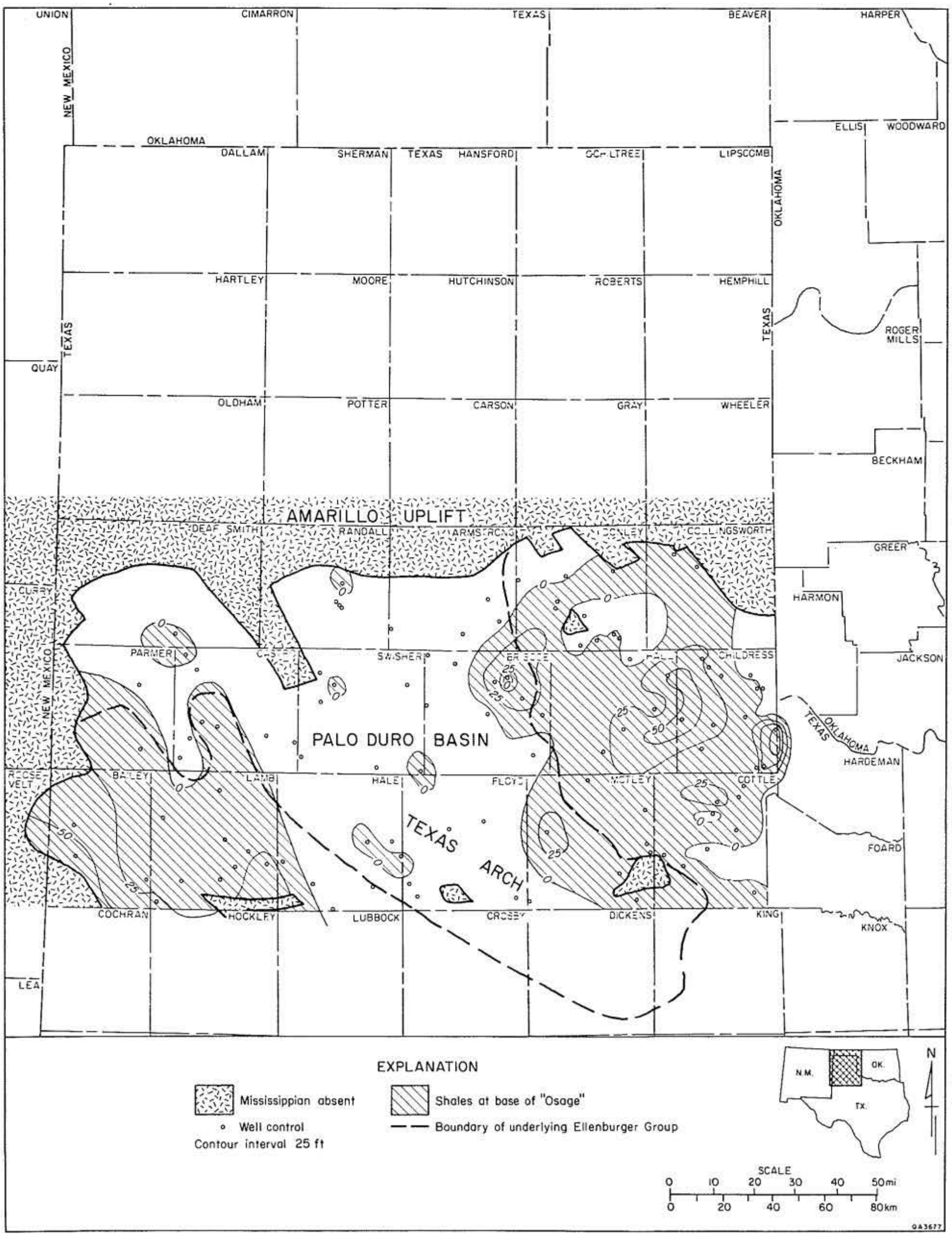


Figure 17. Map showing thickness and distribution of basal Mississippian shales in the Palo Duro Basin. Note similarity of distribution to that of the underlying Ellenburger Group (Lower Ordovician). This pattern of distribution suggests that the Texas Arch was still a positive feature at the beginning of Mississippian deposition.

Sand) and shale in the Hardeman Basin, but these deposits appear to be thin and only locally developed. Basal Mississippian deposits in this area are probably also more properly assigned to the "Osage."

"Kinderhook" rocks apparently represent basal transgressive sediments formed at the beginning of Mississippian deposition in the Panhandle. Although the exact age of these deposits cannot be determined, relationships with the underlying Woodford Formation (Amsden and others, 1967; Gutschick and Moreman, 1967) indicate that they are Early Mississippian or younger. The distribution of "Kinderhook" coarse clastics (fig. 16) suggests a possible source in the vicinity of the Amarillo Uplift (Gray and Carson Counties, Texas). The thin shales at the base of the Mississippian represent the first sediments deposited during the initial Mississippian transgression of the Palo Duro Basin area (fig. 17). Although these shales may be "Kinderhook" equivalents, there is no solid evidence to substantiate this. Biostratigraphic data instead suggest that this transgression occurred as late as late Osagean or early Meramecian time. The apparent relation between the distribution of these deposits and the position of the Texas Arch suggests that the latter had some positive expression until at least this time.

"Osage"

"Osage" rocks are the most extensive of all Mississippian units in the area (fig. 18). These deposits are more than 300 ft (90 m) thick in the Palo Duro Basin, where they overlie Ellenburger Group dolomites or rest directly on Cambrian(?) sandstones or Precambrian basement. Although the "Osage" is not easily recognized in the Hardeman and Hollis Basins, thicknesses of about 400 ft (122 m) have been recorded from the western edge of the Hardeman Basin in eastern Childress County (fig. 18). In the Dalhart Basin the "Osage" thins to a maximum of about 175 ft (53 m). Thicknesses of more than 1,000 ft (305 m), however, are encountered in the Anadarko Basin immediately north of the Amarillo Uplift (Wheeler and Hemphill Counties).

Throughout the Palo Duro, Dalhart, and Anadarko Basins, "Osage" rocks are gray to brown, commonly argillaceous, cherty limestones and dolomites. Locally they include large amounts of gray to green shale. Glauconite and pyrite are minor accessories. Dolomite content increases progressively east to west across the Texas Panhandle (fig. 19). The boundary between relatively pure limestones in the east and more dolomitic limestones and dolomites in the west roughly corresponds to the erosional edge of the underlying Ellenburger Group (fig. 7). In the western and northwestern parts of the basin, the "Osage" is composed almost entirely of dolomite (fig. 19). Most of the "Osage" in the Dalhart and western Anadarko Basins is also dolomite.

"Osage" cores are available from only the northeastern (Donley County) and extreme eastern (Childress County) edges of the Palo Duro Basin (fig. 1). In Childress County (fig. 20), the "Osage" (figs. 21 and 22) is composed primarily of alternating, locally silicified layers of laminated brown wackestone and skeletal lime-silt grainstone (figs. 23 and 24). The grainstone contains well-sorted, silt-size skeletal debris, predominantly echinoderms and bryozoan fragments. Some grainstone displays weak normal grading (fig. 23). The wackestone contains abundant laminations of skeletal debris (fig. 25) similar to that found in the grainstone (fig. 26). The interlayering of these two lithologies occurs at a variety of scales ranging from submillimeter to several decimeters. Relatively thick layers of coarser skeletal grainstone are locally present in the section (fig. 21). These deposits are contorted and contain numerous truncation surfaces (fig. 27). The coarse grainstone is commonly dolomitized and heavily burrowed (fig. 28) or silicified. Present although not common in the Childress 10 core are layers of sedimentary breccia (figs. 29 and 30). The angularity of the clasts making up these breccias indicates that these deposits were formed by movement after partial lithification of the sediment. Thin layers of dark-gray spiculitic wackestone (fig. 31) represent a minor part of the "Osage" in the Childress 10 well. Silicification in the "Osage" seems to be associated with these layers, suggesting that sponge spicules, now calcitized, may represent one source of the silica. The upper contact of the "Osage" with the overlying grainstones of the "Meramec" is gradational through a 10-ft (3-m) interval.

"Osage" deposits in the Childress 10 core seem to indicate that deep-water conditions extended from the Hardeman Basin at least as far west as Childress County during the deposition of these rocks (Ruppel, 1984). The spiculitic wackestone is

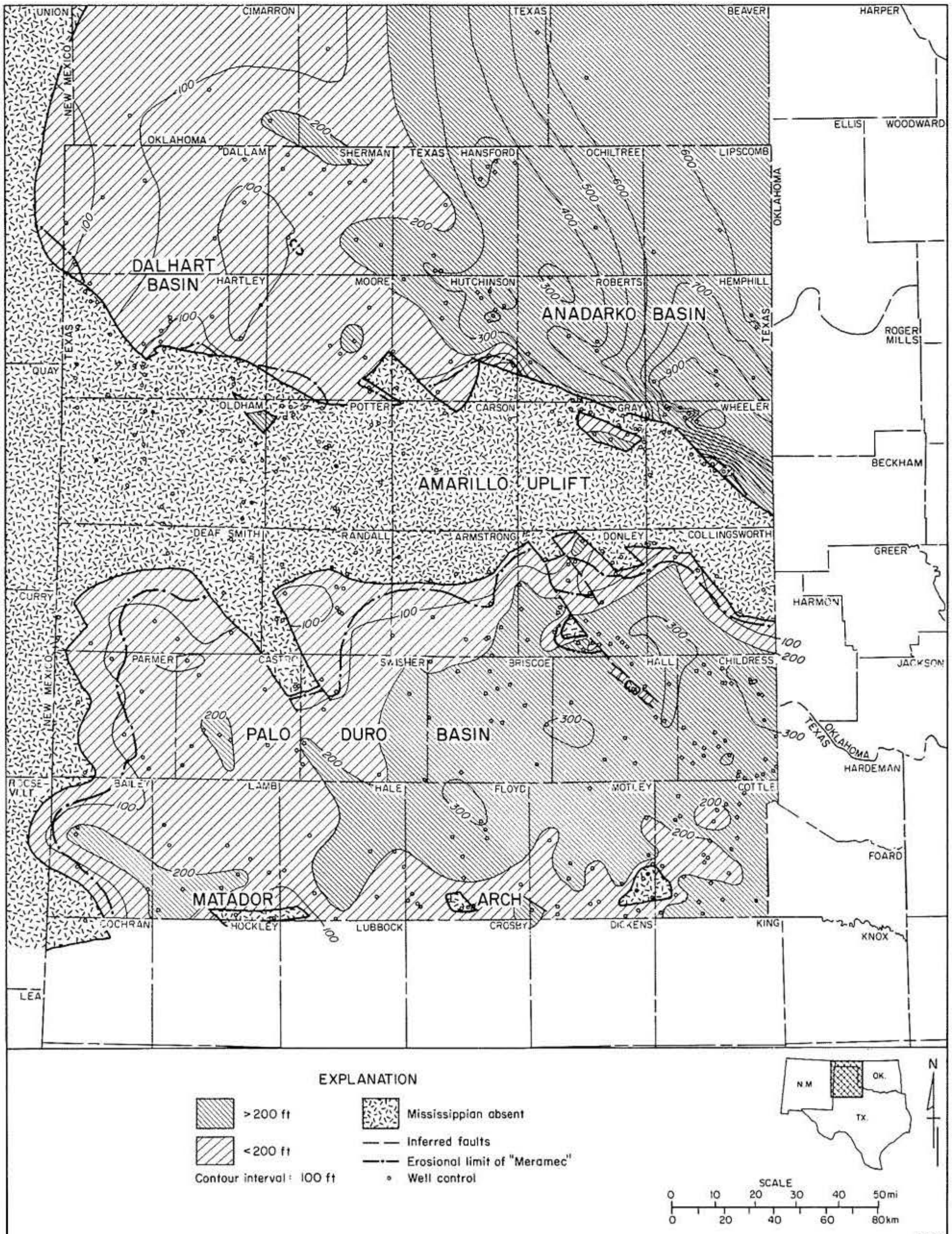


Figure 18. Map showing thickness of the "Osage." The "Osage" is not easily defined in the Hardeman Basin. Maximum thickness in the Palo Duro Basin is about 300 ft (90 m).

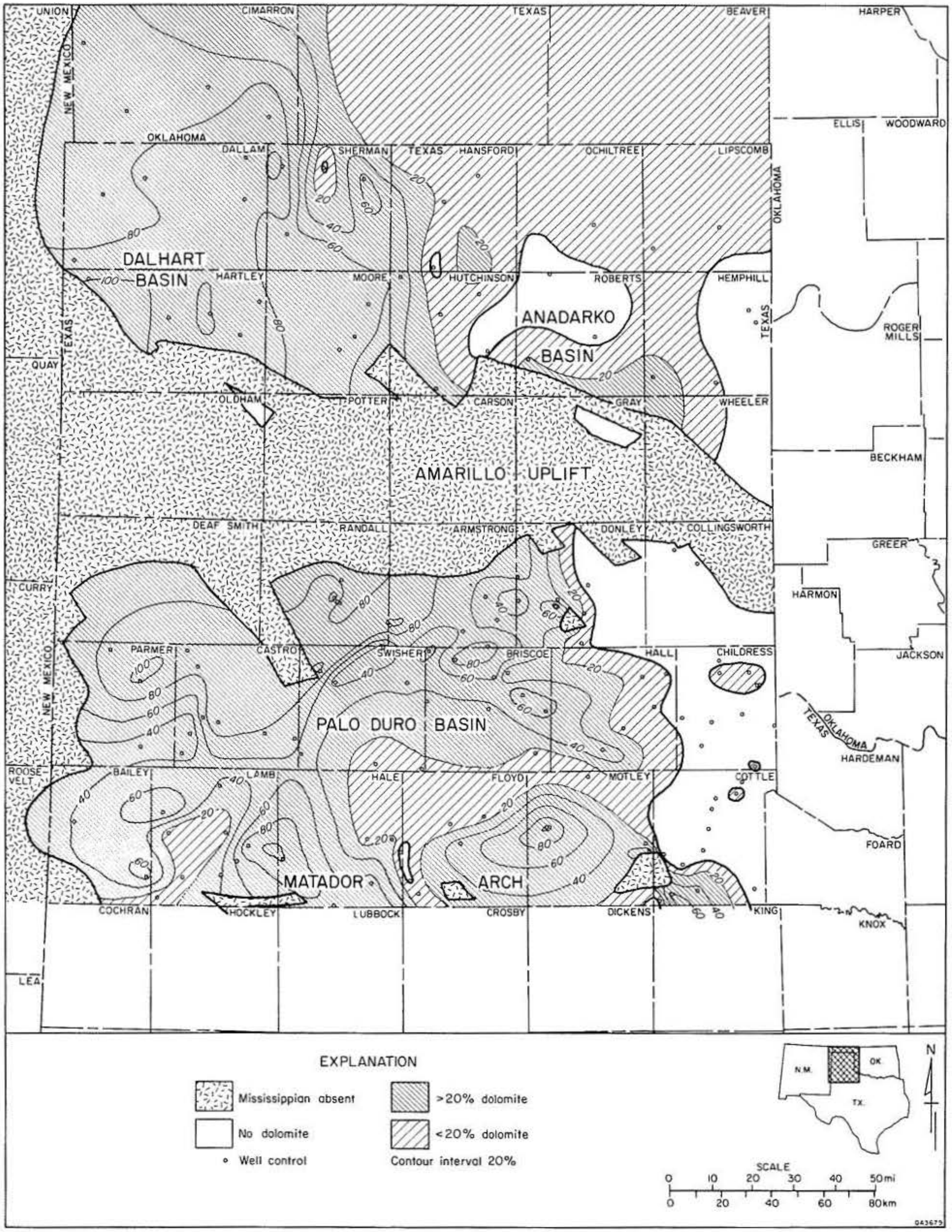


Figure 19. Dolomite-percent map, "Osage." Dolomite content is lowest in the eastern Palo Duro Basin, where pure limestones make up the unit. A similar relationship exists in the Anadarko Basin.

similar to that interpreted by Allison (1979) and Asquith (1979) as a deep-water, interbuildup deposit in the Hardeman Basin. The wackestone probably represents an in situ sediment that accumulated in a quiet water, probably below fair-weather wave-base, open-platform setting. Alternating layers of lime-silt grainstone and wackestone record the intermittent influx of allochthonous skeletal debris into this quiet-water environment. These limestone turbidites in Childress County may represent finer grained, more distal equivalents of breccias similar to those associated with carbonate buildups in the Hardeman Basin (Ross, 1981). This relationship suggests that buildup growth similar to that in Hardeman County may have extended as far west as Childress County.

The upper part of the "Osage" was cored in Donley County immediately south of the Amarillo Uplift (fig. 1). "Osage" deposits in this core (figs. 32 and 33) are markedly different from those in Childress County. They comprise (1) alternating layers of argillaceous, red and green spiculitic dolomite (fig. 34) and (2) red to green to gray, medium- to coarse-grained skeletal grainstone composed primarily of echinoderms and bryozoans (fig. 35). The dolomite contains laminations of skeletal debris and is burrowed in argillaceous zones (figs. 34 and 36). Possible mud cracks are present at some horizons (fig. 36). Siliceous sponge spicules are common in the dolomites (fig. 37). The grainstone contains numerous stylolites but is otherwise massive.

"Osage" rocks in the Donley 3 well appear to characterize a gradual but progressive change from peritidal deposition, in the lower half of the core (dolomite), to more normal subtidal deposition, in the upper part (grainstone). Although it is uncertain whether this sequence is the result of continued transgression or of lateral migration of environments, it seems clear that all of the "Osage" represented in the Donley 3 core was deposited in a shallow-water, inner-platform setting.

The exact depositional conditions under which "Osage" rocks formed in the interior of the Palo Duro Basin are more difficult to determine owing to the lack of core. Regional relationships indicate a general east-to-west shallowing of water across the Texas Panhandle during deposition of "Osage" rocks. Sediments in the Palo Duro Basin were probably formed in shallow-water, inner-platform conditions. The sequence in the Donley 3 core may thus be characteristic of "Osage" deposits formed throughout much of the basin. Since the interior of the Palo Duro Basin contains predominantly dolomitic rocks, these deposits may represent the shallowest areas of deposition. This interpretation is consistent with indications that the Texas Arch remained a positive feature during Early Mississippian deposition.

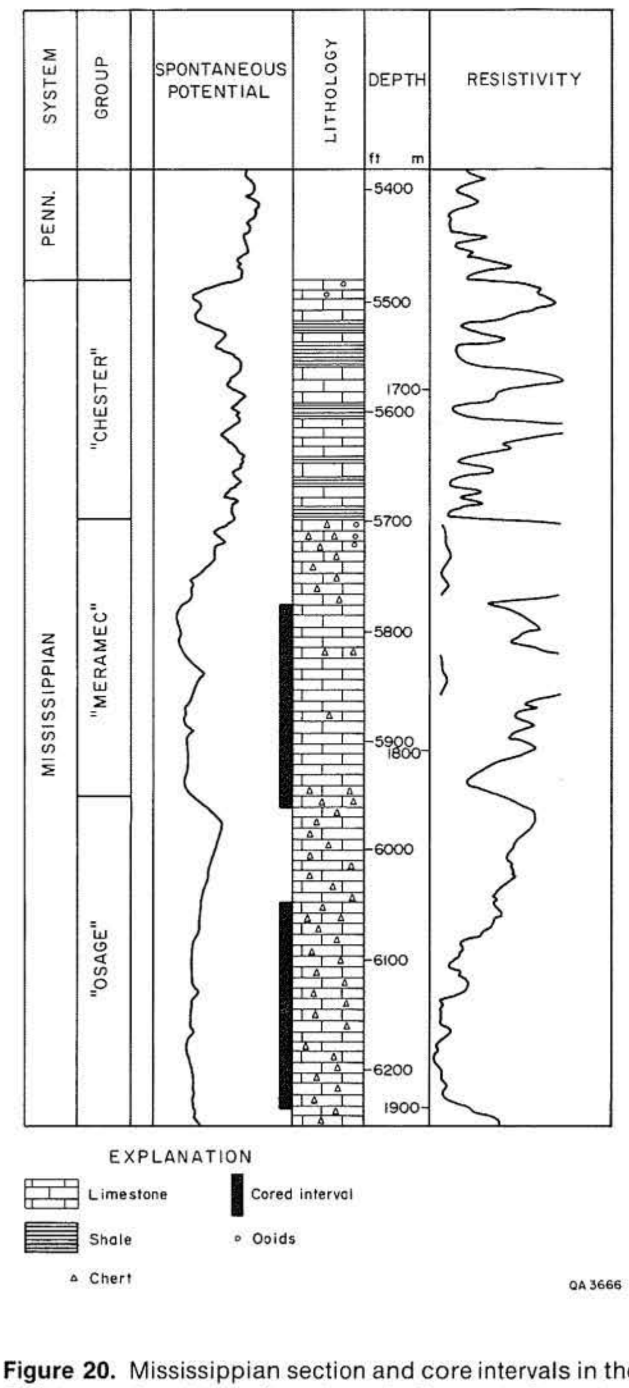


Figure 20. Mississippian section and core intervals in the Childress 10 well (location shown in figure 1). Conodont faunas indicate that both the "Meramec" and "Osage" in the Childress 10 well are actually Meramecian in age.

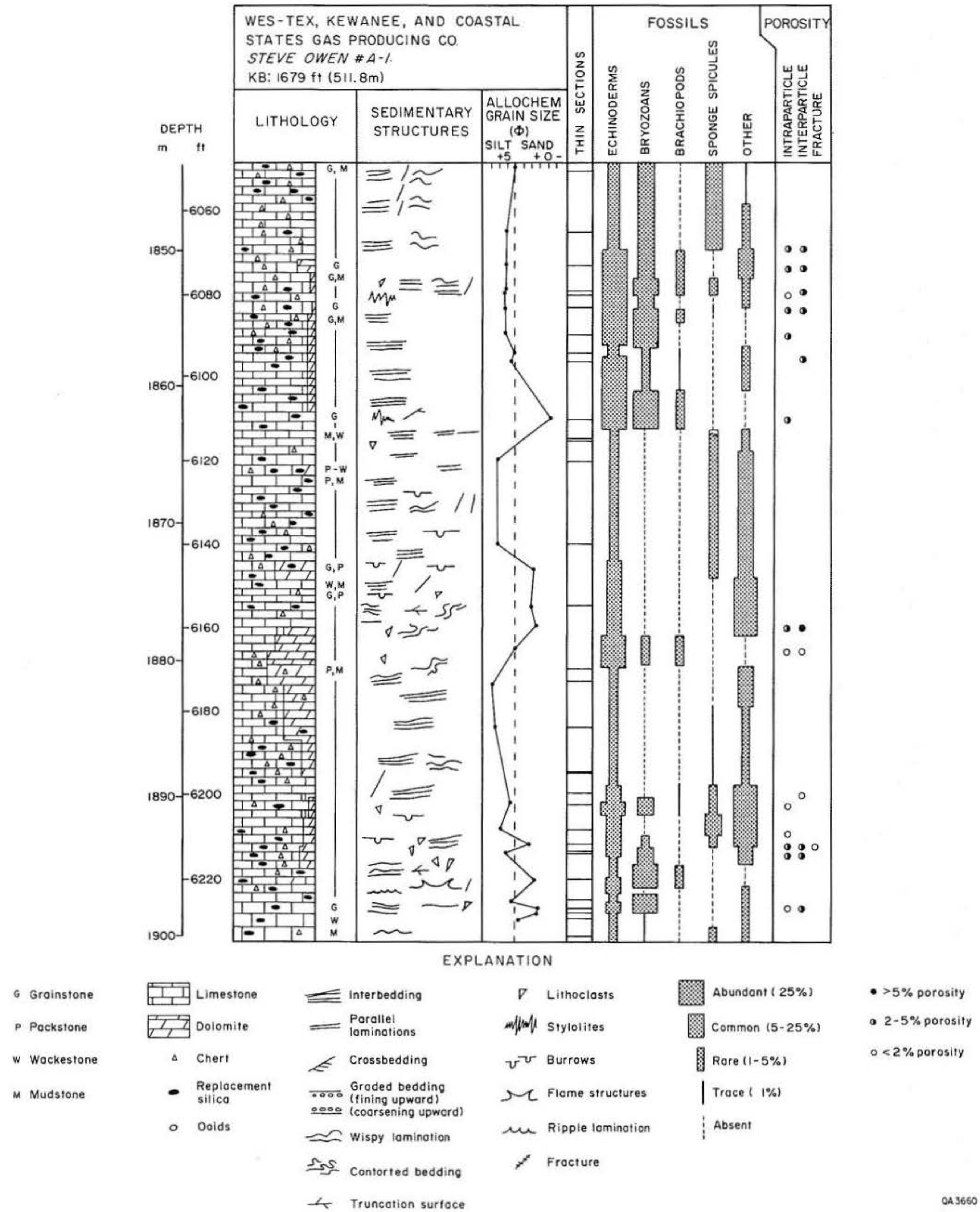


Figure 21. Core description of the lower "Osage" (lower Chappel), Childress 10 well. Location shown in figure 1. See figure 20 for relative position of core in section.

