DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

PETROLEUM GEOLOGY AND HYDROCARBON PLAYS OF THE PERMIAN BASIN PETROLEUM PROVINCE WEST TEXAS AND SOUTHEAST NEW MEXICO

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature.

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Introduction

The Permian basin is one of the largest Hercynian (Middle Devonian-Middle Triassic) structural basins in North America. It encompasses a surface area in excess of 82,000 mi^2, which includes all or parts of 52 counties located in West Texas and southeast New Mexico (fig. 1). In areal extent, the basin is slightly asymmetrical with the configuration of an irregular shaped octagon, separated into eastern and western halves by a north-south trending central ridge or platform (fig. 2). In cross-section, the basin is an asymmetrical feature, the western half of which contains a thicker and more structurally deformed sequence of sediments than the eastern half (fig. 3). Galley (1958, 1971), and Dolton and others (1979), have characterized the Permian basin as a large structural depression, formed as a result of downwarp in the Precambrian basement surface located at the southern margin of the North American craton. The basin was penecontemporaneously filled with Paleozoic and, to a much lesser extent, younger sediments. It acquired its present structural form by early Permian time and was further accentuated by tectonic activity and downwarping during the Permian and Triassic Periods (fig. 4).

This report represents an evolutionary stage in an ongoing process of U.S. Geological Survey resource assessment in west Texas and southeastern New Mexico. The report draws heavily on previous work such as Galley (1971); Dolton and others (1979); Geological Survey Circular 828 (1980); and, most recently, Galloway and others (1983). The discussion of geologic framework closely follows that of Dolton and others, 1979 which arrived at estimates of in-place undiscovered oil and gas. The 1979 estimates were grouped according to geologic age (Permian, Carboniferous, and older Paleozoic) and depth (0-10, 10-20, and greater than 20 thousand feet). These estimates were based on a review of the geologic framework of each major stratigraphic unit assessed and the exploration histories and production statistics through 1976 for all oil and gas accumulations of the Permian Basin equal to or exceeding 1000 bbls oil or 1 million cu ft. gas.

The current study uses a more detailed play analysis approach and follows as closely as practical the play definition of Galloway and others 1983. Major differences in objectives and data sets have dictated a number of differences in play characterization by the U.S. Geological Survey and the Texas Bureau of Economic Geology. The Texas Bureau studies focused on oil accumulations (exceeding cumulative productions of 10 million bbls oil that generally have been found earlier in the Permian Basin's exploration history. The U.S. Geological Survey's play analysis considers accumulations of all sizes and the total Permian Basin exploration history. However, the objective of estimating undiscovered recoverable hydrocarbons in plays focuses on the more recent exploration history and therefore on smaller fields (lower cut-off limits are 1 million bbls oil and 6 billion cu ft. gas. Fields smaller than the lower cut-off limit were assessed separately.

The general geologic framework and structural development of the Permian basin is extensively documented in the literature. Among others, Galley (1958, 1971); Landes (1970); Hill (1971); Hartman and Woodard (1971); Dolton and others (1979); Wright (1979); Fisher and Galloway (1983); Galloway and others (1983); and Tyler and others (1984), have studied and discussed the Permian basin in detail. All these publications contain comprehensive bibliographies. During the compilation of this report, considerable reference to the publications of

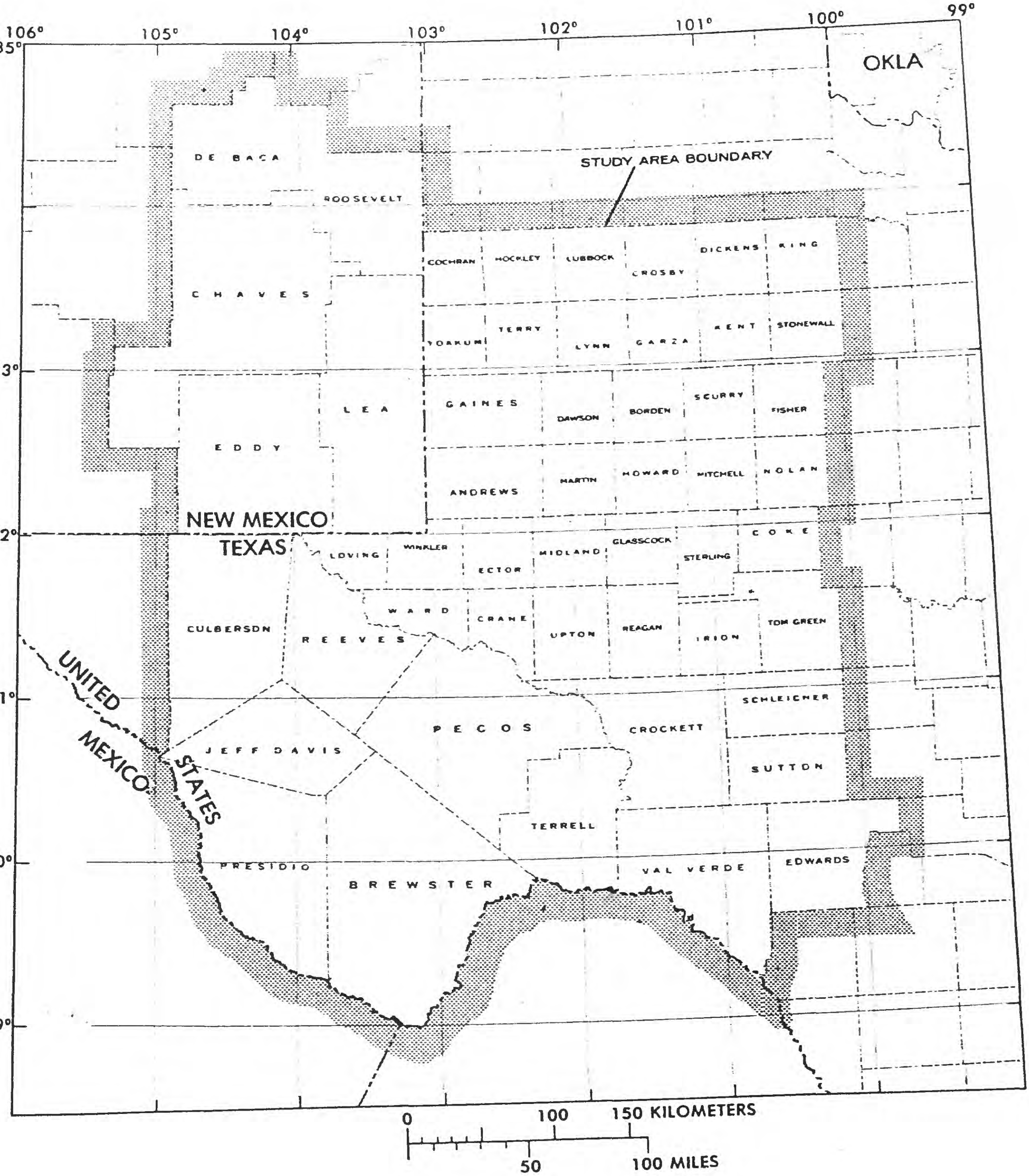


Figure 1.--Index map of the Permian basin, southeast New Mexico, and west Texas.

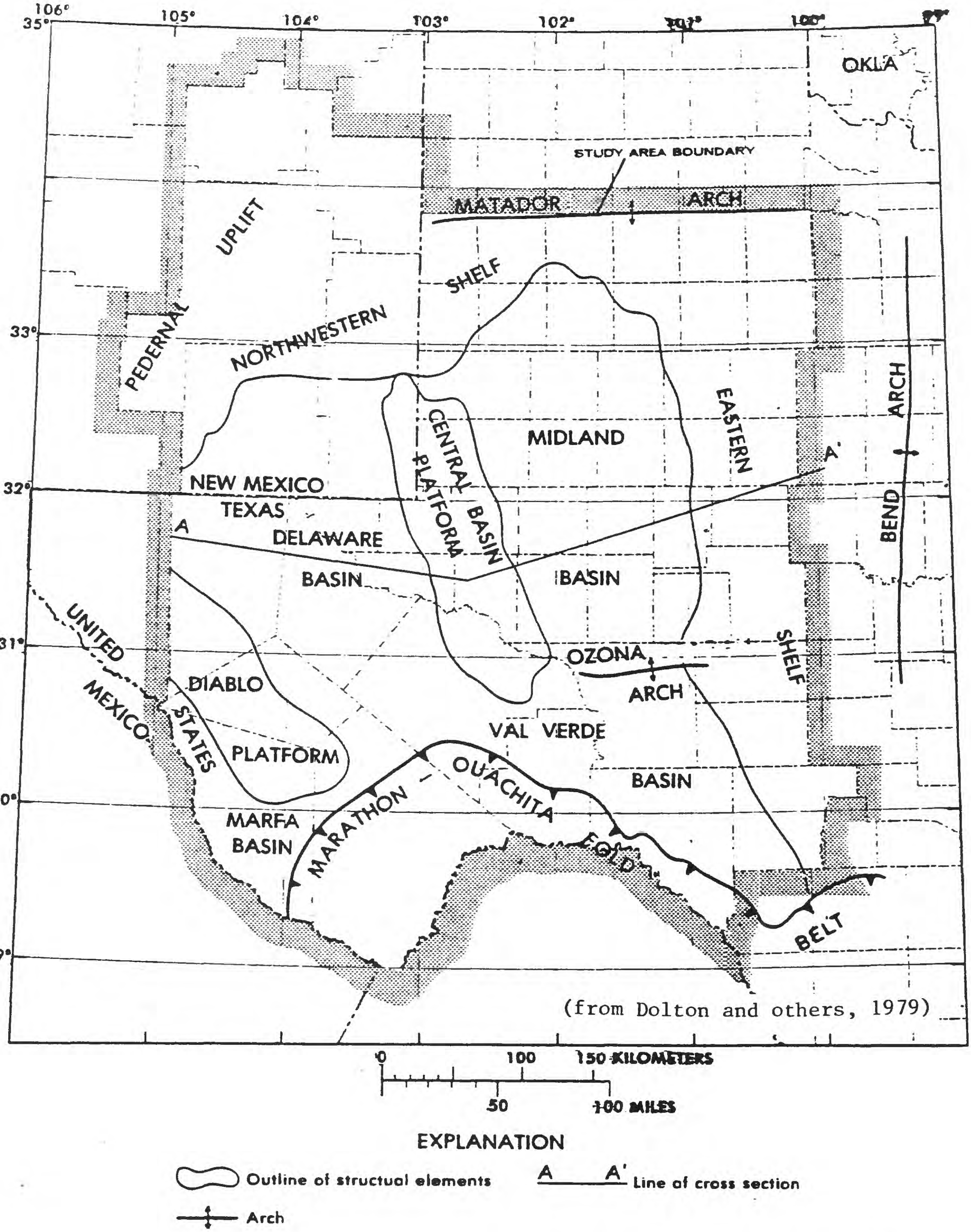
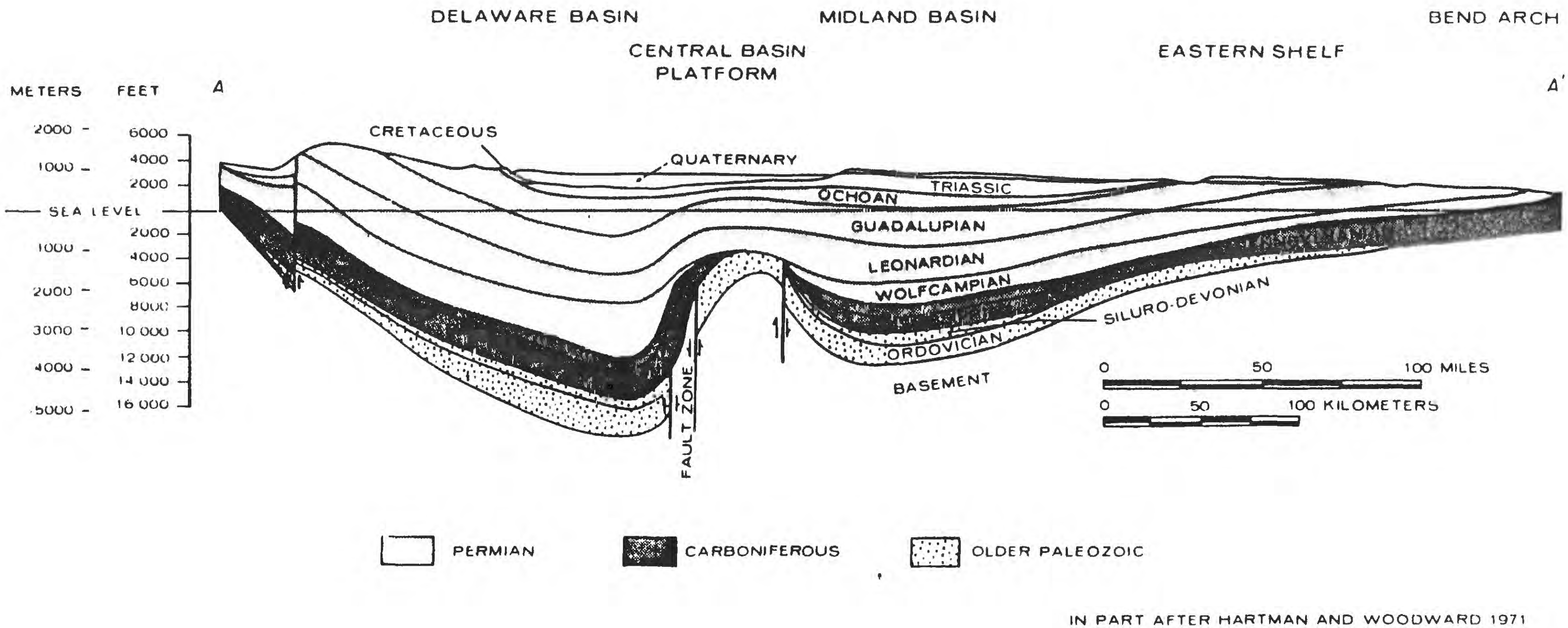


Figure 2.--Structural elements in the Permian basin.



(from Dolton and others, 1979)

Figure 3 --Geologic cross section A-A'.

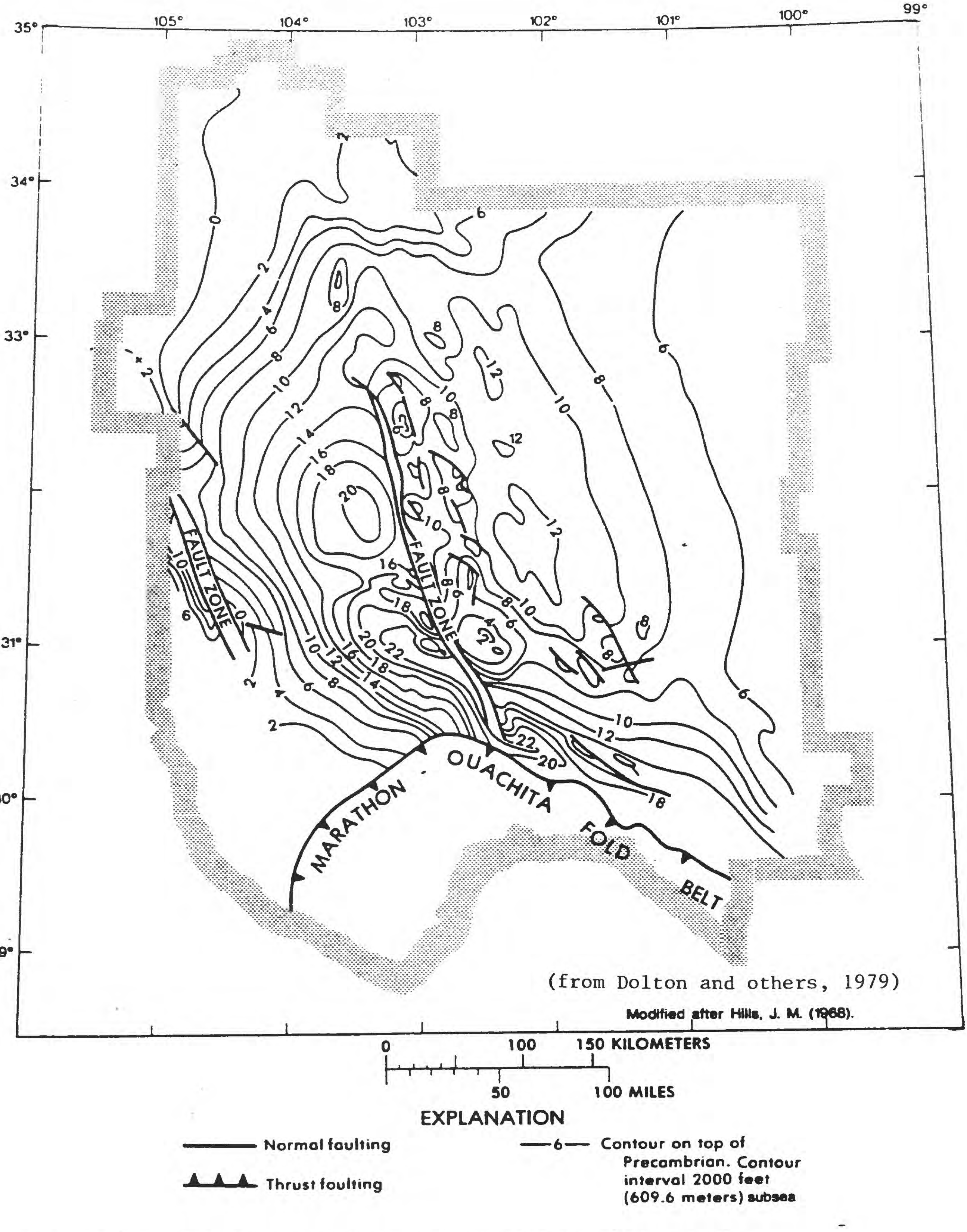


Figure 4 -- Structure contour map, top of Precambrian rocks.

Dolton and others (1979); Wright (1979); and Galloway and others (1983), has been made throughout.

Geologic Framework and Structural Setting

Structurally, the Permian basin is bounded on the south by the Ouachita-Marathon fold belt; on the west by the Diablo Platform and Pedernal Massif; on the north by the Matador-Red River Arch; and on the east by the Eastern Shelf and peripheral west flank of the Bend Arch (fig. 5). The region is readily divisible into several distinct structural and tectonic elements. They are the Central Basin Platform and the Ozona Arch, which separate the Delaware and Val Verde Basins on the west from the Midland Basin on the east; the Marfa Basin, separated from the Delaware Basin by the Diablo Platform; the Northwestern Shelf on the southern extremity of the Pedernal Uplift and Matador Arch; and the Eastern Shelf on the western periphery of the Bend Arch (fig. 5).

A generalized cross-section, A-A′ (fig. 3, location fig. 2), shows existing stratigraphic and structural relationships within the Permian basin. Dolton, and others (1979), state that from Cambrian through Late Mississippian time the Permian basin region was a relatively stable, gently dipping, uniform marine shelf area, which gradually developed into a marine basin with surrounding peripheral shelves. The basin, named the Tobosa basin (Galley, 1958), and associated shelf areas, was the site of extensive marine carbonate and secondary fine grained clastic sedimentation. The deepest part of the ancestral Tobosa basin was in the approximate vicinity of the present Delaware Basin (fig. 6). Only mild structural movement and deformation occurred during this early period, producing local unconformities and forming structural anomalies of low broad relief. During Mississippian time, a gradual increase in the amount of fine clastic sediments began to occur and accumulated in the deeper parts of the basins.

