THE PERMIAN BASIN: GEOLOGY AND HYDROCARBON ACCUMULATION

A. E. PALK
PETRO-PAK RESOURCES LTD.

ABSTRACT

Schematic Cross-Section, West to East of the Permian Basin of West Texas and Southeast New Mexico (Fig. 1) is drawn with vertical:horizontal exaggeration of approximately 50:1. This presentation will cover 600 million years of basin formation and sedimentation and about 70 years of petroleum exploration and development in thirty minutes. This will require exaggeration on a scale greater than 100:1, megascale oversimplification and omission of all Aggie jokes. The presentation will describe how the basin formed, dominant time-stratigraphic units and typical hydrocarbon traps.

SCALE: Space and Time

A cross-section of the stratigraphic column of rocks along a traverse from El Paso to Fort Worth, Texas, (Fig. 1) has been drawn on a scale of one inch = one hundred miles (1:6,336,000) as a six-inch profile through the Permian Basin and the Eastern Shelf Province. The El Paso to Fort Worth traverse would properly be drawn in true scale with the land surface elevated slightly above sea level on a six inch segment of a circle having a radius of about forty inches (Fig. 2). Maximum depression of the stratigraphic section of the five mile deep Basin plots only about one-twentieth of an inch below sea level. A geological formation 500 feet thick would plot less than the thickness of a line on true scale.

While most geologists are willing to concede that Earth is a sphere and that the "level" of the seas which cover about seventy percent of its surface is best drawn in conformity to Earth's curvature, sketches herein show "sea level" as a flat line. The sea level line is the usual reference datum for geological work. An immediate conceptual error is introduced thereby. The thirty percent of the Earth's surface that exists as land (above sea level) was for much of Earth's history beneath the seas. At any particular time the part that was above sea level was being eroded, even as now, and the erosional particulate material was ultimately transported to adjacent seas and distributed on the sea floor, covering earlier sediments. Because even the deepest basins have never been truly significant depressions below sea level and the highest mountains have never "towered majestically above the horizons" on true scale, the forces of gravity, erosion and sedimentation have been consistently effective in maintaining integrity of the sphericity of Earth. Even the twenty-seven mile equatorial bulge distorts true spherical shape by no more than four-tenths of one percent.

The present sedimentary basins of Earth started as gentle depressions consistent in scale with the larger playa lakes or "Buffalo Wallows" of the High Plains. As basinal subsidence continued, carbonate beds formed on landward margins of the seas, usually with a principal framework of the shells of organisms. Discrete mounds or banks of shell-related carbonates will herein be referred to as "reefs", although they may not meet all the established criteria for such designation. Shales, silts and sand sized particles were transported to the seas by wind and rivers and were spread over the shallow and deep parts of the basins by wave and current action and by gravity slides or turbidity currents. At various times parts of basinal areas were elevated above sea level by a rise of landmass or lowering of sea level. The deeper parts of the basin remained submerged and received clastics from erosion of the earlier sediments, so that the basins usually remained relatively filled with sediments and the seas were relatively shallow. There were a few occurrences of sudden (catastrophic) events, but not often did "everything West of the San Andreas fault slide into the Pacific Ocean". In true scale of time and space, nothing has happened on Earth's surface so relatively significant as when a child dumps a spoonful of sand into a pan of water. Basins subsided and filled slowly. Highlands eroded slowly. Landmasses emerged slowly from the seas, and faults displaced rocks only a few feet at a time. These processes continue today.

GEOLOGICAL OVERVIEW OF THE PERMIAN BASIN

The discussion for which this paper is to be a guide will be illustrated principally by Geological Cross-Sections published by the West Texas Geological Society. The Sections may be purchased from WTGS in Midland.