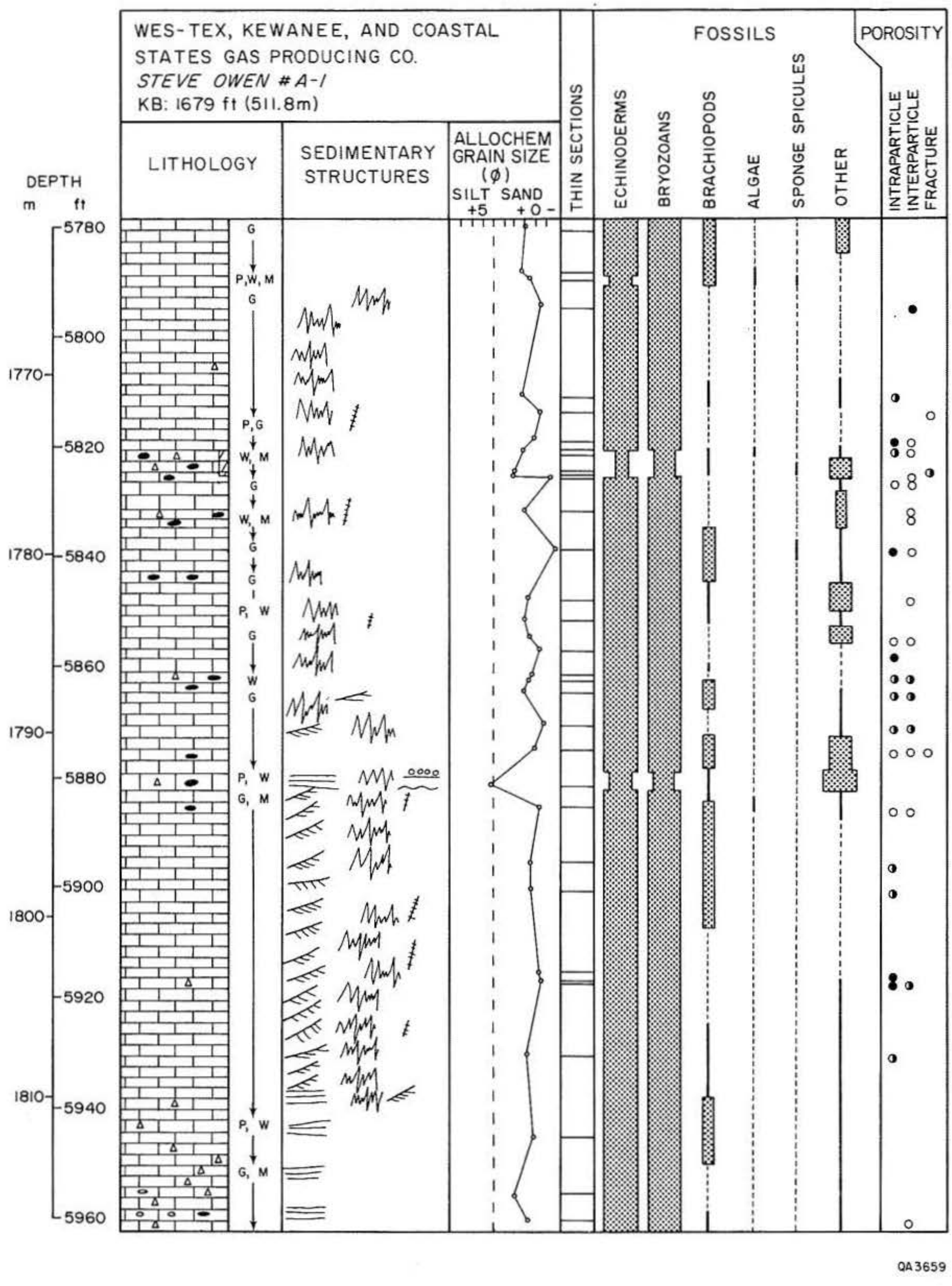


Figure 22. Core description of the "Meramec" and upper "Osage," Childress 10 well. Location shown in figure 1. Contact between "Osage" and "Meramec" is gradational through the 5,940 to 5,960 ft (1,810 to 1,816 m) interval. See figure 20 for relative position of core in section.

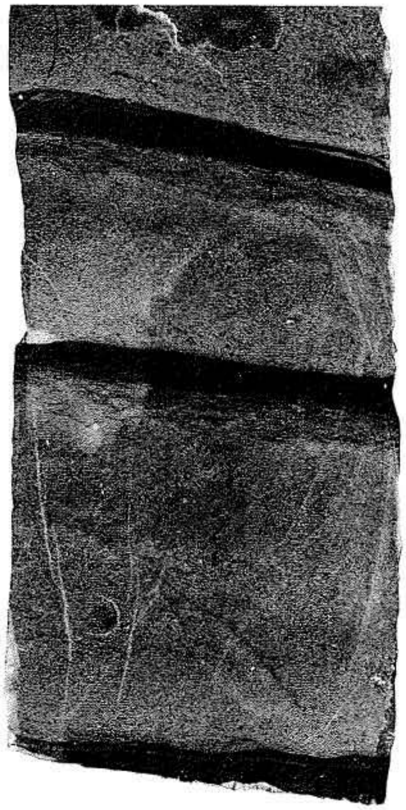


Figure 23. Alternating layers of skeletal lime-silt grainstone and dark-colored wackestone typical of lower "Osage," Childress 10 well. Grainstones contain well-sorted fragments of echinoderms and bryozoans; note weak grading. Wackestone commonly contains laminations of fine-grained skeletal debris. Note flame structures at top of lower wackestone layer. Childress 10 well, 6,218 ft (1,895.2 m). Core is 9 cm wide.

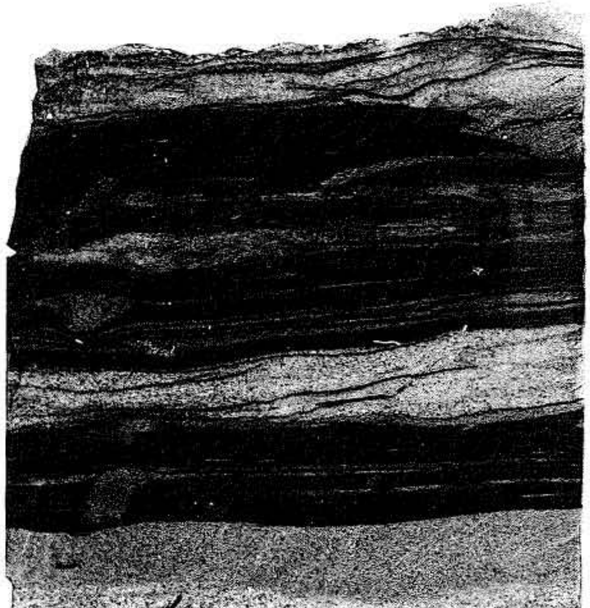


Figure 24. Alternating layers of grainstone and wackestone similar to those shown in figure 23. Lighter colored areas of grainstone are silicified. Abundant pseudonodules of grainstone occur within wackestone layers. Childress 10 well, 6,081 ft (1,853.5 m). Core is 9 cm wide.

Figure 25. Photomicrograph of skeletal wackestone similar to that shown in figures 23 and 24. Laminations contain skeletal debris (principally echinoderms) similar to that found in grainstone. Childress 10 well, 5,945 ft (1,812 m).

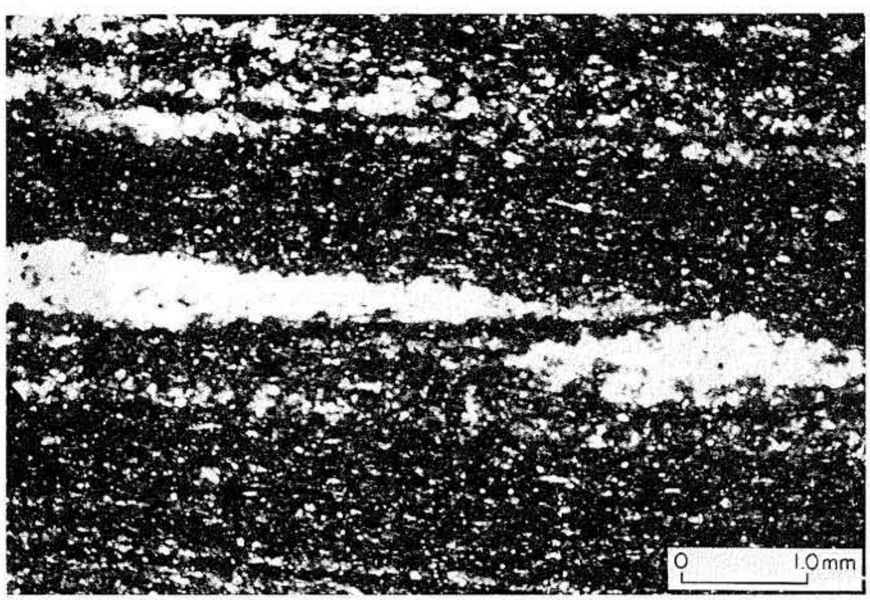


Figure 26. Photomicrograph of dark-brown, laminated skeletal wackestone similar to that illustrated in figures 23 and 24. Note both planar and ripple laminations. Childress 10 well, 6,115 ft (1,863.9 m).

Figure 27. Skeletal lime-sand grainstone having contorted laminations and mud-lined truncation surfaces. Lower "Osage," Childress 10 well, 6,161 ft (1,877.9 m). Core is 9 cm wide.

Figure 28. Burrow-mottled, skeletal lime-sand grainstone with disrupted wackestone laminations. Lower "Osage," Childress 10 well, 6,147 ft (1,873.6 m). Core is 9 cm wide.

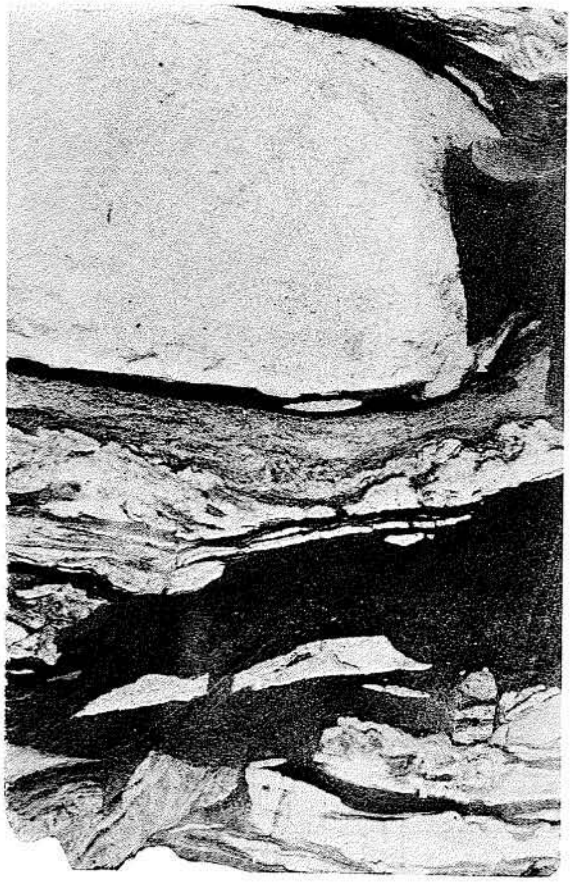


Figure 29. Breccia bed composed of clasts of lime-silt grainstone and silicified, laminated grainstone in matrix of partly laminated skeletal wackestone. Most clasts have angular borders, which suggests movement after at least partial lithification. Lower "Osage," Childress 10 well, 6,211 ft (1,893.1 m). Core is 9 cm wide.

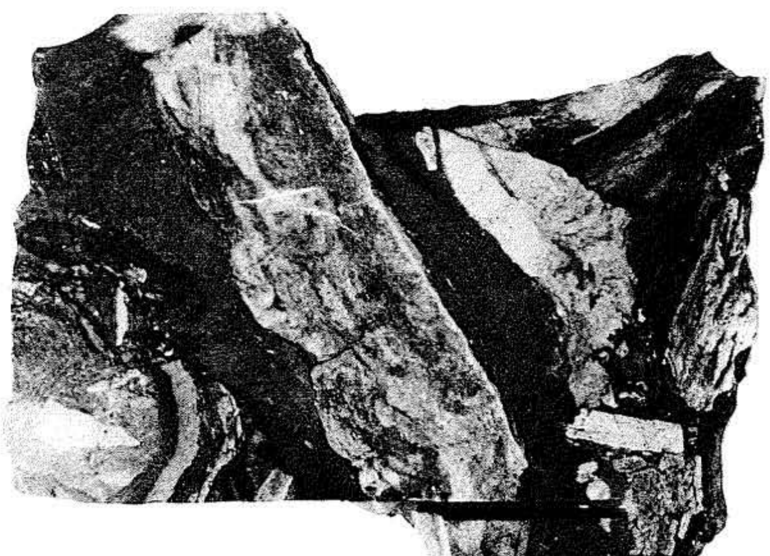


Figure 30. Breccia bed similar to that in figure 29. Contains clasts of silicified grainstone and interbedded grainstone and wackestone. Matrix is skeletal wackestone. Lower "Osage," Childress 10 well, 6,214 ft (1,894 m). Core is 9 cm wide.

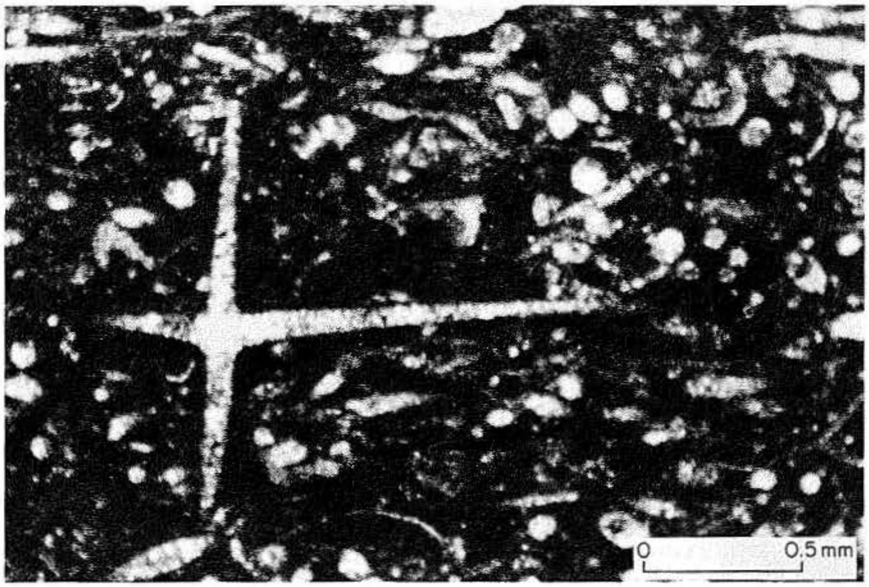


Figure 31. Photomicrograph of dark-gray, spiculitic wackestone containing sponge spicules and rare skeletal debris. Characteristically, these wackestones are unlaminated. "Osage," Childress 10 well, 6,050 ft (1,844 m).

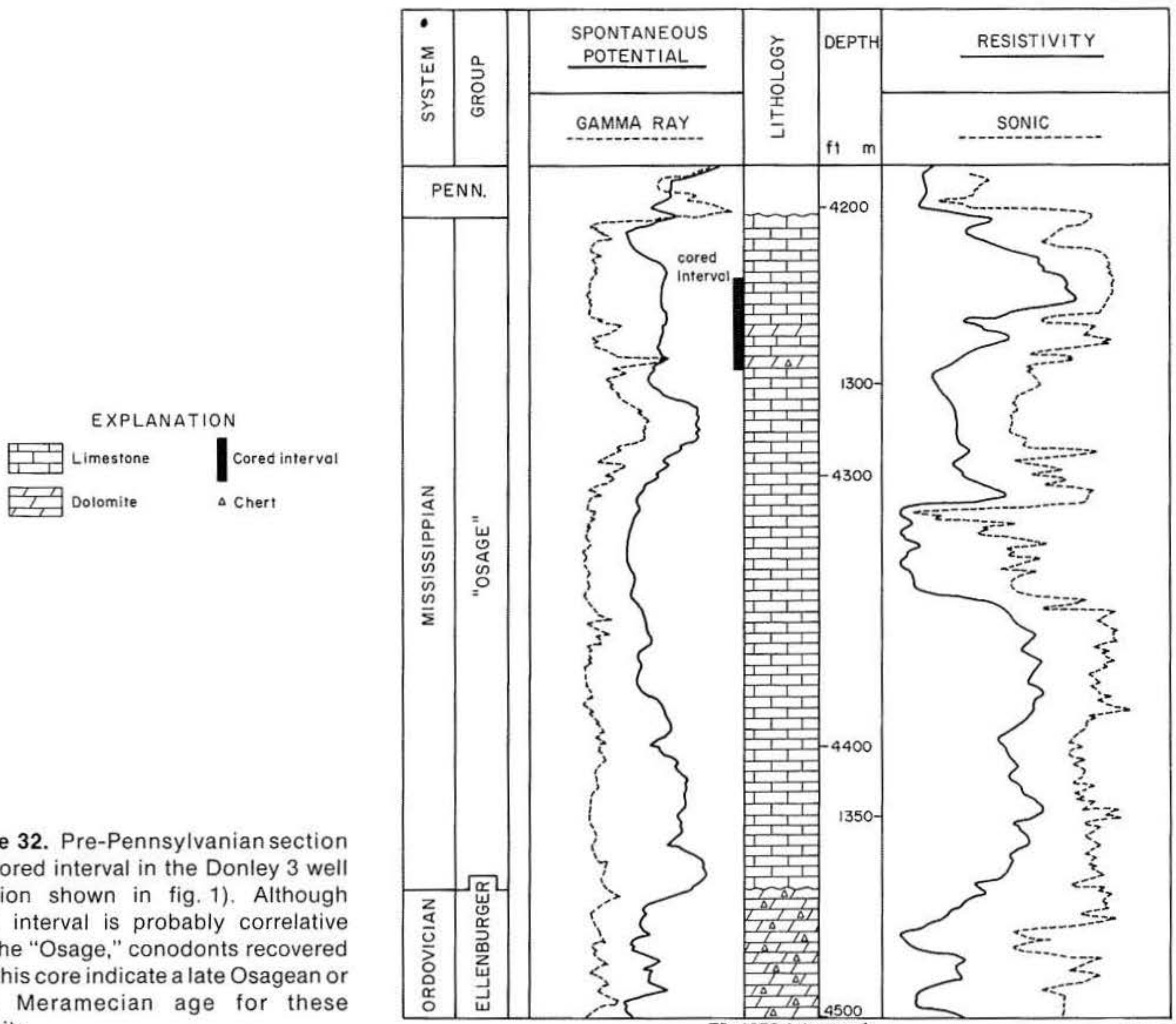


Figure 32. Pre-Pennsylvanian section and cored interval in the Donley 3 well (location shown in fig. 1). Although cored interval is probably correlative with the "Osage," conodonts recovered from this core indicate a late Osagean or early Meramecian age for these deposits.

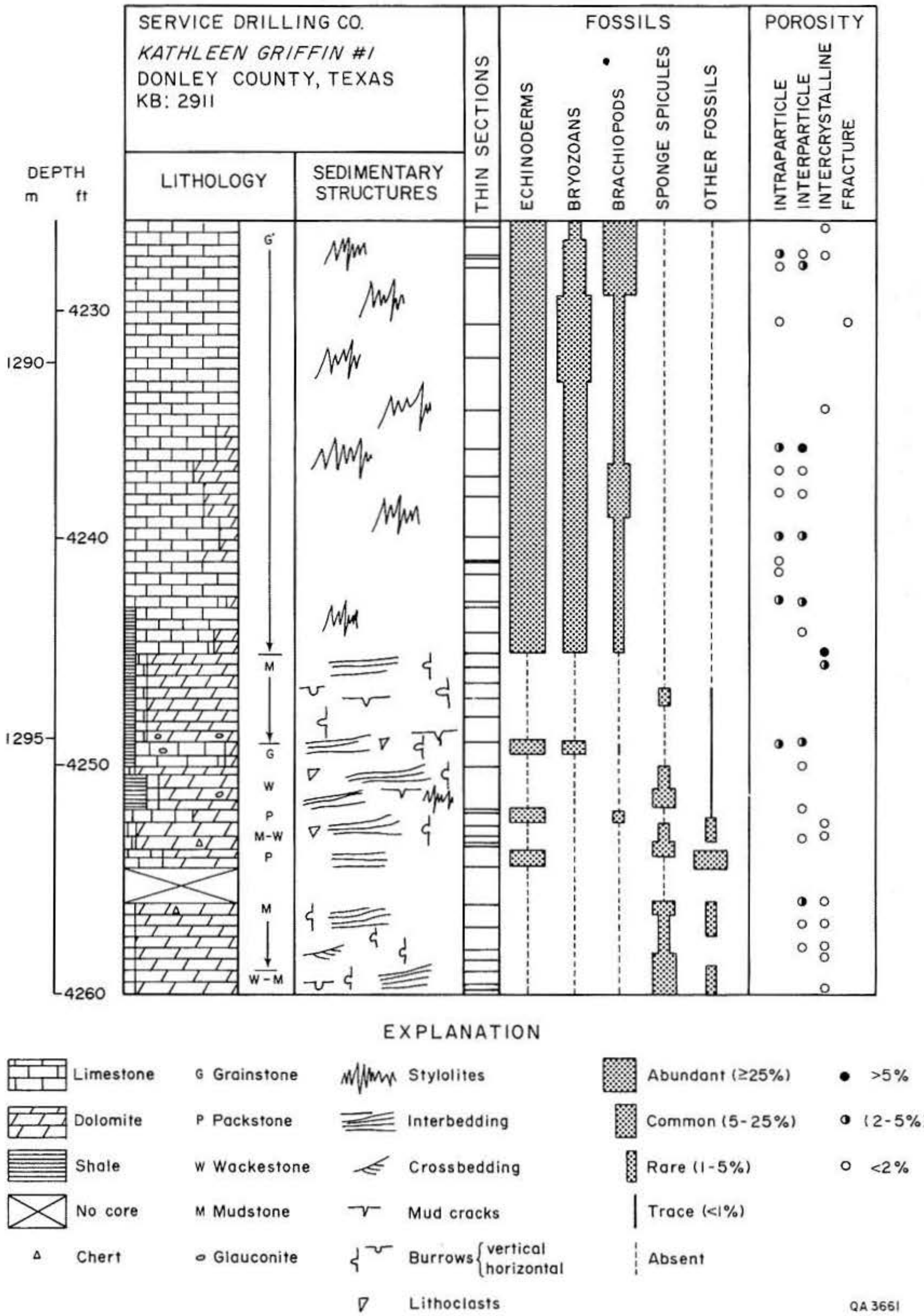


Figure 33. Description of "Osage" core in the Donley 3 well.

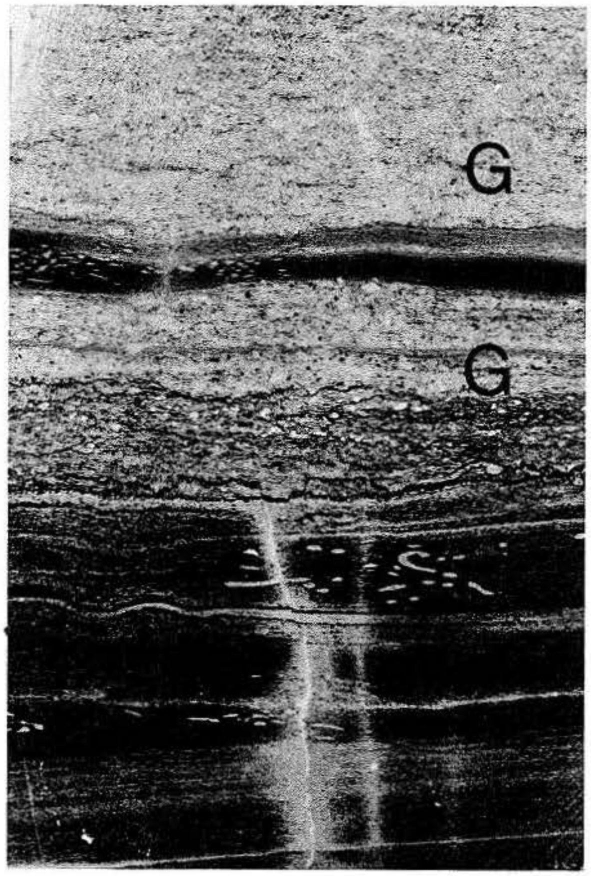


Figure 34. Interbedded spiculitic dolomite and skeletal grainstone (G). Note burrows in argillaceous dolomite layers. "Osage," Donley 3 well, 4,248 ft (1,294.8 m). Core is 7 cm wide.

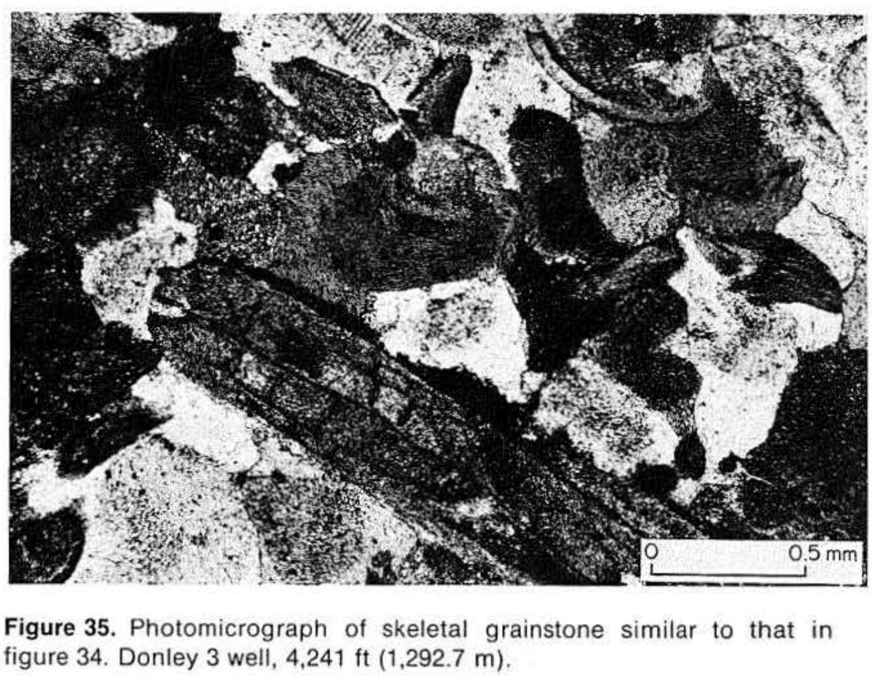


Figure 35. Photomicrograph of skeletal grainstone similar to that in figure 34. Donley 3 well, 4,241 ft (1,292.7 m).

Figure 36. Laminated and heavily burrowed, argillaceous, spiculitic dolomite. Note mud cracks. "Osage," Donley 3 well, 4,247 ft (1,294.5 m). Core is 7 cm wide.