From Late Mississippian, through Pennsylvanian, to Early Permian time, the region was subjected to intense structural deformation and orogenic movement. This culminated in the development of the present identifiable tectonic elements (fig. 5) and provided an entirely different and varied depositional environment from the older Paleozoic stable basin-shelf association. The tectonic features included the Diablo and Central Basin platforms, the deep Delaware, Val Verde and Midland basins, and the peripheral Northwestern and Eastern shelf areas. Coarse clastic sediments were deposited near the basin shorelines and graded seaward into limestones and extensive reef development. In Pennsylvanian time the physical environment was characterized by areally restricted deep marine basins surrounded by carbonate depositional shelves, organic reef growths and evaporitic lagoons. By the close of the Pennsylvanian Period, only thin marine shales were being deposited in the deeper basins. Pennsylvanian rocks are frequently absent in many localities, due either to erosion or nondeposition. This is particularly true on and around the Central Basin Platform.

During Permian time, the tectonic setting and sedimentation patterns developed during the Pennsylvanian Period continued. Reef development was extensive, especially along basin hingelines and the deep basins became progressively smaller as they became sediment filled. The Paleozoic era was brought to a close with the widespread formation of evaporite and red bed sequences in the Late Permian.

(from Hartman and Woodard, 1971)

Fig. 5—Index map showing significant geologic features.

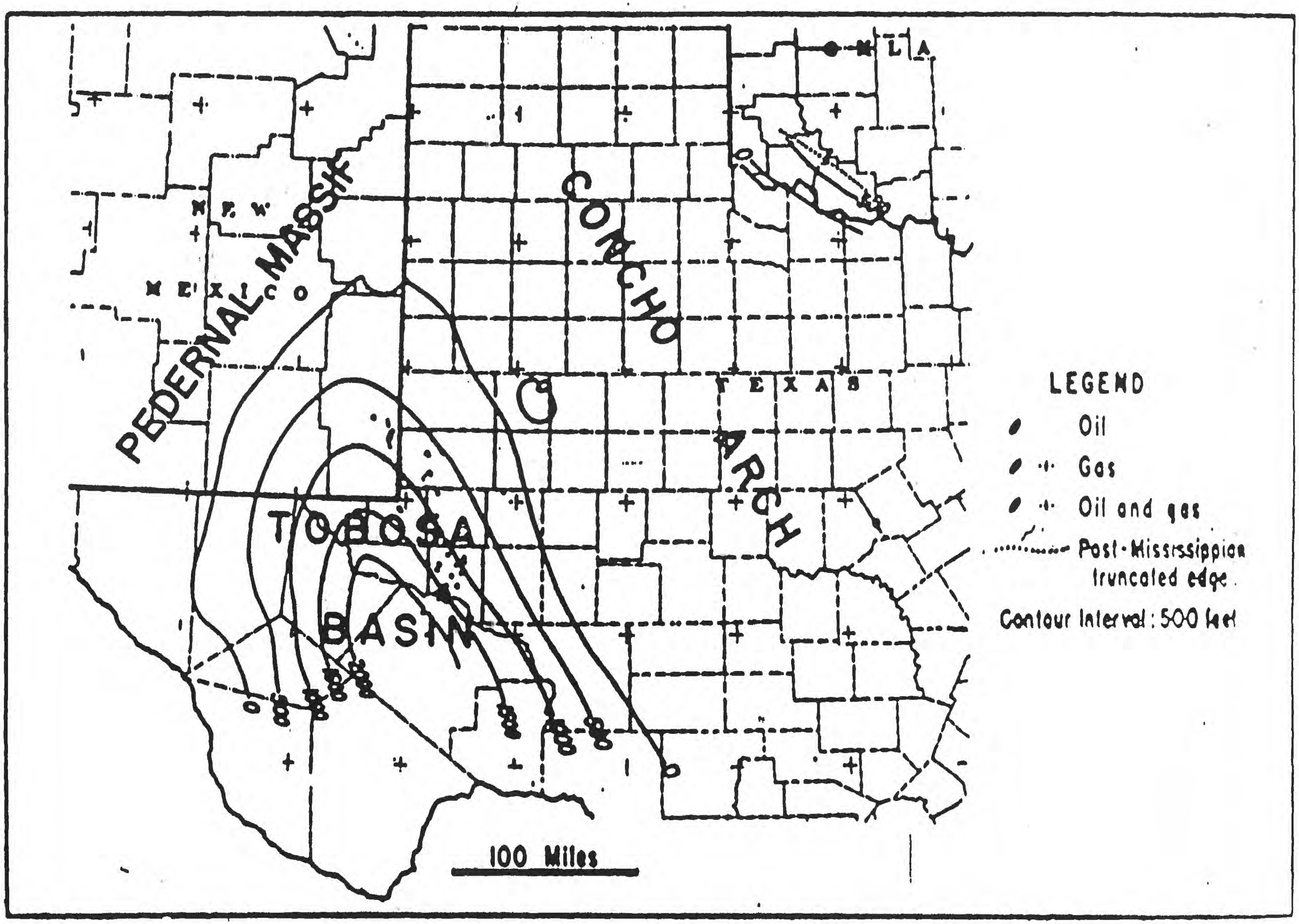


Fig 6 –Tobosa basin, as seen in isopach contours of Simpson (Middle Ordovician) strata (from Galley, 1958, Fig. 9).

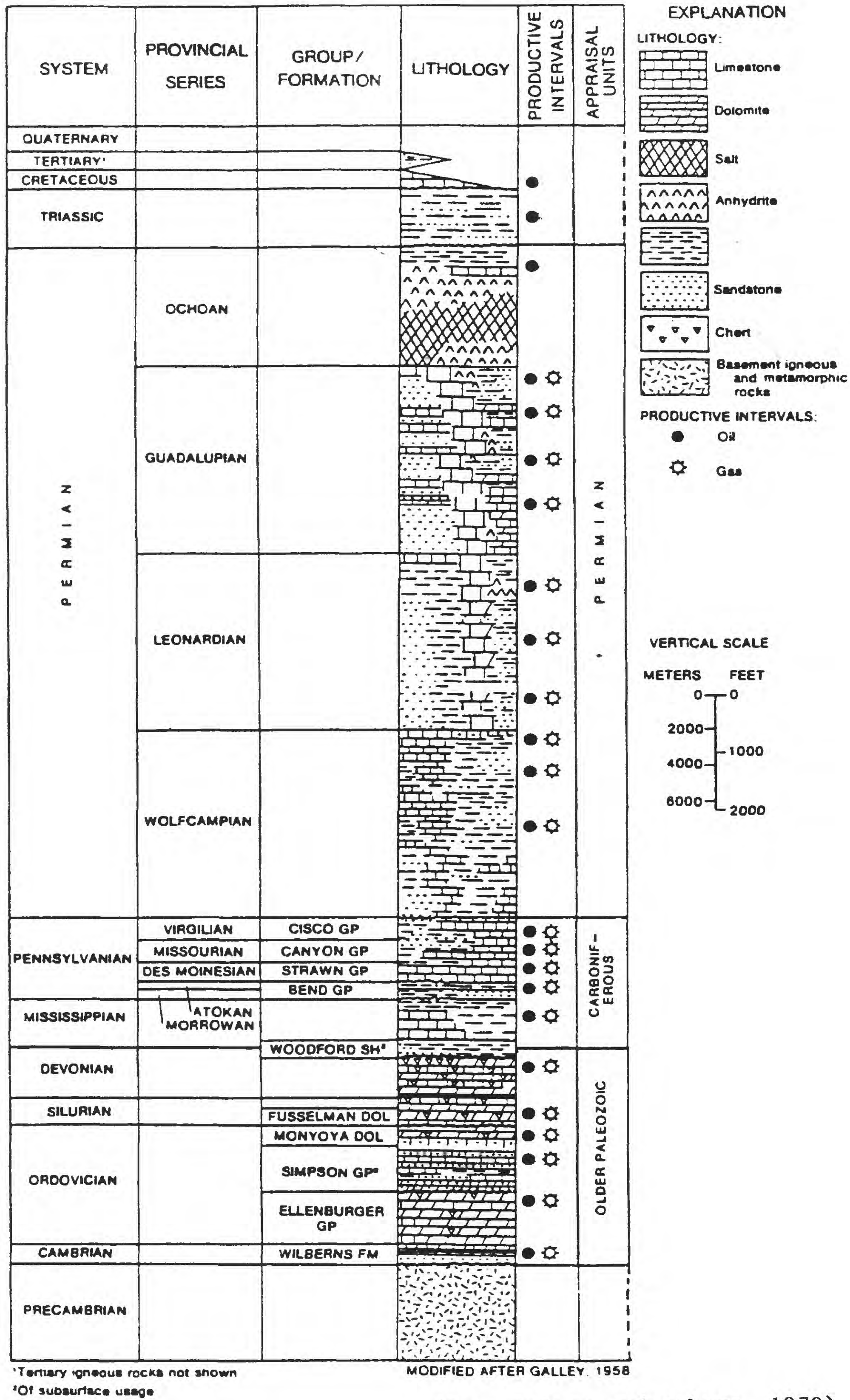
Stratigraphy and Sedimentation

Rocks encountered in outcrop or by the drill in the Permian basin range in age from Precambrian to Recent (fig. 7). However, rocks of Jurassic age are entirely missing. The stratigraphy of the Permian basin is discussed in detail in papers by Galley (1971); Hill (1971); Hartman and Woodard (1971); and by Wright (1979).

Representative stratigraphic sections of all Paleozoic systems are present and reach a maximum combined thickness in excess of 25,000 feet (fig. 8). However, with the possible exception of parts of the Delaware, Val Verde and Midland basins, complete vertical sequences of Paleozoic strata are rare. Continuous sedimentation was interrupted by penecontemporaneous and subsequent orogenic movement and structural deformation, on both localized and regional scales. This was accompanied by erosion and nondeposition of sediment. Figures 9 through 13 (from Dolton and others, 1979), are geologic slice maps at 5,000 feet depth increments from the surface through the present configuration of the Permian basin. They graphically demonstrate the diminishing areal and vertical distribution of Paleozoic sediments with age and depth in the confines of the overall basin. Most of the sediments are restricted to depths of less than 15,000 feet, and the thickest sections are contained in the subdivisional basin areas. At 25,000 feet only rocks of older Paleozoic age are present, located in the vicinity of the southeastern part of the Delaware basin. The maps also aptly demonstrate the effect of superimposed structure on the Paleozoic sediments, the Central Basin platform appearing as a large positive uplift and erosional feature in Figure 9. Cambro-Ordovician to Upper Permian strata are, in succession, unconformably overlain by continental Triassic, marine Cretaceous and continental Tertiary deposits.

The Paleozoic section of the Permian basin may be conveniently divided into three major stratigraphic units. The units are the older Paleozoic (Cambrian through Devonian) systems, the Carboniferous system and the Permian system. The Devonian-Mississippian Woodford Shale is included with the older Paleozoic sequence in this report.

The older Paleozoic systems (Cambrian through Devonian) are representative of sedimentary rocks deposited in the ancestral Tobosa basin (fig. 6). As described earlier, the Tobosa basin was an extensive, stable marine basin, surrounded by peripheral shelf areas, and formed as a result of downwarp on the southern margin of the North American craton. The Tobosa basin occupied the whole of the present day Permian basin region. The Carboniferous systems, particularly the Pennsylvanian Period, are representative of a period of transition, characterized by intense structural deformation, orogenic movement, uplift and erosion, increased clastic sedimentation, and the development of present identifiable tectonic elements (fig. 5). The Permian system was characterized by a long period of sedimentation following cessation of the main Lower Permian-Pennsylvanian tectonism. Permian age sediments and reef growths accumulated in and on the recently formed Delaware, Val Verde and Midland basins, on the uplifted Central Basin Platform, and on the surrounding Northwestern and Eastern Shelf areas (fig. 5). The Permian Period culminated in the sedimentary in-fill of the basins, the demise of peripheral reef growth and the development of widespread evaporite and red bed sequences which blanketed the region.



(from Dolton and others, 1979)

Figure 7 -- Generalized stratigraphic and lithologic column showing productive intervals.

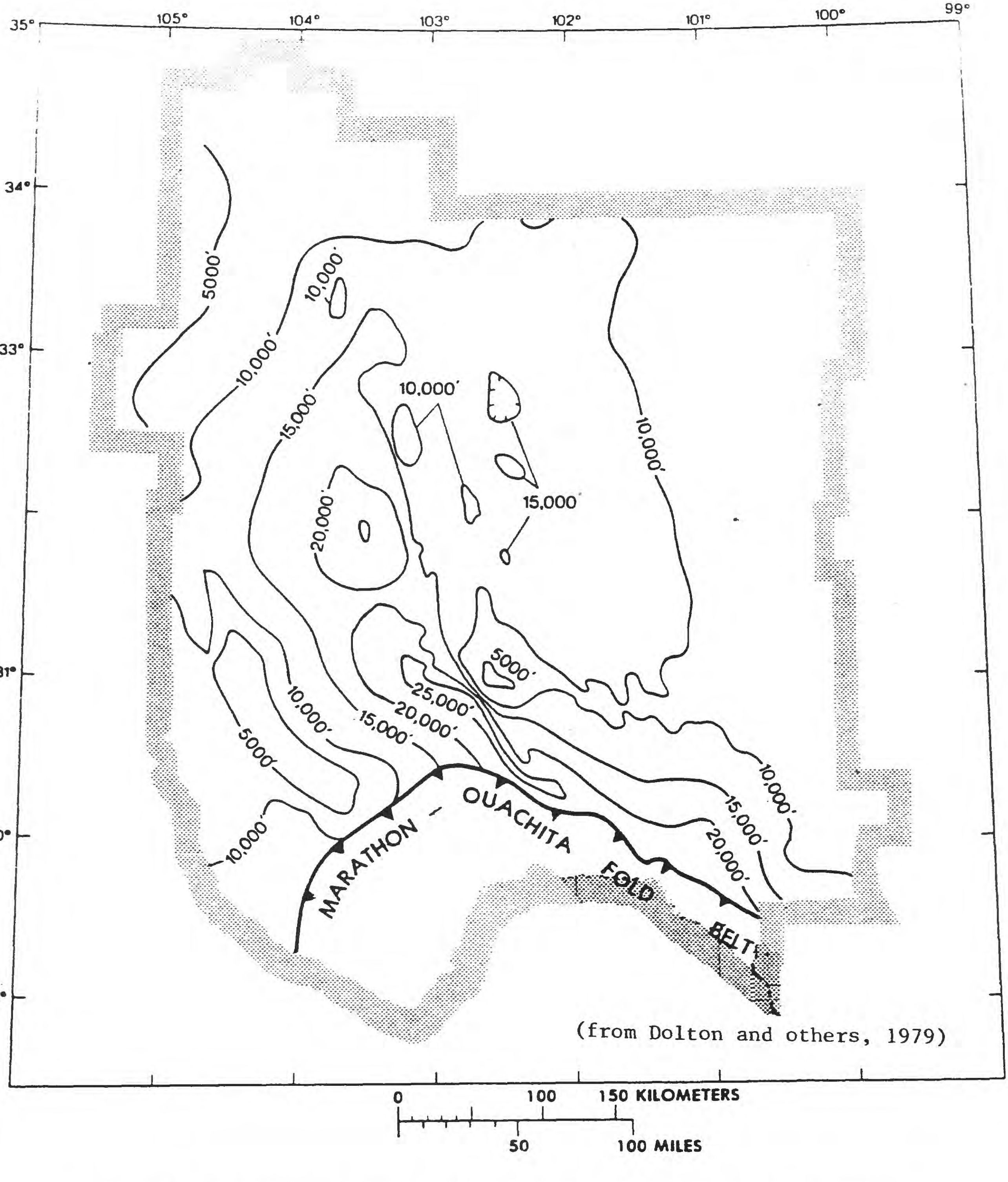


Figure 8.--Isopach of total sedimentary section, in feet. Contour interval 5,000 feet.

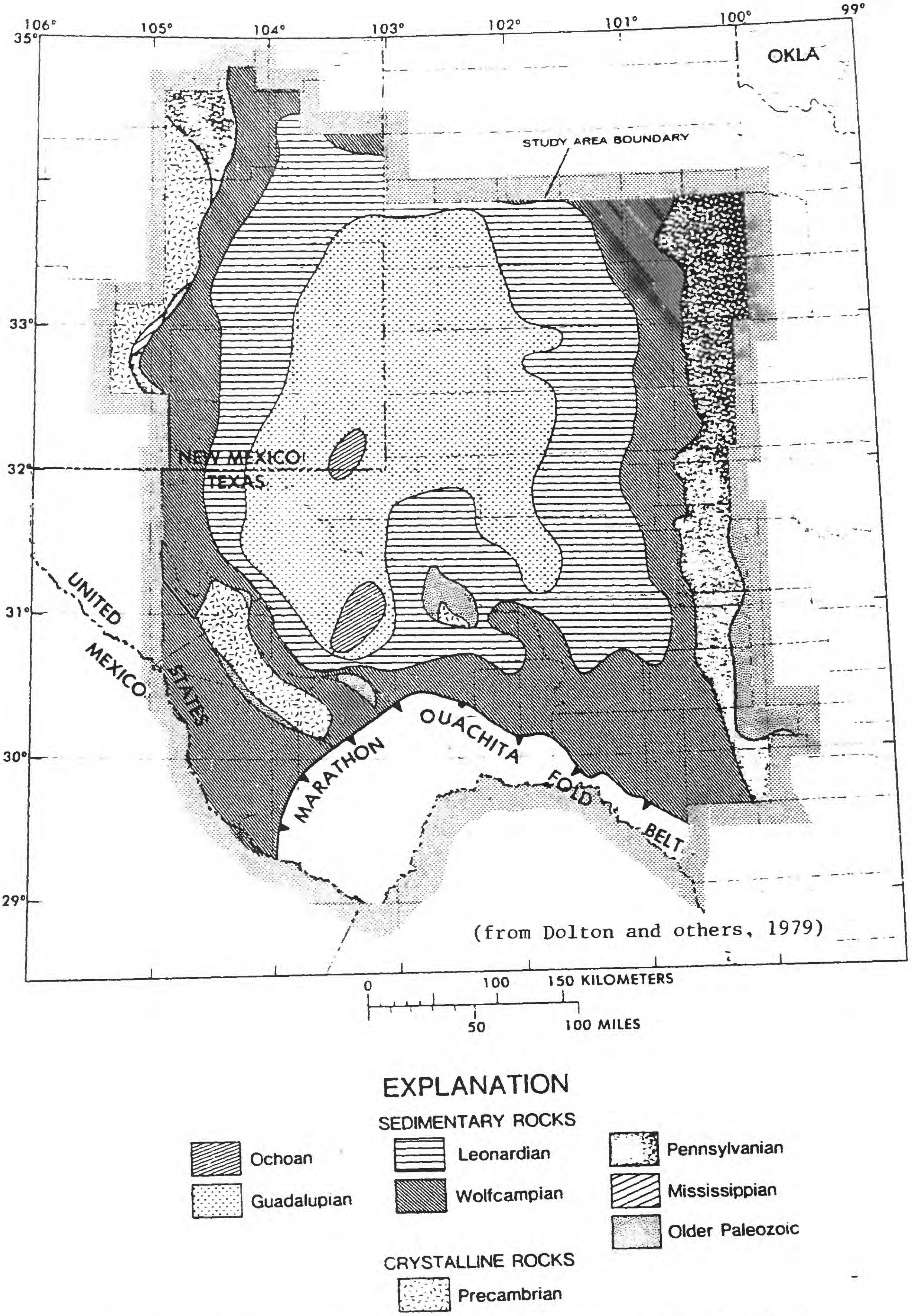


Figure 9.--Geologic map at 5,000-foot depth, Permian Basin.