A shallow sea covered much of West Texas and Southeast New Mexico, the area now known as the Permian Basin (Plate 1) from middle Cambrian through middle Ordovician time. Cambrian and Ordovician periods of geological history were the times of first life forms (common cold virus?) in the seas and first widespread sedimentation, beginning about 600 million years ago. The Ordovician Ellenburger formation was deposited as a fairly consistent thickness of uniform, planar carbonate over much of the Mid-Continent region of the U. S. Gentle downwarp of early Permian Basin started in later Ordovician time along an axis roughly coincident with what is now the Central Basin Platform. Downwarp continued through Silurian and most of Devonian time. Older sediments were progressively eroded from margins of the basin and spread over the sea floor as alternate layers with precipitated carbonates. Carbonates precipitated during times of low amounts of clastic influx into the basin. Mississippian age carbonate and clastic sedimentation nearly kept pace with renewed basinal subsidence during that period of time. Reefs developed on the basin margins, particularly on the Eastern Shelf. Accelerated subsidence and downwarp of the basin center in the last part of Mississippian time resulted in clastics covering the western part of the system from adjacent highlands. This situation prevailed through earliest Pennsylvanian time, depositing the Morrow and Atoka sands and shales of Southeast New Mexico. The Central Basin Platform was elevated in early Pennsylvanian time as an island string in the middle of the Basin. The Matador Peaks across the southern part of the Texas Panhandle were first emergent as isolated islands during this period. Reefs rimmed the margins of the later Pennsylvanian (Strawn) age seas. The Central Basin Platform was rimmed with carbonate banks, some of which demonstrate true reef characteristics. Limestone shelves were formed as reefs were inundated by deepening water and the carbonate-shelled organisms retreated toward the basin margins - particularly on the Eastern shelf. This condition persisted throughout the remainder (Canyon and Cisco Epochs) of Pennsylvanian time.

The Permian Basin, as related to the Permian Epochs of geological time, was a relatively deep basin at the end of Pennsylvanian time. There was little clastic influx into the basin during the late Pennsylvanian. The Central Basin Platform remained submerged and was covered by reefs and back-reef carbonates, forming a prominent submarine ridge that divided the Midland and Delaware Basins. Sediments were eroded from the highlands beyond the basin margins to again fill the basin, keeping pace with subsidence. As the basin filled and its areal limits were reduced, reef ecological systems migrated seaward over older reefs and their talus slopes, restricting clastic influx and circulation of water. Evaporation concentrated salinity in the restricted basin. Dolomitization flourished, with dolomite replacing the calcium carbonate reefs and back-reef limestones. Ultimately, primary dolomite, limestone, gypsum, anhydrite and halite were precipitated to form the evaporite sequences ringing the basin (Plate 1) by middle Permian time. Areal contraction and restriction continued until late in Permian time (Ochoan) when only a remnant of the basin remained in Pecos, Reeves, Ward, Loving and Northern Culberson Counties, Texas and in the southern parts of Lea and Eddy County, New Mexico.

PRE-CAMBRIAN

There is little evidence of presence of seas on Earth's surface prior to Cambrian time. The area that now is beneath the Permian Basin was mostly barren granitic rock until Cambrian seas swept in. A few areas of metasediments have been labelled Pre-Cambrian, but age dating is uncertain. There are no significant hydrocarbon occurrences in the basement crystalline rocks.

CAMBRIAN PERIOD

The Hickory sandstone of the eastern part of the Permian Basin and the later Bliss sandstone of the western part were eroded from the crystalline rocks as the first widely distributed water-laid sediments. Subsequent limestone and sandstone formations were deposited around the southern basin margins, thinning toward the present center of the basin.

Some oil and gas has been found in Cambrian rocks. Best production is from Hickory sandstone on the "Pre-Penn Structural Trend" which extends northward from the town of Bronte in Coke County toward Sweetwater in Nolan County and southward into Tom Green County. Small compressional anticlines were pushed up along this trend and ruptured (faulted) along their shelfward side as shown in Fig. 3. The Hickory sand was faulted up into lateral juxtaposition with early Pennsylvanian organic shales which were the hydrocarbon source. White Flat field in Nolan County is a well documented case of this occurrence.