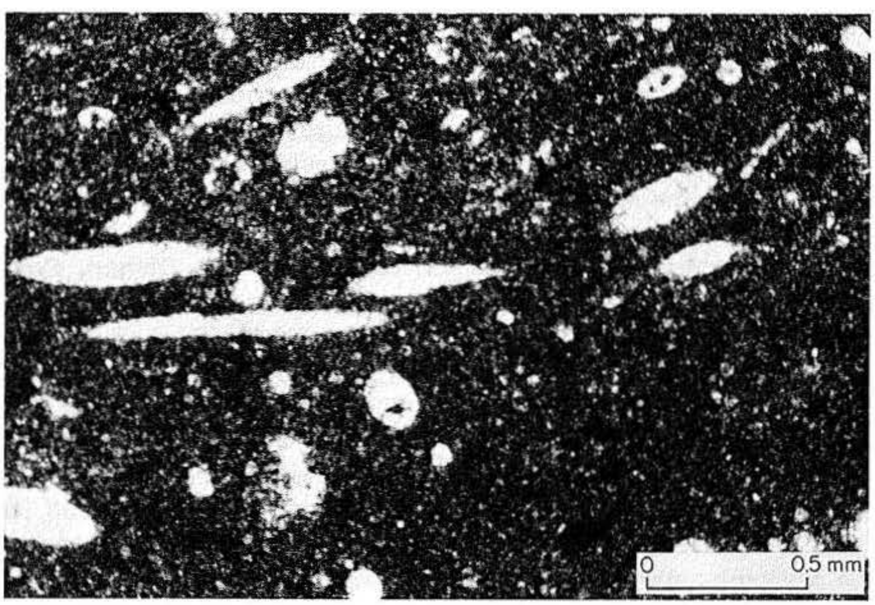


Figure 37. Photomicrograph of spiculitic dolomite. Spicules are siliceous. Donley 3 well, 4,251.8 ft (1,296 m).

"Meramec"

These rocks are consistently thick in the Palo Duro Basin, averaging about 300 ft (91 m) to 350 ft (107 m) except where partly removed by erosion (fig. 38). The "Meramec" and "Osage" cannot be readily distinguished in the Hardeman and Hollis Basins, but an isopach map of the entire interval reveals no obvious thickness trends in the area.

The top of the "Meramec" is easily recognized in the Panhandle by a marked increase in resistivity and a gradual shift in spontaneous potential (SP) on geophysical well logs (fig. 5). In general, the "Meramec" comprises white to buff-colored, fine- to medium-grained limestone. Chert and ooids are locally abundant; fine-grained quartz sandstone is common near the top of the unit in most wells.

In many places, particularly in the Dalhart and western Anadarko Basins, the "Meramec" is divided into three formations: an upper Ste. Genevieve, a middle St. Louis, and a lower Spergen-Warsaw (Cunningham, 1969). The Ste. Genevieve, the only one of these three units easily recognizable in the Palo Duro Basin, is characterized by the presence of quartz sand; the formation is usually no more than 50 ft (15 m) thick.

Although ooids are locally present throughout the "Meramec" in the Texas Panhandle, they are particularly abundant in and typical of the St. Louis Formation. Ooids and fossils are less common in the underlying Spergen-Warsaw, which is composed of dark aphanitic limestone and variable amounts of dolomite, than in overlying parts of the "Meramec." Dolomite, although locally found in the lower St. Louis, is most typical of the Spergen-Warsaw (Cunningham, 1969). The St. Louis and Spergen-Warsaw Formations are not usually recognized in the Palo Duro Basin, although the same general lithologic trends that characterize the units in the northern Panhandle are commonly observable. Spatially, most of the dolomite in the lower "Meramec" is limited to the middle of the basin (fig. 39).

In the Hardeman Basin, the "Meramec" includes the upper Chappel Formation and the St. Louis Formation (fig. 14). The Ste. Genevieve Formation appears to be absent due to facies change.

Core from the Childress 10 well (fig. 22) shows the "Meramec" to be predominantly composed of skeletal grainstone with minor wackestone and mudstone. Echinoderms and bryozoans (both ramose and fenestrate) dominate the fauna. At its lower, gradational contact with the "Osage" (5,940 to 5,960 ft [1,810 to 1,816 m], fig. 22), the "Meramec" is composed of skeletal grainstone and packstone interbedded with thin layers of carbonate mudstone (fig. 40). Above this transition zone, mud content decreases rapidly, and crossbedded skeletal grainstone (fig. 41) composed of well-sorted and layered echinoderm and bryozoan fragments (fig. 42) becomes dominant. The upper part of the "Meramec" consists of massive, poorly sorted, skeletal grainstone (fig. 43) and a few thin intervals of wackestone (fig. 44).

"Meramec" rocks in the Childress 10 well area represent the progressive development of a carbonate, skeletal-sand shoal (Ruppel, 1984). Sample logs suggest that these shoal facies extended westward into the Palo Duro Basin. The presence of dolomite in the lower "Meramec" in the center of the basin, however, may indicate that more restricted conditions developed there before the shoal formed.

Core and sample data indicate that a general shallowing trend occurred during deposition of "Meramec" rocks in the area. Limestone and sandstone conglomerates, sandstones, and shales at the "Meramec"/"Chester" contact indicate that this shallowing culminated in erosion throughout the Panhandle. Abundant quartz sand in the upper part of the "Meramec" (Ste. Genevieve Formation) presages the further uplift and erosion that followed.

"Chester"

Rocks assigned to the "Chester" are much more areally restricted than are underlying "Meramec" or "Osage" deposits (fig. 45). Because of Late Mississippian - Early Pennsylvanian erosion, "Chester" rocks are confined to the central and eastern parts of the Palo Duro Basin and eastern margin of the Dalhart Basin. The maximum thickness of these rocks in the Palo Duro Basin is about 300 ft (90 m). By comparison, as much as 1,750 ft (533 m) of "Chester" has been reported in the Texas part of the Anadarko Basin (Cunningham, 1969).

In the Palo Duro Basin, the "Chester" is primarily composed of white-to-buff, fine-grained, fossiliferous, oolitic limestone. Fossils include echinoderms, brachiopods, and bryozoans. Chert is relatively rare. Commonly interbedded with the limestones are laminated gray, green, red, and brown, calcareous shales. Thin beds of light-

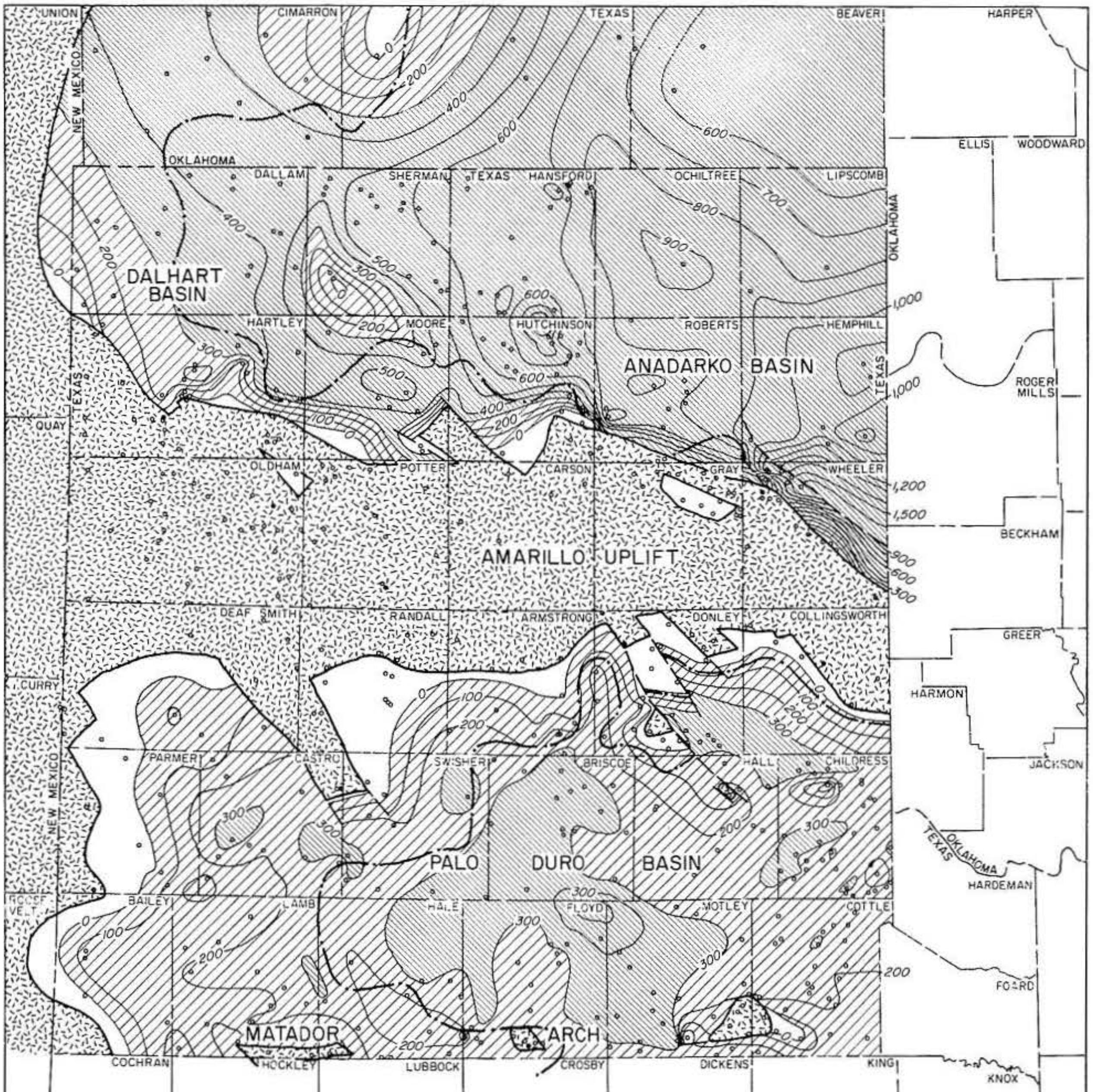


Figure 38. Thickness map, "Meramec." Maximum thickness in the Palo Duro Basin is about 400 ft (120 m). Faults inferred from contour mapping.

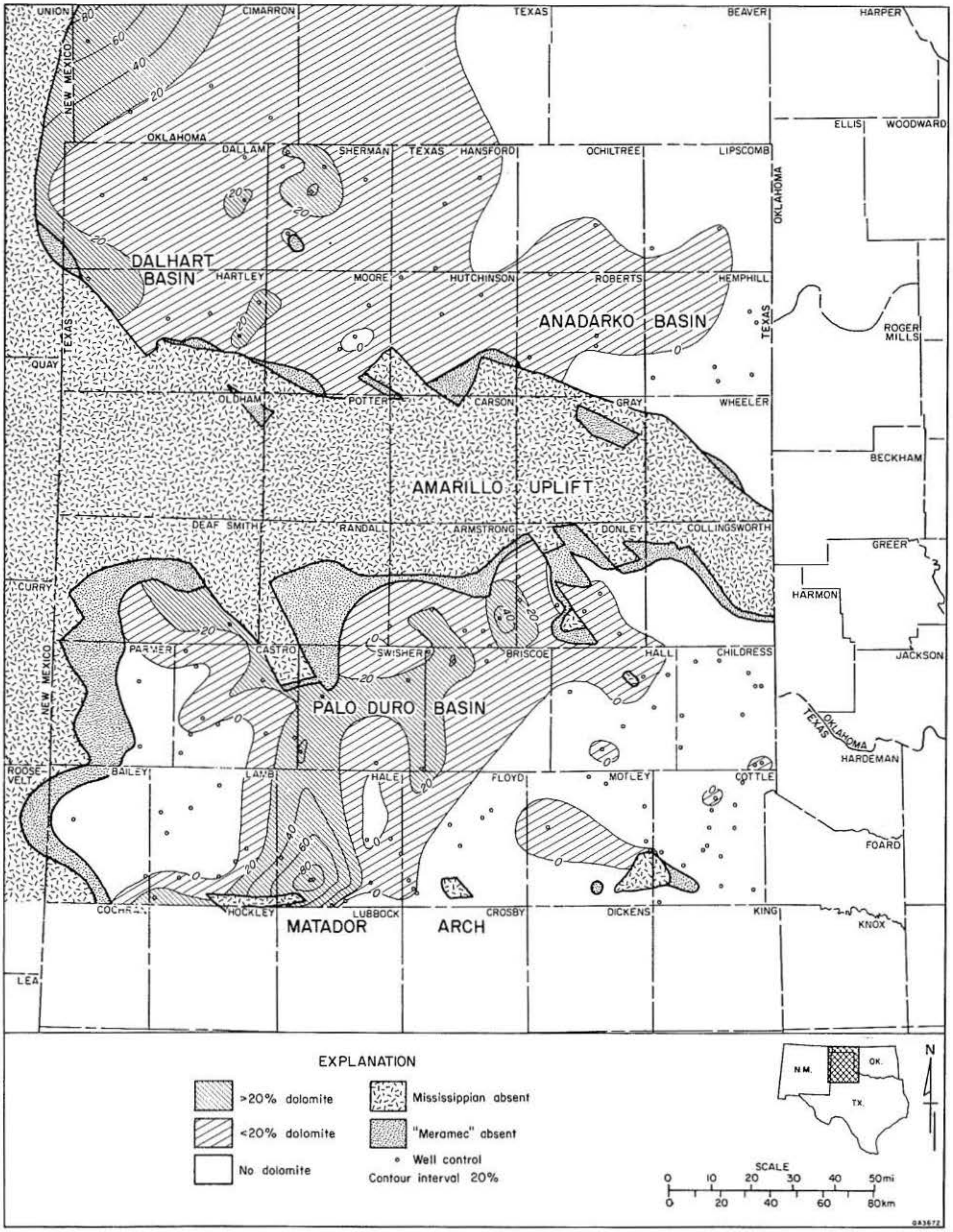


Figure 39. Dolomite-percent map, "Meramec." Much of the Panhandle contains pure or relatively pure limestone. Only the central Palo Duro Basin and a few small, scattered parts of the Dalhart Basin contain more than 20 percent dolomite.

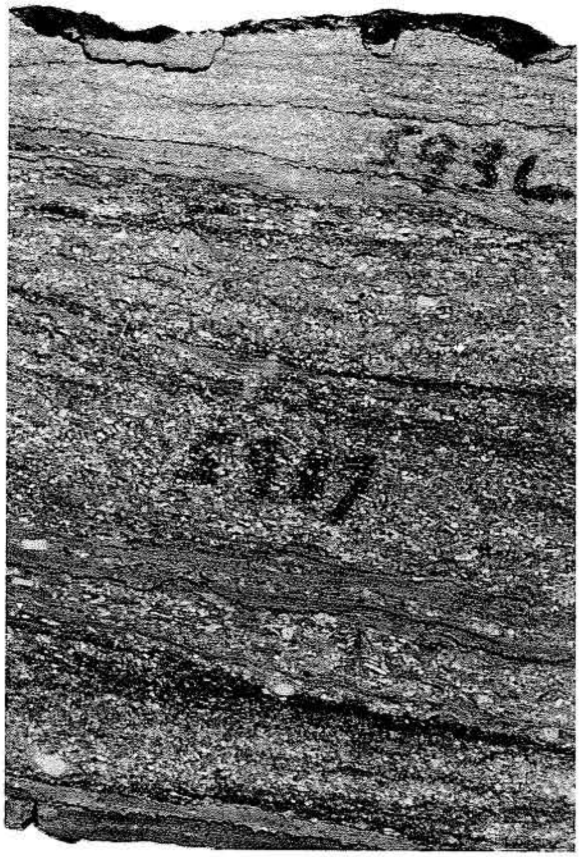


Figure 40. Interlayered skeletal grainstone and wackestone and mudstone common near the base of the "Meramec," Childress 10 well. Muddy layers commonly contain internal laminations of skeletal debris similar to that composing grainstone. Childress 10 well, 5,937 ft (1,809.6 m). Core is 9 cm wide.

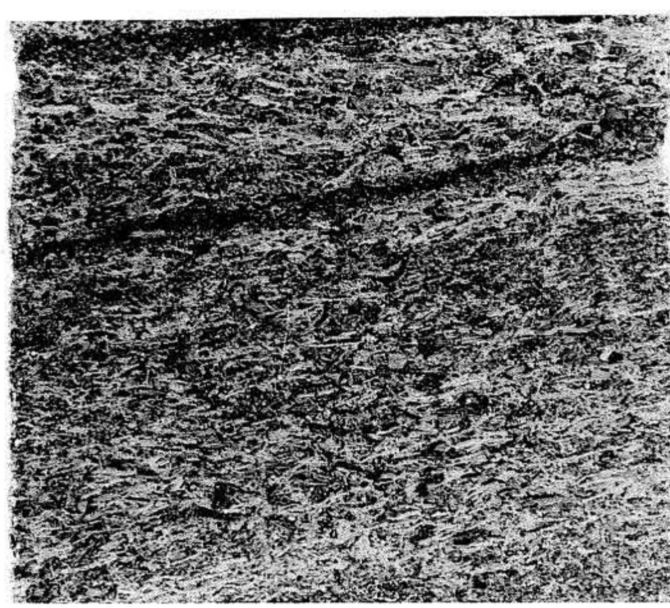


Figure 41. Crossbedded skeletal grainstone. Lower "Meramec," Childress 10 well, 5,887 ft (1,794.4 m). Core is 9 cm wide.

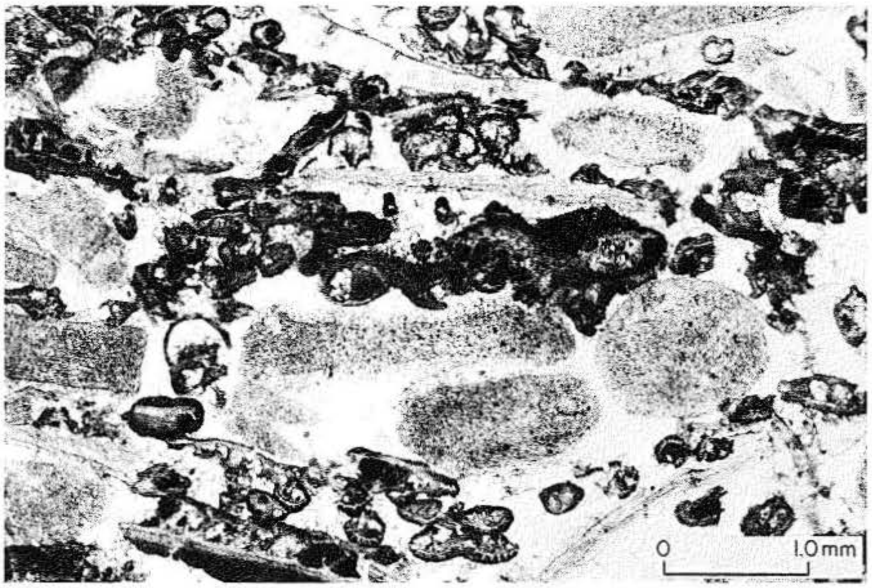


Figure 42. Photomicrograph of skeletal grainstone, similar to that shown in figure 41, containing abundant echinoderms and fenestrate bryozoans. Ramose bryozoans are also abundant at some horizons. "Meramec," Childress 10 well, 5,900 ft (1,798.3 m). Note layering of echinoderm grains.

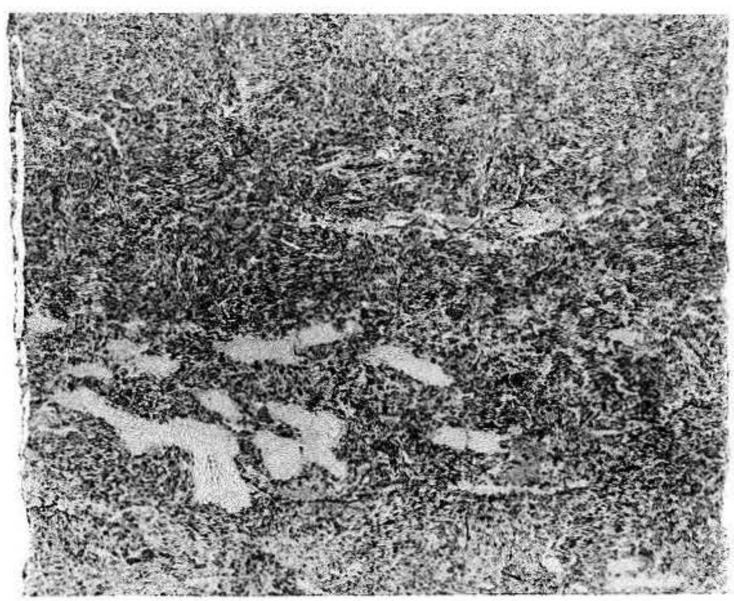


Figure 43. Thickly bedded to massive, poorly sorted skeletal grainstone common in upper part of "Meramec." Note common large ramose bryozoans. Carbonate mud is absent. Childress 10 well, 5,718 ft (1,742.8 m). Core is 9 cm wide.

Figure 44. Layer of dark, thinly laminated skeletal wackestone. Such layers, which are irregularly scattered throughout the upper "Meramec" in the Childress 10 core, contain well-preserved fenestrate bryozoans and sponge spicules. Wackestone grades upward through skeletal packstone into grainstone typical of the upper "Meramec" in this area. Such carbonate-mud-rich deposits probably formed in isolated slack-water areas on a carbonate sand shoal. Childress 10 well, 5,897 ft (1,791.9 m). Core is 9 cm wide.

colored, calcareous sandstone are locally present. The lower "Chester" in the Hardeman Basin (between the underlying St. Louis Formation and overlying Barnett; fig. 14) is quite similar.

"Chester" shales and sandstones are most abundant in an elongate swath through the eastern part of the Palo Duro Basin (fig. 46). Clastic content is also higher in the west-central part of the basin (southwestern Swisher County) and along the Matador Arch (southern Motley County); lowest shale contents are found in the middle of the basin (fig. 46). The amount of shale and sandstone in the "Chester" is much higher north of the Amarillo Uplift (fig. 46). Greatest amounts (nearly 100 percent shale and sandstone) are found in the northwestern corner of the Texas and Oklahoma Panhandles (Dallam and Hartley Counties, Texas, and Texas and Cimarron Counties, Oklahoma).

The contact between the "Chester" and the underlying "Meramec" is sharp at most places in the Palo Duro and Dalhart Basins. The basal "Chester" is composed of limestone and quartz conglomerates and quartz sandstones throughout the central Palo Duro Basin (Donley, Briscoe, Hall, and Floyd Counties). In the eastern (Cottle, Childress, and Motley Counties) and west-central (Swisher and Hale Counties) parts of the basin, the contact is gradational or is marked by basal "Chester" quartz sandstones and shales. A gradational contact also appears to exist in the Hardeman Basin. In the northern Panhandle, the contact is sharp in the west and northwest and gradational in the east (Anadarko Basin). In the northwestern corner of the Panhandle, limestone pebble conglomerates are ubiquitous at the base of the "Chester."

"Chester" rocks represent continued shallow-water marine deposition of ooid and/or skeletal sands. The abundance of clastics, however, contrasts with older Mississippian deposits and indicates that sources of terrigenous clastics developed during the Late Mississippian. The sharp contact between "Chester" and "Meramec" rocks throughout the area indicates that a period of erosion preceded "Chester" deposition. Limestone pebble conglomerates in the Palo Duro Basin and in the northwestern Panhandle indicate at least local erosion of underlying "Meramec" rocks. The more gradational "Meramec"/"Chester" contact in the Anadarko, Hollis, and Hardeman Basins indicates that erosion was minor or nonexistent in the eastern Panhandle of Texas at this time. Distribution of basal "Chester" lithologies thus suggests that the uplift that accounted for this erosion was greatest in the northwest and least in the east. This upwarped area apparently trended generally northwest-southeast, parallel to that of the Texas Arch (fig. 7).

Sandstone and shale distribution in the "Chester" suggests that at least one source of clastics was to the northwest (fig. 46). Lithofacies mapping in this area (Craig and Connor, 1979) suggests that this source may have been in Colorado. It is difficult to determine how many other sources of terrigenous clastics may have developed during the Late Mississippian. Northwest-southeast-trending tongues of clastics in the eastern Palo Duro Basin

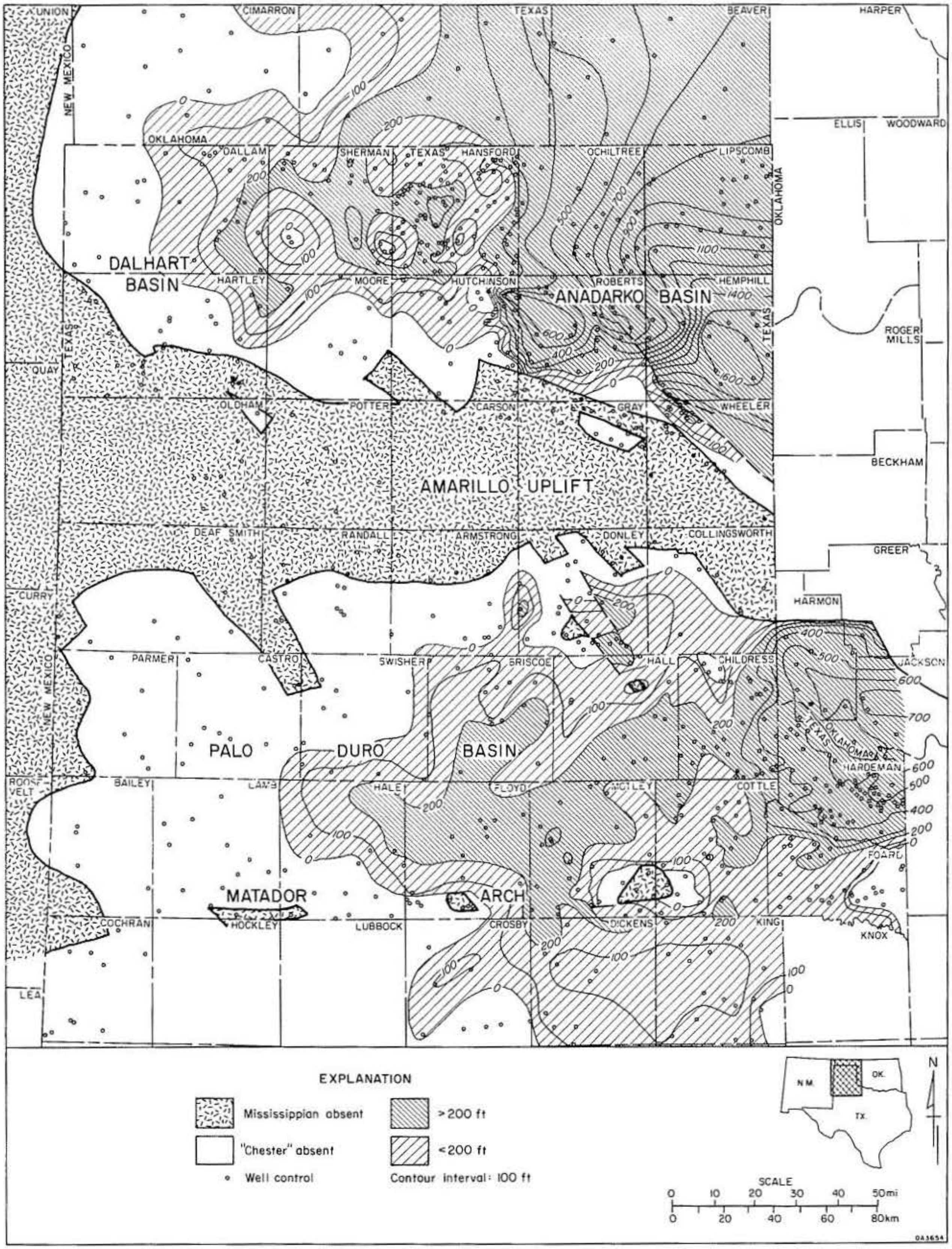


Figure 45. Thickness map, "Chester." Maximum thickness of the "Chester" in the Palo Duro Basin is about 300 ft (90 m). Faults inferred from contour mapping.