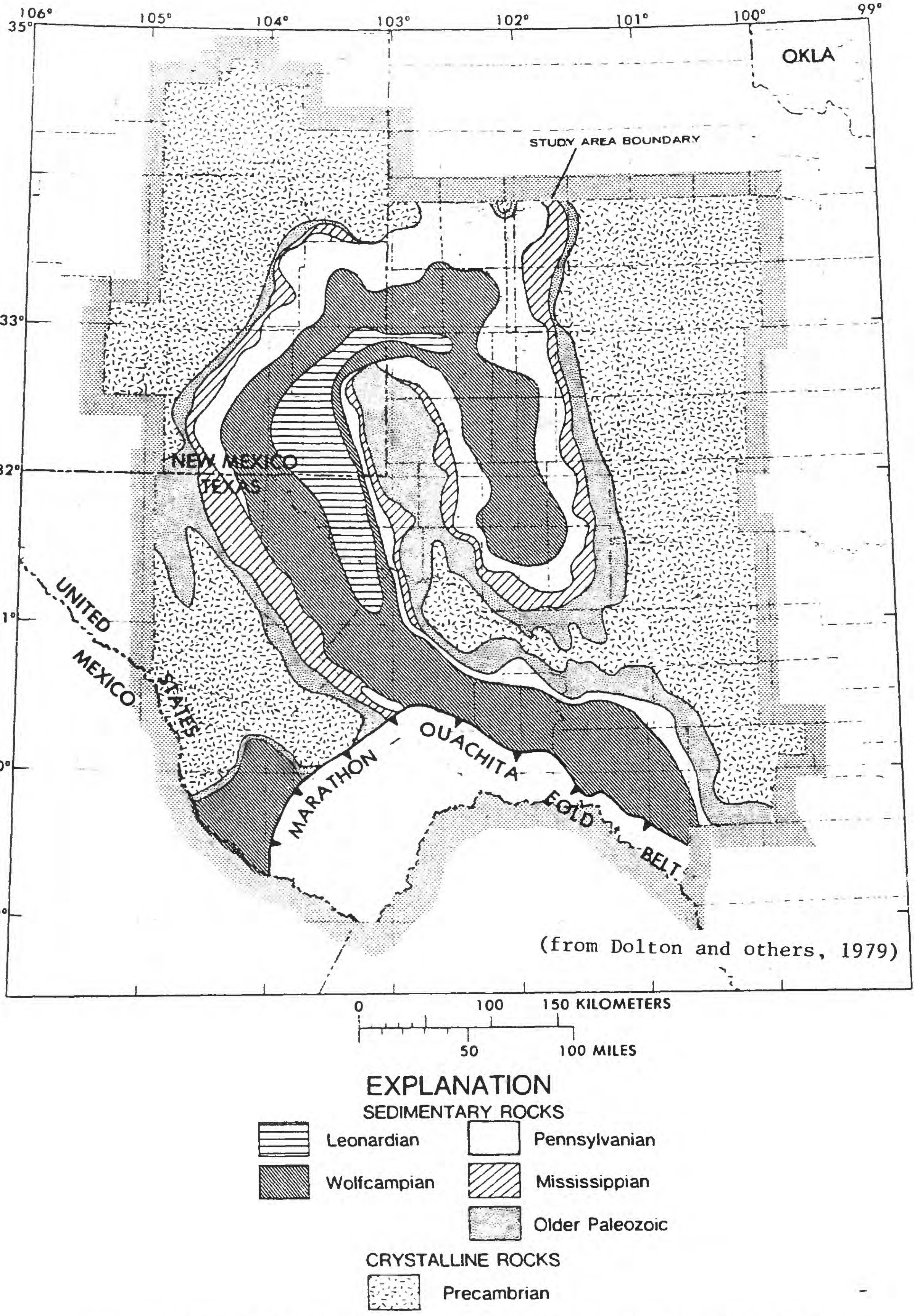


Figure 1c.--Geologic map at 10,000-foot depth, Permian Basin.

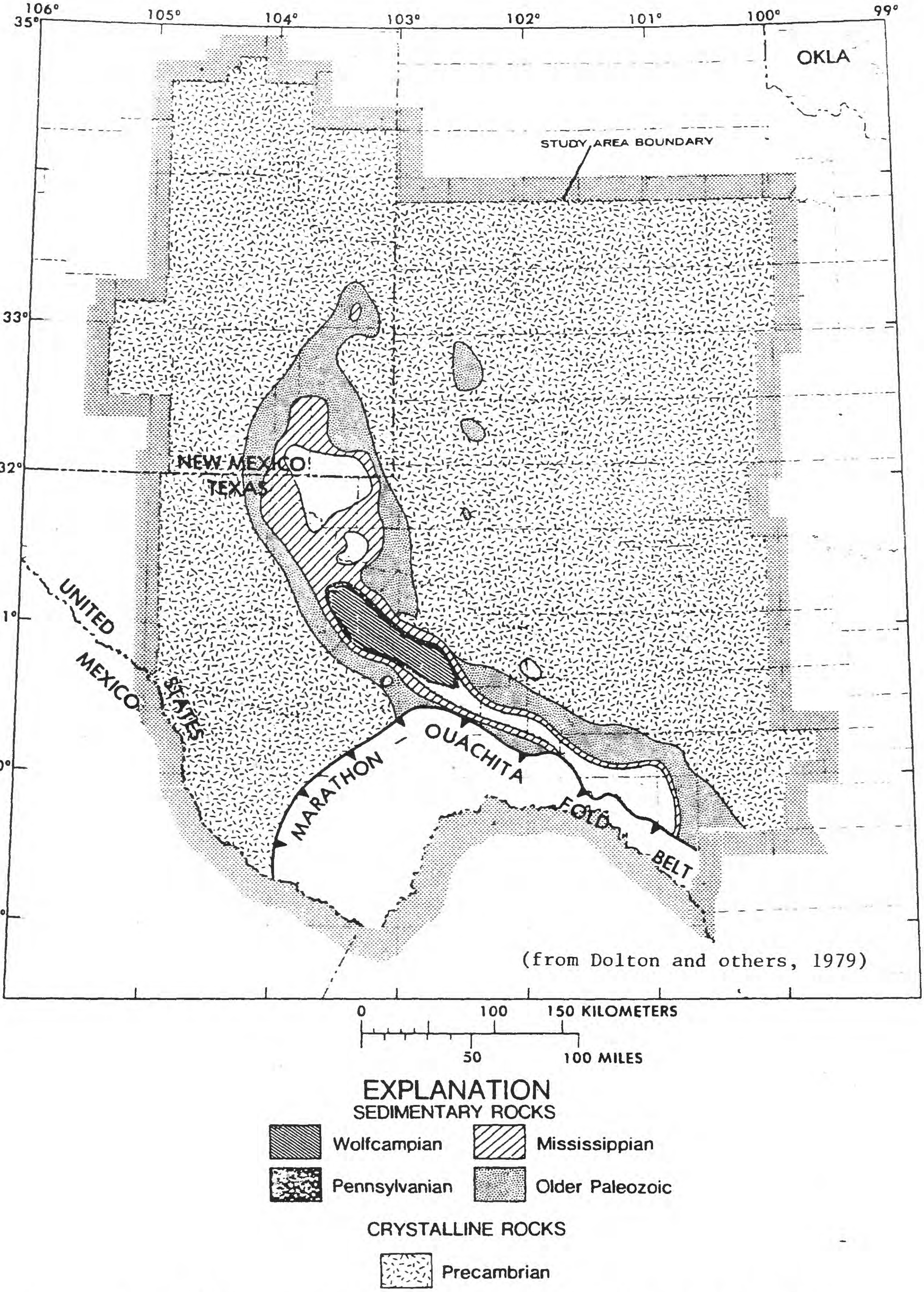


Figure 11.--Geologic map at 15,000-foot depth, Permian Basin.

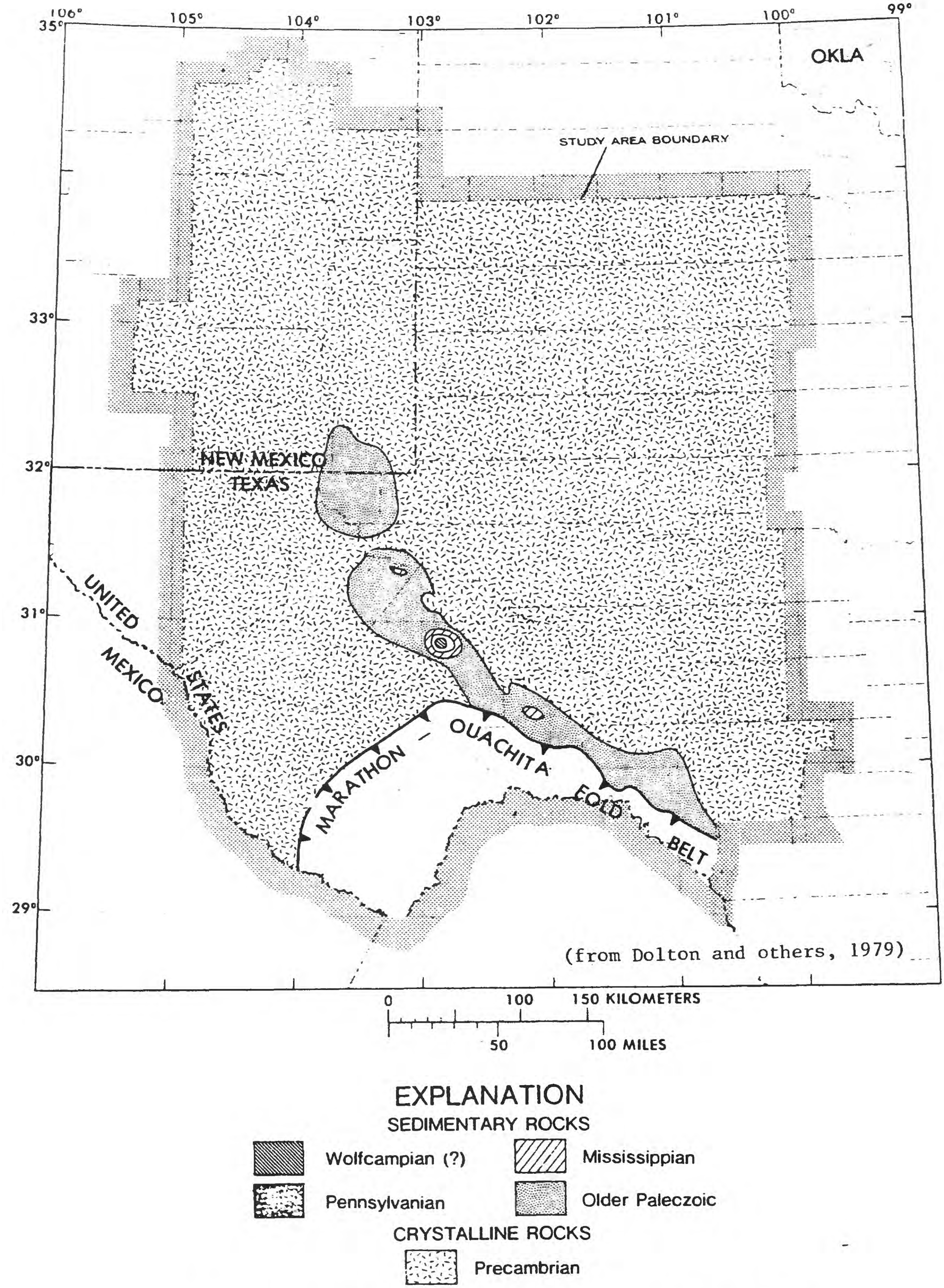


Figure 12.--Geologic map at 20,000-foot depth, Permian basin.

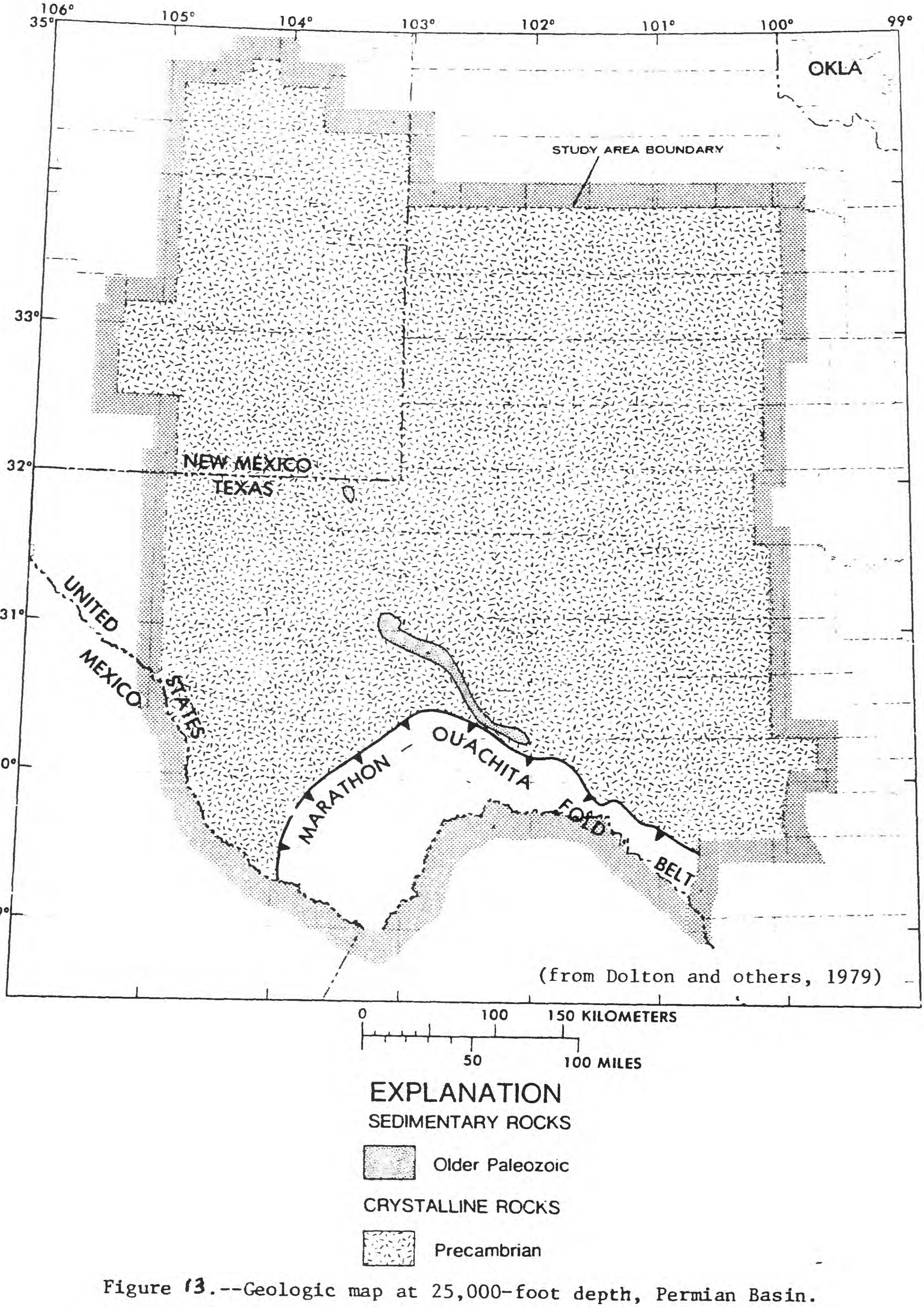


Figure 13.--Geologic map at 25,000-foot depth, Permian Basin.

Older Paleozoic Systems

The older Paleozoic rocks occupy an area of over 73,500 square miles in the region of study and consist of sediments of Cambrian, Ordovician, Silurian and Devonian age. The combined average thickness of the older Paleozoic is 1,700 feet and ranges from zero to a maximum of 4,700 feet. The calculated sediment volume is in excess of 25,000 mi^3, of which approximately 86 percent occurs between depths of 5,000 to 20,000 feet. Because of offset depositional centers, individual average thicknesses of systems within the older Paleozoic vary considerably from the combined average. Devonian sediments average 950 feet, Ordovician average 2,300 feet and the highly variable and erratically distributed Cambrian sediments average on the order of less than 100 feet in thickness.

Dolton and others (1979) state that with the exclusion of the Devonian-Mississippian Woodford Shale, dominant lithologies in the older Paleozoic rocks are limestone (40 percent), dolomite (30 percent), shale (20 percent), and sandstone (10 percent). The depositional sequence consists of basal Cambrian clastic sediments unconformably deposited on the Precambrian cystalline basement, overlain by Ordovician Ellenburger carbonate rocks which were deposited on a shallow stable marine shelf. These, in turn, were overlain by younger Ordovician, Silurian and Devonian carbonate and clastic sediments deposited in the Tobosa Basin and on the surrounding shelf. The Tobosa basinal setting (fig. 6), persisted throughout mid-Ordovician, Silurian, and Early Devonian time with only minor periods of uplift and erosion. From Late Devonian through Early Mississippian time, a widespread quiescent, euxenic, marine environment promoted the extensive deposition of black mud and siliceous ooze. This is the present day Woodford Shale.

Carboniferous System

Dolton and others (1979) state that Carboniferous rocks cover an area of about 74,000 mi^2 within the region of study. Mississippian rocks range in thickness from 0 to 2,600 ft., and Pennsylvanian rocks from 0 to 3,050 ft. The calculated sediment volume of the Mississippian is approximately 6,000 cu mi, and that of the Pennsylvanian is approximately 14,000 mi^3. About 85 percent of all Carboniferous rocks occur between depths of 5,000 and 15,000 ft.

Mississippian rocks consist of approximately 60 percent shale, 40 percent limestone, and minor amounts of chert. The shale and chert occur predominantly in the southern half of the Permian basin and grade to limestone in the northern part of the basin. The depositional environment through Late Mississippian time was a continuation of that established during the older Paleozoic, a shallow marine environment with carbonate deposition occupying the gently dipping shelf of the Tobosa basin (fig. 6). Marine shales were deposited in the deeper, southern, part of the shelf and basin. Mississippian sediments are absent either due to nondeposition or erosion over a large part of the present northwest, southwest, and southeast portions of the Permian basin.

Pennsylvanian rocks consist of about 48 percent limestone, 42 percent shale, and minor quantities of sandstone and siltstone. Reef facies make up a large percentage of the limestone deposits.

The depositional sequence of Pennsylvanian sediments was strongly influenced by active tectonism that began in Late Mississippian and continued with varying degree of intensity throughout the Pennsylvanian. The tectonism resulted in the formation of more dynamically active and changing basins, shelves, and platforms that represented a depositional setting totally different from the relatively stable, quiescent, Tobosa basin environment which existed prior to this time. Mountainous, detrital source areas ringed the basin, although rapidly expanding seas removed these areas to considerable distances from depositional centers, thus limiting the influx of coarse clastics. These sediments were confined to the periphery of the basins and graded seaward into shallow water, carbonate shelf, limestone accumulations with active organic reef developments on the shelf edges. The deeper parts of the marine basins became sediment starved and only thin marine shales were deposited in the centers of the Delaware, Val Verde and Midland basins. Because of continuing tectonism throughout the Pennsylvanian Period, these sediments are absent in many localities, particularly along the trend of the Central Basin and Diablo Platforms, due to erosion and/or nondeposition.

Permian System

Dolton and others (1979) state that Permian rocks cover practically the entire study area. They are divided into the Wolfcampian, Leonardian, Guadalupian, and Ochoan Provincial Series. The thickness of the Permian ranges from zero to over 17,000 ft., with an average of 7,500 ft. Calculated sediment volume is about 118,000 mi^3, of which 99 percent occurs at depths of less than 15,000 ft.

Ochoan sediments average 1,800 ft. in thickness, Guadalupe sediments average 2,900, Leonard average 2,900 ft., and Wolfcamp sediments average 1,500 ft. in thickness but vary widely from zero to 14,740 ft.