ORDOVICIAN PERIOD

Ellenburger, Simpson and Montoya formations were deposited with consistent thickness and rock characteristics in the Permian Basin. Erosion in later periods reduced thickness or truncated the formations totally in local areas on the Central Basin Platform and toward the Eastern Shelf, but the lower Ordovician (Ellenburger - Arbuckle) dolomite and limestone facies remain as the principal deep hydrocarbon target over much of the Mid-Continent region. A granite highland existed in northern New Mexico, with a peninsula extending southeastward into the Texas Panhandle nearly to Lubbock. A Simpson age basin extended northwestward into southeast New Mexico from El Paso and eastward to Borden County along the line of cross-section Fig. 1. Depocenter for Simpson sediments up to 2,000 feet thick and Montoya limestone up to 400 feet thick was primarily in Reeves County. The thin Sylvan shale separating Montoya and Fusselman formations is usually considered uppermost Ordovician.

Hydrocarbons are often present in Simpson and Montoya rocks. Porosity and permeability of the sandstones is usually low. The Montoya limestone seldom has measurable porosity. Limited production from these formations is mostly in the Central Basin Platform or in closely adjacent structures. Best Ellenburger production is found in the same areas where folding and faulting of the more brittle dolomitic facies resulted in intensive fracturing of the rocks (Fig. 4). Gomez and Puckett gas fields of Pecos County are typical of these faulted anticlinal structures.

SILURIAN PERIOD

The Fusselman, typically a pink crystalline dolomitized limestone, is the principal formation of the Silurian Period in the Permian Basin. Where the Sylvan shale is absent, differentiation of Montoya and Fusselman often depends on correlation of insoluble residues after digestion of the carbonate samples in acid. Upper Silurian limestone, usually very pale green colored, overlies the Fusselman. Thickest Silurian section is found in the southeastern corner of New Mexico. The giant Fusselman gas reservoirs now being developed in and around Loving County, Texas and southeastward are located on anticlines which formed in this thick Fusselman section (Fig. 5).

Denton Field in Lea County, New Mexico is a giant oil field producing from upper Silurian limestone. Production from the eastward pinchout of Fusselman rocks (affected by later truncation and some anticlinal closures) is significant on a trend from Glasscock County northwestward through Howard and Borden Counties into Terry County (Fig. 6). Oil is produced from many localized anticlinal closures in the Midland Basin and on the Central Basin Platform.

DEVONIAN PERIOD

Devonian limestone deposition was not so widespread in the Permian Basin as was the Silurian. This "offlap" of sediments may be regarded as a normal consequence of constriction of the basin by filling in of the basin margins during time of static level of the sea relative to bordering landmasses. Another explanation is that the overlying Devonian was eroded farther basinward than were the underlying rocks at a later time of erosion which levelled the rock surfaces at wave base or on a low coastal plain. In either case, there was a demonstrable regression of the sea from the eastward limits of Devonian deposition. The non-indurated limestone surface was dissected in subaerial and very shallow marine environments. This dissection resulted in a "hill and valley" topography on the limestone surface. Significant alterations of the chemical and textural properties of the limestone matrix also occurred. Locally, original porosity of the limestone was plugged by calcite, shale and chert precipitated from circulating ground waters or subaqueous currents. In some cases, notably in several large oil fields in Gaines County, Texas, original porosity was partially preserved by dolomitization on submarine high areas. Whether the submarine high areas were a result of anticlinal folding or preservation as erosional remnants has not been fully investigated.

Significant Devonian production is found on local structures in the Midland Basin in Upton, Ector, Andrews and Gaines Counties, and the Central Basin Platform. Alteration of primary matrix porosity sometimes results in finding only tight Devonian limestone in the center of Devonian producing fields.

In latest Devonian time the "Pre Woodford Unconformity" was a period of truncation of pre-Mississippian rocks. Base of the Woodford formation is a prominent wireline log marker which makes a convenient mapping horizon. "Subcrop Maps" identifying the age of formations immediately underlying the Woodford Shale are extremely useful in delineating structural and erosional anomalies.