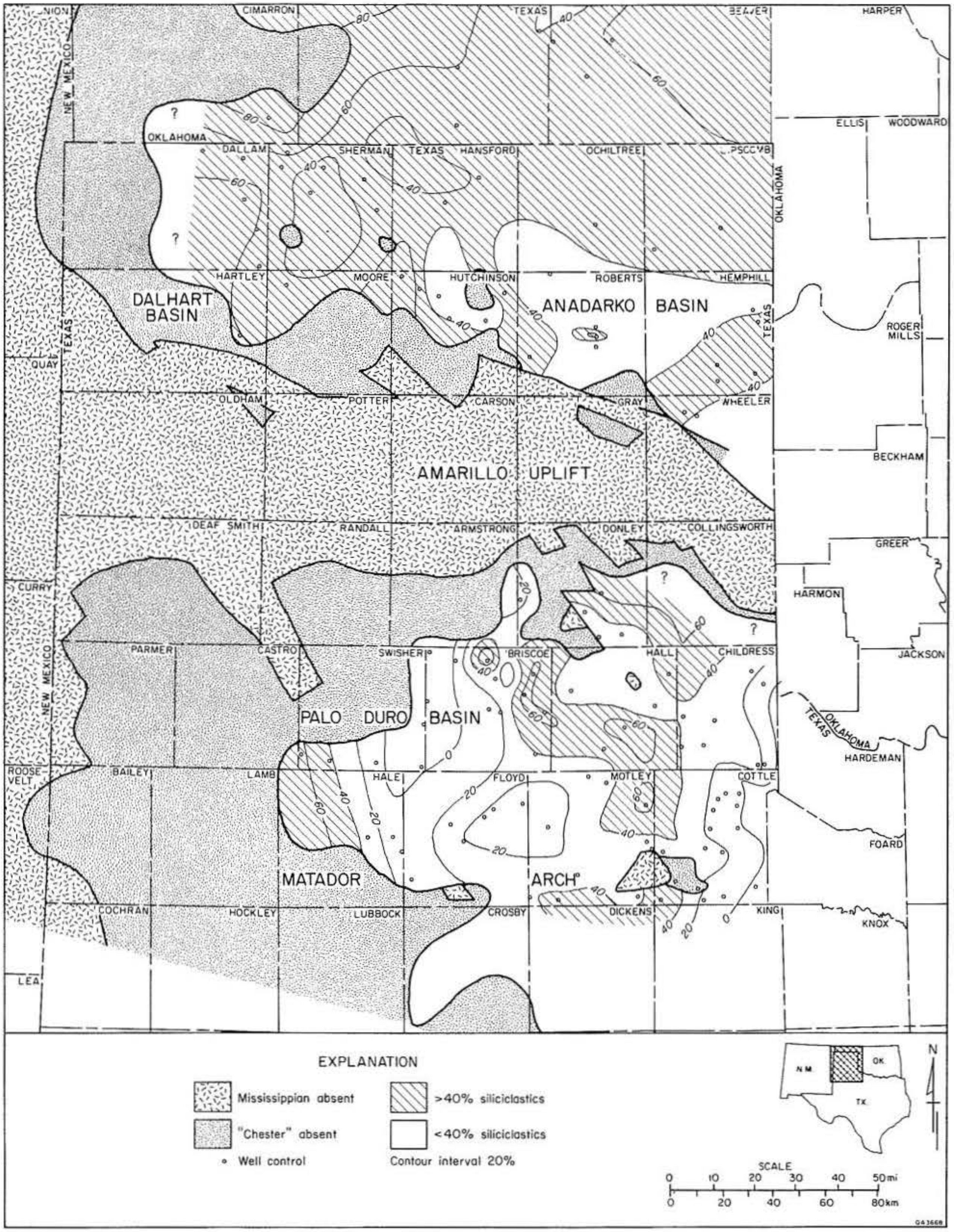


Figure 46. Map showing percent siliciclastics in the "Chester." Note the elongate northwest- to southeast-trending areas of higher percent siliciclastics (shale and minor amounts of sandstone) in the eastern Palo Duro Basin. A similarly trending area of relatively pure limestone is apparent in the central part of the basin.

could have been produced by erosion on uplifted blocks along the Amarillo Uplift in Potter and Carson Counties. Basal Pennsylvanian clastics also appear to be derived from such a source (Dutton, 1980a, her fig. 14). Higher concentrations of terrigenous clastics are also noted in the "Chester" in southeastern Motley County and southwestern Cottle County (fig. 46), suggesting that uplift may have occurred along the Matador Arch at this time as well. The development of an area of relatively pure "Chester" carbonates in the center of the basin (fig. 46) may have been a function of distance from such terrigenous sources. "Chester" rocks are in many respects more similar to Pennsylvanian deposits than to the underlying Mississippian. This similarity suggests that the forces that acted to shape the area into basins and uplifts in the Pennsylvanian had already become active during the Late Mississippian.

The Mississippian/Pennsylvanian Boundary

The base of the Pennsylvanian in the southern Texas Panhandle is conventionally placed at the lowest occurrence of coarse, commonly arkosic, siliciclastic deposits (sandstones and conglomerates); such deposits characterize the Lower Pennsylvanian throughout the area. Limestones, which differ from those in the underlying Mississippian chiefly in the absence of oolites, are locally interbedded with these clastics. Most researchers (for example, Frezon and Dixon, 1975; Mapel and others, 1979; Dutton, 1980a, 1980b) consider the Mississippian/Pennsylvanian boundary to be unconformable, as is true in the western Palo Duro Basin, where Pennsylvanian strata overlie truncated Mississippian rocks (fig. 14). In the interior of the Palo Duro Basin and eastward into the Hardeman Basin, however, the presence of an unconformity is not unequivocal. There is good evidence, for example, that the apparent east-to-west truncation of the upper "Chester" in the area between the Palo Duro and Hardeman Basins (fig. 14) is actually an artifact of lithologic correlation based on facies change rather than actual erosion of the Upper Mississippian. Comparison of geophysical and sample logs in Childress County indicates that rocks considered to be Mississippian in the Hardeman Basin are correlative with those commonly assigned to the Pennsylvanian a few miles west in the Palo Duro Basin (fig. 14). This inconsistency has developed because siliciclastics typical of Pennsylvanian deposition are present much lower in the section in the Palo Duro Basin than to the east. Thus, in at least the eastern Palo Duro Basin, the placement of the Mississippian/Pennsylvanian boundary has been based on a change in depositional setting. Similar examples of the contact being picked on facies change are suggested westward in the Palo Duro Basin. Conventional stratigraphy suggests that thinned "Chester" sequences in the Swisher 13 and Briscoe 23 wells (fig. 14) are due to differential erosion of the "Chester" at the end of the Mississippian. Log data, however, suggest that, as in Childress County, these "thinned" areas may represent depositional sites that received early influxes of clastic sediment relative to surrounding thicker areas. These correlations indicate that the Mississippian/Pennsylvanian boundary is not unconformable throughout the entire region. Because of the lithologic variability that characterizes the sequence formerly assigned to the lowest Pennsylvanian in the Palo Duro Basin, it is impossible without biostratigraphic control to accurately position the Mississippian/Pennsylvanian boundary. However, in the eastern part of the basin the contact should probably be placed 100 to 200 ft (30 to 60 m) higher than is conventionally done on the basis of lithologic change.

Age Relationships

Identifiable conodont faunas were recovered from four well cores: Donley 3, Childress 10, Hardeman 42, and Hardeman 44 (fig. 1). Childress 10 is perhaps the most instructive of these because it has long cores in both the "Meramec" and "Osage" (fig. 20). Conodonts recovered from the Childress 10 cores reveal that both cored intervals are Meramecian in age. Even though conodonts were recovered from within about 60 ft (18 m) of the base of the Mississippian, no Osagean or even early Meramecian faunas were recovered. This indicates that little or no Mississippian deposition occurred in this area until Meramecian time. Although core available for biostratigraphic analysis in Hardeman County is largely from the upper Chappel Formation ("Meramec" equivalent) only, faunas recovered from these cores are supportive of temporal interpretations based on the Childress 10 faunas.

Conodont faunas collected from the Donley 3 core, which is from the lowermost Mississippian "Osage" (fig. 32), are older than those observed in Childress and Hardeman Counties. These faunas suggest an early Meramecian or possibly late Osagean age for the uppermost part of the "Osage" in this area. Since the Donley 3 well apparently contains about 190 ft (58 m) of Mississippian rock below the cored interval (fig. 32), true Osagean rocks may be present in the northern part of the Palo Duro Basin. The age of the basal Mississippian section in the remainder of the basin, however, is not known because of the absence of core. Ruppel (1983, 1984) suggested that Osagean rocks are confined to the northern edge of the basin and that most rocks south of the Amarillo-Wichita Uplift are Meramecian or younger. A more comprehensive treatment of the conodont data and their implications is in preparation. However, data now available permit a tentative revision of Mississippian stratigraphy in the southern Panhandle (fig. 47).

Combined biostratigraphic and sedimentologic evidence indicates that Mississippian rocks in the Palo Duro Basin are no older than Meramecian. Accordingly, both the "Meramec" and "Osage" of popular usage are herein assigned to the Meramecian Series (fig. 47). Biostratigraphic evidence from the Hardeman Basin is inconclusive but suggests a similar situation there. It is possible, however, that true Osagean rocks exist in the eastern part of that basin.

Recovered conodont faunas also suggest that the Ste. Genevieve Formation forms the top of the Meramecian Series in the Palo Duro Basin; the St. Louis Formation occupies a temporally equivalent position in the Hardeman Basin (figs. 14 and 47).

Temporal relationships in the upper part of the Mississippian are not as straightforward due to the lack of biostratigraphic control. The "Chester," as defined in the Palo Duro Basin, is lithologically correlative with the lower "Chester" (referred to by

SYSTEM	SERIES	PALO DURO BASIN		HARDEMAN BASIN	
		GROUP	FORMATION	GROUP	FORMATION
MISSISSIPPIAN	CHESTERIAN	"CHESTER"		"CHESTER"	COMYN
					BARNETT
	MERAMECIAN	"MERAMEC"	STE. GENEVIEVE	"MERAMEC"	ST. LOUIS
					CHAPPEL
		"OSAGE"		"OSAGE"	
				?	?
	OSAGEAN				
	KINDERHOOKIAN				

QA3656

Figure 47. Revised stratigraphy of the Mississippian System in the Palo Duro and Hardeman Basins. Osagean rocks may be locally present in the eastern Hardeman Basin. The exact position of the Mississippian/Pennsylvanian boundary is unknown.

others as the Ste. Genevieve Formation) in the Hardeman Basin. The overlying Barnett and Comyn Formations of the Hardeman Basin (upper "Chester") have no equivalent in the Palo Duro Basin due to erosion (fig. 2) according to conventional correlation. Current studies, however, suggest that the Barnett and Comyn are correlative with at least some of the rocks referred to as lower Pennsylvanian in the Palo Duro Basin (fig. 14). If this is true, at least three scenarios are possible.

If the top of the Comyn Formation marks the Mississippian/Pennsylvanian boundary in the Hardeman Basin, as generally assumed, at least some of the mixed carbonates and clastics assigned to the lowermost Pennsylvanian in the Palo Duro Basin must be Mississippian in age. If so, the top of the Mississippian lies somewhere in this interval of mixed, mostly noncorrelatable lithologies.

If, however, the Mississippian/Pennsylvanian boundary is approximately correct as it is conventionally recognized in the Palo Duro Basin (at the earliest influx of coarse siliciclastic deposits), then the Comyn and Barnett Formations, which correlate in part with these clastics, may be Pennsylvanian in age. Each of these scenarios requires that the tops of lithologically correlative units be coeval. Although conodont data suggest that the top of the "Meramec" is synchronous throughout the area, no biostratigraphic control exists for the overlying units.

A third possibility arises if "Chester" lithologic units are not synchronous across the Palo Duro and Hardeman Basins. If the "Chester" (Palo Duro Basin)-lower "Chester" (Hardeman Basin) lithologic unit (fig. 14) is older in the Hardeman Basin than in the Palo Duro Basin, then present age assignments for both areas may be correct. No decision on which of these possibilities, or some combination thereof, applies can be made until additional biostratigraphic or chronostratigraphic data become available. Figure 47 is correct for the first and third scenarios.

POROSITY AND PERMEABILITY

Estimates of Porosity

Unfortunately, no porosity and permeability data based on core analysis are available from the southern Texas Panhandle. To assess the reservoir quality of the pre-Pennsylvanian rocks, porosity estimates were made for 56 wells in the Palo Duro Basin (table 1) using borehole logs. For most (49) of these wells, only sonic logs were available; for the rest (7), bulk density or neutron logs were used to calculate porosity. Comparisons among the three types of logs showed no significant differences in porosity values. Average porosity values were determined for 10-ft intervals throughout the pre-Pennsylvanian section; from these, average values were calculated for each lithologic unit in each well.

Basal (Cambrian?) sandstones in the eastern Palo Duro Basin (fig. 6) are locally porous. Although no logs are available for calculating quantitative values, resistivity logs indicate significant porosity in most wells where these sandstones occur (fig. 6).

Dolomites of the Ellenburger Group exhibit the highest (average 7.7 percent) and most uniform porosities observed in the pre-Pennsylvanian rocks of the area (table 1). No general vertical or horizontal porosity trends are apparent in the Ellenburger in the Palo Duro Basin, although in some producing areas higher porosity values due to erosion have been reported from the top of the unit (Bradfield, 1964).

Although the average porosity calculated for the "Osage" is relatively low (average 6.5 percent), many wells exhibit significantly higher porosities (table 1). Higher porosity values (greater than 6.5 percent) are observed in the central and western parts of the Palo Duro Basin (fig. 48), where the "Osage" is characterized by high proportions of dolomite (fig. 19). In addition to having higher average porosities, the "Osage" in these areas contains several intervals in which porosities exceed 10 percent (fig. 49). Areas that contain primarily clean limestone, on the other hand, such as the northeastern, eastern, and southern parts of the basin, are characterized by low porosity values (fig. 48).

Sample log data generally support porosity trends indicated by borehole logs. Minor increases in apparent porosity observed at the base of the "Osage" section in some wells in the southern and eastern parts of the basin are caused by the presence of shales of the so-called "Kinderhook" and are probably noneffective. Basal "Osage" ("Kinderhook"?) sandstones present in the northern part of the Palo Duro Basin in Donley County are exceptions. In the Donley 50 well, for example, the approximately 50-ft (15.2-m) section of sandstone at the base of the Mississippian has a log-derived average porosity of about 23 percent (maximum of 31 percent).

"Meramec" rocks appear to be the least porous pre-Pennsylvanian deposits in the area (average 4.4 percent). Because the "Meramec" is homogeneous (little shale or dolomite is present), calculated log porosity values are probably more accurate for it than for other Mississippian units. Although porosities appear to be relatively consistent throughout the lateral and vertical extent of the "Meramec" (fig. 50), some trends are apparent. With few exceptions, average well porosities of greater than 5 percent occur only in the northern and western parts of the basin where overlying "Chester" rocks have been removed by erosion. In fact, porosity in the "Meramec" seems to vary directly with distance from the "Chester" erosional limit (fig. 50). This trend strongly suggests that "Meramec" porosity in the northern and western Palo Duro Basin may have been enhanced by local uplift and partial erosion at the end of the Mississippian. Similar erosion-related porosity is known from the "Chester" and "Meramec" in the Anadarko Basin.

In many wells, a slight increase in porosity is noted where the upper "Meramec" grades downward into the generally more porous "Osage." Visible porosity reported on sample logs from wells, in southern Hale County for example, also indicates this trend. The "Meramec" is particularly porous in northwestern Briscoe County; 20 to 100 ft (6 to 30 m) of porous carbonate has been reported for every well there.

Porosity data for the "Chester" are largely restricted to the eastern Palo Duro Basin. Wells in this area exhibit generally similar average porosity values, the overall average being 7.2 percent (table 1). However, within the "Chester" a wide variation in porosity is indicated (0 to 33 percent/10 ft interval). Many of the high values observed, however, probably indicate the presence of noncarbonate lithologies. The "Chester" is known to contain large quantities of shale and sandstone throughout the basin (fig. 45). Because a limestone matrix was assumed for the entire unit, these zones appear as anomalously high porosity intervals. Therefore, the overall porosity of the "Chester" is probably somewhat less than is indicated.

Although porosity log data on the "Chester" were obtained only from the eastern part of the basin, sample logs record visible porosity in wells that have penetrated an area of relatively clean carbonates in the central part of the basin (fig. 46). No porosity logs are available for quantitative estimates, but these sample logs indicate that at least part of the "Chester" in this area exhibits significant porosity.

According to Levorsen (1967), most hydrocarbon reservoirs contain porosities of 5 to 30 percent. Thus, except for the "Meramec," all pre-Pennsylvanian carbonates in the Palo Duro Basin are sufficiently porous to act as petroleum reservoirs; the "Chester," "Osage," and "Ellenburger" each exhibit average porosities of greater than 5 percent. Actually, because carbonates may

Table 1. Average well porosities in the pre-Pennsylvanian sequence, Palo Duro Basin.

	Mean (%)	Range (%)	Standard deviation (%)	Number of wells
Mississippian				
"Chester"	7.2	3.2-19.0	3.2	36
"Meramec"	4.4	1.6-10.9	1.9	45
"Osage"	6.5	2.1-13.2	3.1	47
Ordovician				
Ellenburger	8.8	5.1-17.9	3.1	18

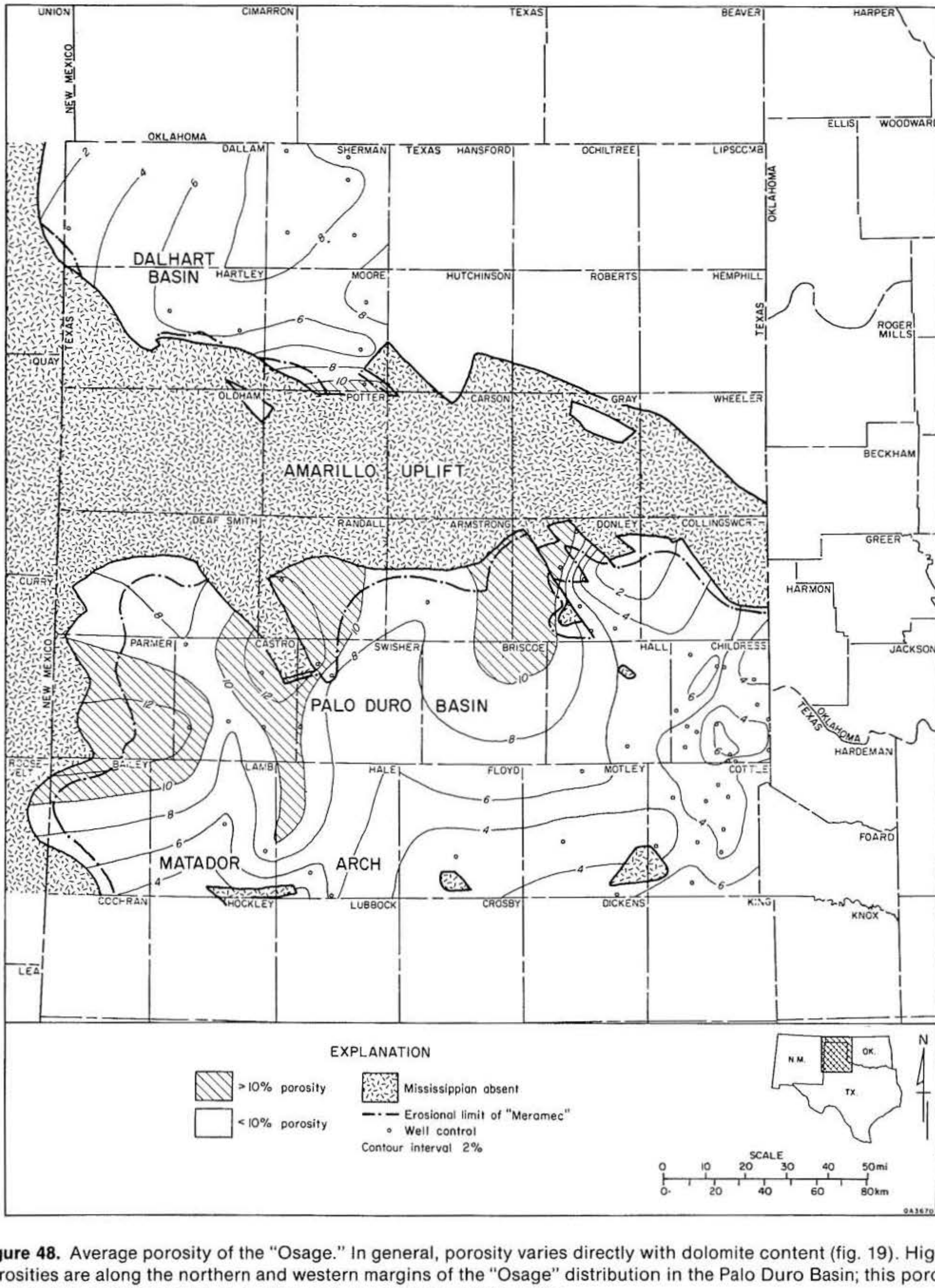


Figure 48. Average porosity of the "Osage." In general, porosity varies directly with dolomite content (fig. 19). Highest porosities are along the northern and western margins of the "Osage" distribution in the Palo Duro Basin; this porosity trend may in part be related to erosion and removal of overlying units.

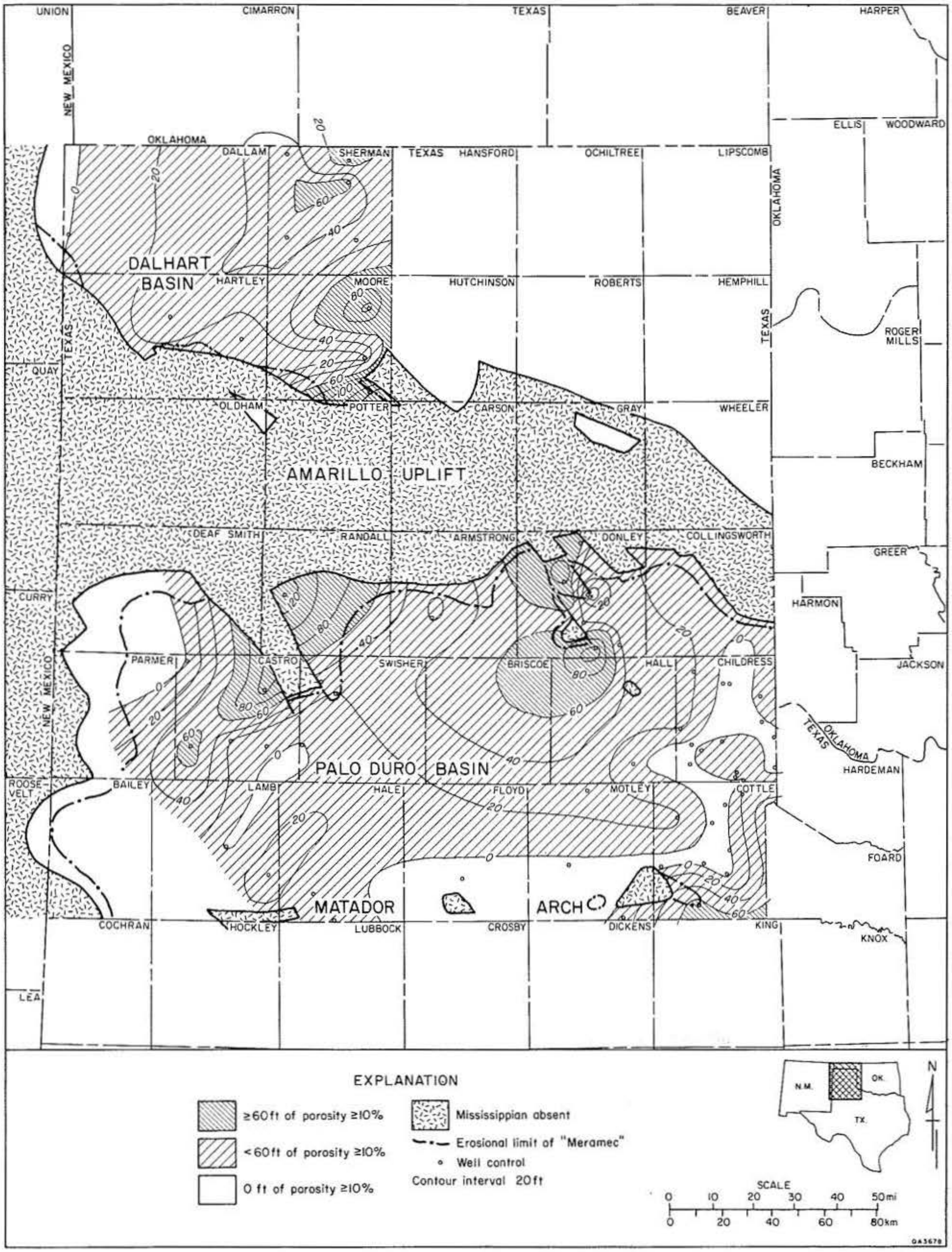


Figure 49. Thickness of "Osage" rocks having greater than 10 percent porosity. Greatest thicknesses occur in a northwest-to southeast-trending area in Randall and Castro Counties.