Permian rocks are extremely varied, generally grading upward from a clastic-carbonate sequence into an evaporite-red bed sequence. The Ochoan consists of 65 percent evaporites and 35 percent combined limestone, shale and sandstone, while the underlying Guadalupe, Leonard and Wolfcamp series consist of approximately 48 percent limestone, 24 percent shale, 20 percent sandstones and 8 percent evaporites. Of the latter, most are confined to the Guadalupe. Thus the Permian grades upward from a carbonate-clastic sequence into an evaporite-red bed lithology. The depositional history was marked in Early Permian time by the conclusion of the intense orogenic movement and tectonism which had begun in the Early Pennsylvanian and had resulted in extensive faulting, folding and mountain building. After tectonism had ceased, the area became tectonically stable and was characterized by deep marine basins that slowly decreased in area as they filled with sediment. Clastics were deposited in these basins which were surrounded by reefs and carbonate shelves that graded shoreward into evaporitic lagoons. By Late Permian time, evaporitic sabkha conditions existed over the entire area of deposition.

Source Rocks

Organic rich rocks capable of being primary source beds for the generation of oil and/or gas are distributed throughout the Paleozoic systems. Although not of outstanding thickness, these potential source rocks are extremely rich in organic material.

As mentioned previously, in late Devonian through early Mississippian time, a widespread quiescent, euxenic, marine environment covered the whole area and promoted the extensive deposition of black mud and siliceous ooze. Dolton and others (1979) and Wright (1979) suggest these organic-rich muds, now represented by the Woodford shale, are considered to be important source rocks (Hill, 1971, p. 745; Salisbury, 1968, p. 1443). Although the principal indigenous lower Paleozoic source rock appears to be the Woodford shale, hydrocarbons may also have been derived from shales of the Simpson Group equivalents and from younger rocks (Frenzel 1968; Williams and Coester 1968; Holmquest 1966; Kvenvolden, 1967).

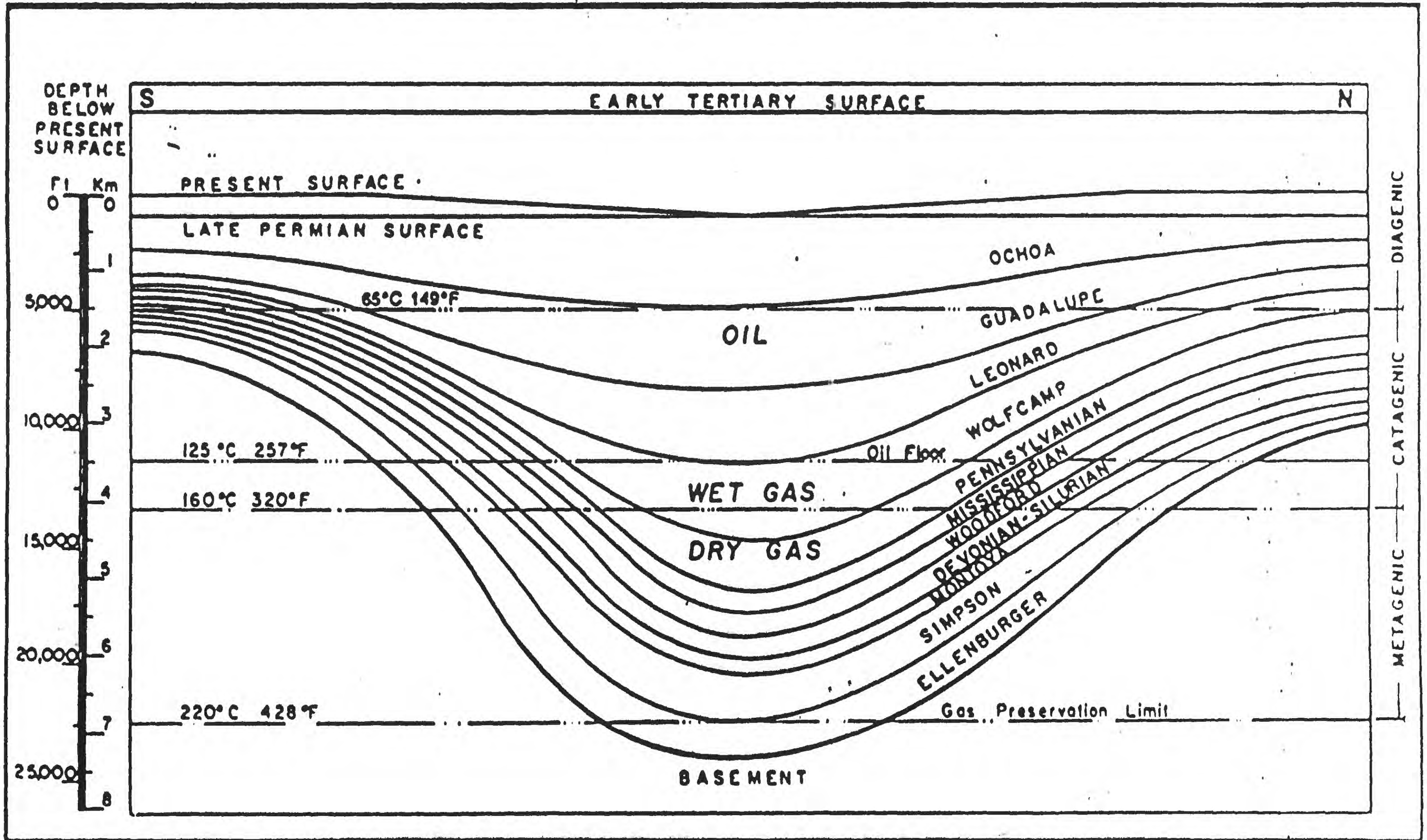
In the Carboniferous system, organic rich shales and limestones are considered to be important hydrocarbon source beds. This is particularly true of organic rich Upper Mississippian and Pennsylvanian rocks. Similarly, in the Permian system organic rich shales and shaly limestones are considered to be primary and important indigenous hydrocarbon source beds (Landes, 1970, p. 329, 336).

Burial History, Thermal Maturity, and Migration

Data on the burial history, thermal maturity and migration of hydrocarbons from source rocks in the Permian basin has not been widely published. However, it is safe to infer that the burial history of source beds in the Paleozoic rock systems was adequate to ensure thermal maturity of the organic rich sediments. The shallower, younger rocks tend to be oil prone, whereas the deeper, older Paleozoic rocks tend to be gas prone. The latter is especially true in the deep basins. Galley (1971); Hill (1971); Hartman and Woodard (1971); Wright (1979); and Galloway and others (1983) suggest that in general source beds were relatively close to existing reservoirs in most cases. However, these same authors also suggest that the migration of hydrocarbons, both occurred laterally and vertically, along existing faults and fracture systems, occurred. This is especially true of fields in the Central Basin Platform area.

Hills (1984) in a paper on hydrocarbon generation in the Delaware Basin, suggests that during much of the Paleozoic Era, the Delaware Basin formed as a confined depression surrounded by carbonate shelves, in which organic debris was preserved. Large amounts of organic material accumulated in the deep, poorly oxygenated, marine basin and was subsequently converted to hydrocarbons. Following conversion to hydrocarbons, these fluids migrated into traps both within the basin and into peripheral shelf carbonate rocks surrounding it. Thick evaporite deposits developed during the late Permian formed an effective reservoir seal. With progressively deeper burial in the basin, the heavier hydrocarbons were converted into gas.

Temperature gradients in the Delaware Basin appear to vary between 1°F and 1.5°F/100 ft (Hills, 1984). Hills (1984) constructed a generalized diagram showing the relationship of hydrocarbon maturation zones to the generalized stratigraphic column (fig. 14). Three major sources were identified for hydrocarbon generation in the Delaware Basin, which correspond to those suggested earlier. They are:



14.
Figure ~~13~~—Generalized north-south cross section showing oil- and gas-generating conditions in Delaware basin. Thickness of formations is corrected for erosion and compaction. (From Hills, 1984, Fig. 13)

1) Middle Ordovician shales and limestones
2) Upper Devonian and Mississippian shales and shaly limestones
3) Basinal organic rich facies of the Pennsylvanian and Permian rocks.

These source rocks underwent maturation and the generation of liquid hydrocarbons at different periods of geologic time in response to progressively increasing depths of burial.

Hydrocarbon Occurrence

Dolton and others (1979) consider the Permian basin to be in the mature stage of petroleum exploration and development. Oil and natural gas have been found in rocks ranging in age from Cambrian to Cretaceous. However, virtually all of the known hydrocarbons have been found in rocks of Paleozoic age (fig. 14). The Paleozoic reservoirs produce oil from depths of less than 500 ft. to slightly more than 14,000 ft., and natural gas from depths of less than 500 ft. to more than 21,000 ft.

Although almost the entire Permian basin is productive, discovered hydrocarbons show pronounced distributional patterns. Permian rocks, at relatively shallow depths, have accounted for approximately 71 percent of the oil and dissolved/associated gas discovered to date. In contrast, the older sequence of pre-Mississippian rocks has contained the major quantities of non-associated gas. The Central Basin Platform is the major productive tectonic element for both oil and dissolved/associated gas, producing principally from the Permian Captain reef and back reef complex and from lower Paleozoic reservoirs. The Midland Basin is an important oil and dissolved gas producing area while the Northwestern Shelf and the Eastern Shelf produce oil and dissolved/associated gas in smaller quantities. The western part of the Permian basin, particularly the Delaware and Val Verde basins, and western parts of the Northwestern Shelf have produced most of the non-associated gas.

For the purpose of the discussion of hydrocarbon occurrence, the Paleozoic section is treated as three readily identifiable units. These are the same units as discussed previously under the section on stratigraphy. They are:

a) Older Paleozoic Systems (Cambrian through Devonian)
b) Carboniferous System
c) Permian System

Reference to the distribution and occurrence of hydrocarbons in figures 15a and 15b substantiates this as a logical division.

Older Paleozoic Systems

It is estimated that approximately 65 percent of the hydrocarbon traps in the Older Paleozoic rocks are structural in nature, 15 percent are stratigraphic and the remaining 20 percent are a combination of these two trap types. Primary sealing rocks are impervious carbonates and shales. Reservoir lithologies are primarily dolomite and organic to inorganic limestones, together with lesser amounts of sand and silty clastics.

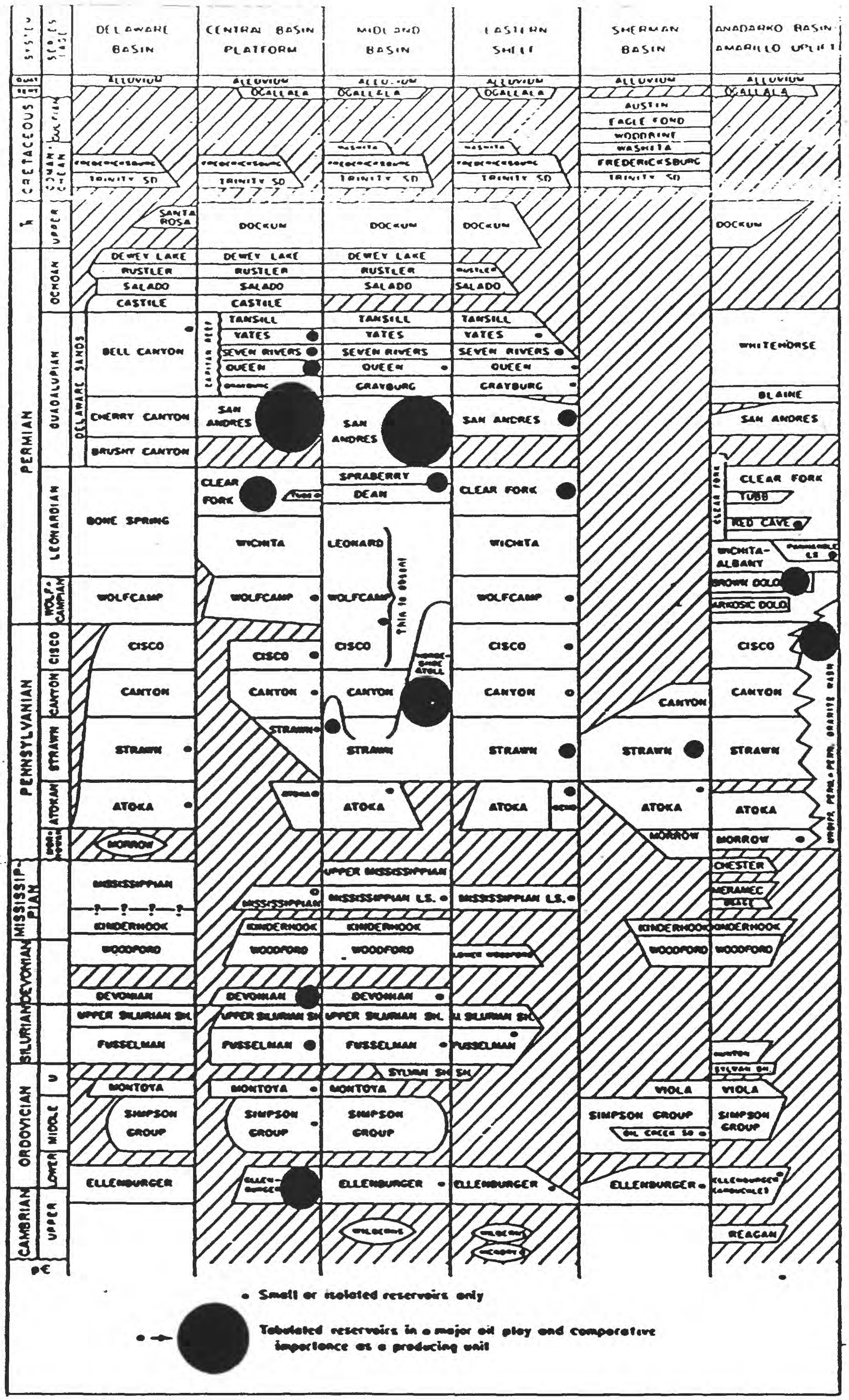


Figure 15a. Simplified geologic age relations of the principal oil-producing stratigraphic units of the North-Central, Panhandle, and West Texas basins. (From Galloway and others (1983).

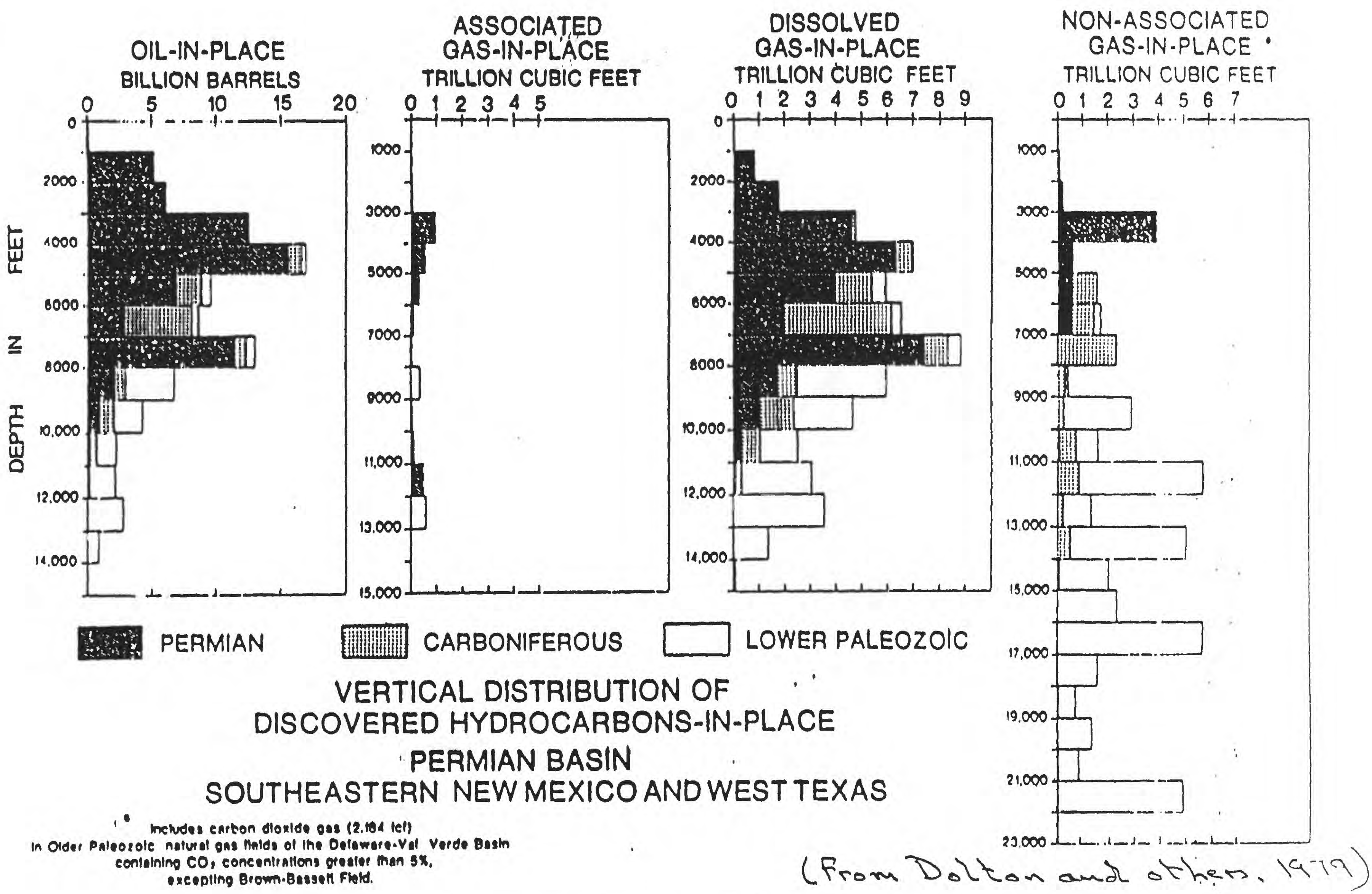


Figure 15b.-Vertical distribution of occurrence of discovered hydrocarbons in-place, Permian basin.

Dolton and others (1979) state that the pre-Mississippian sequence produces oil and gas form rocks as old as Cambrian. Principal oil reservoirs are in the Devonian and in the Ordovician Ellenburger Group, each providing approximately 44 percent of the older Paleozoic discovered oil and dissolved/associated gas-in-place, and 28 and 52 percent respectively of the discovered non-associated gas. Less important reservoirs are in the Silurian Fusselman Dolomite, Ordovician Montoya Dolomite, Simpson Group equivalent rocks, and Cambrian formations.

Older Paleozoic oil and natural gas are not evenly distributed throughout the Permian basin. The Central Basin Platform accounts for 60 percent of the discovered oil in-place, followed by the Midland Basin with 24 percent. In contrast, the Delaware-Val Verde Basin accounts for about 80 percent of the discovered non-associated gas in-place, followed by the Central Basin Platform with about 11 percent, and the Midland Basin with less than 10 percent. Most of the "dry" gas fields of the Delaware and Val Verde basins also produce appreciable condensate. Dissolved/associated gas/oil ratios increase toward the southern end of the Midland Basin and Central Basin Platform. Most of the discovered oil and dissolved/associated gas are found at depths between 8,000 and 14,000 ft. Non-associated gas is concentrated between depths of 9,000 and 22,000 ft.