MISSISSIPPIAN PERIOD

The Woodford Shale (as discussed above) varies in thickness from the non-depositional areas around the basin margins to more than 200 feet. This shale is carbon (organic) rich and has higher radioactive mineralization than other Permian Basin sediments. It was probably a hydrocarbon source for both the overlying Mississippian limestone and underlying Silurian or Devonian carbonates.

Massive "Lower Mississippian Limestone" 600 to 800 feet thick, Barnett Shale 100 to 300 feet thick and "Upper Mississippian Limestone" up to 500 feet thick overlie the Woodford Shale in the central part of the Permian Basin. These sediments were the first to cover most of the north half of the state of New Mexico. Mississippian limestones are usually cherty and retain little porosity or permeability. Only sparse production has been established from these rocks in the Permian Basin. Fracturing techniques continue to offer hope that greater producibility may be induced.

PENNSYLVANIAN PERIOD

Sand and shale was transported into the western part of the Permian Basin from highlands rejuvenated in late Mississippian time. Morrow and Atoka sandstones of the northern Delaware Basin were distributed by river and submarine currents as bars, channels and banks. The sandstone members are laterally discontinuous (lensatic) and are encased in shales which are hydrocarbon source rocks. Oil and/or gas production are found where porosity and permeability facilitate recovery at the updip limit of each discrete lens of sandstone. Atoka shales are also present in the Midland Basin, with a few lensatic sands capable of production.

Mentioned under "Cambrian Period" is the "Pre-Penn Structural Trend" of the Eastern Shelf. Structures along this trend formed during late Mississippian or Morrow time. The source rock for Cambrian and Ellenburger production on this trend is at least partly Atoka age shale. The first appearance of the Matador Peaks across the Texas Panhandle was generally time coincident with the Pre-Penn Trend.

By mid-Pennsylvanian time the widespread "Lower Strawn Limestone" formation had been deposited in relatively clastic-free waters of the Permian Basin. The Central Basin Platform formed an island landmass by this time. Lower Strawn limestone has local intercalations of sand and shale, but is usually recognizable as a marker bed almost as widespread as the Ellenburger. Reefs in Schleicher County at Cooper-Page, Hulldale and Neva West are of Strawn age, growing above the base of lower Strawn limestone.

The "Horseshoe Reef" of Kent, Scurry, Borden, Dawson, Gaines and Terry Counties and the Eastern Shelf-Edge reefs of Tom Green, Coke, Nolan, Fisher and eastern Scurry Counties had their greatest periods of vertical development in upper-middle Pennsylvanian time, during the Canyon Epoch. Reefing in some areas continued as vertical development through the end of the Pennsylvanian Period (Cisco Epoch) and into lower

Permian (Wolfcamp) time, as at Wellman field in Terry County. The shale encased reefs are prolific oil producing "stratigraphic structures".

Center of the Permian Basin began to downwarp more rapidly at the end of Strawn time. The basin received little clastic sediment during this period. As the sea transgressed its former margins, reefs had to develop vertically to maintain position in favorable depth environment, or else the organisms forming the reef framework retreated shoreward, forming broad banks with biostromal mounds on the limestone surface. The banks and mounds produce from relatively shallow depths on the Eastern Shelf (Fig. 8).

Most post-Atoka Pennsylvanian hydrocarbon production, other than in reef stratigraphy, is found where Strawn limestone is folded or faulted, almost always over deeper seated structure. As with Devonian production, Strawn limestone production in the Midland Basin and on the Central Basin Platform is dependent on preservation or enhancement of matrix porosity in areas of local anomaly.

Since Strawn limestone has historically been the principal intermediate-depth production objective in the Permian Basin, maps on the limestone topography have become important to geologic interpretations. Because they are topographic maps they often do not reflect true structural attitudes of underlying formations.