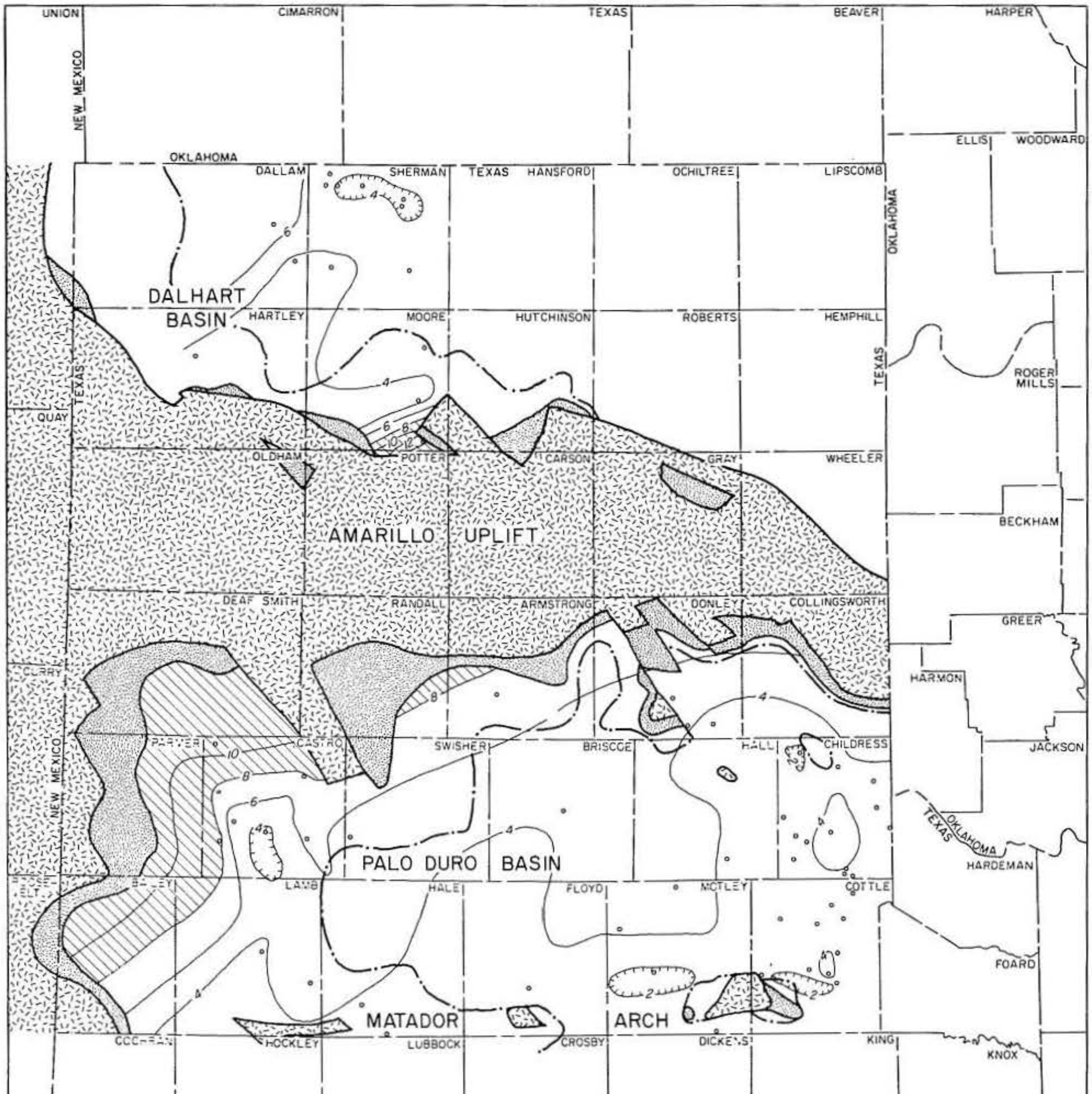


Figure 50. Average porosity of the "Meramec." Low porosities (less than 5 percent) are common throughout the Palo Duro Basin; porosities slightly higher are along the northern margin.

contain secondary as well as interparticle porosity, some of these units (including the "Meramec") may have higher porosities than have been calculated. Sonic logs tend to underestimate total porosity where secondary porosity is present (Schlumberger, 1972). Examination of available core confirms that secondary porosity is locally present in these rocks.

Porosity Types

The scarcity of cores from the Dalhart and Palo Duro Basins makes porosity characterization difficult. Core studies from producing areas in the Anadarko, Hardeman, and Midland Basins indicate that all types of porosity, including interparticle, vugular, and fracture porosity, are encountered in the Mississippian and Ordovician (Ellenburger). In the productive Mississippian carbonate buildups in the Hardeman Basin, for example, secondary porosity produced by dolomitization is combined with fracture porosity to produce highly permeable reservoirs (Allison, 1979).

Although no Ellenburger cores are available from the Palo Duro or Dalhart Basins, core has been examined from wells in the Hardeman Basin. In these cores, the Ellenburger contains primarily intercrystalline (fig. 51a) and fracture porosity (fig. 9). Small vugs are observed in some zones (fig. 51b). Sample logs from the Palo Duro Basin record vuggy and cavernous porosity.

Several porosity types are also observed in cores from the Childress 10 well (figs. 21 and 22). Most of the porosity in the "Osage" (fig. 21) is concentrated in skeletal grainstone (which makes up only 17 percent of the lower Chappel Formation in the Childress 10 well). Most of this porosity is in the form of intraparticle voids in bryozoan colonies (fig. 52), much of which may be noneffective because of the lack of interconnections between void spaces. Secondary porosity probably accounts for most of the porosity in the "Osage." In most places, it is related to dolomitization or silicification of the grainstone (fig. 53). Some fracture porosity

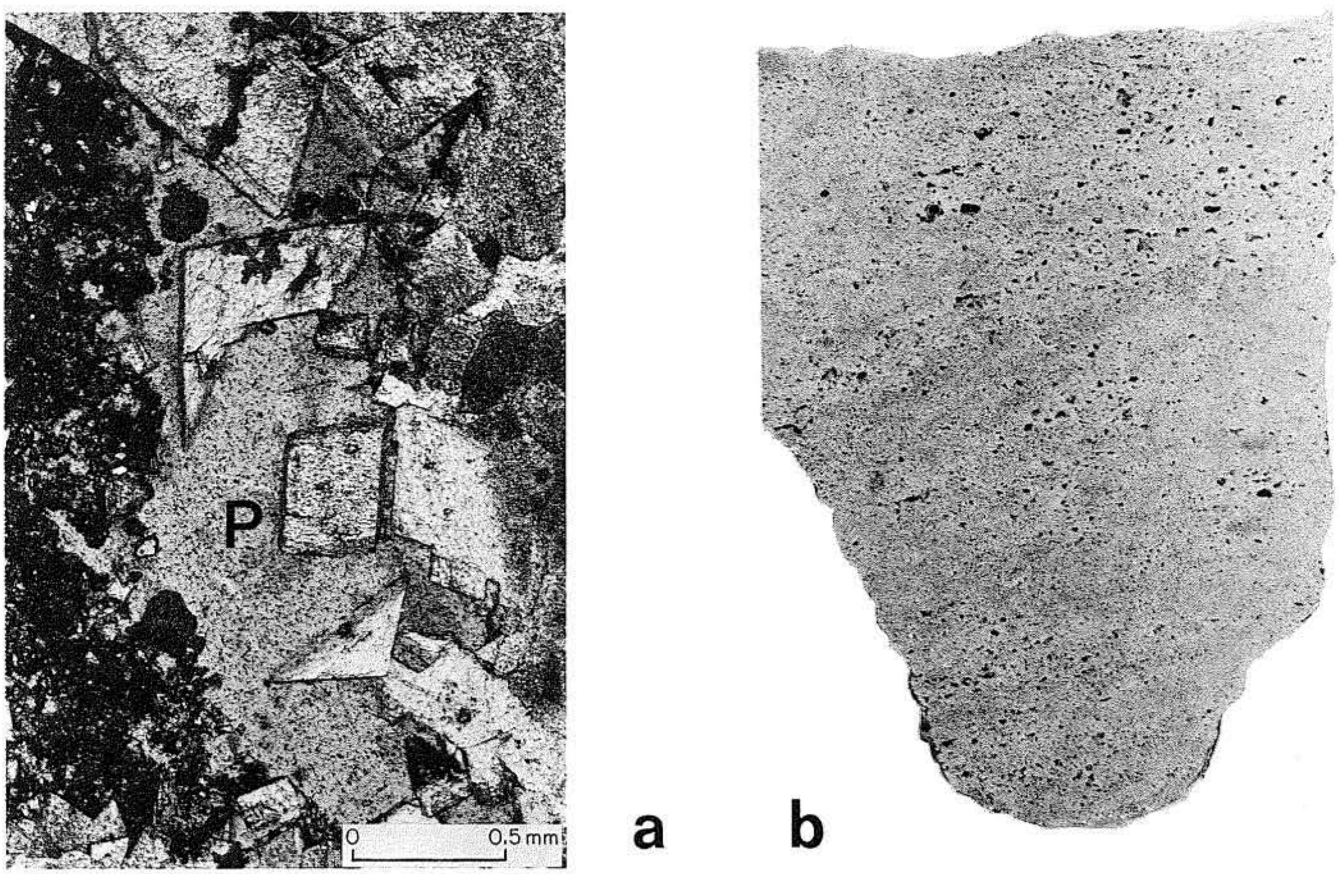


Figure 51. Porosity in the Ellenburger Group as shown by (a) photomicrograph of intercrystalline porosity (P), Hardeman 45 well, 8,097.8 ft (2,468 m) and (b) small vugs and moldic porosity, Hardeman 43 well, 8,496 ft (2,590 m). Core is 8 cm wide.

also exists. Minor intraparticle porosity is ubiquitous in the "Meramec" grainstone (fig. 22) as well. As in the "Osage," most commonly, this porosity takes the form of original void space in bryozoan zooecia (fig. 54). Primary intercrystalline and interparticle porosity is also present. Traces of secondary interparticle and intraparticle porosity and microfracture porosity are less common.

Only "Osage" rocks were cored in the Donley 3 well (fig. 32). These rocks contain no primary porosity, but because of extensive dolomitization, both interparticle and intraparticle porosity is common (fig. 33). Highest porosities are usually observed in the partially dolomitized grainstone, but minor moldic porosity exists in some of the dolosiltstone.

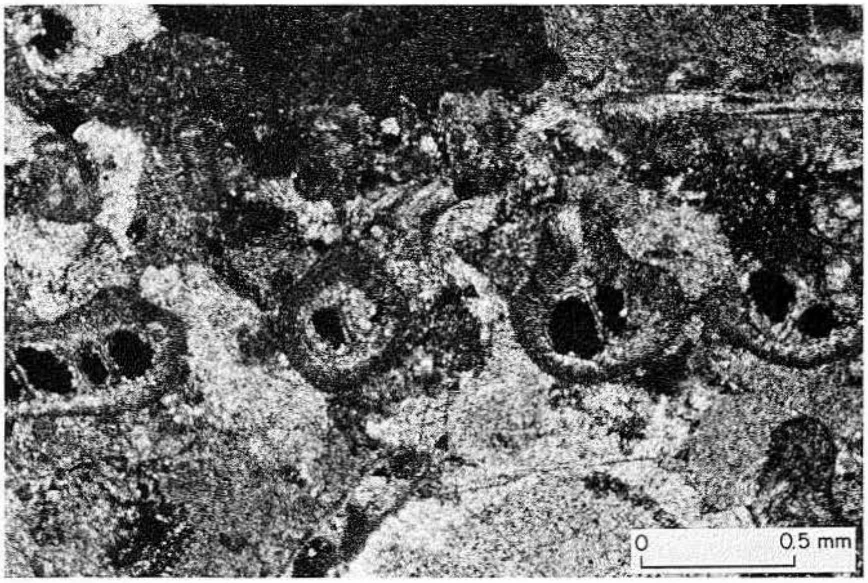


Figure 52. Photomicrograph showing intraparticle porosity developed in zooecia of fenestrate bryozoans in skeletal lime-sand grainstone. "Osage," Childress 10 well, 6,110 ft (1,862 m).

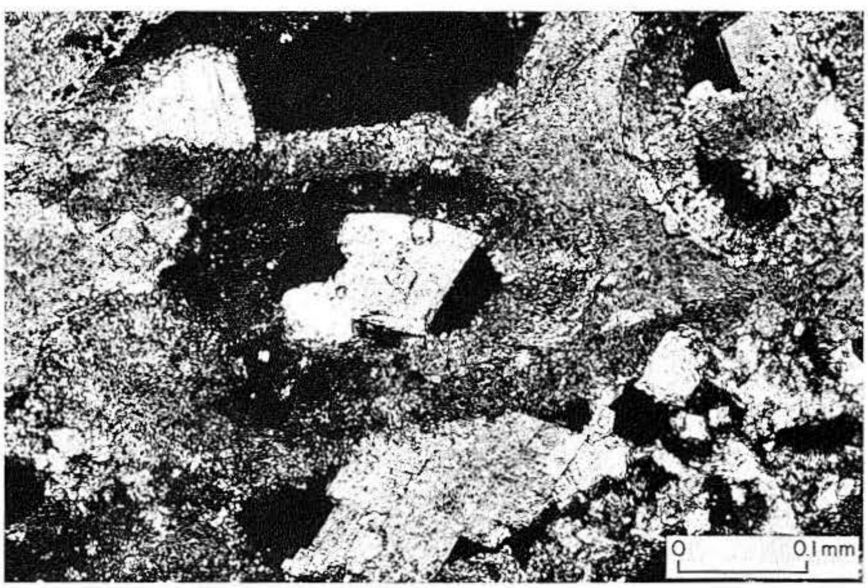


Figure 53. Photomicrograph showing secondary intraparticle porosity associated with dolomitization of skeletal lime-sand grainstone. "Osage," Childress 10 well, 6,159.6 ft (1,877.4 m).

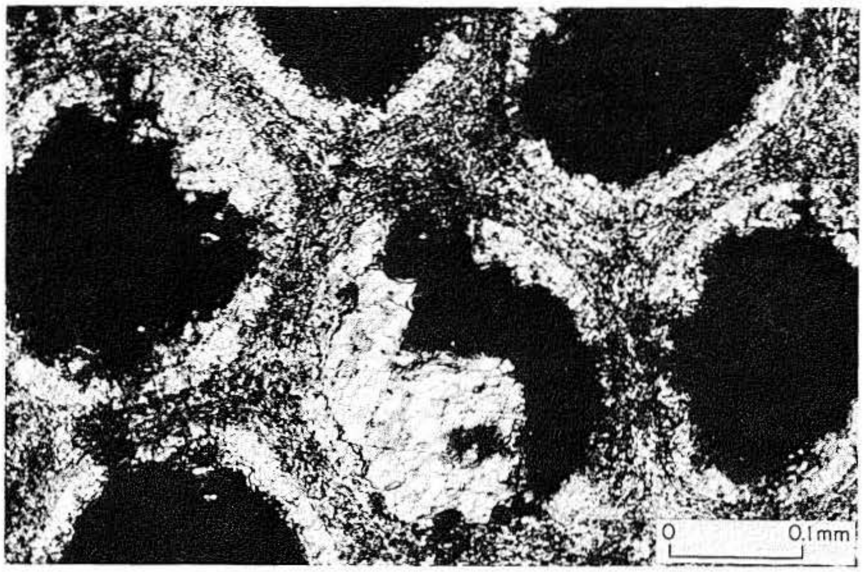


Figure 54. Photomicrograph showing primary intraparticle porosity in bryozoan zooecia. Note partial filling of some zooecia by blocky calcite. "Meramec," Childress 10 well, 5,818.2 ft (1,773.4 m).

Permeability

High-quality quantitative pressure data, from which permeabilities could be calculated, are available from only a few wells in the area. In these wells, porosity and permeability are directly related, as expected (table 2). Highest permeabilities are encountered in the Ellenburger (table 2). Fair (Levorsen, 1967) permeabilities have been recorded for the "Chester" and "Osage." These data tend to indicate that permeabilities in the pre-Pennsylvanian carbonates are somewhat higher than would be expected considering their porosities (Levorsen, 1967). In general, permeabilities of pre-Pennsylvanian rocks in the Palo Duro Basin are comparable to those observed in producing horizons in the Hardeman Basin (Montgomery, 1984).

Table 2. Permeability data, Palo Duro Basin.

	Calculated Permeabilities*				Permeability/Porosity Interrelationships*		
	No. of tests	Avg. (md)	Std. dev. (md)	Range (md)		K (md)	Ø (%)
Mississippian					Mississippian		
"Chester"	3	3.7	4.1	0.2-8.3	Donley 31	0.7	3.2
"Meramec"	1	0.7	---	---	Donley 50	12.9	19.3
"Osage"	3	7.1	5.8	1.3-12.9	Ordovician		
Total	7	4.7	4.8	0.2-12.9	Cottle 17	1.6	5.6
Ordovician					Donley 31	127.0	10.7
Ellenburger	4	38.6	60.1	.001-127.0			

*All permeability values calculated from drill-stem test data except Donley 50 ("Osage"), for which pumping-test data were used.

SOURCE ROCK POTENTIAL

The source rock quality of any rock (that is, a rock's potential for producing hydrocarbons) is dependent on (1) the amount of organic matter present, (2) the type of organic matter, and (3) the thermal maturity of the organic matter. Because shales commonly contain large amounts of organic matter, they are usually considered to have the greatest source rock potential. Carbonate rocks, however, can also produce hydrocarbons; in fact, because these rocks commonly contain organic matter that is more oil-prone than that found in shales, carbonates can actually be more effective than shales as source rocks (Hunt, 1979). It is generally accepted that shales must contain a minimum of 0.5 percent total organic carbon (TOC) to produce commercial quantities of hydrocarbons (Tissot and Welte, 1978). Although a value of 0.3 percent TOC is commonly given as a minimum for carbonate source rocks (Tissot and Welte, 1978; Hunt, 1979), hydrocarbons have been generated from rocks having less than 0.25 percent TOC (Hunt, 1979).

Hydrocarbon shows have been reported from both Ordovician (fig. 55) and Mississippian (fig. 56) rocks in the Palo Duro Basin, indicating that oil has been generated. The source of this oil, however, is unknown. Therefore, it is important to consider the source rock potential of the pre-Pennsylvanian sequence in the Palo Duro Basin even though the sequence contains relatively little shale.

Organic Matter Content

Analyses for total organic carbon were performed on samples from 51 wells in the Palo Duro and Dalhart Basins; samples from seven additional wells in the Hardeman Basin were analyzed for comparison (figs. 57 and 58). In all, 113 samples were analyzed (table 3), 72 from cuttings and 41 from core. To avoid possible contamination from Pennsylvanian shale cavings, all cuttings were picked to remove most shale fragments. Complete TOC data are presented in appendix B.

In general, the TOC content of the pre-Pennsylvanian carbonates of the Palo Duro Basin is low. The average value, 0.107 percent (table 3), is lower than average values reported for carbonate rocks elsewhere (0.20 percent TOC; Tissot and Welte, 1978; Hunt, 1979) and is also below the minimum usually required for carbonate source rocks (0.12 to 0.30 percent TOC). The pre-Pennsylvanian units are heterogeneous, however (table 3).

Ellenburger carbonates generally contain little TOC (average 0.09 percent). This value agrees with those observed by Cardwell (1977) in the largely equivalent Arbuckle Group in southern Oklahoma. Cardwell (1977) concluded that the Arbuckle and the Ellenburger have little potential to generate hydrocarbons because of low organic matter content. Limestones of the "Meramec" in the Palo Duro and Dalhart Basins also contain small amounts of TOC and are thus unlikely source rocks. Values obtained from "Chester" rocks are higher; however, this may be due to the difficulty of obtaining clean carbonate samples from this commonly shaly interval. The problem in distinguishing Pennsylvanian shale cavings precluded TOC analysis of "Chester" shales.

Total organic carbon in the "Osage," although variable, is generally higher than in other pre-Pennsylvanian carbonates. The average value recorded for the "Osage" (0.128 percent TOC) is marginally above the minimum for carbonate source rocks determined by some laboratories (GeoChem Laboratories, 1980). However, 38 percent of the "Osage" samples contained more than 0.16 percent TOC, and 18 percent contained more than 0.20 percent TOC. Highest TOC values in the "Osage" are found in the northeastern and eastern edges of the Palo Duro Basin (fig. 59). These areas coincide with those thought to represent deeper, more open-marine conditions. Organic matter content here is consistently above 0.10 percent TOC and in some cases above 0.25 percent TOC. Therefore, although TOC values are generally low in the pre-Pennsylvanian, local areas with at least minimal amounts of organic matter do exist. However, only rarely is TOC content greater than 0.3 percent, the commonly accepted minimum for effective carbonate source rocks (Tissot and Welte, 1978; Hunt, 1979).

Carbonate rocks in the hydrocarbon-producing Hardeman Basin have TOC contents similar to those observed in the Palo Duro and Dalhart Basins, although one sample produced a high value of 0.668 percent TOC. Two samples from shales of the Barnett Formation contain even higher amounts of TOC, an indication that this unit is a much more likely source rock (table 3).

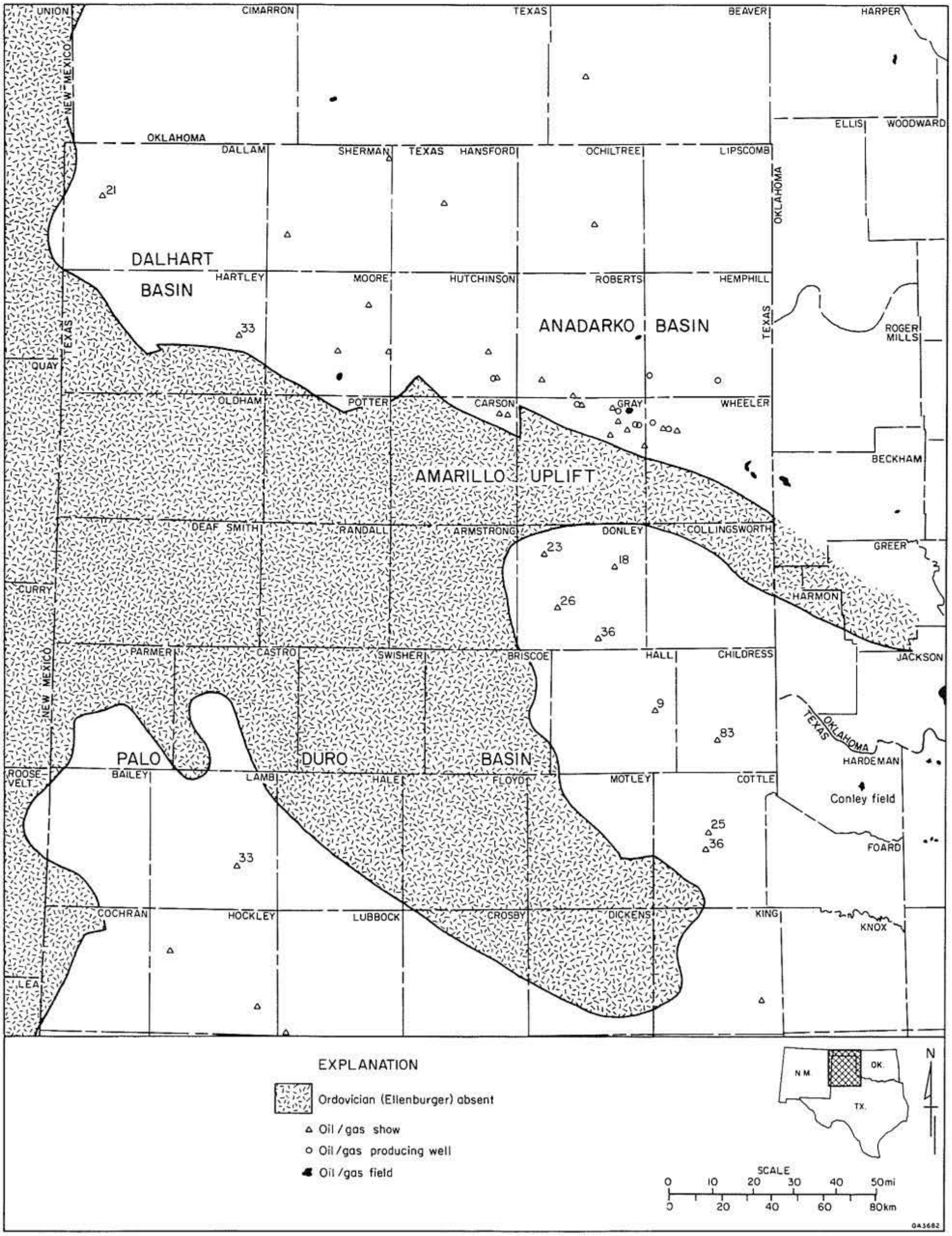


Figure 55. Distribution of oil and gas shows and producing wells and fields in the Ellenburger Group, Texas Panhandle. Conley field (Hardeman Basin) is the only producing field in the southern Panhandle. Data on producing wells in the Anadarko Basin modified from Petroleum Information Corp. (1982). Names of wells in the Palo Duro and Dalhart Basins (numbered) given in appendix A.