Lithologically, the older Paleozoic reservoirs are primarily carbonates. Dolomites make up 67 percent of oil reservoirs and 86 percent of non-associated gas reservoirs; limestones 21 percent and 9 percent, respectively. The other reservoirs are sandstone, chert, and tripolitic chert. Individual reservoir thicknesses range from as little as 10 ft. for the sandstone reservoirs of the Simpson Group equivalent rocks, to more than 1,000 ft. for dolomites of the Ellenburger. Reservoir properties of the principal producing carbonates vary considerably. Intergranular matrix porosity of the Ellenburger dolomite reservoirs usually ranges form 1 to 7 percent; however, joints and fractures augment this intergranular porosity and provide permeability, especially on tightly folded anticlines. Porosity of the Silurian and Devonian limestone and dolomite reservoirs is usually between 4 and 25 percent, and may even become locally cavernous; however, permeability is often low. In these reservoirs fracturing over anticlinal structures is also an important factor in reservoir performance. Recovery factors of the older Paleozoic reservoirs average 26 percent for oil and 70 percent for non-associated gas.

Older Paleozoic reservoirs are found productive in anticlinal traps, most of which are faulted. Many of these structures produce from several older Paleozoic pools as well as overlying pools. Structural closure of several hundred feet is common; closure of more than 1,000 ft. is reported in several major fields. Although structural traps account for more than 80 percent of all oil and gas accumulations, stratigraphic and combination traps are also significant. Locally, Devonian and older rocks are absent from the tops of anticlinal features as a consequence of early growth and erosion, but may be present and productive in truncation traps on the flanks, particularly on the Central Basin Platform. Elsewhere, erosion is more regional in character and produces truncation traps in Ordovician, Silurian, and Devonian reservoirs. Reservoirs seals are primarily shales and impermeable carbonates.

Carboniferous System

The most prevalent traps in Mississippian rocks are structural in nature in combination with, or separate from, secondary, but important, stratigraphic traps. Primary hydrocarbon seals are impervious carbonates or shales. Reservoir lithologies are mostly dolomite, limestone or cherty carbonates.

The hydrocarbon traps in the Pennsylvanian are both stratigraphic or structural in nature, either singly or in combination. Primary seals are impermeable carbonates or shales. Reservoir lithology is variable, consisting of porous and permeable reef and bioherm developments, limestone, and sandstone lenses and pinchouts. Tight silty and shaley sandstone reservoirs are also widely developed.

Dolton and others (1979) state that the Pennsylvanian system contains more than 99 percent of the hydrocarbons discovered in Carboniferous rocks. Oil and gas occur in both structural and stratigraphic traps, and in combinations of both. Structural trap types include anticlines, fault-bounded anticlines, plunging structural "noses", and fault-bounded monoclines. Stratigraphic-trap types include reef mounds, bioherms and atolls, sandstone bodies deposited in littoral and nearshore marine environments, and carbonate porosity and permeability traps. Local porosity has developed in weathered cherty limestone beds of Mississippian age. The seals for all Carboniferous traps are either shales or impervious limestone beds.

Permian System

The hydrocarbon traps in the Permian are stratigraphic and structural in nature, either singly or in combination. Primary seals are dense carbonates, evaporites or shales. Reservoir lithology is variable, consisting of porous and permeable reef and bioherm developments, dolomites, limestones and sandstone lenses and pinchouts of the platform interior. Over 94 percent of the hydrocarbons in Permian reservoirs is contained in rocks of Guadalupe and Leonard age.

Permian rocks account for more than 70 percent of the total oil, and almost 40 percent of the gas found in the Permian basin. The gas percentage however, will probably decrease as exploration proceeds in the deep basin areas.

Dolton and others (1979) state that in Permian rocks more than 99 percent of the oil in-place and more than 97 percent of the total gas in-place have been found at depths of less than 10,000 ft. and most of it at depths less than 5,000 ft. There is relatively little known non-associated gas in Permian strata. Most Permian gas occurs dissolved in the crude oil and is produced with it.

The four provincial series of the Permian do not contain hydrocarbons in equal amounts. The largely evaporitic Ochoan rocks account for less than 0.01 percent of the Permian's contained oil. Therefore, the Ochoan rocks are not considered to have significant potential for large hydrocarbon accumulations.

By contrast, the Guadalupian has accounted for 67 percent of all Permian oil found and 61 percent of all Permian gas. The Leonardian follows with 28 percent of the oil and 31 percent of the gas. The Wolfcampian contains 5 percent of the oil and 8 percent of the total Permian gas. These amounts are directly related to the progressive development of reefs and back-reef lagoons beginning in the Wolfcampian, increasing in the Leonardian, and culminating in the development of the Capitan Reef complex in the Guadalupian.

Hydrocarbon traps in Permian rocks are largely a combination of stratigraphic and structural types, although each type does occur alone. The intricate stratigraphic interfingering of lithologies responsible for trapping much of the Permian oil has resulted largely from the constantly shifting reef and back-reef sedimentary environments. Primary seals are impervious carbonates, evaporites or shales.

About 40 percent of the reservoirs are limestone, 29 percent are dolomite and 29 percent are sandstone. Porosities range from 1.5 to 25 percent and reservoir permeabilities from 0.02 to 200 millidarcies.

Recovery factors range from a low of 5 percent to a high of 47.5 percent. The fractured siltstone Spraberry reservoir of the Midland Basin has a very low recovery factor, although the volume of oil in-place is the largest of any single Permian pool. The average recovery factor for the Permian System is 25 percent (Dolton and others, 1979).

Data Sources and Analysis

Field size data in the current analysis are derived from the NRG Associates "Significant Oil and Gas field file of the United States", (1986). The U.S. Geological Survey's approach in making its estimates has been to consider all available geological, geophysical, drilling and field size data to arrive at an understanding of each play's geologic and exploration history. Total discovery history is compared to the most recent exploration experience (post-1961 discoveries) to gain a feeling for current finding rates and field size distributions. Reservoirs were allocated to different plays as deemed appropriate. These data provide the basis for estimates of numbers and sizes of undiscovered accumulations.

Details of the assessment methodology and analysis of data are contained in a working paper for the National Assessment, U.S. Geological Survey Open-File Report 88-373.

Play Identification

The Permian basin is a prolific petroleum province and is considered to be in a mature stage of petroleum exploration and development. The plays selected for assessment are well recognized and demonstrated producing intervals. The plays are based primarily on stratigraphy, lithology, location within the basin, reservoir type and trapping mechanism, age, and expected hydrocarbons. Because of the innumerable combinations of defining parameters which occur throughout the Permian basin, some overlap of plays cannot be avoided. The plays, in some cases, represent aggregations of individual subplays or sets. If the myriad of individual hydrocarbon associations were separately assessed, the number for evaluation would be unmanageable within the limitations of this study. Ten plays were established and assessed for undiscovered oil and gas resources in the Permian basin. They are:

1) Delaware Sandstone - Upper Permian
2) Northwestern Shelf - Pennsylvanian and Permian
3) Central Basin Platform - Upper Pennsylvanian - Permian sequence
4) Spraberry-Dean Sandstone - Lower Permian Sequence
5) Delaware and Val Verde Basin Gas Play - Pennsylvanian - Lower Permian sequences
6) Eastern Shelf and Midland Basin - Pennsylvanian and Permian shelf sequence
7) Horseshoe Atoll - Pennsylvanian
8) Northwestern Shelf and Eastern Shelf - Older Paleozoics
9) Central Basin Platform and Midland Basin - Older Paleozoics
10) Deep Delaware - Val Verde Basins - Older Paleozoics

Principal Plays

Play 1: Delaware Sandstone - Upper Permian

Play Description and Type

The Delaware Sandstone Play is an oil and gas play, the hydrocarbons occurring in deep basinal sandstone reservoirs in combination structural/stratigraphic traps, sealed by updip pinch-outs and facies changes. The play is principally confined to the Delaware Basin (fig. 16) in rocks of Upper Permian age. Some shelf margin sandstone reservoirs in the adjoining Sheffield Channel and Ozona Arch areas were included in this play because of reservoir similarities with the Delaware sandstone unit. The sandstone unit is the basinal equivalent of the platform sequence. Primary reservoir lithology is fine grained sandstone and possibly open shelf basal sandstones in the Ozona area.

Reservoirs

Galloway and others (1983), state that the reservoir rocks consist of fine grained sandstone interbedded with laminated siltstone, organic rich shale, limestone and dolomite. The reservoirs are contained in the Upper Permian Rustler Formation of the Ochoan series, and the Bell Canyon, Yates, Queen and Cherry Canyon formations of the Guadalupian Delaware Sands Series. Porosity values average 20 to 25 percent with moderate to low permeability. The sandstone bodies are lenticular fills deposited in broad anastomosed, internally braided, submarine channels.

Traps and Seals

Primary trapping mechanisms are stratigraphic, in updip pinch-outs of channel-fill sandstone bodies in the Delaware Basin. In the Ozona Arch area, anticlinal structure and combination structural/stratigraphic traps are present. Seals are generally impervious silty shales.

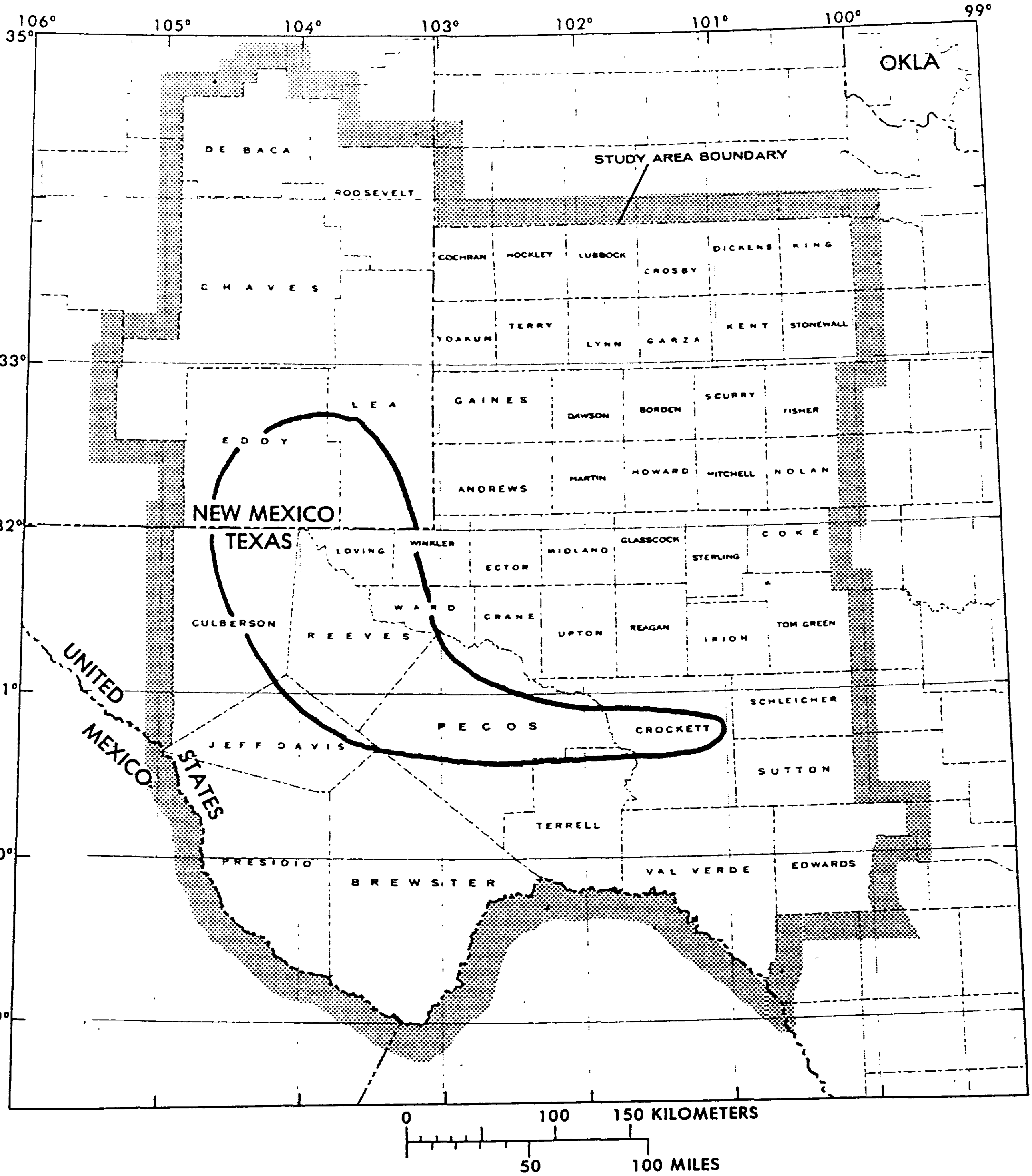


Fig. 16 Location map, Play 1: Delaware Sandstone - Upper Permian

Source Rocks and Geochemistry

Source rocks are assumed to be organic rich basinal shales of Permian age.

Timing and Migration

Galloway and others (1983), suggest that hydrocarbon generation occurred during Middle and Upper Permian time. The relatively low permeability of the reservoir rocks suggests that hydrocarbons were generated from sources near the reservoirs and that migration distances were short.

Depth of Occurrence

Stratigraphically and structurally entrapped hydrocarbons in this play occur at depth ranges from 1,000 to 7,000 feet and average about 4,000 feet.

Exploration Status

The first exploration discoveries were in the 1920's but the majority of large oil discoveries were made during the 1950's. Approximately 14 fields larger than 1 million bbls oil and 6 billion cu. ft. gas have been discovered since 1961, 9 of which are oil and 5 are gas fields. Since 1961 approximately 26 million bbls oil, 124 billion cu. ft. gas and 30 million bbls of natural gas-liquids have been discovered. The largest gas field discovered is the Waha Delaware field with 126 billion cu. ft. recoverable gas. The average field size since 1961 approximates 14 billion cu. ft.

Play 2: Northwestern Shelf - Pennsylvanian and Permian Sequence

Play Description and Type

The Northwestern Shelf - Pennsylvanian and Permian Sequence play is predominantly oil, together with lesser amounts of gas. The hydrocarbons occur in shelf margin and interior facies of carbonate and subordinate fine grained clastic sediment reservoirs; in stratigraphic, combination stratigraphic/structural and structural traps; and sealed by evaporites, impermeable dolomites and red beds. The play covers the whole of the Northwestern Shelf area south of the Matador Arch and southeast of the Pedernal Massif (fig. 17) and also extends into a small, northern, part of the Midland Basin. The rocks in the play are Pennsylvanian to Middle Permian (Guadalupian) in age and primarily oil prone with minor associated and non-associated gas. Reservoir lithology is mostly limestone and dolomite together with minor amounts of interbedded fine grained sandstone.

Reservoirs

Galloway and others (1983), state that reservoir rocks consist of porous limestone, dolomite, dolomitized mudstone and wackestone, and lesser amounts of fine grained clastics, frequently associated with evaporites, red beds and sabkha facies. The reservoir rocks appear to have been deposited in a strandline, intertidal to supratidal and restricted shelf environment associated with reef growth. The reservoirs are contained in Pennsylvanian Strawn and Cisco Formations; Permian Wolfcampian; Leonardian, Bone Spring and Clear Fork

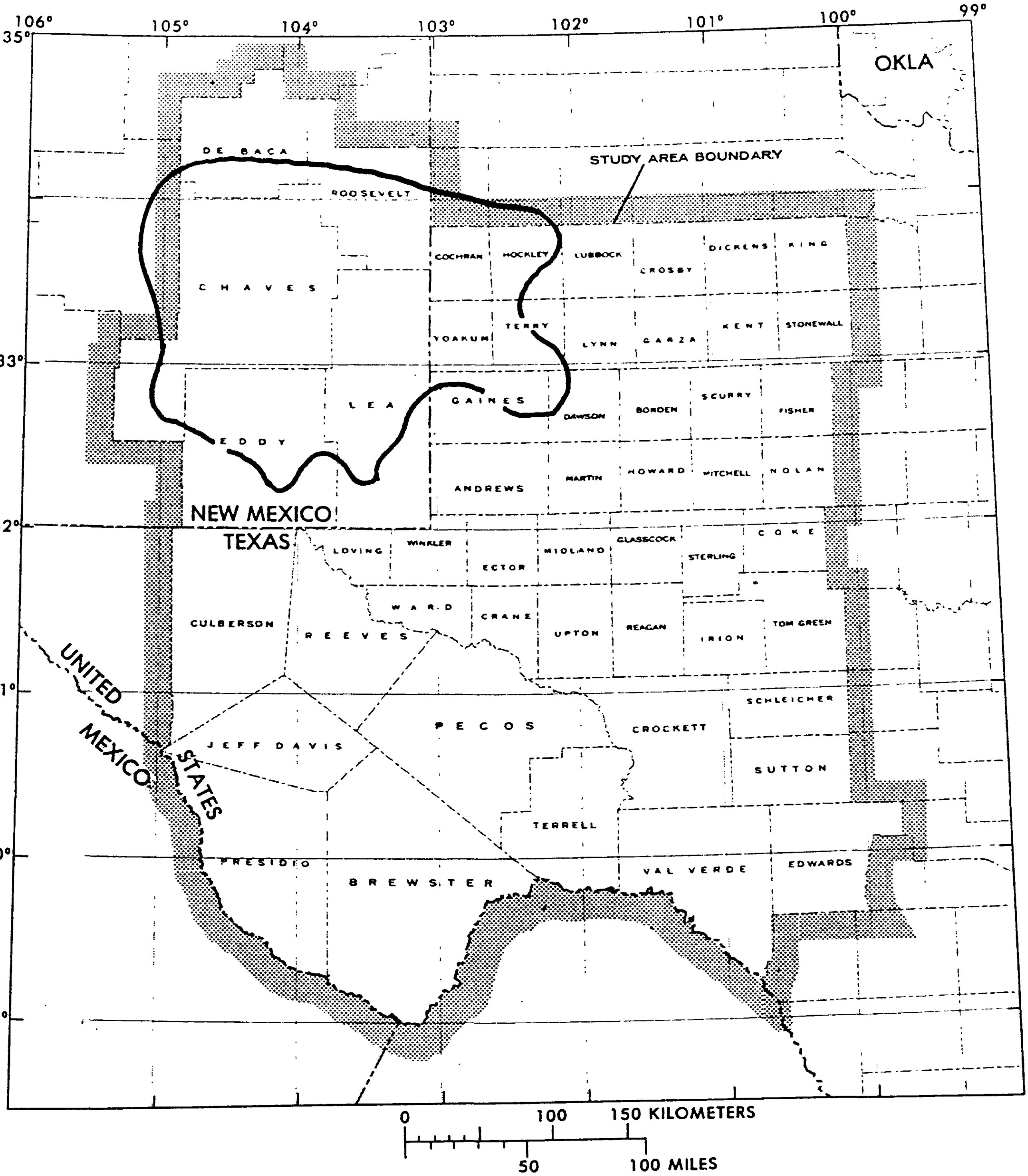


Fig. 17 Location map, Play 2: Northwestern Shelf - Pennsylvanian and Permian

Formations; and Guadalupian; San Andres, Grayburg, Queen, Seven Rivers and Yates Formations. Porosities average 10 percent and permeabilities 6 millidarcies.

Traps and Seals

Galloway and others (1983), and Wright (1979), suggest that primary trapping mechanisms are stratigraphic, structural and combined stratigraphic-structural. The stratigraphic traps in the shelf sequence are formed by lateral facies changes into non-porous and non-permeable strata. The structural traps are generally simple anticlinal closures which had topographic relief during the Permian. Buried reef traps are also present. Seals consist of anhydrite, salt beds, nonporous dolomites and red beds.

Source Rocks and Geochemistry

Source rocks are assumed to be indigenous organic rich calcareous shales and shaly limestones of Permian-Pennsylvanian age. It is inferred that lower Permian sediments are the primary source beds. Under restricted shelf, intertidal and lagoonal environments, source beds are probably extremely rich in organic material.