PERMIAN PERIOD

Discussions of the Permian Period of sedimentation of the Permian Basin require the broadest generalizations and greatest abbreviation. As the center of the basin continued to downwarp through late Pennsylvanian and early Permian time, highlands began to emerge to the East (Ouachita Uplift) and West (ancestral Rocky Mountains). Compressional forces along the axis of the basin elevated the Central Basin Platform and depressed the adjacent limbs of the Delaware and Midland basinal salients. Highest parts of the Central Basin Platform were truncated back to pre-Cambrian basement at the Fort Stockton High. An intensified network of folds, faults, fractures and truncation surfaces formed hydrocarbon traps atop the Platform and in adjacent basinal segments. The Midland Basin, Delaware Basin and Val Verde Basin (south of the south plunge of the Platform) became more easily differentiated by sedimentary characteristics and dip attitudes relative to basin margins and the Central Basin Platform.

Great masses of reefs and interreef and backreef carbonate banks began to develop on the Central Basin Platform and on the northern and eastern perimeters of the basin. These banks of carbonate formed an almost continuous ring around the periphery of the Permian Basin. As the basin continued to subside the reefs developed upward and basinward over their forereef detritus to form the Carbonate Band (illustrated on Plate 1) by late Wolfcamp or early Leonard (Lower Permian) time. The carbonate band restricted circulation of basinal water. Evaporites and red-beds were precipitated on broad, shallow, backreef shelves.

Dean and Spraberry sands - properly siltstones - were deposited with organic shales in the restricted Midland Basin. Bone Spring sands of the northern Delaware Basin were overlaid with basinal shales and limestones and later the Delaware Mountain (Brushy Canyon, Cherry Canyon and Bell Canyon) sands and intervening shales.

Toward the end of the Permian Period, in the Ochoan Epoch, the Castille evaporites and red-beds (some green shale) of the Delaware Basin and the Queen-through-Tansill evaporites and sands of the Midland Basin were precipitated. Finally only the Delaware Basin remained as a closed saline system.

Last Permian sediments were the Dewey Lake, Rustler and Salado evaporites which cover a broad area nearly coincident with the presently defined limits of the Permian Basin. These sediments were deposited or precipitated in an extremely shallow sea or saline lake.

Most Permian hydrocarbon production is stratigraphically trapped. Oil is produced from preserved reefs and from backreef carbonates at the updip porosity limit effected by permeability barriers of evaporitic - usually anhydritic - seals. San Andres and Grayburg dolomites are the most prolific reservoirs. Wichita-Albany, Clearfork and Abo have yielded great amounts of oil. Dean and Spraberry of the Midland Basin have produced hundreds of millions of barrels of oil from hydrocarbon saturated sand lenses encased in shales. The Permian sands of the Delaware Basin have not yet produced as much as the volume of reservoir would indicate, but improved completion practices and fracturing techniques are adding to expectations.

"Moving up dip from a show of oil" in Permian carbonates often results in finding the objective reservoir plugged by evaporites, but sometimes results in finding a porous productive section above or below the anticipated pay. Since most of the oil in the Permian Basin has been produced from Permian rocks, it seems logical to assume that most future production may be found in those same rocks.