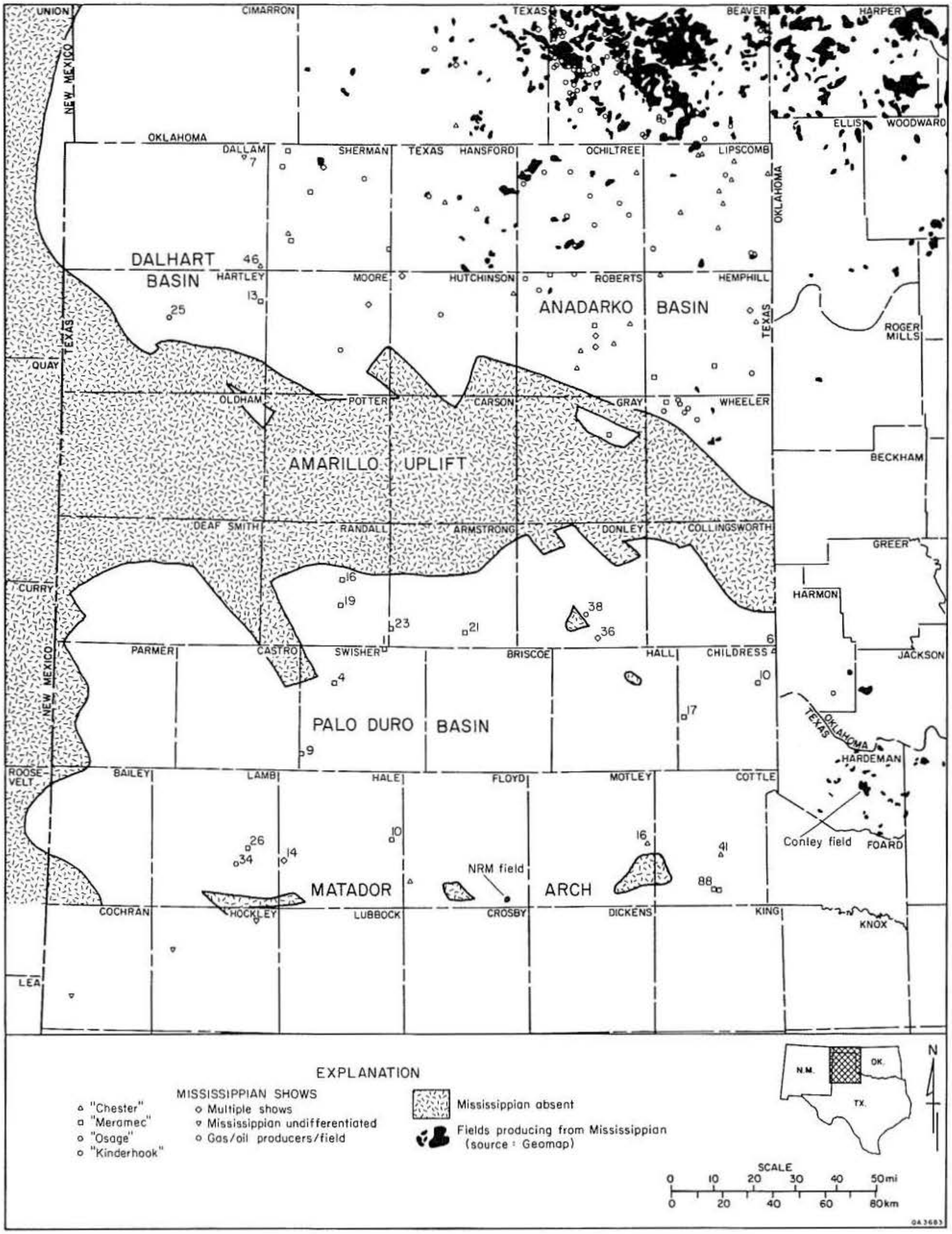


Figure 56. Distribution of oil and gas shows and producing wells and fields in Mississippian rocks of the Texas Panhandle. Numerous fields in the Hardeman Basin produce from the Chappel Formation (mostly "Meramec" equivalent). Most shows in the Palo Duro Basin are in the "Meramec." The NRM field produced briefly from "Chester" strata along the Matador Arch at the southern edge of the Palo Duro Basin. Data on producing wells in the Anadarko Basin from Petroleum Information Corp. (1982); field outlines from GEOMAP Company (1982a, b). Names of wells in Palo Duro and Dalhart Basins having oil or gas shows (numbered) given in appendix A.

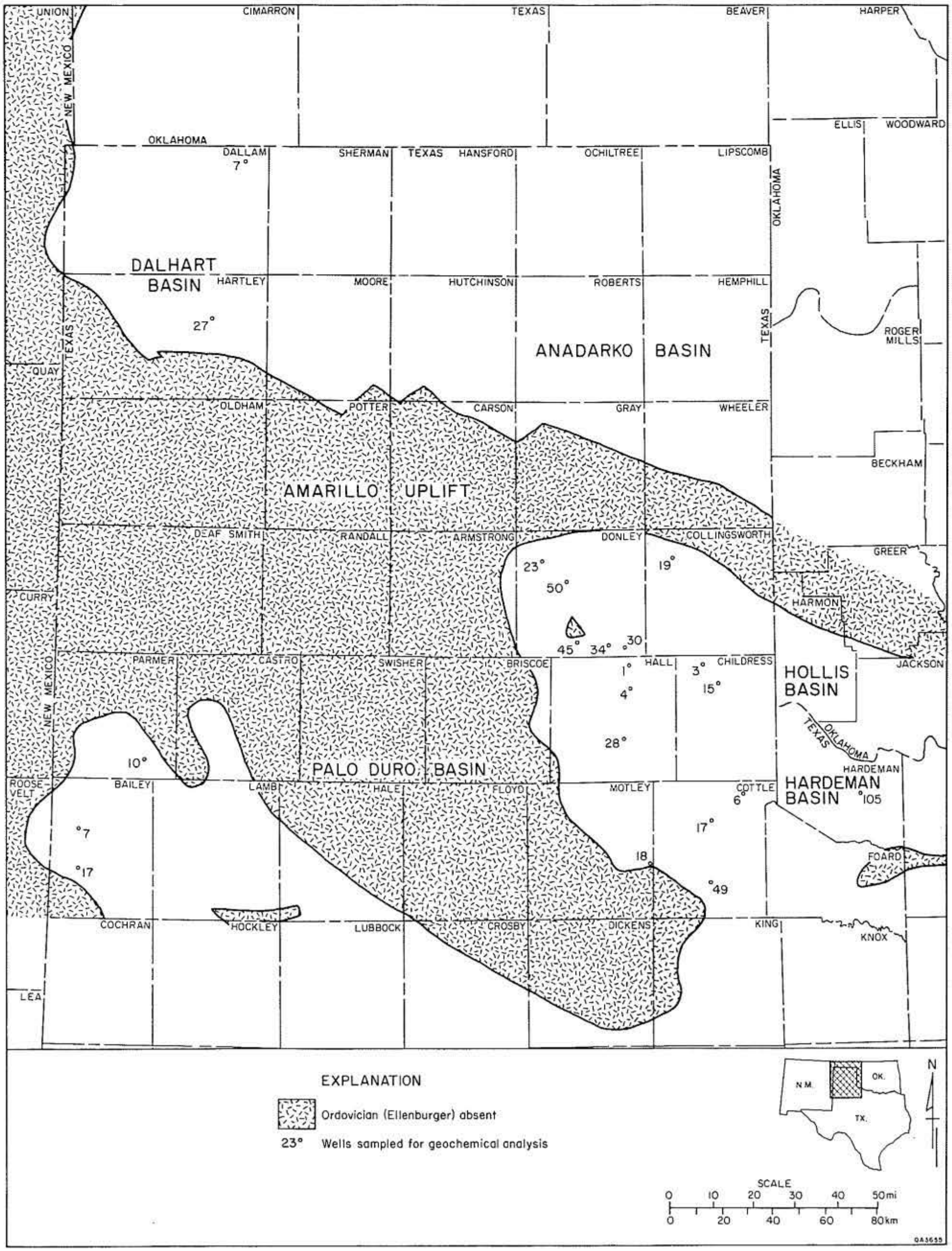


Figure 57. Wells in the Ellenburger Group sampled for geochemical analysis. Names of wells given in appendix A.

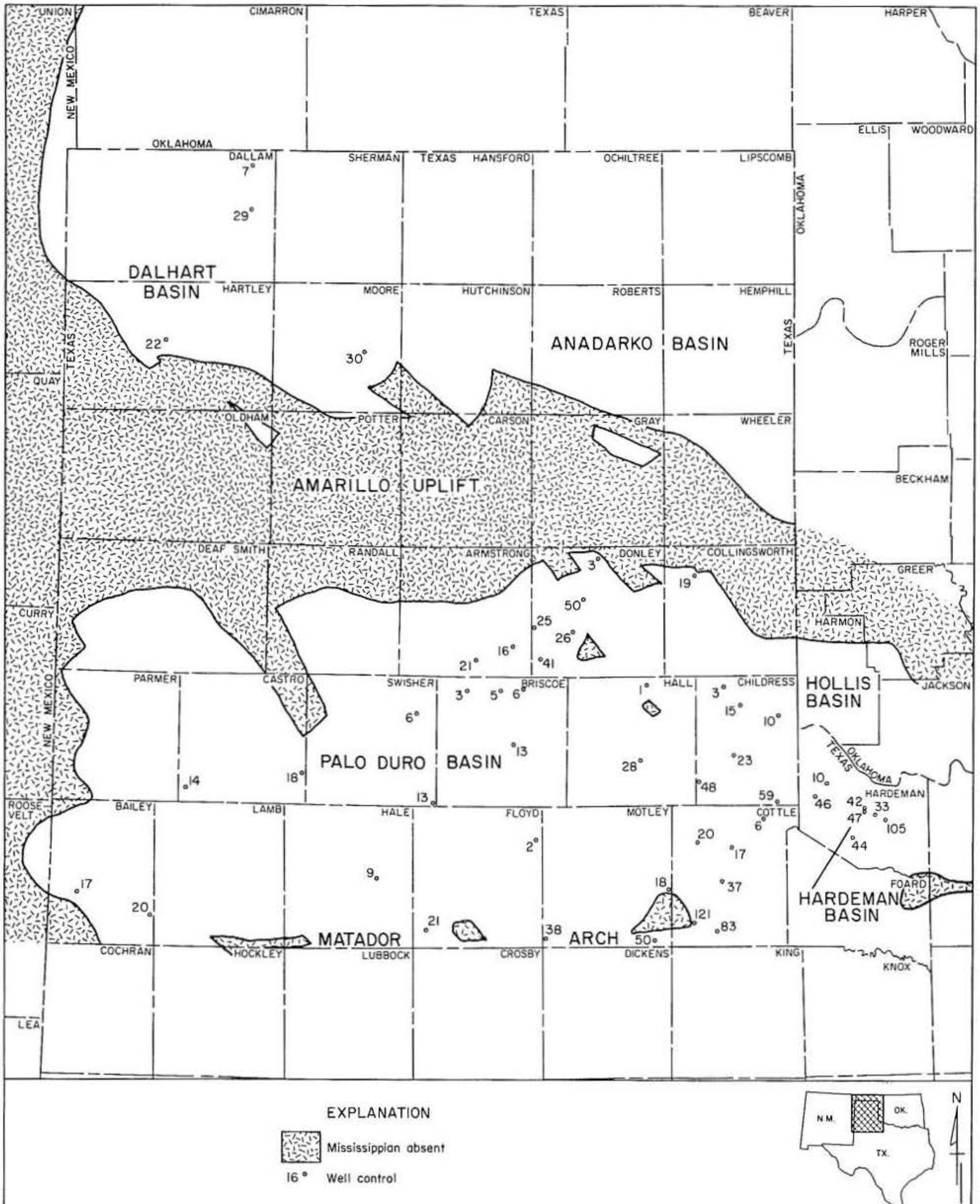


Figure 58. Wells in the Mississippian System sampled for geochemical analysis. Names of wells given in appendix A.

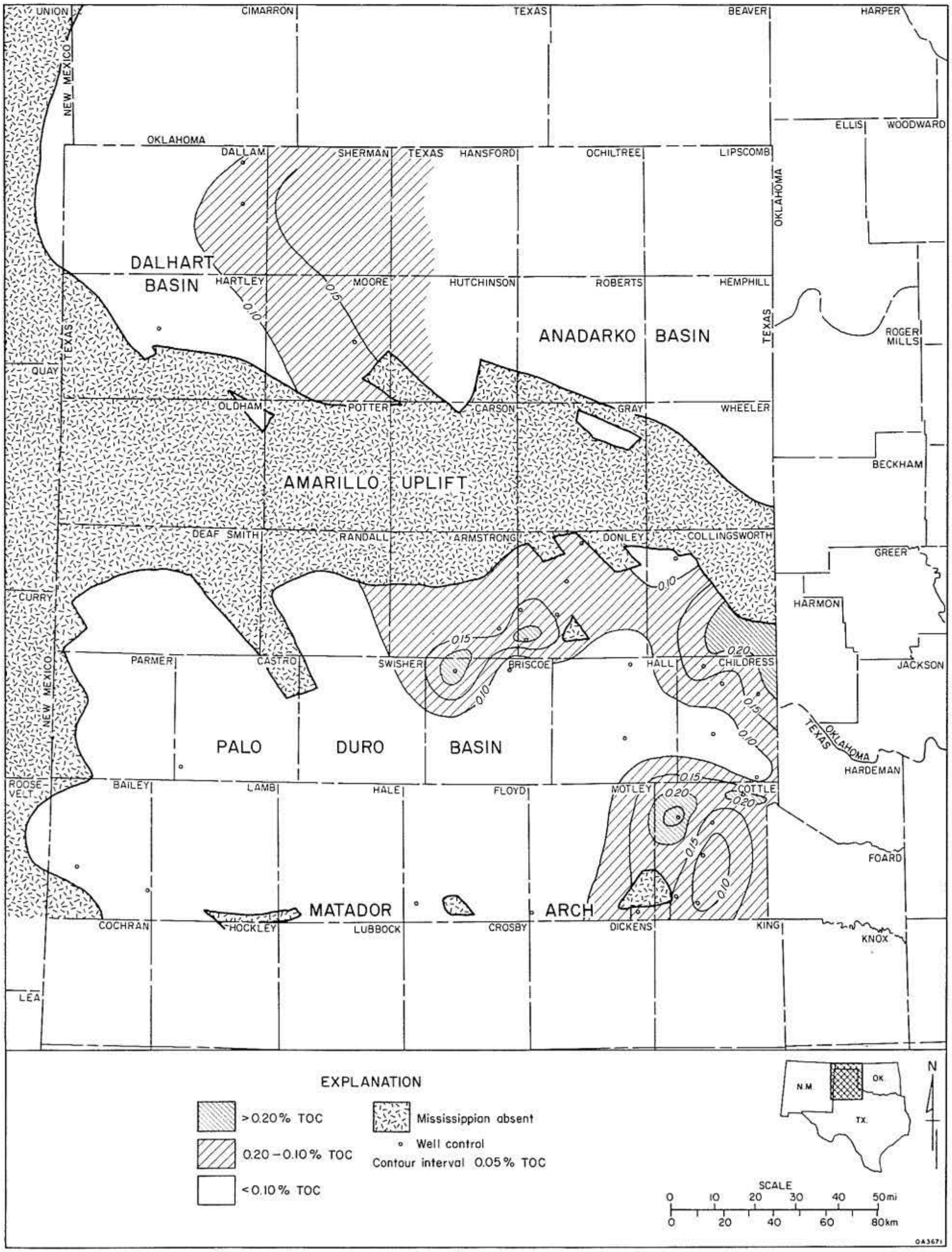


Figure 59. Distribution of total organic carbon (TOC) in the "Osage." Highest TOC values are in the northeastern and eastern Palo Duro Basin.

Table 3. Summary of total organic carbon data.

Unit	Number of analyses	% Total organic carbon (TOC)				
		High	Low	Mean	Std. dev.	Median
			Palo Duro and Dalhart Basins			
Mississippian	66	0.460	0.000	0.111	0.088	0.096
"Chester"	2	0.322	0.100	0.211	0.157	-----
"Meramec"	20	0.208	0.000	0.071	0.054	0.066
"Osage"	44	0.460	0.014	0.128	0.090	0.112
Lower Ordovician						
Ellenburger	21	0.306	0.002	0.090	0.080	0.080
Cambrian(?)	1	0.026	0.026	0.026	----	----
Totals	88	0.460	0.000	0.107	0.086	0.094
			Hardeman Basin			
Mississippian	20	0.934	0.002	0.183	0.253	0.058
Carbonate	18	0.668	0.002	0.109	0.160	0.062
Barnett Shale	2	0.934	0.726	0.830	0.147	----
Ordovician						
Ellenburger	3	0.288	0.120	0.196	0.085	0.180
Totals	23					

Organic Matter Type

Only the fraction of organic matter contained in sedimentary rocks that is insoluble in organic solvents (kerogen) has potential for producing hydrocarbons. Kerogen is composed of both sapropelic and humic materials. Sapropel consists of plant material (algal and amorphous debris) primarily of aquatic origin (Hunt, 1979). Because this material is rich in lipids, it is the most likely source of liquid hydrocarbons. Humus, in contrast, is kerogen derived primarily from terrestrial plants. Woody humic material (vitrinite) has limited potential for oil generation but can produce gas, usually at somewhat higher temperatures. Inertinite, humic kerogen that consists of carbonized and decomposed plant materials, has no potential for hydrocarbon generation.

Kerogen contained in the pre-Pennsylvanian carbonates of the Palo Duro and Dalhart Basins is predominantly sapropelic (average 70 percent; table 4). Amorphous kerogen (presumably sapropel) and exinite (herbaceous sapropel that has a somewhat lower oil-generating potential) are generally subequal in these rocks. "Osage" rocks contain a high amount of amorphous sapropel even though identifiable algal material is rare. Vitrinite is relatively uniform (average 16 percent) throughout. Organic matter indices (OMI, see appendix C), a technique devised by Geo-Strat Inc., also indicate that the best organic matter assemblages occur in the "Osage." The geographic distribution of these values reveals a close relationship between the interpreted depositional setting of the "Osage" and the distribution of organic matter (fig. 60). Highest percentages of sapropelic kerogen (lowest OMI values) are found in the eastern Palo Duro Basin, where deeper water depositional conditions apparently prevailed. A similar relation between water depth and kerogen type was observed in Pennsylvanian rocks (Dutton, 1980b). Although the "Osage" contains the most oil-prone organic matter among pre-Pennsylvanian carbonates, organic matter of younger (Pennsylvanian and Permian) shales are generally better (that is, they have a lower OMI).

Results of kerogen analysis of samples from the Hardeman Basin are comparable to Palo Duro and Dalhart Basin sample results. The percent of sapropelic kerogen is similar; purer carbonates tend to have slightly higher values than do shales or mixed lithologies (table 5).

Thermal Maturity

According to Hunt (1979), the thermal history of a source rock is the most important factor in hydrocarbon generation. Hydrocarbons will not be produced no matter how much organic matter is present if a certain level of thermal maturity has not been reached. Although there is some disagreement about the amount of heating required to generate hydrocarbons, most geologists agree that whereas minor amounts of hydrocarbons may be generated during diagenesis of sediments, most oil production occurs during catagenesis (122° F to 300° F; 50° C to 150° C). Intense oil generation generally occurs between 150° F (65° C) and 300° F (150° C), a range known as the oil window (Pusey, 1973). Duration of heating, however, is also significant (Connan, 1974). Thus, the thermal history determines the maturity of organic matter.

Table 4. Kerogen data, Palo Duro and Dalhart Basins.

							Kerogen Types (%)		
							Sapropel	Humus	
Well name	Depth (ft)	Unit	Lithology	R_o (%)	TAI*	OMI*	Liptinite	Vitrinite	Inertinite
Briscoe 3	8,280-8,300	"Osage"	Dolomite	0.52	3.00	4.47	71	18	11
Briscoe 13**	8,310-8,390	"Chester"	Limestone	0.55	3.00	5.30	50	30	20
Briscoe 13**	8,810-8,890	"Osage"	Limestone	0.52	3.00	4.95	63	16	21
Childress 10	6,069	"Osage"	Limestone	0.41	2.85	3.63	81	6	13
Childress 10	6,228	"Osage"	Limestone	0.45	3.00	3.65	82	6	12
Cottle 20	7,680-7,710	"Osage"	Limestone	0.50	3.00	3.65	76	18	6
Cottle 41**	7,060-7,140	"Chester"	Limestone	0.54	3.00	4.50	84	8	8
Dallam 7	5,230-5,260	"Osage"	Limestone	--	3.00	4.30	65	15	20
Dallam 29	6,050-6,090	"Osage"	Shaly dolomite	0.44	3.00	4.40	65	10	25
Donley 3	4,260	"Osage"	Sandy limestone	0.37	2.85	4.78	61	28	11
Donley 41	6,390-6,420	"Osage"	Limestone	0.53	3.43	3.95	72	14	4
Moore 30	5,850-5,870	"Osage"	Shaly limestone	--	3.00	3.23	84	8	8
Motley 18	7,700-7,770	"Osage"	Shaly limestone	--	3.43	3.67	78	11	11
Parmer 10	8,840-8,870	Ellenburger Gp.	Shaly limestone	0.52	3.14	4.89	61	22***	17
Swisher 13	9,310-9,340	"Meramec"	Limestone	--	3.50	5.20	50	35	15
			Average	0.44	3.08	4.34	70	16	14
			Standard deviation	0.07	0.21	0.21	11	9	4

*TAI (thermal alteration index) and OMI (organic matter index) from Geo-Strat, Inc. See appendix C for explanation.
**From Dutton (1980b).
***Reported as vitrinite by laboratory.

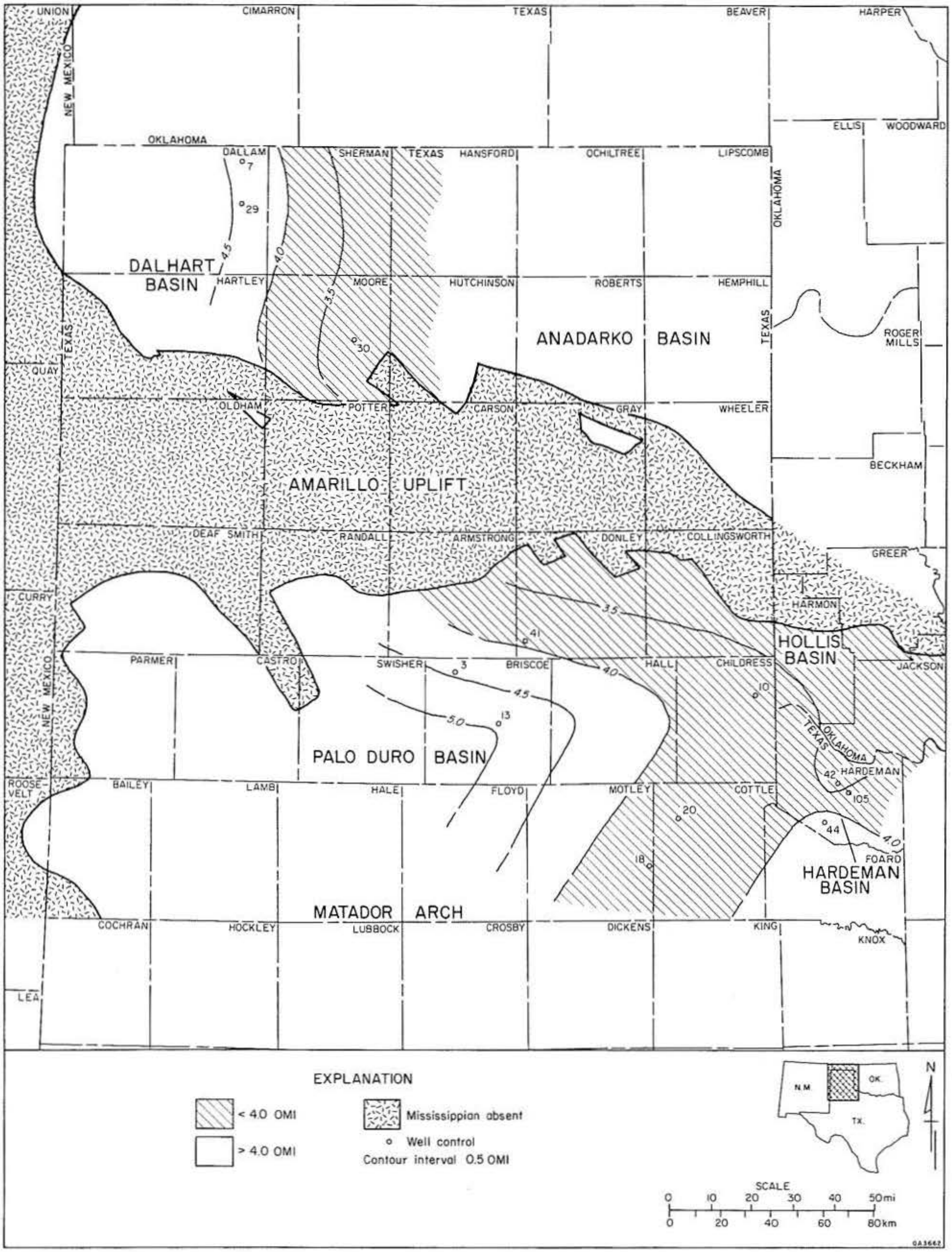


Figure 60. Distribution of organic matter index (OMI) values in the "Osage." Lower values reflect increasingly higher quality organic matter. In the southern Panhandle, OMI generally decreases to the northeast and east. The Palo Duro and Dalhart Basins contain relatively poor quality organic matter. See appendix C for an explanation of OMI. Data are given in tables 4 and 5. Names of wells are given in appendix A.

Table 5. Kerogen data, Hardeman Basin.