Timing and Migration

Hydrocarbon generation probably occurred during Middle and Upper Permian time. The hydrocarbon fluids migrated laterally and upward into the present porous reservoir rocks simultaneously with generation.

Depth and Occurrence

Stratigraphically and structurally entrapped hydrocarbons in this play occur at depths of 1,000 to 11,000 feet, with an average of 5,100 feet.

Exploration Status

The first exploration discovery was in 1923 at the Artesia-Malzamar field, but most discoveries were made during the 1950's and 1960's. Approximately 55 fields larger than 1 million bbls oil and 6 billion cu. ft. gas have been discovered since 1961, 46 of which are oil and 9 are gas. These contain approximately 225 million bbls of oil, 627 billion cu. ft. of gas and 11 million bbls of natural gas-liquid have been discovered. Galloway and others (1983) state that this oil play contains more than 12 billion bbls oil-in place. One of the largest oil fields discovered is Wasson with approximately 2 billion bbls recoverable oil. The largest gas field discovered is Pecos Slope, located in Chavez County, New Mexico, with 225 billion cu. ft. recoverable gas.

Play 3: Central Basin Platform - Upper Pennsylvanian - Permian Sequence

Play Description and Type

This play is predominantly an oil play together with lesser amounts of gas. The hydrocarbons occur in a platform sequence of carbonate and subordinate fine-grained clastic sediment reservoirs; in combination stratigraphic-structural and structural traps; sealed by evaporites and impervious carbonates.

The play covers the Central Basin Platform, (fig. 18). Rocks in the play are primarily Lower and Middle Permian (Guadalupian and Leonardian) in age, together with Upper Pennsylvanian, and is primarily oil prone with associated gas. Reservoir lithology is predominantly limestone and dolomite together with lesser amounts of fine grained sandstone.

On the Central Basin Platform, data volume alone necessitated lumping several reservoir families or plays, as may be reasonably identified, into a single composite play. This play which occupies an area approximately 40 miles wide and 120 miles long, contains 8 of the Texas Bureau of Economic Geology's Permian Basin oil plays. The U.S. Geological Survey's approach to the Central Basin Platform has been to group these 8 plays into one composite play. The platform plays are old and shallow. Although they are of importance to the subject of enhanced recovery and for determination of cumulative production history, their potential for undiscovered recoverable resources is limited.

Reservoirs

Galloway and others (1983), state that reservoir rocks consist of porous and permeable dolomitized carbonates, limestone and fine grained sandstone. reservoir rocks in this play contain all the facies typical of a platform complex. These include skeletal grainstones, dolomite, limestone, calcareous and silty sandstones, sponge and algal dolomitized limestones, dolomitized mud and wackestones, and vuggy to cavernous carbonates. The carbonate rocks were deposited in open to restricted platform and margin systems, associated with sea level fluctuations, shelf margin reef development, evaporite and sabkha deposits. Reservoir quality is enhanced by selective dolomitization, dissolution, fracturing and leaching. The reservoirs are contained in the Permian Guadalupian San Andres, Grayburg, Queen, Seven Rivers and Yates Formations, in the Leonardian Clear Creek formation, in the Wolfcamp Formation, and in the Pennsylvanian Strawn, Canyon and Cisco Formations. Porosities average 12 percent and permeabilities 18 millidarcies.

Traps and Seals

Galloway and others (1983), and Wright (1979), suggest that primary trapping mechanisms are generally a combination of structural and stratigraphic features such as anticlinal noses and domes which are associated with stratigraphic depositional and diagenetic facies changes. Large, simple, anticlinal closures also are present. Seals consist of impervious dolomites, shaly carbonates, anhydrites and other evaporite facies.

Source Rocks and Geochemistry

Galloway and others (1983), consider source rocks to be indigenous organic rich calcareous shales and shaly limestones of Permian Wolfcampian and Leonardian age. Deposited under shallow platform, supratidal to marsh lagoonal strandline environments, associated with sea level fluctuations, these source beds are probably extremely rich in contained organic material. Organic rich shales of Pennsylvanian age are assumed to be the source rocks for hydrocarbons contained in the Pennsylvanian formations.

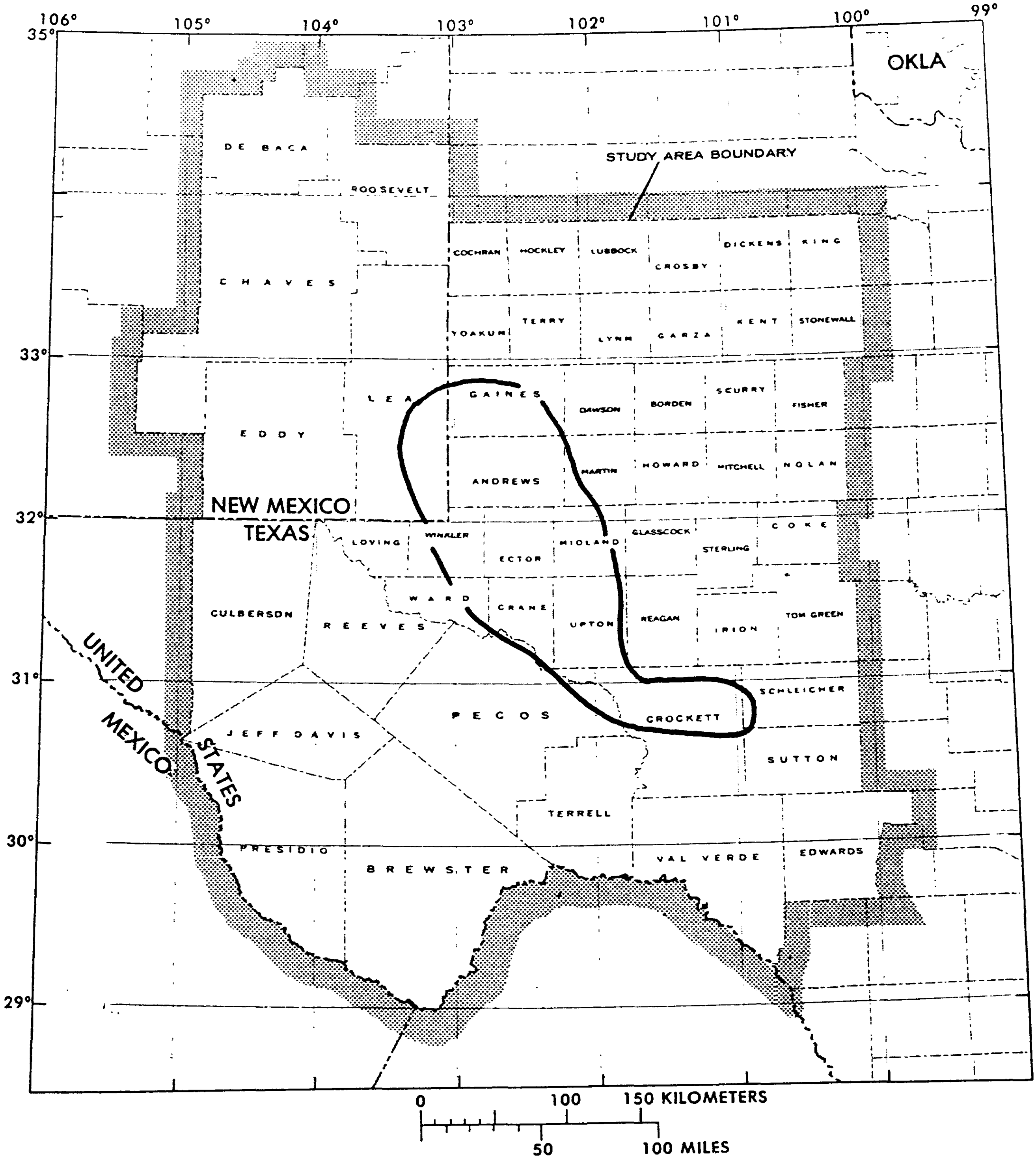


Fig. 18 Location map, Play 3: Central Basin Platform - Pennsylvanian and Permian

Timing and Maturation

It has been suggested that hydrocarbon generation occurred during Middle and Upper Permian time. The fluids migrated laterally and upward into the present reservoirs.

Depth of Occurrence

Structurally and stratigraphically entrapped hydrocarbons in this play occur at depths of 1,000 to 5,500 feet, average 4,300 feet, in Permian rocks. Pennsylvanian reservoirs produce from depths of 8,500 to 10,000 feet.

Exploration Status

The first exploration discovery in Permian reservoirs was in 1925 at the McCamey field, but most discoveries were made during the late 1920's to 1960's. Pennsylvanian age reservoirs were primarily discovered and developed during the 1950's. Rocks of these ages in the Central Basin Platform area have been extensively explored and drilled.

Approximately 31 fields larger than 1 million bbls oil and 6 billion cu. ft. gas have been discovered since 1961, 29 of which are oil and 2 are gas fields. The Yates field, discovered in 1926, is the largest field discovered, containing more than 2 billion bbls of recoverable oil. Since 1961, approximately 102 million bbls oil, 231 billion cu. ft. of gas and 12 million bbls of natural gas-liquids have been discovered. Original oil in place has been estimated to be in excess of 13 billion bbls (Galloway and others, 1983).

Play 4: Spraberry-Dean Sandstone - Lower Permian

Play Description

The Spraberry-Dean Sandstone is essentially an oil play together with associated gas. The hydrocarbons occur in deep basinal sandstone reservoirs in stratigraphic, combination stratigraphic/structural and, to a lesser extent, structural traps, sealed by updip pinch-outs, interbedded shales and carbonates, and facies change permeability barriers. The play covers the Midland Basin, located between the Central Basin Platform and the Eastern Shelf (fig. 19). The play is lower to middle Permian, Leonardian, in age and primarily oil prone with associated gas and gas-liquids. The lithology consists of sandstones, shales and siltstones interbedded with impure limestone and dolomitic limestone. The sediments were deposited in a deep basinal area and the sandstone resulted from a system of submarine fans, originating from the surrounding basinal margins and shelves, that poured huge amounts of sand and detrital debris down submarine canyons.

Reservoirs

Galloway and others (1983), state that reservoir rocks consist of broad laminated sandstone, muddy burrowed sandstone, muddy siltstone and mudstone tongues, which are all interlaminated, make poor reservoirs. The sediments were deposited as channel fills, as channel-margin bars and as play-like distal fans in a deep submarine environment. The reservoirs are contained in the Permian Leonardian Spraberry and Dean formations. A prolific amount of-oil-in-place

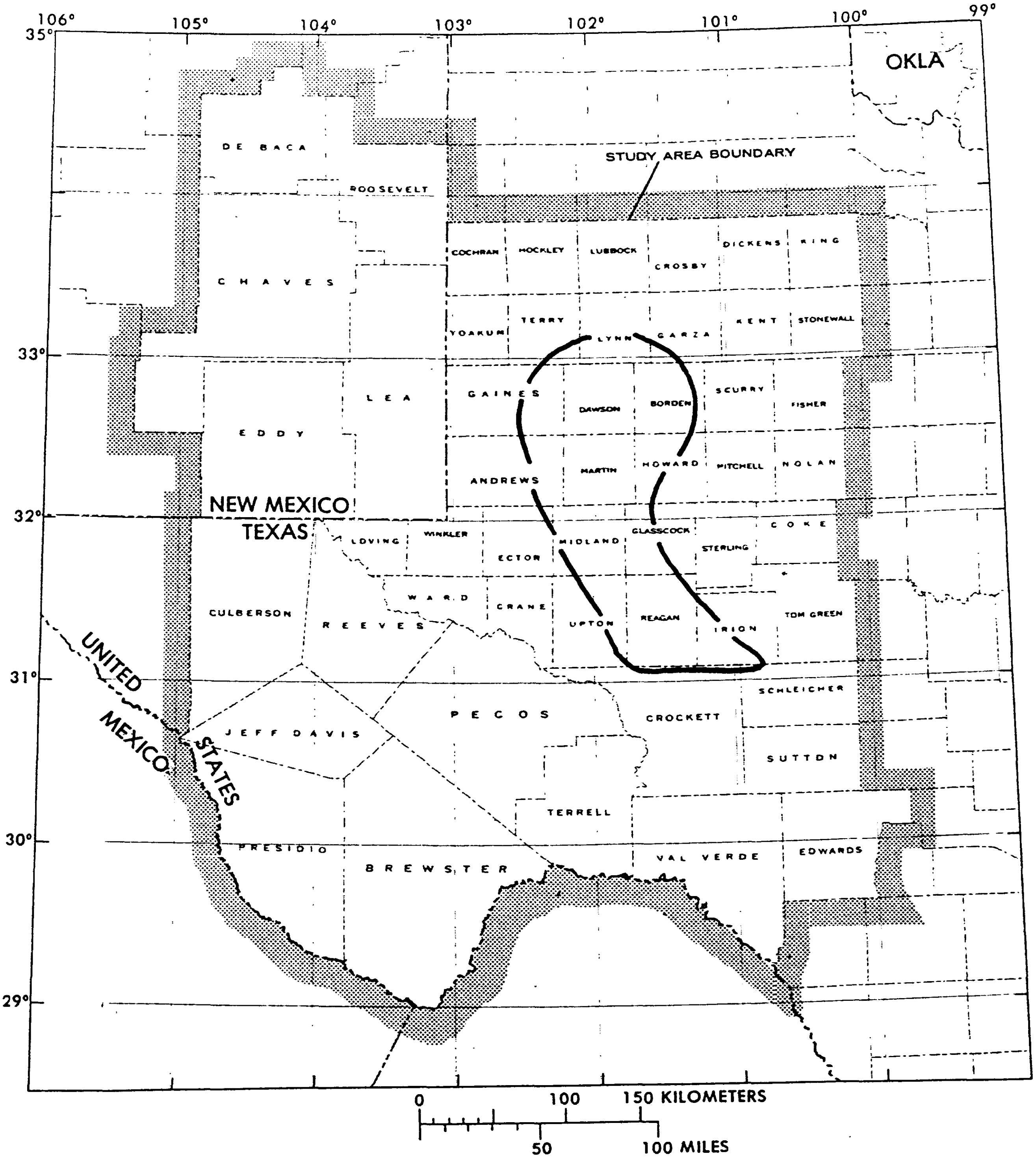


Fig. 19 Location map, Play 4: Spraberry/ Dean Sandstone - Lower Permian

exists but porosities (11 percent) and especially permeabilities (1 millidarcy) are very low.

Traps and Seals

Galloway and others (1983), state that primary trapping mechanisms are stratigraphic with some associated structural traps and combinations of both stratigraphic and structural. Up-dip thinning and pinch-outs of sandstones on the marginal slope of the Eastern Shelf are very prevalent. A few simple anticlinal structures also exist and reference is made to fields contained within a single isolated, and elongate, sandstone lens. Seals consist of non-porous interbedded shales, dolomitic and impure limestones, and porosity and permeability barriers within the interlaminated reservoir sequences. Organic rich black shales, in addition to being high quality source rocks, also act as effective seals.

Source Rocks and Geochemistry

Handford (1981) states that thin black shales are widely distributed in the Spraberry-Dean system. The shales are interbedded with sandstones and siltstones, and generally contain 1 to 3 percent total organic carbon. Most of the organic carbon consists of oil-prone algal and amorphous types. The organic rich black shales provide optimum, self contained, source rocks within the system, immediately adjacent to the sandstone reservoirs.

Timing and Migration

Hydrocarbon generation from the organic rich black shales probably occurred during Middle and Upper Permian time. The hydrocarbon fluids are considered to have simultaneously accumulated in the juxtaposed sandstone bodies.

Depth of Occurrence

Stratigraphic and structurally entrapped hydrocarbons in this play occur at depths of 4,500 to 9,500 feet, with an average of approximately 7,500 feet.

Exploration Status

The first exploration discovery was in 1949 at the Spraberry Trend field, but most discoveries were made in the 1950's and 1960's.

The Spraberry-Dean play has been extensively drilled and explored. Current recovery of in-place hydrocarbons is low. Recovery factors for in-place oil in the Spraberry-Dean play rarely exceed 15 percent and average about 6 percent (Galloway and others, 1983).

Approximately 13 oil fields larger than 1 million bbls oil, have been discovered, since 1961,containing more than 96 million bbls of oil, 287 ft^3 of associated gas and 40 million bbls of natural gas-liquids. Original oil in place has been estimated to be in excess of 10 billion bbls (Galloway and others, 1983.

Play 5: Delaware and Val Verde Gas basin - Pennsylvanian - Lower Permian sequence

Play Description

Hydrocarbons, primarily gas, in the Delaware and Val Verde Basin gas play occur in porous and permeable sandstone and subordinate dolomite and limestone reservoirs, in combination stratigraphic/structural, stratigraphic and, to a lesser extent in structural traps, sealed by updip, pinch-outs, overlying shales and dense carbonate rock, and by facies change permeability barriers.

The play covers most of the Delaware and Val Verde Basins and extends onto the southwestern perimeter of the Northwestern Shelf (fig. 20). The play is in Lower Permian Leonardian and Wolfcampian to primarily Pennsylvanian rocks and is primarily gas prone with relatively small amounts of associated oil and natural gas-liquids. Reservoir lithology is predominantly sandstone with a large proportion of associated limestone. Pennsylvanian gas fields located in the western part of the Northwestern Shelf area are included in this play rather than in Play 2.

Reservoirs

Galloway and others (1983), and Wright (1979) state that reservoir rocks consist of porous and permeable sandstone, which is locally coarse grained conglomeratic, together with subordinate dolomite and limestone carbonates. The most important reservoirs occur in clastic sediments of the Pennsylvanian Morrow, Atoka, Strawn, Canyon and Cisco Formations, and in sandstone and carbonate rocks of the Lower Permian Wolfcampian and Leonardian Wichita Formation. Reservoir rocks on the southern part of the Northwestern Shelf are primarily carbonate.

The Canyon Formation reservoirs are sandstones interbedded with shale. The Wolfcamp formation located in the western part of the Val Verde Basin contains clean, porous and permeable, medium to coarse grained sandstone reservoirs draped over older structural features. The reservoirs are a succession of sandstone beds, 5 to 10 feet in thickness, scattered through a vertical sequence of 600 feet. Total net pay varies from 20 to 100 feet.

Traps and Seals

Trapping mechanisms are predominantly a combination of structural and stratigraphic features. Anticlinal structures are generally associated with lateral facies changes, together with nosing and up-dip lensing. Lenticular sandstone bodies are numerous. Seals are considered to be overlying shale and dense carbonate rocks.

Source Rocks and Geochemistry

Galloway and others (1983), suggest that source rocks are assumed to be associated dark shales and argillaceous limestones in the Atoka Series of Lower Pennsylvanian age. Shales of the Wolfcampian and Leonardian Bone Springs Formation are thought to be source rocks for gas in reservoirs of Lower Permian age.