TRIASSIC AND JURASSIC PERIODS

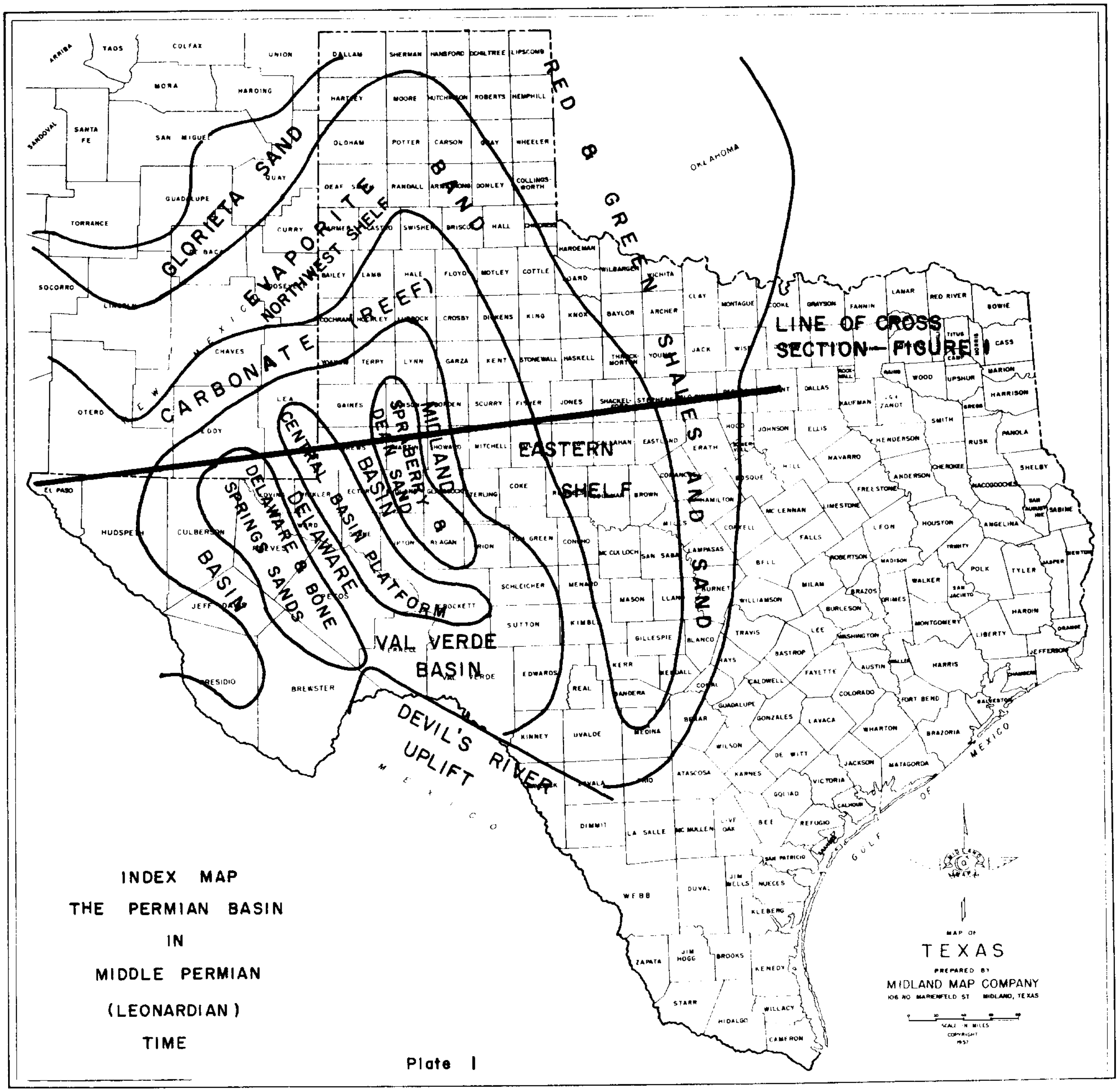
The Permian Basin was a landmass throughout most of Jurassic and Triassic periods. The Dockum group of evaporites of New Mexico and West Texas, with maximum thickness of about 2,000 feet in Cochran County was probably deposited in an inland sea. No significant production has been found in rocks of these periods.