Well name	Depth (ft)	Unit	Lithology	R_o (%)	TAI*	OMI*	Kerogen Types (%) Sapropel Liptinite	Kerogen Types (%) Humus Vitrinite	Kerogen Types (%) Humus Inertinite
Hardeman 33	8,390-8,400	Barnett Fm.	Shale and limestone	0.86	3.33	4.33	61	17	22
Hardeman 42	8,874	Chappel Fm.	Dolomite	--	5.00	3.37	79	16	5
Hardeman 44	8,143	Chappel Fm.	Limestone	0.85	3.33	4.21	70	10	20
Hardeman 44	8,306	Chappel Fm.	Limestone	0.76	3.33	4.33	84	8	8
Hardeman 44**	8,306	Chappel Fm.	Limestone	--	--	--	86	14	0
Hardeman 46	8,185	Chappel Fm.	Limestone	0.60	3.33	3.33	87	7	7
Hardeman 47	8,110-8,120	Barnett Fm.	Shale/limestone	--	3.33	4.33	61	17	22
Hardeman 105	7,967	Chappel Fm.	Dolomite/limestone	--	--	--	84	16	0
Hardeman 105	8,018	Chappel Fm.	Dolomite/limestone	0.64	3.43	3.63	75	19	6
Hardeman 105**	8,018	Chappel Fm.	Dolomite/limestone	--	--	--	100	0	0
Hardeman 105	8,085	Chappel Fm.	Dolomite/limestone	0.77	--	--	100	0	0
Hardeman 105	8,113	Ellenburger Gp.	Dolomite	--	4.20	3.90	80	5***	15
Hardeman 105	8,164	Ellenburger Gp.	Dolomite	--	4.33	5.17	45	22***	33
			Average	0.75	3.73	4.06	78	12	11
			Standard deviation	0.11	0.62	0.58	16	7	11

*TAI (thermal alteration index) and OMI (organic matter index) from Geo-Strat, Inc. See appendix C for explanation.
**Duplicate analysis performed by a second laboratory.
***Reported by laboratory as vitrinite.

Current temperatures in the Palo Duro Basin area can be estimated by calculating geothermal gradient from subsurface borehole log data. Where possible, only temperatures recorded in carbonate (Mississippian or Ordovician) or basement rocks were used in gradient determinations; this was done to reduce the local perturbations in gradient that are common in more heterogeneous lithologies because of differences in thermal conductivity. Analysis of these data reveals no systematic variations between data from carbonates and that from crystalline basement rocks. Because measured bottom-hole temperatures generally underestimate true conditions (Connan, 1974; Tissot and Welte, 1978), log temperatures were corrected using an empirical curve developed for the Anadarko Basin by Cheung (1975). The resulting map (fig. 61) is similar to most determinations of geothermal gradients in the area (American Association of Petroleum Geologists and U.S. Geological Survey, 1976). This map differs significantly, however, from that published by Dutton (1980a); Dutton's map shows generally lower gradients because she used a mean surface temperature of 75° F (24° C) for the area. Climatic data for the region indicate that mean surface temperatures range from 55° F (13° C) to 62° F (17° C) in the area.

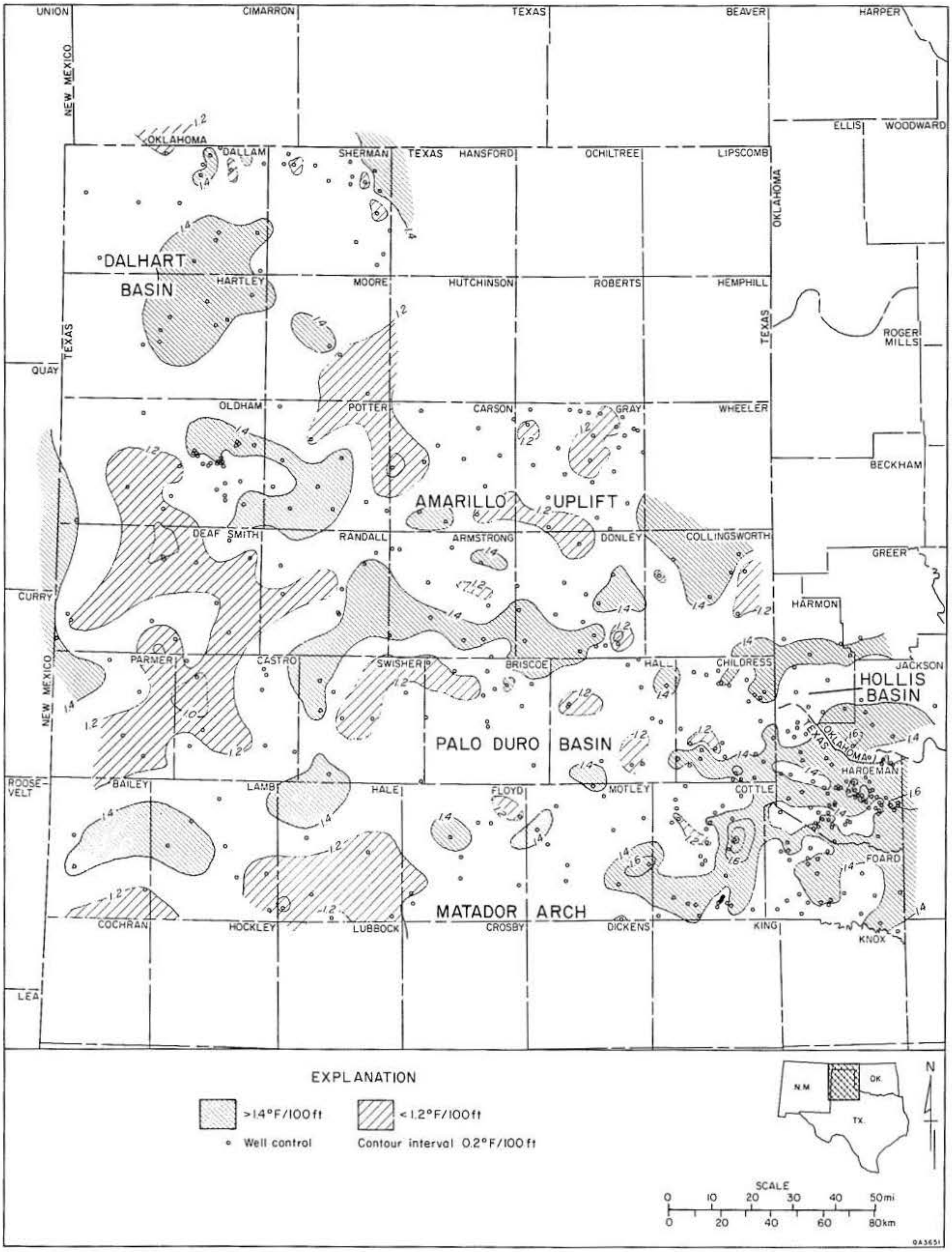


Figure 61. Geothermal gradients in the Palo Duro, Dalhart, Hardeman, and Hollis Basins. Gradients are based on bottom-hole temperatures recorded on geophysical well logs; a correction for nonequilibration was applied on the basis of a study by Cheung (1975).

Birsa (1977) also derived lower gradients for the area, but his data were not corrected to account for nonequilibration of borehole temperatures.

Geothermal gradient across the Texas Panhandle increases west to east (fig. 61). Lowest gradients are found in Deaf Smith and Castro Counties. The average gradient for the Palo Duro Basin, however, is about 1.3°F/100 ft (23.7°C/km). Such a gradient implies that sufficient heating to produce catagenesis and the beginning of oil generation (122°F; 50°C) occurs at a depth of about 4,800 ft (1,463 m). The zone of maximum oil generation (the oil window) should be encountered at about 7,000 ft (2,135 m). Most pre-Pennsylvanian rocks in Palo Duro and Hardeman Basins lie well below 7,000 ft (2,135 m). Therefore, unless the geothermal gradient was lower in the past, these deposits have reached at least the minimum temperatures necessary to generate hydrocarbons; many have reached considerably higher temperatures.

To estimate thermal maturity it is necessary to know the duration of heating. Because the Mississippian in most of the Palo Duro Basin is overlain by at least 7,000 ft (2,135 m) of Pennsylvanian and Permian rocks, most pre-Pennsylvanian deposits acquired temperatures sufficient to generate significant quantities of hydrocarbons (150°F; 65°C) at least 230 mya (the end of the Permian). Application of these data to any of the methods of estimating thermal maturity (Lopatin, 1971; Pusey, 1973; Connan, 1974; Barker, 1979) indicates that most pre-Pennsylvanian rocks in the Palo Duro Basin should have entered the zone of maximum oil generation.

These conclusions are based on the assumptions that (1) the geothermal gradient was not significantly lower during the past 230 mya than it is today and (2) the Palo Duro Basin can be considered a continuously subsiding basin. Although periods of nondeposition or erosion or both occurred in the Mesozoic and early Cenozoic, probably very little of the sedimentary column has been removed. This implies that burial depths were never substantially greater than they are now. Therefore, the area can be assumed, for modeling purposes, to have continuously subsided throughout most of its history (Mississippian to late Cenozoic). The assumption that heat flow (geothermal gradient) has remained constant is more difficult to confirm.

Changes in geothermal gradient during basin evolution are most commonly interpreted by observation of changes in organic materials. Studies have shown that organic matter alters predictably and irreversibly owing to heating through time. Changes in kerogen color, vitrinite reflectance, and conodont color are some of the more popular methods used to determine thermal maturity.

Kerogen color ranges from yellow to black, depending on the degree of heating it has undergone. Staplin (1969) related these color changes to a numerical scale, creating a thermal alteration index (TAI), which has been modified by others (Schwab, 1977; GeoChem Laboratories, 1980; see appendix D). Although based on subjective determinations, TAI is widely used in assessing thermal maturity. In this study, TAI values were obtained for 15 samples (13 wells) in the Palo Duro and Dalhart Basins (table 4) and 9 samples (6 wells) in the Hardeman Basin (table 5). An average TAI value of 3.08 for the pre-Pennsylvanian carbonates of the Palo Duro and Dalhart Basins suggests that these rocks are transitional between immature and mature (Schwab, 1977). This value, which is based primarily on Mississippian samples, agrees with data gathered by Dutton (1980b) on younger rocks: Pennsylvanian, 3.01 TAI; Permian Wolfcamp, 2.95 TAI; Permian Leonard, 2.91 TAI. Although these data reflect a general increase in maturity with geologic age, they also suggest that most of the rocks in the Palo Duro or Dalhart Basins have not matured beyond the transition between immature and mature. Hardeman Basin TAI values average 3.73, indicating that the pre-Pennsylvanian there is substantially more mature. This interpretation correlates with the higher geothermal gradient (1.4°F/100 ft; 25.5°C/km) now observed in that area (fig. 61).

Usable measurements of vitrinite reflectance (R_o) were obtained from 11 samples in the Palo Duro and Dalhart Basins and from 6 samples in the Hardeman Basin (tables 4 and 5). Data from the Palo Duro and Dalhart Basins average 0.44 percent R_o, but are directly proportional to depth (fig. 62). Although vitrinite reflectance data are commonly used to determine thermal history, the interrelationships between reflectance and paleotemperature are incompletely understood. Dow (1977) stated that although catagenesis and initial oil formation begins at 0.5 percent R_o, the peak zone of generation is associated with maturation levels of 0.6 percent R_o. Other researchers have suggested minimum maturation levels as low as 0.40 to 0.45 percent R_o.

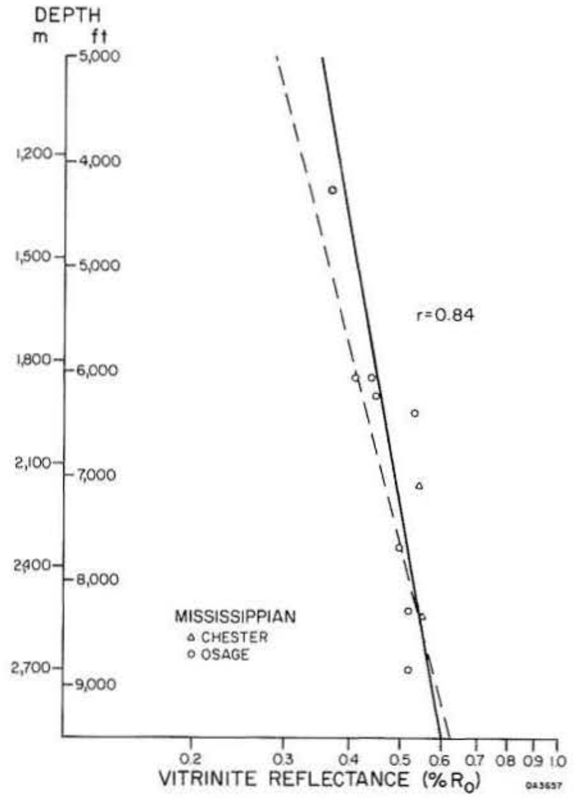


Figure 62. Plot of vitrinite reflectance (R_o) data versus depth, Palo Duro Basin. Solid line is a least-squares regression (correlation coefficient = 0.84). This line indicates that an R_o of 0.5 percent is reached at about 7,500 ft (2,285 m). Dashed line is the predicted relationship assuming a geothermal gradient of 1.3°F/100 ft (23.7°C/km) and an R_o of 0.2 percent at the surface (Dow, 1977). Correlation between predicted and observed values suggests that (1) current thermal conditions are representative of those in the past and (2) only insignificant amounts of sediment were removed from the stratigraphic section. Wells and plotted values are listed in tables 4 and 5.

Many, however, associate a reflectance value of 0.5 percent R_o with the onset of peak oil generation (Tissot and Welte, 1978; van Gijzel, 1982), although Tissot (1984) pointed out that this peak is dependent on the type of organic matter present. Reflectance data from the Palo Duro and Dalhart Basins (fig. 62) suggest that, on the average, 0.5 percent R_o is reached at a depth of about 7,500 ft (2,285 m); however, values of 0.5 percent R_o or more occur as shallow as 6,400 ft (1,950 m). Much of this spread in the data can be explained by local variations in the geothermal gradient. Comparison of vitrinite reflectance (R_o) values with temperatures calculated from geothermal gradient data indicates that an R_o of 0.5 percent is associated with a current temperature of about 158°F (69°C) in the Palo Duro Basin (fig. 63). Thus, the degree of maturation expected, based on present thermal conditions, agrees with actual maturation observed, based on vitrinite reflectance. Together these data suggest that conditions conducive to major oil generation (0.5 percent R_o, 150°F [65°C]) are reached at about 7,500 ft (2,285 m) in the Palo Duro Basin. The similarity between expected and observed maturation levels in the Palo Duro and Dalhart Basins indicates that (1) the geothermal conditions in the past were not substantially different from those today and (2) the area has behaved as a continuously subsiding basin that was not buried much deeper in the past than it is today.

A different situation exists in the Hardeman Basin. Vitrinite reflectance values obtained from samples in Hardeman County (table 5) are much higher (average 0.75 percent R_o). Although the present geochemical gradient is generally higher in the Hardeman Basin (average 1.4°F/100 ft; 25.5°C/km),

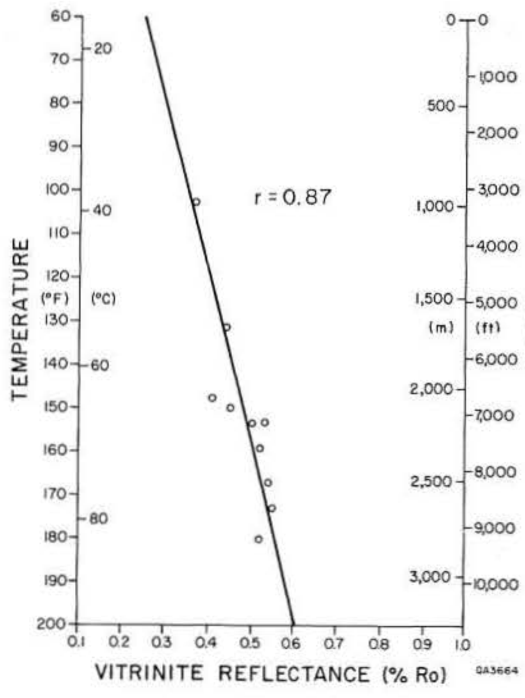


Figure 63. Plot of vitrinite reflectance (R_o) versus temperature in the Palo Duro Basin. Least-squares regression shows a direct correlation with depth (correlation coefficient = 0.87). An R_o of 0.5 percent occurs at a temperature of about 158°F (70°C).

R_o values are greater than those expected at current depths and temperatures. Such values imply the existence of a higher geothermal gradient or a greater burial depth in the past. More data are necessary to fully evaluate these possibilities.

Conodont color can also be used as a guide to thermal maturity. Epstein and others (1977) devised a color alteration index (CAI) based on observed color changes in experimentally heated and naturally occurring conodonts. Colors range from pale yellow (CAI = 1) to black (CAI = 5). Conodonts have been recovered from core taken in four wells in the Palo Duro and Hardeman Basins. Average CAI values increase with depth (fig. 64), as expected. Epstein and others (1977) calibrated conodont CAI with R_o on the basis of relatively few measurements of vitrinite reflectance and suggested that a CAI of 2.0 is equivalent to at least 0.85 percent R_o. Data from the present study, however, indicate that their correlations need to be revised; comparison of R_o values and CAI in the Palo Duro and Hardeman Basin area indicates, for example, that a CAI of 2.0 is equivalent to about 0.5 percent R_o (fig. 64). All data from the current study indicate that CAI values represent R_o values lower than those suggested by Epstein and others (1977).

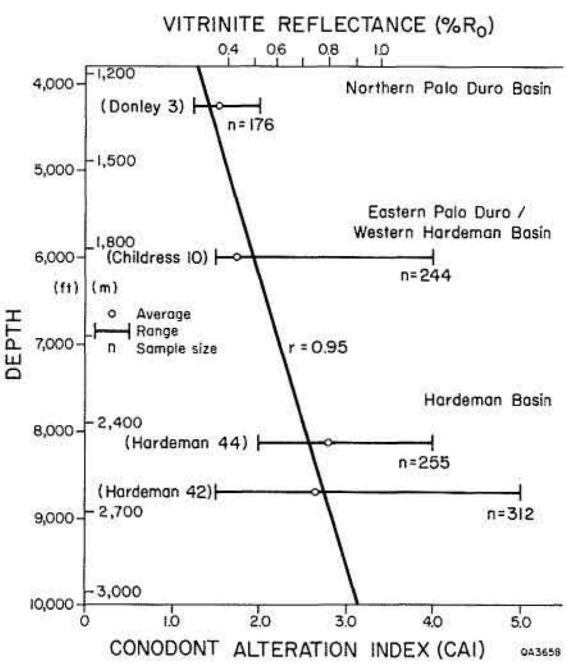


Figure 64. Plot of conodont alteration index (CAI) with depth, showing a nearly linear relationship (0.95 correlation coefficient) between CAI and depth. On the basis of average vitrinite reflectance values obtained from these four wells (tables 4 and 5), a CAI value of about 2.0 is equivalent to 0.5 percent R_o.

Pre-Pennsylvanian Carbonates as Source Rocks

Studies of vitrinite reflectance indicate that most pre-Pennsylvanian rocks in the Palo Duro and Dalhart Basins should have reached the minimum level of thermal maturity necessary for liquid hydrocarbon generation. Kerogen analyses show that suitable organic matter is present. However, most of these deposits probably contain insufficient TOC to be potential source rocks. The Mississippian "Osage" may be an exception, especially in the northeastern and eastern parts of the Palo Duro Basin, where some of these rocks have TOC contents of 0.2 percent and higher. Pre-Pennsylvanian hydrocarbons are much less likely to be generated elsewhere in the Palo Duro (or in the Dalhart) Basin. The upper Mississippian "Chester" shales are a possible exception. Since they were not studied in this report, their source rock quality is unknown. They may have some potential to generate hydrocarbons.

Source rock potential is much greater in the Hardeman Basin. Thermal maturity is significantly higher, and some Mississippian carbonates contain as much as 0.6 percent TOC. The Barnett Shale, which contains higher amounts of TOC, is the most likely source of liquid hydrocarbons in this area.

Other Potential Sources

Pennsylvanian and Permian shales in the Palo Duro Basin have good source rock potential (Dutton, 1980a, 1980b; Dutton and others, 1982); these deposits contain 1.0 percent or more TOC. Pennsylvanian rocks are marginally mature (average 0.52 percent R_o), and Permian rocks are marginally immature (average 0.49 percent R_o), as indicated by vitrinite reflectance data (Dutton and others, 1982). Based on these data, Pennsylvanian rocks appear to be slightly more mature than older (Mississippian) rocks. This may relate to apparently higher threshold temperatures required for hydrocarbon generation from carbonates than from shales that Connan (1974) attributed to the catalytic effect produced by clays in shales. Vitrinite reflectance data on Pennsylvanian rocks indicate that 6,000 ft (1,830 m) to 7,000 ft (2,135 m) of burial are required to produce sufficient heating (150°F; 65°C) to generate significant quantities of liquid hydrocarbons (Dutton, 1983). Therefore, although slightly different, these calculations generally agree with those of pre-Pennsylvanian rocks and support the conclusion that present geochemical gradients and burial depths are not greatly changed from those in the past.

POTENTIAL TRAPS AND TRENDS

In productive areas of the Texas Panhandle, such as the Anadarko and Hardeman Basins, Mississippian and Ordovician rocks produce from stratigraphic and structural traps (Beebe, 1959; Cole, 1964; Freeman, 1964). Porosity development appears to be the major control of hydrocarbon occurrence. "Chester" and "Meramec" rocks, for example, are productive at many locations along the margins of the Anadarko Basin where they have been partly truncated by erosion (Beebe, 1959). Porosity and permeability of these units have apparently been enhanced by this erosion. Similar truncations of these units exist in the Palo Duro Basin (fig. 14). Several hydrocarbon shows have been reported from the "Meramec" in the northern part of the basin where these rocks and the overlying "Chester" have been truncated (fig. 56); these areas are thus possible exploration targets. Since the overlying Pennsylvanian deposits in most of this area are composed of granite wash (Handford and others, 1981; Dutton and others, 1982), however, an effective top seal may be lacking.

Most of the major structures in the Palo Duro Basin have been drilled. Some highs that may not have been adequately tested are in southwestern Parmer County and north-central Armstrong County (fig. 4). Other structurally interesting areas are (1) the margins of the northwest-trending, upfaulted block in Deaf Smith, Randall, Castro, and Swisher Counties and (2) highs developed on the upthrown side of an apparently east-west-trending fault in Floyd County (fig. 4). The latter feature is noteworthy, because of its association with an area of clean, porous carbonate in the "Chester" (fig. 46) and especially because of its position in the deeper part of the basin, where conditions for hydrocarbon generation are more favorable.

Although not indicated by structural mapping on pre-Pennsylvanian horizons, evidence from seismic and shallower subsurface mapping indicates the presence of numerous faults in the Palo Duro Basin (Gustavson and Budnik, 1985), particularly along the northern margins in Armstrong and Randall Counties (fig. 4). Whether these or any other apparent structures indicated by subsurface mapping have potential for actual exploratory drilling will probably be determined only by high-quality seismic data. Evaluation of these features is thus beyond the scope of this report.

Combined stratigraphic/structural traps that are not apparent on structure maps may exist along the eastern edge of the Palo Duro Basin. Small carbonate buildups in the Chappel Formation contain most of the oil discovered to date in the Hardeman Basin (Montgomery, 1984). Although small (maximum dimensions of about 1,500 ft [457 m] by 3,000 ft [914 m]; Montgomery [1984]), these buildups can be recognized with the aid of close well control or good seismic data. Environmental reconstruction of the area (Ruppel, 1984) indicates that such buildups probably extend at least as far west as the extreme eastern Palo Duro Basin (Childress County). These buildups are commonly associated with faults, and an overlying shale unit forms a potential seal at the top of the St. Louis Formation. The actual trapping mechanism, however, appears to be local porosity and permeability variations. Although all production from these features has so far been restricted to the central and eastern parts of Hardeman County, it is possible that similar although probably smaller features exist to the west.

The eastern Palo Duro Basin is promising for oil and gas exploration for two additional reasons. First, "Osage" rocks in this area have the most potential as source rocks (figs. 59 and 60); the Barnett Shale and the basal Pennsylvanian shales are also possible sources. Second, the geothermal gradient is generally higher in the east than in the rest of the Palo Duro Basin (fig. 61), which means that any source rocks present in the eastern Palo Duro Basin are much more likely to have generated hydrocarbons.

Perhaps the most likely area for pre-Pennsylvanian oil and gas, particularly in Mississippian rocks, is the southern part of the Palo Duro Basin along the Matador Arch. This area contains numerous fault-bounded structural highs (fig. 4). The NRM field in Floyd County, which is the nearest pre-Pennsylvanian (Mississippian) field (now abandoned) to the Palo Duro Basin proper (fig. 56), appears to have produced from such a structural setting.

The Matador Arch area in southern Floyd and Motley Counties is attractive because the deepest part of the Palo Duro Basin lies in this area (fig. 4); the depth to the top of the Mississippian approaches 11,000 ft (3,353 m). Such depths are exceeded only in the Texas Panhandle in the Whittenburg Trough (Soderstrom, 1968), in northeastern Oldham County, and in the deep Anadarko Basin (fig. 4). Large quantities of oil and gas have been generated in the Anadarko Basin, and the Whittenburg Trough is thought to be the source area for oil reservoirs in Oldham County (Dutton and others, 1982) on the northwestern edge of the Palo Duro Basin (fig. 1). Corrected present-day geothermal gradients in southern Floyd and Motley Counties indicate temperatures of greater than 200°F (93°C) for pre-Pennsylvanian rocks, which implies that these deposits are well within the zone of maximum oil generation.

The overlying Pennsylvanian in the Matador Arch area contains a sequence of shales and limestones (Dutton, 1980a) that reach depths of more than 10,000 ft (3,050 m). These deposits are also possible sources of hydrocarbons in pre-Pennsylvanian strata uplifted along the Matador Arch. Basal Pennsylvanian shales here are much more likely to provide an effective top seal than are the coarser clastics common in many parts of the Palo Duro Basin.