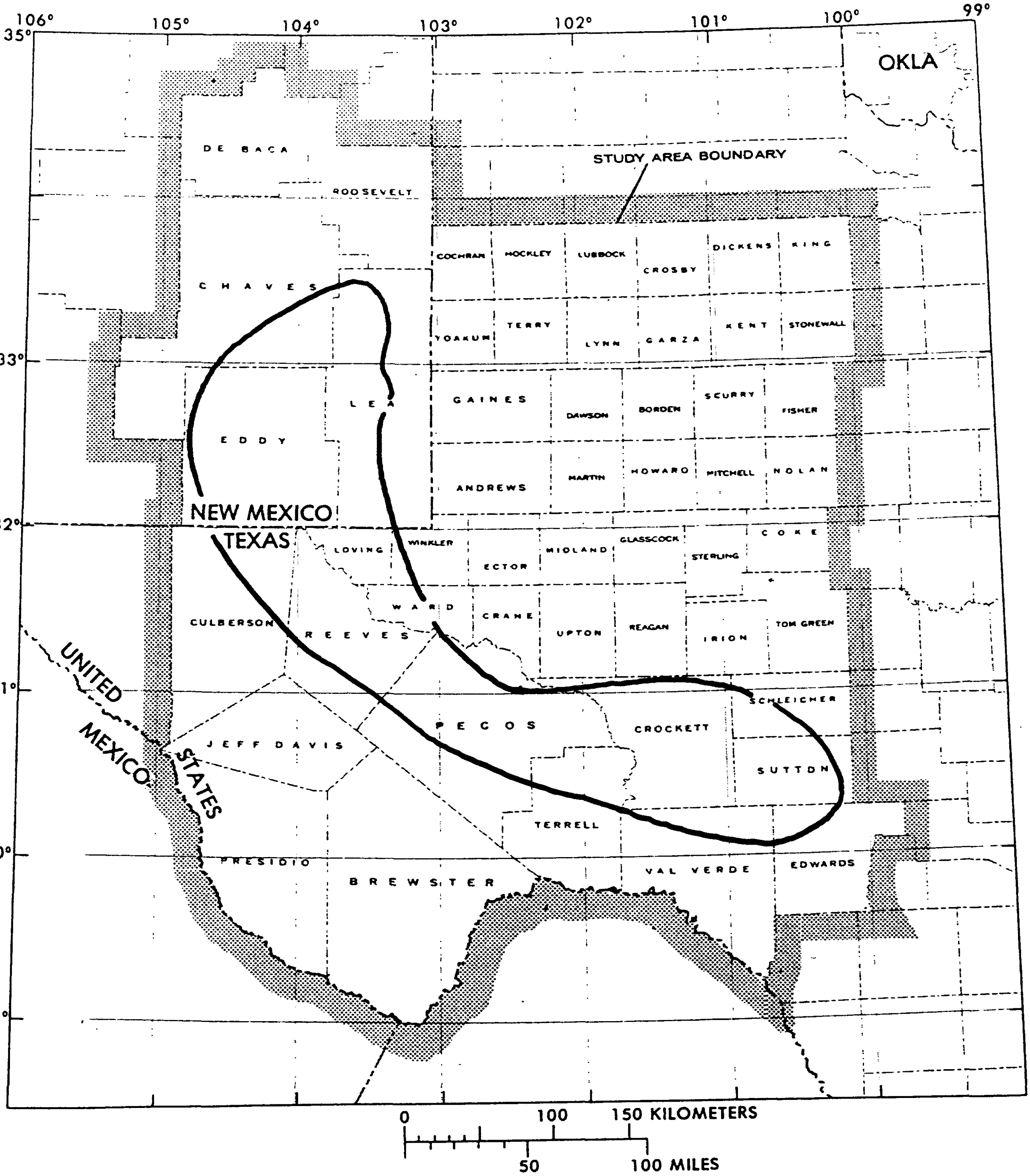


Fig. 20 Location map, Play 5: Delaware and Val Verde Basins Gas - Pennsylvanian and Lower Permian

Timing and Migration

Hydrocarbon generation from organic shales and argillaceous limestone source rocks possibly occurred during two periods, one in Middle Pennsylvanian, and one in Early and Middle Permian times. The gas readily migrated into adjacent reservoirs.

Depth of Occurrence

Reservoirs in the Permian Wolfcamp Formation vary in depth from 5,500 to 6,500 feet. In the Pennsylvanian Canyon Formation, reservoir rocks vary from depths of 6,100 to 7,000 feet, and in the Morrow Formation from 9,000 to 13,000 feet.

Exploration Status

The first gas field developed in this play was the Miers field, discovered in 1946, but the majority of gas fields were discovered during the 1960's and 1970's. Approximately 107 fields have been discovered, since 1961, larger than 1 million bbls oil and 6 billion cu. ft. gas, 6 of which are oil and 101 are gas. These contain more than 41 million bbls of oil, 6.3 trillion cu. ft. of gas and 150 million bbls of gas-liquid have been discovered. The average size of these oil fields is 5 million bbls, the largest being 16 million bbls. The average size of the gas fields is 60 billion cu. ft., the largest being over 1.3 trillion cu. ft.

Play 6: Eastern Shelf and Midland Basin - Pennsylvanian and Permian Shelf Sequence

Play Description and Type

The Eastern Shelf and Midland Basin - Pennsylvanian and Permian Shelf sequence is predominantly an oil play, together with lesser amounts of gas. The hydrocarbons occur in multiple stacked, shelf sequence dolomite, limestone and subordinate fine-grained sandstone reservoirs, in structural, stratigraphic and reef traps, sealed by updip pinchouts, overlying shale, impermeable limestone and evaporite rocks, and by facies change permeability barriers.

The play covers the Eastern Shelf and Midland Basin (fig. 21). The play is Pennsylvanian to Middle Permian, Guadalupian, in age and primarily oil-prone but containing significant quantities of associated gas. The hydrocarbon occurrences in the Midland Basin were included with those in the Eastern Shelf because of similarities with the multiple stacked sequences on the shelf. Reservoir lithology is predominantly limestone and dolomite, with subordinate sandstone.

Reservoirs

Galloway and others (1983), state that reservoir rocks consist of porous dolomites, limestones and sandstones, which occur in multiple stacked sequences. The reservoir rocks are frequently associated with anhydrite, salt and siltstone red beds. Facies change and intertongue from east to west as the margin of the Eastern Shelf prograded into the Midland Basin. The reservoirs are contained in Pennsylvanian Atoka (Bend), Strawn, Canyon and Cisco Formations, in the Permian, Wolfcampian and Leonardian Clear Fork Formation, and in the Permian Guadalupian

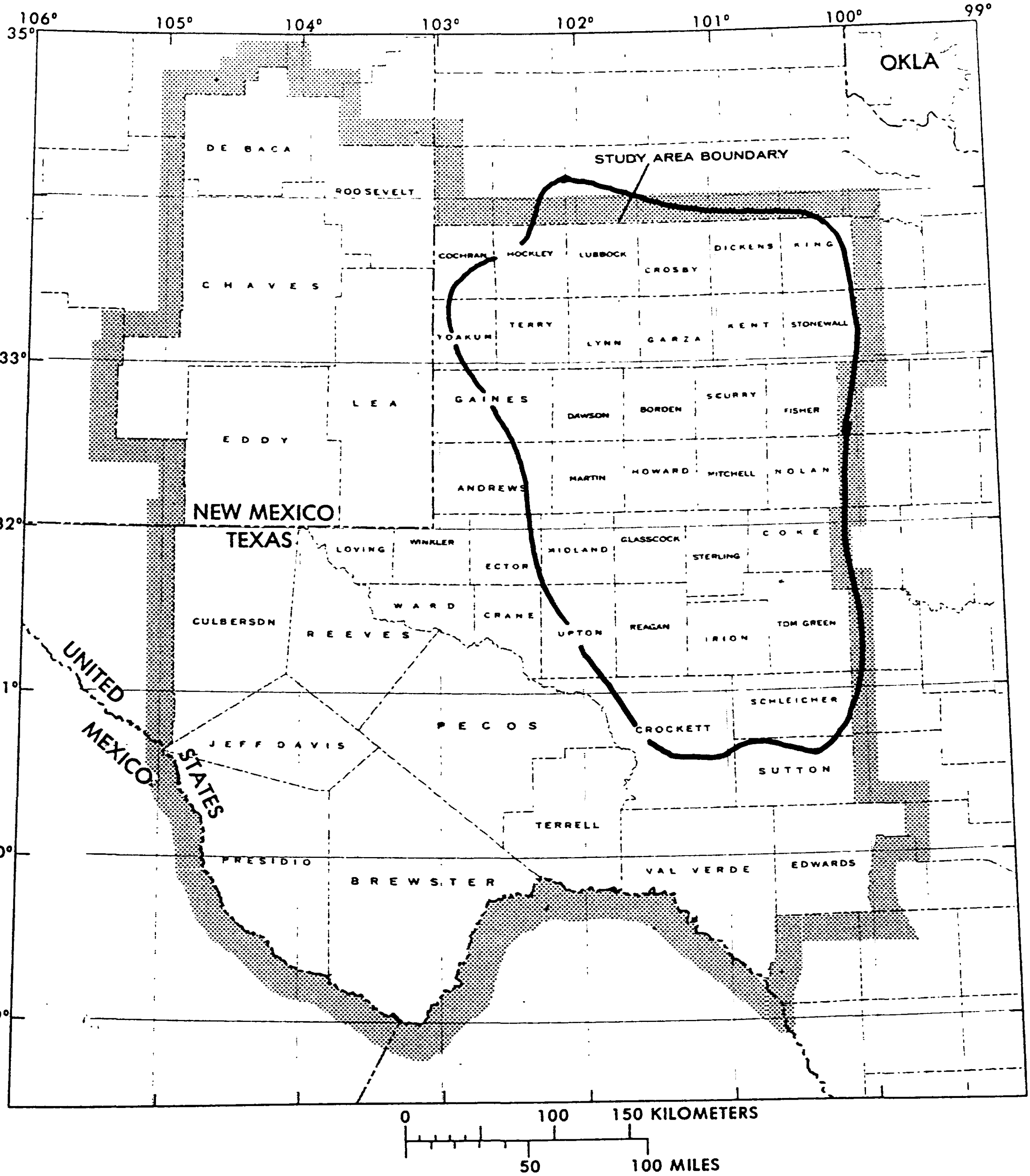


Fig. 21 Location map, Play 6: Eastern Shelf and Midland Basin - Pennsylvanian and Permian

Yates, Seven Rivers, Queen, Grayburg/San Andres Formations. Porosities average 12 percent and permeabilities 15 millidarcies.

Traps and Seals

Trapping mechanisms are predominantly a combination of structural and stratigraphic features. Anticlinal and domal structures are areally extensive and of low-relief. Combined structural and stratigraphic traps frequently consist of reef and structural noses which wedge-out updip and are associated with lateral depositional and diagenetic facies changes. Multiple, stacked, porous reservoir rocks are separated by non-productive impermeable shale and limestone beds which act as effective seals.

Source Rocks and Geochemistry

Galley (1971), considers source rocks for the Pennsylvanian and Permian reservoirs to be widely distributed indigenous bituminous shales of the same age.

Timing and Migration

Hydrocarbon generation from the bituminous shales (Galley, 1971), probably occurred during two periods, one in Upper Pennsylvanian, and one in Middle and Upper Permian time. The generated oil and gas readily migrated into the adjacent reservoirs.

Depth of Occurrence

Entrapped hydrocarbons in this play occur at depths of 1,500 to 3,200 feet, with an average of 2,100 feet.

Exploration Status

The first exploration discovery was in 1920 at the Westbrook field, but most discoveries were made during the 1950's. As is prevalent throughout the Permian Basin plays, the largest fields were discovered during early exploration. The play has been extensively explored and drilled.

Approximately 61 fields larger than 1 million bbls oil and 6 billion cu. ft. gas, have been discovered, since 1961, 49 of which are oil and 12 of which are gas fields. They contain more than 3 billion bbls oil, 4.7 trillion cu. ft. of gas, and 0.5 billion bbls of natural gas-liquids have been produced. The average size of oil fields is 3.1 million bbls. The largest field discovered, Howard-Glasscock, contains 420 million bbls recoverable oil.

Play 7: Horseshoe Atoll - Pennsylvanian

Play Description and Type

The Horseshoe Atoll is an oil play containing associated gas. The hydrocarbons occur in stacked reefoidal carbonate reservoirs, in reef growth and organism-rich carbonate mound traps, sealed by overlying and surrounding impervious mudstones and shales.

The play is a unique feature which consists of a massive reef bank covering areas of the northwestern part of the Eastern Shelf and the northern part of the Midland Basin (fig. 22). The reef bank complex is Pennsylvanian Strawn to Permian Wolfcampian in age and primarily oil prone with associated gas. The reef lithology consists of massive carbonates separated by shaly beds. The massive carbonate consists of numerous organisms, including shell debris, algal, sponge, bryozoan and crinoidal growths. The reef atoll grew in response to subsidence in the Midland Basin and on the western margin of the Eastern Shelf.

Reservoirs

Galloway and others (1983), state that reservoir rocks consist of porous grainstone, algal-mound wackestone and boundstone contained within stacked, massive limestones and dolomitic limestones. The reservoirs are contained in Pennsylvanian Strawn, Canyon and Cisco Formations. Porosities average 9 percent and permeabilities 28 millidarcies.

Traps and Seals

Trapping mechanisms are stratigraphic reef growths and associated organism rich carbonate rocks. Seals consist of thick sequences of impervious mudstones and shales which surround and cover the former reef.

Source Rocks and Geochemistry

Galloway and others (1983), consider source rocks for the Pennsylvanian reef reservoirs to be adjacent organic-rich shales and shaly limestones of the sediment starved basin.

Timing and Migration

Hydrocarbon generation from the indigenous organic-rich shales and shaly limestones probably occurred during Middle and Upper Permian times. The generated hydrocarbons readily migrated into the nearby porous atoll limestones.

Depth of Occurrence

Entrapped hydrocarbons in this play occur at depths of 5,000 to 10,000 feet, with an average of about 7,400 feet.

Exploration Status

The first exploration discoveries were in 1948 at the Scurry and Vealmoor fields, but most discoveries were made during the 1950's. The play has been extensively explored and drilled.

Approximately 8 oil fields larger than 1 million bbls have been discovered, since 1961. They contain approximately 14 million bbls oil and approximately 10 billion ft^3 of associated gas and 0.5 billion bbls of natural gas liquids.

The average size of these oil fields is 1.7 million bbls. The largest field in the play is the Scurry Field with more than 1.6 billion bbls of recoverable oil.

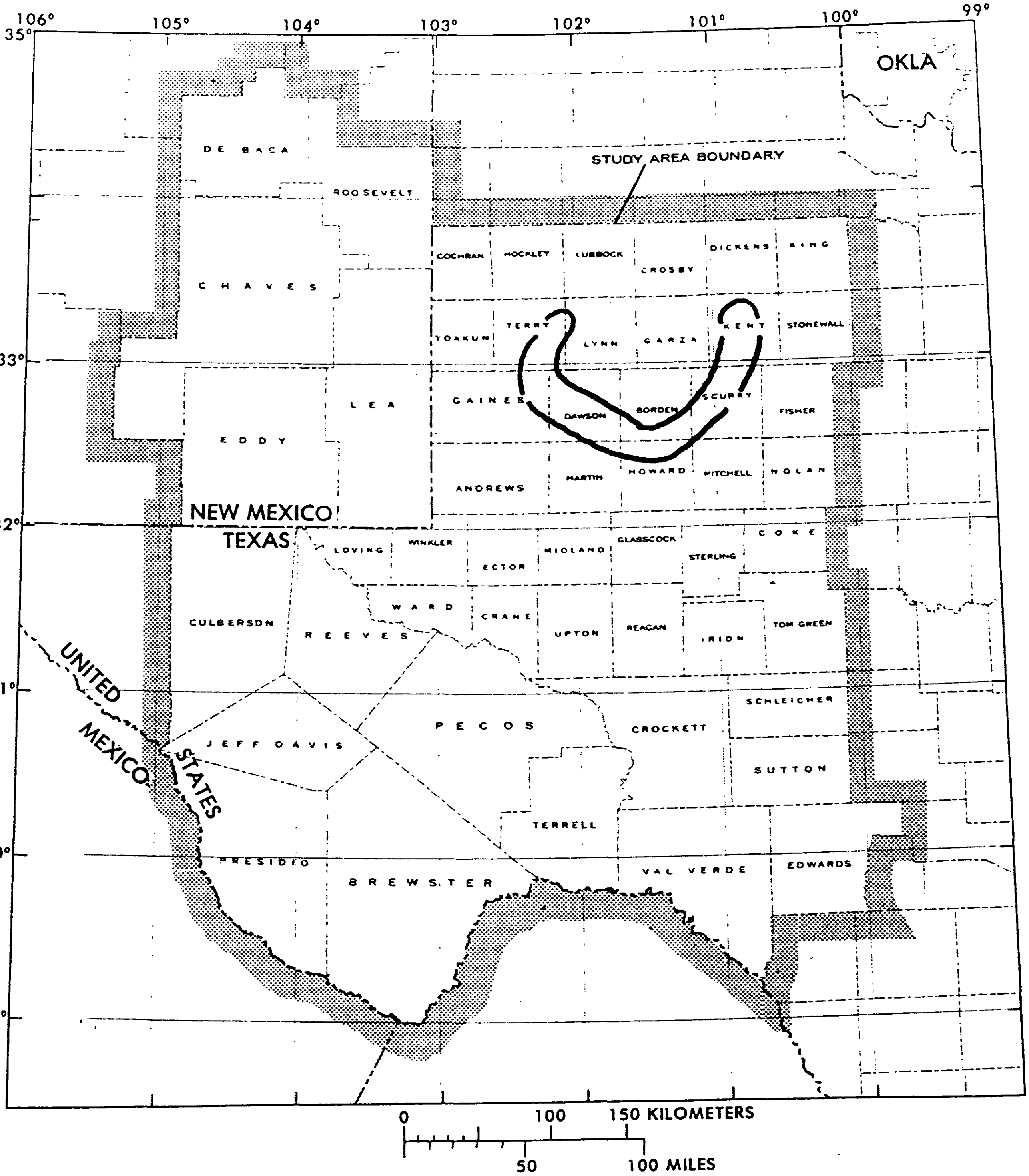


Fig. 22 Location map, Play 7: Horseshoe Atoll - Pennsylvanian

Play 8: Northwestern Shelf and Eastern Shelf - Older Paleozoics

Play Description and Type

The Northwestern and Eastern Shelf-Older Paleozoics is an oil play containing associated gas. The hydrocarbons occur in limestone, dolomite and subordinate sandstone reservoirs, in combination structural/stratigraphic, structural and, to a lesser extent stratigraphic traps, sealed by interbedded shales and impervious argillaceous carbonate rocks, updip pinchouts, truncations and facies change permeability barriers.

The play covers a large area of the Permian basin Province, encompassing the northern part of the Eastern Shelf, the northern part of the Midland basin and a large part of the Northwestern Shelf (fig. 23). The play is Cambrian to Lower Mississippian in age and primarily oil prone with associated gas, together with subordinate nonassociated gas. Reservoir lithology is mostly limestone and dolomite together with subordinate amounts of associated sandstone.

Reservoirs

Galloway and others (1983) and Wright (1979) state that reservoir rocks consist of Ordovician to Mississippian limestones and dolomites, together with lesser amounts of Cambrian sandstones. The Cambrian sandstone reservoirs are relatively insignificant. The significant reservoirs are in Lower Ordovician Ellenburger and Simpson Group Formations, in Upper Ordovician Montoya, in Silurian Fusselman and Upper Silurian Shale formations, and in Devonian and Mississippian carbonate rock formations.

Galloway and others (1983), consider the Cambrian sandstones to be alluvial-fan and beach deposits. The Ellenburger carbonates are fractured and consist of interbedded limestone and dolomite, thought to have been deposited in platform and strandline environments associated with evaporitic tidal flat sabkha facies. The limestones and dolomites are frequently associated with mudstone, algal boundstone, wackestone and oolitic grainstone. The succeeding Silurian, Devonian and Mississippian carbonates are similar to those of the Ordovician Ellenburger, however they were probably deposited in a more open-shelf or ramp environment. The carbonates are relatively pure in composition, with less sabkha influences, and are frequently associated with chert, which indicates a deeper water environment. Porosities average 8 percent and permeabilities 60 millidarcies. The latter is extremely variable and is dependent on the degree of fracturing.

Traps and Seals

Trapping mechanisms are essentially a combination of structural and stratigraphic features. Simple and faulted anticlines exist, together with stratigraphic updip pinch-outs, reservoir rock truncations, porosity barriers, and lateral facies changes. Interbedded shales, source rock shales, and impervious, crystalline and argillaceous carbonates act as effective seals.

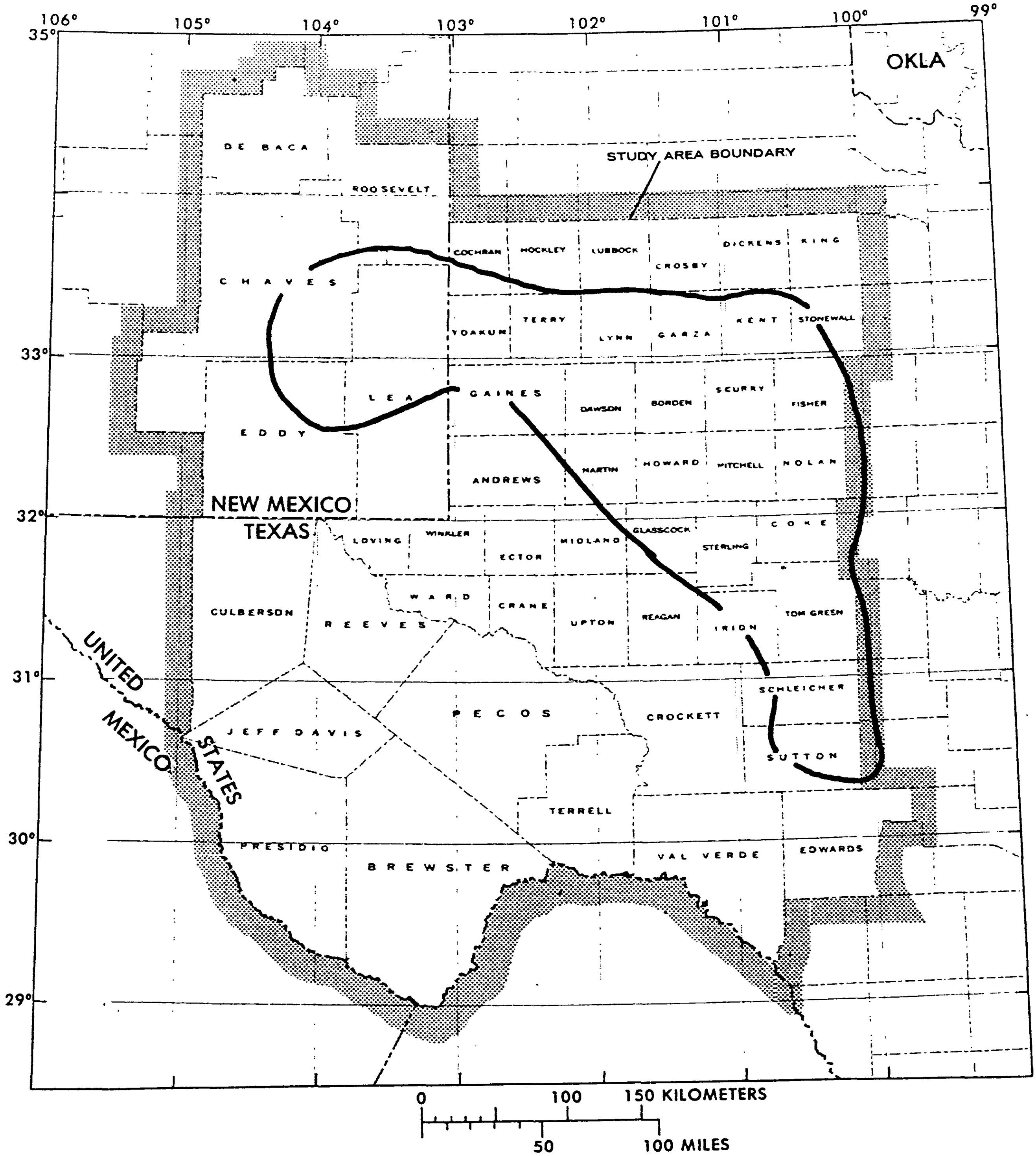


Fig. 23 Location map, Play 8: Northwestern Shelf and Eastern Shelf - Older Paleozoics

Source Rocks and Geochemistry

Wright (1979), suggests that source rocks in the older Paleozoics are both variable and in many instances, poorly understood. In general, he considers part of the source rocks to be indigenous shales, argillaceous limestones, and mudstones. However, a large part of the hydrocarbons could have migrated considerable distances along extensive fault and fracture systems from over and underlying source beds. Source rocks for Cambrian reservoirs are thought to be shales in the Simpson Group. In the Ordovician-Mississippian reservoirs, source rocks are considered to be primarily Woodford, Simpson and indigenous organic rich shales.

Timing and Migration

Hydrocarbon generation in Lower Paleozoic source rocks probably occurred during Permian time. The generated hydrocarbons readily migrated into the adjacent reservoirs.

Depth of Occurrence

Entrapped hydrocarbons in this play are extremely variable and generally range from 5,000 to 13,000 feet, depending on the location within the play.

Exploration Status

The first exploration discovery was in 1927, but most discoveries were made during the 1950's and 1960's. Since 1961, 23 fields have been discovered larger than 1 million bbls oil and 6 billion cu. ft. gas, 20 of which are oil and 3 are gas fields. These contain more than 103 million bbls of oil, 82 billion ft^3 of gas and 3.5 million bbls of natural gas-liquids. The average size of these oil fields is 5.1 million bbls. The average size of the gas fields, since 1961, is 9.7 billion cu. ft.

Play 9: Central Basin Platform and Midland Basin - Older Paleozoics

Play Description and Type

The Central Basin Platform and Midland Basin Older Paleozoics is primarily an oil play containing associated gas and minor quantities of nonassociated gas. The hydrocarbons occur in weathered carbonate, chert and sandstone reservoirs below a major unconformity, in combination structural/stratigraphic and extensively faulted structural traps, sealed by overlying shales and impervious carbonate rocks, updip pinch-outs, erosional truncation and facies change permeability barriers. The play covers the Central Basin Platform, the southern part of the Midland Basin and the Ozona Arch (fig. 24). The play primarily involves Lower Ordovician to Devonian reservoirs. It is essentially oil and, to a lesser extent, gas prone. Minor production from Pennsylvanian reservoir rocks was included in the historic data set of this essentially lower Paleozoic play in order to facilitate data analysis. Reservoir lithology is predominantly carbonate and weathered chert, with subordinate amounts of sandstone. This play aggregates 4 Lower Paleozoic oil plays of the Texas Bureau of Economic Geology.

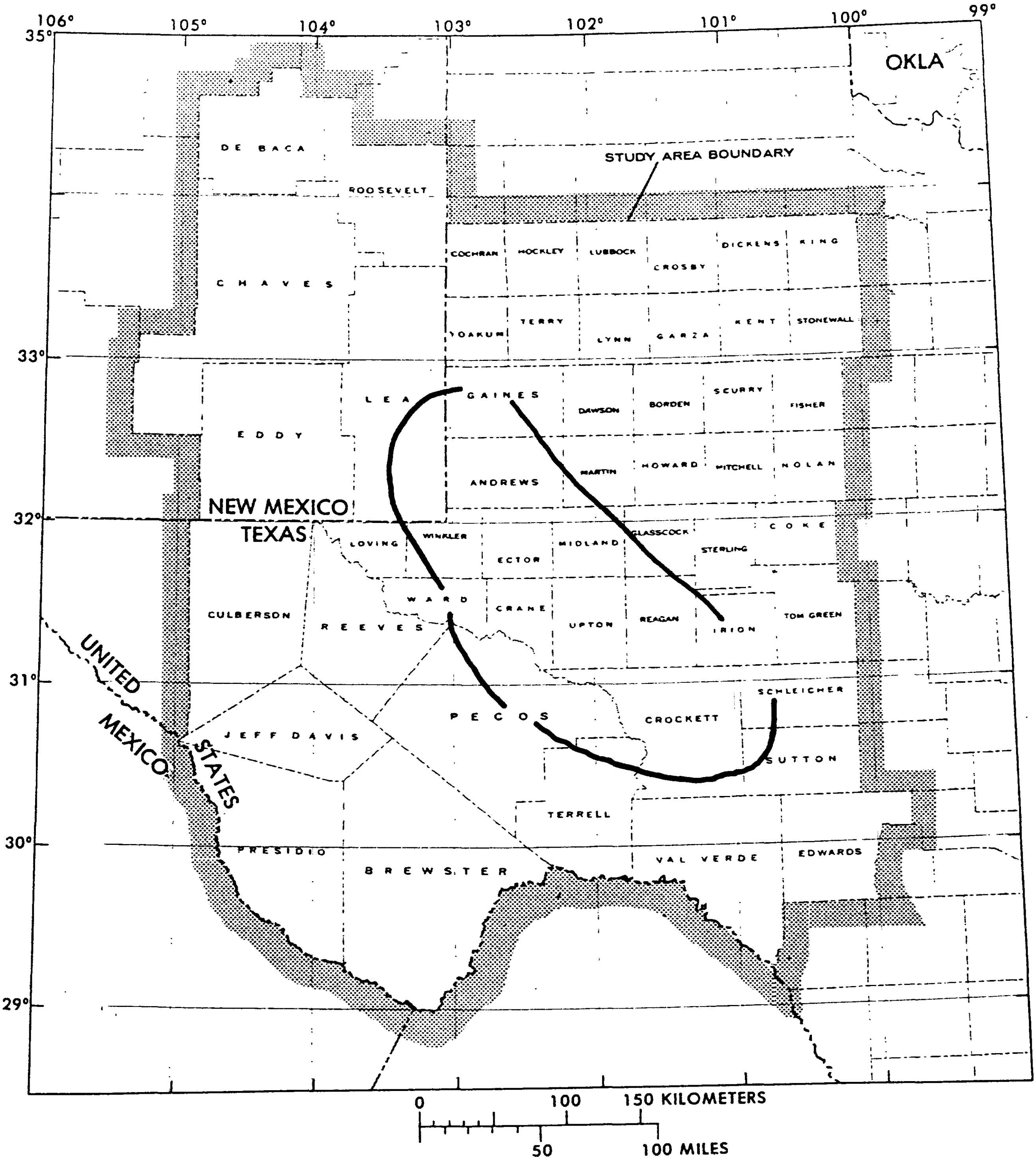


Fig. 24 Location map, Play 9: Central Basin Platform and Midland Basin - Older Paleozoics

Reservoirs

Galloway and others (1983) and Wright (1979), state that reservoir rocks consist of Ordovician to Mississippian weathered carbonates, cherts and sandstones located below a major Permian-Pennsylvanian unconformity, which formed as a result of tectonism, paleoweathering and erosion in post Mississippian time. The play reservoirs are contained in lower Ordovician Ellenburger and Simpson Groups, in Upper Ordovician Montoya, Silurian Fusselman, in Devonian, and the Pennsylvanian Strawn Formations included in this play. The principal reservoirs are Devonian.

Galloway and others (1983), suggest that the lower Paleozoic rocks were deposited under various environmental conditions, varying from shallow open-shelf, to ramp and deep basin, to restricted shallow-water platform. However, they all exhibit a common trapping mechanism, they are all located below a major unconformity, and have all undergone weathering and diagenetic alteration. Porosities average 10 percent and permeabilities 55 millidarcies.

Traps and Seals

Trapping mechanisms are a combination of both structure and stratigraphy. Structural traps are anticlinal, fault blocks and domes. Stratigraphic traps are especially prevalent on the Central Basin Platform and are pinch-out, eroded up-dip truncation, and facies change controlled. Seals are thought to consist of the Devonian-Mississippian Woodford Shale, Upper Pennsylvanian carbonates, and Lower Permian shales and carbonates.

Source Rocks and Geochemistry

Galloway and others 91983), consider adjacent and indigenous, organic-rich, Devonian-Mississippian Woodford shales to be prolific source beds.

Timing and Migration

Hydrocarbon generation from the rich Woodford Shale probably occurred during Lower and Middle Permian time. The generated hydrocarbons were trapped below the unconformity and migrated into nearby weathered reservoir rocks.

Depth and Occurrence

Entrapped hydrocarbons occur at depths of 4,500 to 12,000 feet, with an average of approximately 9,500 feet.

Exploration Status

The first exploration discovery in this play occurred in the Ozona Arch area in the 1920's. Most discoveries were made during the 1940's and 1950's. Since 1961, approximately 27 fields have been discovered, since 1961, larger than 1 million bbls oil and 6 billion cu. ft. gas, 21 of which are oil and 6 are gas. more than 1.2 billion bbls of oil, 3.7 trillion cu. ft. of gas and 0.5 billion bbls of gas-liquid have been produced. The average size of these oil fields is 3.3 million bbls. The average size of the gas fields, since 1961, is 15.5 billion cu. ft.

Play 10: Deep Delaware-Val Verde Basins Gas - Older Paleozoics

Play Description and Type

The Deep Delaware-Val Verde Basins - Older Paleozoics is a non-associated gas play. The hydrocarbons occur in vuggy, fractured and faulted, cherty, dolomite and limestone reservoirs, in structural and, to a much lesser extent, combination structural/stratigraphic traps, sealed by shale and impermeable carbonate rocks.

The play covers the Delaware and Val Verde Basins (fig. 25). The reservoirs are Lower Ordovician to Silurian in age. Reservoir lithology is often vuggy and cherty limestone and dolomite.

Reservoirs

Wright (1979), states that reservoir rocks consist of Ordovician to Silurian solution porosity, fractured, vuggy, intercrystalline cherty dolomite and limestone deposited in the ancestral Tobosa basin. The reservoirs are contained in The Lower Ordovician Ellenburger and Simpson Groups, in the Upper Ordovician Montoya and Silurian Fusselman Formations.

The lower Paleozoic rocks were deposited in a shallow marine environment in the gently subsiding Tobosa basin and on surrounding shelves. Fractures and joints in the carbonate rocks form adequate porosity and permeability conduits for gas production.

Traps and Seals

Trapping mechanisms are mostly structural, in faulted, fractured and jointed anticlinal features. Seals are thought to consist of overlying carbonate and shale strata which have not been fractured or jointed.

Source Rocks and Geochemistry

Wright (1979), considers that organic-rich, indigenous carbonate rocks and the Woodford Shale are source beds. He also suggests that a large part of the hydrocarbons probably migrated considerable distances along extensive fault and fracture systems from over and underlying source beds. Hills (1984), suggests three chief sources for the hydrocarbons in the basins: a) Middle Ordovician shales and limestones, b) Upper Devonian and Mississippian shales and shaly limestones, and c) the basinal facies of the Pennsylvanian and Permian rocks.

Timing and Migration

Major hydrocarbon generation probably occurred in Permian time. The generated hydrocarbons easily migrated into the porous fractures and joints in the lower Paleozoic carbonates. Hills (1984), however, believes that hydrocarbon generation in the Delaware Basin occurred in four major time intervals: 1) Middle Ordovician, 2) Late Devonian and Early Mississippian, 3) Middle Pennsylvanian, and 4) Early and Middle Permian. However, unless geothermal gradients were radically higher than at present, major hydrocarbon generation does not appear to have started until Middle Pennsylvanian time.

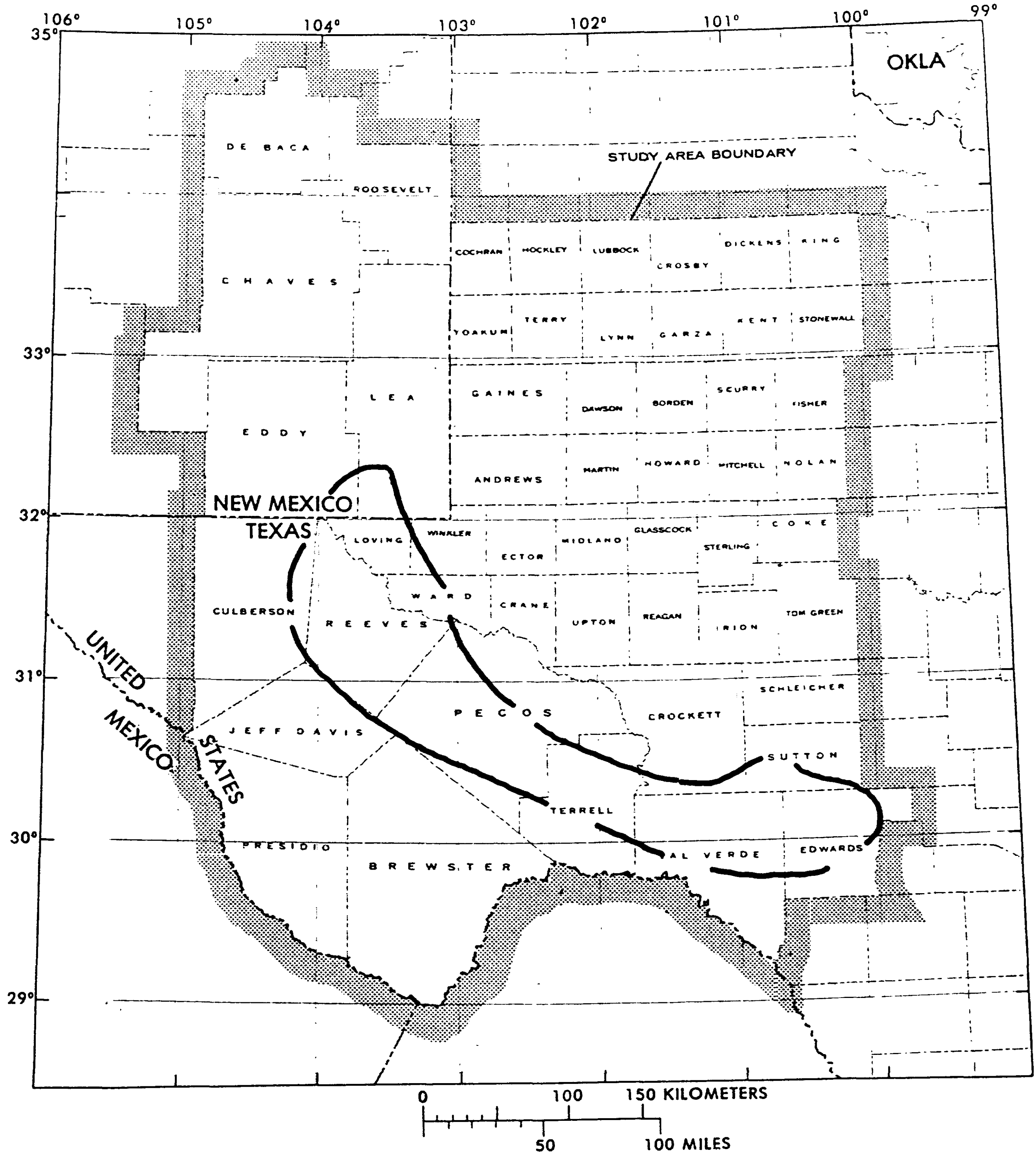


Fig. 25 Location map, Play 10: Deep Delaware and Val Verde Basins Gas - Older Paleozoics

Depth of Occurrence

Entrapped hydrocarbons occur at approximate depths of 10,000 to 22,000 feet in Ordovician rocks and at depths in excess of 8,000 feet in Silurian rocks.

Exploration Status

The first significant exploration discovery was in 1952 at the Puckett field, but most discoveries were made during the 1960's and 1970's. Since 1961, 55 non-associated gas fields larger than 6 billion ft^3 gas have been discovered. These contain more than 15 trillion cubic feet of gas. The Gomez field, Pecos County, Texas, discovered in 1963, contains more than 5.5 trillion cu. ft. of recoverable non-associated gas. Average field-size discovered since 1961 is 273 billion cubic feet.

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