SUMMARY AND CONCLUSIONS

The pre-Pennsylvanian sequence of rocks in the Palo Duro Basin is similar to that in much of the southern and western Texas Panhandle. Transgressive sandstones of probable Cambrian age form the base of the sequence. These deposits are lithologically similar throughout the area; they are thickest and most common, however, in the Palo Duro Basin. Dolomites of the Ellenburger Group (Lower Ordovician) overlie the basal clastics or rest directly on Precambrian basement. The Ellenburger, which was originally deposited in a broad, inland shallow sea that extended well beyond the Panhandle, is limited in extent in the Palo Duro Basin because of erosion that occurred during the middle Paleozoic along the Texas Arch and during the Early Pennsylvanian along the Wichita-Amarillo Uplift. Mississippian limestones overlie the Ellenburger or rest directly on basement rock. These deposits, which formed during the renewed submergence of the area following Middle-Late Devonian uplift and erosion, are generally the thickest, most diverse, and most widespread of all pre-Pennsylvanian rocks in the area. In general, Mississippian rocks in the Palo Duro Basin record (1) inundation ("Osage"), (2) shallowing ("Meramec"), and finally (3) the initial stages of terrigenous influx ("Chester") that culminated in the Pennsylvanian as tectonic activity increased throughout the region. Although the exact timing of these events is unknown, initial Mississippian transgression in the Palo Duro Basin and surrounding areas apparently did not begin until late Osagean or early Meramecian time.

Thicknesses and burial depths of pre-Pennsylvanian rocks in the Palo Duro Basin are generally representative of those throughout the southern and western Texas Panhandle. Greatest depths are encountered in the southern Palo Duro Basin. Although the structure of the area is poorly known, the structural settings of the Palo Duro and surrounding basins appear to be similar. Permeabilities and amounts and types of porosity are also comparable.

Despite the overall similarity of the Palo Duro Basin to nearby basins, the variations in the pre-Pennsylvanian sequence within the Panhandle have some significance for hydrocarbon exploration. Particularly notable are differences in the lithology of Mississippian deposits and the levels of thermal maturity in the Palo Duro and Dalhart Basins versus those in the Hardeman Basin to the east. The Lower Mississippian ("Osage") of the Palo Duro and Dalhart Basins is dolomitic and apparently represents shallow-water, perhaps even partly restricted, depositional conditions. Equivalent deposits to the east in the Hardeman Basin (Chappel Formation) document a deeper water setting, at least locally below wave base, in which numerous carbonate buildups developed. Many of these buildups have proved to be prolific oil reservoirs.

Perhaps an even more important variation in the Mississippian section is the presence of the Barnett Formation in the Hardeman Basin. This predominantly shale unit, which has no recognized Mississippian equivalent in most of the Panhandle, is the westward extension of thick basinal shales of the same name in the Fort Worth Basin of north Texas. The presence of the Barnett is significant, partly because its relatively high content of organic carbon makes the Barnett a prime candidate as a source rock. In addition, oil production in the Hardeman Basin has been tied closely to the source rock quality of the overlying Barnett. Also, the presence of the Barnett along with other shales lower in the section increases the likelihood of effective top seals for porous carbonate reservoirs. No equivalent shales have been noted in the Palo Duro or Dalhart Basins.

The thermal maturity of pre-Pennsylvanian rocks in the Hardeman Basin is substantially higher than that observed in the Palo Duro and Dalhart Basins, probably because of the presence of higher geothermal gradients to the east. Organic matter maturation levels, however, indicate that the Hardeman Basin was subjected to greater depths of burial or higher heat flows, or both, in the past than were the Palo Duro and Dalhart areas. Therefore, although superficially similar, pre-Pennsylvanian rocks in the Palo Duro and Dalhart Basins differ greatly from equivalent deposits in the Hardeman Basin, especially in details pertinent to hydrocarbon accumulation.

There is still reason for optimism in regard to the petroleum potential of the Palo Duro Basin, however. First, potential source rocks do exist in at least some areas. "Osage" rocks in the eastern parts of the basin at least locally meet the minimum requirements to be petroleum source rocks. Kerogen-rich Pennsylvanian shales are abundant in the central part of the basin. Both these units have the required thermal maturity to generate oil. Second, pre-Pennsylvanian, especially Mississippian, rocks in the Palo Duro Basin contain appropriate porosities and permeabilities to form reservoirs. Potential structural traps appear to exist in the southern part of the basin, particularly along the Matador Arch. Carbonate buildups similar to those that are so prolific in the Hardeman Basin may be present in the eastern part of the basin.

The Palo Duro Basin as a whole does not appear to have the same potential for hydrocarbon accumulation as its small neighbor to the east, the Hardeman Basin. Nevertheless, hydrocarbons have been generated and have migrated through pre-Pennsylvanian rocks in the Palo Duro Basin, and at least small accumulations of hydrocarbons probably remain. Discovery of these reservoirs will require a synthesis of seismic data, subsurface maps, and geochemical analyses. The latter may be the most important guide to areas in which the best source rock quality and maturity can be found.

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Appendix A. Wells referenced in this report.

BEG designation	Operator	Well name
Armstrong 16	Hassie Hunt Trust Estate	J. A. Cattle Company #1
Armstrong 21	H. L. Hunt	Ritchie #4
Armstrong 23	Burdell Oil Co.	McGehee Strat Test #1
Bailey 7	El Paso Natural Gas Co.	West Texas Mortgage and Loan #1
Bailey 17	Phillips Petroleum Co.	Stephens A#1
Bailey 20	Shell Oil Co.	Nichols #1
Briscoe 3	Hassie Hunt Trust Estate	Owens #1
Briscoe 5	H. L. Hunt	Ritchie #9
Briscoe 6	H. L. Hunt	Ritchie #2
Briscoe 13	W. J. Weaver	Adair #1
Briscoe 21	Cockrell Corp.	C. O. Allard #1
Briscoe 23	Amerada Petroleum Corp.	J. C. Hamilton #1
Castro 11	Sun Oil Co.	Herring #1
Castro 14	Sun Oil Co.	A. L. Haberer #1
Castro 16	Ashmun and Hilliard	John L. Meritt #1
Castro 18	Anderson-Prichard Oil	Fowler-McDaniel #1
Childress 3	The Texas Co.	P. B. Smith #1
Childress 6	Skelly Oil Co.	H. A. Painter #1
Childress 10	Wes-Tex Kewanee, and Coastal States Gas Producing Co.	Steve Owens #A-1
Childress 15	Skiles Oil Corp.	Cliff Campbell #1
Childress 17	Paul C. Teas	T. R. Shields #1
Childress 23	The Texas Co.	F & M Trust Co. #1
Childress 48	U. H. Griggs	Smith #1
Childress 49	Sinclair Oil and Gas Co.	Willard Mullins #1
Childress 59	The Texas Co.	Hughes #1
Childress 74	British-American Oil Prod. Co.	E. V. Perkins Co. #1
Childress 83	Page Petroleum, Inc.	Seal #1-632
Collingsworth 19	Superior Oil Co.	M. F. Brown #85-75
Cottle 6	Falcon Seaboard Drilling Co.	Yarborough #1
Cottle 17	Great Western Drilling Co.	Portwood #1
Cottle 20	Meeker and Gupton	Carroll #1
Cottle 25	Skelly Oil Co.	L. R. Parrack #1
Cottle 36	Shell Oil Co.	Paducah Area, Williford #1
Cottle 37	Humble Oil and Refining Co.	Matador L & C Co. #J-1
Cottle 41	Baria and Werner et al.	Lloyd Mayes #1
Cottle 49	Stanolind Oil and Gas Co.	T. J. Richards #1
Cottle 83	Robinson Bros. Drilling Co.	Harrison #1
Cottle 88	Robinson Bros. Oil Producers	Barron #2
Cottle 121	Signal Oil and Gas Co.	Swenson #1
Dallam 7	Humble Oil and Refining Co.	Sheldon #1
Dallam 21	Continental Oil Co.	Willis #1

Appendix A. (cont.)

BEG designation	Operator	Well name
Dallam 29	Humble Oil and Refining Co.	Belo #1
Dallam 46	Pure Oil Co.	Cleavenger #1
Donley 3	Service Drilling Co.	Kathleen C. Griffin #1
Donley 18	Magnolia Petroleum Co.	W. J. Lewis #1
Donley 23	Humble Oil and Refining Co.	T. L. Roach #1
Donley 25	Placid Oil Co.	W. R. Kelly #1
Donley 26	Rip Underwood and Corsica Oil Co.	V. W. Carpenter #1
Donley 30	Stanolind Oil and Gas Co.	Troy Broome #1
Donley 31	Shell Oil Co.	Finch #1
Donley 34	E. B. Clark and General Crude Oil Co.	P. B. Gentry #1
Donley 36	Maynard Oil Co.	Molesworth #1
Donley 38	J. S. Michael Co.	Thelma Clements #1
Donley 41	H. L. Hunt	Ritchie #5
Donley 45	Lazy R. G. Ranch Co.	Welch #1
Donley 50	Stone and Webster Engineering Corp.	Sawyer #1
Floyd 2	E. B. Clark Drilling Co.	Hall #1
Floyd 3	Ralph J. Abbey et al.	Howard #1
Floyd 5	Cockrell Corp.	Wells #1
Floyd 10	Sinclair Oil and Gas Co.	Massie #1
Floyd 13	Cockrell Corp.	Karstetter #1
Floyd 14	Cockrell Corp.	Thomas #1
Floyd 21	Poff-Brinsmere	Krause #1
Floyd 39	Harken Oil and Gas Inc.	Pigg #1
Hale 9	Honolulu Oil Corp.	Clements #1
Hale 10	Amerada Petroleum Corp.	W. W. Kurfees #1
Hale 14	Honolulu Oil Corp.	Mrs. Lida E. Jones #1
Hall 1	Amarillo Oil Co.	Grace Cochran #1
Hall 4	Humble Oil and Refining Co.	Moss #1
Hall 9	Edward Nepple	Hutchins #1
Hall 18	Amerada Petroleum Corp.	Hughes #1
Hall 28	Phillips Petroleum Co.	Hughes #1
Hardeman 10	Magnolia Petroleum Co.	S. E. Malone #1
Hardeman 27	Wayne Moore	Swindell #1
Hardeman 33	Sun Oil Co.	Eugene B. Smith #1
Hardeman 42	Sun Oil Co.	Quanah Townsite Unit #1
Hardeman 43	Humble Oil and Refining Co.	Williams #1
Hardeman 44	Standard Oil Co. of Texas	R. H. Coffee #1
Hardeman 45	Shell Oil Co.	Conley "A" #1
Hardeman 46	Humble Oil and Refining Co.	Kent McSpadden #1
Hardeman 47	Sun Oil Co.	J. A. Thompson #1
Hardeman 105	Shell Oil Co.	Schur #2
Hardeman 108	J. K. Wadley and K. E. Jennings	Bell & Michael #1
Hartley 13	Standard Oil Co. of Texas	Jessie Herring Johnson et al. #1
Hartley 22	Standard Oil Co. of Texas	Alice Walker #1-26-1

Appendix A. (cont.)

BEG designation	Operator	Well name
Hartley 25	Phillips Petroleum Co.	Cattle #A-1
Hartley 27	Pure Oil Co.	Lankford #1
Hartley 33	Cities Service Oil Co.	Jackson #D-1
Lamb 26	Stanolind Oil and Gas Co.	J. W. Hopping #1
Lamb 33	The Texas Co.	Chisholm #1
Lamb 34	J. M. Wellborn	Martin #1
Moore 30	Shamrock	Taylor #2
Motley 16	Humble Oil and Refining Co.	Matador Land and Cattle Co. "H" #1
Motley 18	Humble Oil and Refining Co.	Matador Land and Cattle Co. #2-H
Motley 38	Humble Oil and Refining Co.	Matador #4-B
Motley 50	Skelly Oil Co.	Tom Windham #1
Parmer 10	Sunray Oil Corp.	Kimbrough #1
Parmer 12	Convest Energy Corp.	O. L. Jarman #1
Randall 16	Texaco Inc.	G. H. Lesberg #1
Randall 19	Frankfort Oil Co.	Grogan #1
Swisher 1	Frankfort Oil Co.	Wesley #1
Swisher 4	Frankfort Oil Co.	Bradford #1
Swisher 6	Standard Oil Co. of Texas	Johnson #1
Swisher 9	Humble Oil and Refining Co.	Nanny #1
Swisher 12	Frankfort Oil Co.	Sweatt #1
Swisher 13	Sinclair Oil and Gas Co.	Savage #1

Appendix B. Total organic carbon (TOC) data from the Texas Panhandle.

Well	Depth (ft)	Unit	Type of sample	TOC (%)	Dominant lithology
Armstrong 16	6,840-6,910	"Osage"	cuttings	0.140	cherty limestone
Armstrong 21	6,580-6,600	"Meramec"	cuttings	0.092	cherty limestone
Bailey 7	8,700-8,750	Ellenburger Gp.	cuttings	0.030	dolomite
Bailey 17	7,890-8,000	"Osage"	cuttings	0.014	cherty limestone
Bailey 17	8,050-8,130	Ellenburger Gp.	cuttings	0.012	dolomite
Bailey 20	8,580-8,700	"Meramec"	cuttings	0.074	cherty limestone
Bailey 20	8,750-8,850	"Osage"	cuttings	0.036	cherty dolomite
Briscoe 3	8,280-8,300	"Osage"	cuttings	0.246	cherty dolomite
Briscoe 3	8,040-8,060	"Meramec"	cuttings	0.076	limestone/dolomite
Briscoe 3	7,800-7,820	"Meramec"	cuttings	0.112	cherty limestone
Briscoe 5	7,240-7,400	"Meramec"	cuttings	0.208	cherty limestone
Briscoe 6	6,850-6,880	"Osage"	cuttings	0.062	cherty dolomite
Briscoe 13	8,500-8,650	"Meramec"	cuttings	0.148	limestone
Castro 14	8,680-8,750	"Osage"	cuttings	0.018	cherty limestone
Castro 18	9,260-9,290	"Meramec"	cuttings	0.066	cherty limestone
Childress 3	5,400-5,430	Ellenburger Gp.	cuttings	0.132	cherty dolomite
Childress 3	5,240-5,270	"Osage"	cuttings	0.188	cherty limestone
Childress 10	5,847	"Meramec"	core	0.032	limestone
Childress 10	5,860	"Meramec"	core	0.052	limestone
Childress 10	5,878	"Meramec"	core	0.024	limestone
Childress 10	5,915	"Meramec"	core	0.026	limestone
Childress 10	6,055	"Osage"	core	0.094	limestone
Childress 10	6,069	"Osage"	core	0.460	limestone, clay, chert
Childress 10	6,114.5	"Osage"	core	0.244	limestone
Childress 10	6,160	"Osage"	core	0.142	limestone
Childress 10	6,204.5	"Osage"	core	0.034	limestone
Childress 10	6,228	"Osage"	core	0.078	limestone
Childress 15	4,640-4,660	"Osage"	cuttings	0.114	cherty limestone
Childress 15	4,810-4,830	Ellenburger Gp.	cuttings	0.074	cherty dolomite
Childress 23	7,430-7,580	"Osage"	cuttings	0.086	shaly, cherty limestone/dolomite
Childress 48	7,250-7,350	"Chester"	cuttings	0.322	shaly limestone
Childress 59	8,170-8,180	"Osage"	cuttings	0.042	cherty limestone
Childress 59	8,000-8,020	"Osage"	cuttings	0.086	cherty limestone
Collingsworth 19	4,529-4,619	"Osage"	cuttings	0.024	cherty limestone
Collingsworth 19	4,790-4,850	Ellenburger Gp.	cuttings	0.010	cherty dolomite
Collingsworth 19	5,415-5,495	Ellenburger Gp.	cuttings	0.024	dolomite
Collingsworth 19	5,640-5,680	Cambrian System	cuttings	0.026	sandstone
Cottle 6	7,650-7,700	"Osage"	cuttings	0.104	cherty limestone
Cottle 6	7,790-7,880	"Osage"	cuttings	0.328	cherty, shaly limestone
Cottle 6	7,940-8,000	Ellenburger	cuttings	0.142	cherty dolomite
Cottle 17	7,980-8,010	Ellenburger	cuttings	0.102	cherty dolomite
Cottle 17	7,830-7,860	"Osage"	cuttings	0.112	cherty limestone
Cottle 20	7,680-7,710	"Osage"	cuttings	0.270	cherty limestone
Cottle 37	7,630-7,660	"Osage"	cuttings	0.078	cherty limestone
Cottle 49	7,820-7,860	Ellenburger Gp.	cuttings	0.010	dolomite
Cottle 83	6,420-6,450	"Osage"	cuttings	0.090	shaly, cherty limestone

Appendix B. (cont.)

Well	Depth (ft)	Unit	Type of sample	TOC (%)	Dominant lithology
Cottle 121	5,400-5,430	"Osage"	cuttings	0.148	chert
Dallam 7	5,230-5,260	"Osage"	cuttings	0.104	dolomite, cherty limestone
Dallam 7	5,760-5,780	Ellenburger Gp.	cuttings	0.034	cherty dolomite
Dallam 29	5,860-5,880	"Meramec"	cuttings	0.036	shaly limestone
Dallam 29	6,050-6,090	"Osage"	cuttings	0.138	shaly, cherty dolomite
Donley 3	4,228.3	"Osage"	core	0.034	limestone
Donley 3	4,242.3	"Osage"	core	0.102	limestone, claystone
Donley 3	4,247	"Osage"	core	0.100	siltstone
Donley 3	4,250	"Osage"	core	0.128	siltstone/claystone
Donley 3	4,253.5	"Osage"	core	0.112	silty limestone
Donley 3	4,259	"Osage"	core	0.228	silty claystone
Donley 3	4,260	"Osage"	core	0.264	calcareous sandstone
Donley 23	5,050-5,200	Ellenburger Gp.	cuttings	0.156	dolomite
Donley 25	6,850-6,950	"Osage"	cuttings	0.156	shaly, cherty limestone
Donley 26	5,630-5,690	"Osage"	cuttings	0.148	cherty dolomite
Donley 30	6,390-6,465	Ellenburger Gp.	cuttings	0.166	dolomite
Donley 34	6,710-6,750	Ellenburger Gp.	cuttings	0.180	dolomite
Donley 41	6,390-6,420	"Osage"	cuttings	0.204	limestone
Donley 45	5,140-5,160	Ellenburger Gp.	cuttings	0.184	dolomite
Donley 50	4,520-4,530	"Osage"	cuttings	0.116	limestone
Donley 50	4,650-4,660	Ellenburger Gp.	cuttings	0.080	dolomite
Floyd 2	9,400-9,468	"Meramec"	cuttings	0.030	limestone
Floyd 21	7,700-7,750	"Meramec"	cuttings	0.070	cherty limestone
Hale 9	9,710-9,770	"Meramec"	cuttings	0.018	cherty limestone
Hall 1	6,150-6,330	"Osage"	cuttings	0.054	cherty limestone
Hall 1	6,480-6,600	Ellenburger Gp.	cuttings	0.070	dolomite
Hall 4	4,700-4,750	Ellenburger Gp.	cuttings	0.002	cherty dolomite
Hall 28	7,760-7,820	"Osage"	cuttings	0.022	cherty limestone/dolomite
Hall 28	7,960-8,000	Ellenburger Gp.	cuttings	0.010	dolomite
Hardeman 10	8,558-8,560	Chappel (base) Fm.	cuttings	0.020	limestone
Hardeman 33	8,390-8,400	Barnett Fm.	cuttings	0.934	shale
Hardeman 42	8,702	St. Louis Fm.	core	0.060	limestone
Hardeman 42	8,720	St. Louis Fm.	core	0.062	limestone
Hardeman 42	8,752	Chappel Fm.	core	0.002	limestone
Hardeman 42	8,790	Chappel Fm.	core	0.016	limestone
Hardeman 42	8,810	Chappel Fm.	core	0.002	limestone
Hardeman 42	8,830	Chappel Fm.	core	0.016	limestone
Hardeman 42	8,850	Chappel Fm.	core	0.016	limestone
Hardeman 42	8,874	Chappel Fm.	core	0.140	dolomite
Hardeman 42	8,907	Chappel Fm.	core	0.010	dolomite
Hardeman 44	8,130	St. Louis Fm.	core	0.076	calcareous shale
Hardeman 44	8,138	St. Louis Fm.	core	0.032	calcareous shale
Hardeman 44	8,143	Chappel Fm.	core	0.668	limestone
Hardeman 44	8,306	Chappel Fm.	core	0.124	limestone

Appendix B. (cont.)

Well	Depth (ft)	Unit	Type of sample	TOC (%)	Dominant lithology
Hardeman 44*	8,306	Chappel Fm.	core	0.120	limestone
Hardeman 46	8,185	Chappel Fm.	core	0.240	limestone
Hardeman 47	8,110-8,120	Barnett Fm.	cuttings	0.726	calcareous shale, shaly limestone
Hardeman 105	7,967	Chappel Fm.	core	0.058	dolomite
Hardeman 105*	7,967	Chappel Fm.	core	0.225	dolomite
Hardeman 105	8,018	Chappel Fm.	core	0.184	dolomite
Hardeman 105*	8,018	Chappel Fm.	core	0.240	dolomite
Hardeman 105	8,085	Chappel Fm.	core	0.236	dolomite
Hardeman 105*	8,085	Chappel Fm.	core	0.290	dolomite
Hardeman 105	8,113	Ellenburger Gp.	core	0.288	dolomite
Hardeman 105	8,164	Ellenburger Gp.	core	0.180	dolomite
Hardeman 105	8,231	Ellenburger Gp.	core	0.120	dolomite
Hartley 22	8,410-8,470	"Osage"	cuttings	0.044	limestone
Hartley 27	7,585-7,590	Ellenburger Gp.	cuttings	0.030	cherty dolomite
Moore 30	5,542-5,546	"Meramec"	cuttings	0.000	cherty limestone
Moore 30	5,850-5,870	"Osage"	cuttings	0.148	shaly, cherty limestone
Motley 18	7,700-7,770	"Osage"	cuttings	0.126	shaly, cherty limestone
Motley 18	7,780-7,820	Ellenburger Gp.	cuttings	0.136	cherty dolomite
Motley 38	9,270-9,340	"Meramec"	cuttings	0.040	cherty limestone
Motley 50	6,750-6,810	"Chester"	cuttings	0.100	shaly, sandy limestone, shale, and sandstone
Motley 50	6,850-7,000	"Meramec"	cuttings	0.096	cherty limestone
Motley 50	7,190-7,240	"Osage"	cuttings	0.166	cherty limestone
Parmer 10	8,840-8,870	Ellenburger Gp.	cuttings	0.306	shaly, sandy, cherty dolomite
Swisher 6	8,820-8,870	"Meramec"	cuttings	0.054	shaly, cherty limestone
Swisher 13	9,310-9,340	"Meramec"	cuttings	0.170	sandy limestone

*Duplicate analysis by second laboratory.

Appendix C. Organic Matter Index (OMI).

The organic matter index was devised by Geo-Strat, Inc., of Houston, Texas, for characterizing the mixture of kerogen types present in a given sample. The OMI is determined by assigning numbers to each kerogen type (see below), then calculating the average value based on the percentage of each type present. Because the lowest numbers are assigned to liptinic kerogens, the lower the OMI, the more oil-prone the kerogen in the sample.

Kerogen type	**OMI number**	
Algae	1	
Amorphous	2	Liptinite
Spores, pollen	3	
Cuticle, membranous debris	4	
Woody structured debris	5	Vitrinite
Coaly debris	6	Inertinite

Appendix D. Thermal alteration index (TAI).

Staplin (1968)	Staplin (expanded)	Geo-Strat, Inc. (1977)	GeoChem Labs (1980)	State of maturation
1.0	1	1.00	1.00	Immature
1.025	1 to 1+	1.125	1.10	Immature
1.05	1 to 1+	1.25	1.20	Immature
1.075	1 to 1+	1.375	1.30	Immature
1.1	1+	1.50	1.40	Immature
*1.2	1+ to 2-	1.75	1.50	Immature
1.25	1+ to 2-	2.00	1.60	Immature
*1.3	1+ to 2-	2.25	1.70	Immature
*1.5	2-	2.50	1.80	Immature
*1.8	2- to 2	2.75	1.90	Immature-mature
*2.3	2- to 2	3.00	2.00	Immature-mature
2.35	2- to 2	3.25	2.10	Mature
2.4	2	3.50	2.20	Mature
2.45	2 to 2+	3.75	2.30	Mature
2.5	2 to 2+	4.00	2.40	Mature
*2.6	2 to 2+	4.25	2.50	Mature
2.65	2+	4.50	2.60	Mature
2.7	2+ to 3-	4.75	2.70	Mature
2.8	2+ to 3-	5.00	2.80	Mature
2.9	2+ to 3-	5.25	2.90	Mature-very mature
*3.0	3-	5.50	3.00	Mature-very mature
3.2	3- to 3	5.75	3.10	Very mature
*3.3	3- to 3	6.00	3.20	Very mature
*3.4	3- to 3	6.125	3.30	Very mature
3.45	3	6.25	3.40	Very mature
*3.5	3 to 3+	6.375	3.50	Very mature
3.55	3 to 3+	6.50	3.60	Very mature
*3.6	3 to 3+	6.625	3.70	Very mature
3.7	3+	6.75	3.80	Very mature
3.75	3+ to 4-	6.80	3.90	Severely altered
*3.8	3+ to 4-	6.85	4.00	Severely altered
3.85	3+ to 4-	6.925	4.10	Severely altered
*3.9	4-	7.00	4.20	Severely altered
*4.0	4- to 4	7.125	4.30	Severely altered
4.1	4- to 4	7.25	4.40	Severely altered
4.2	4- to 4	7.375	4.50	Severely altered
*4.4	4	7.50	4.60	Severely altered (low-grade metamorphism)
4.5	4 to 5	7.625	4.70	Severely altered (low-grade metamorphism)
4.6	4 to 5	7.75	4.80	Severely altered (low-grade metamorphism)
*4.8	4 to 5	7.875	4.90	Metamorphosed
5.0	5	8.00	5.00	Metamorphosed

*Denotes initial 16 of 20 TAI standards devised by Staplin (1969) cross-correlated by Geo-Strat, Inc. All other numbers represent interpolative values assigned by Geo-Strat, Inc., for cross-correlation only.