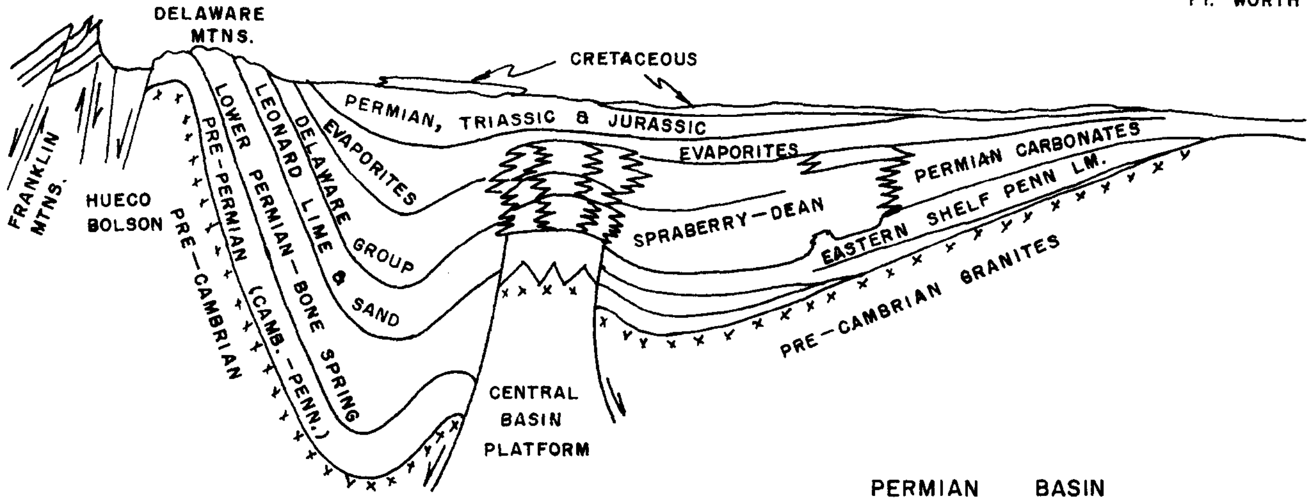
CRETACEOUS PERIOD

Lower Cretaceous seas covered all but the Panhandle of Texas, depositing the uniformly layered limestones, marlstone and sandstones which form the mesas of the High Plains and Trans-Pecos regions. Minor amounts of oil and gas have been found in the Trinity and Fredericksburg sandstone of the Delaware and Val Verde Basins, but no significant production has been established.

SUMMARY

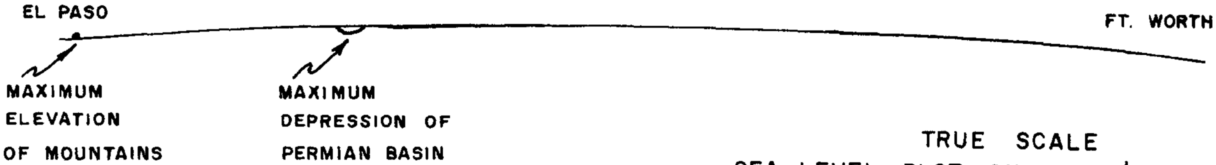
Geologists are people who "dig rocks the most". Geologic data are rock-derived. Log correlations must be rock related outside of closely confined areas. Petroleum is found in porous rocks. It is trapped by impermeable barriers within the rocks above or around the porous rocks. Geologists can be of some aid in finding places where oil is trapped. They can also find many places where oil is not. The best way to find a lot of oil in the Permian Basin is to get started before 1950. If you can't turn back the clock, you may have to settle for a little field on a small lease with low revenue interest, or else buy Marathon from U. S. Steel.


INDEX MAP
THE PERMIAN BASIN
IN
MIDDLE PERMIAN
(LEONARDIAN)
TIME
Plate I
GLORIETA SAND
EVAPORITE
NORTHWEST SHELF
CARBONATE (REEF)
RED & GREEN SHALES AND SAND
BAND
MIDLAND
SPRABERRY &
DEAN SAND
BASIN
CENTRAL BASIN PLATFORM
DELAWARE
DELAWARE & BONE
SPRINGS SANDS
BASIN
EASTERN
SHELF
VAL VERDE
BASIN
DEVIL'S RIVER
UPLIFT
LINE OF CROSS
SECTION—FIGURE I
MAP OF
TEXAS
PREPARED BY
MIDLAND MAP COMPANY



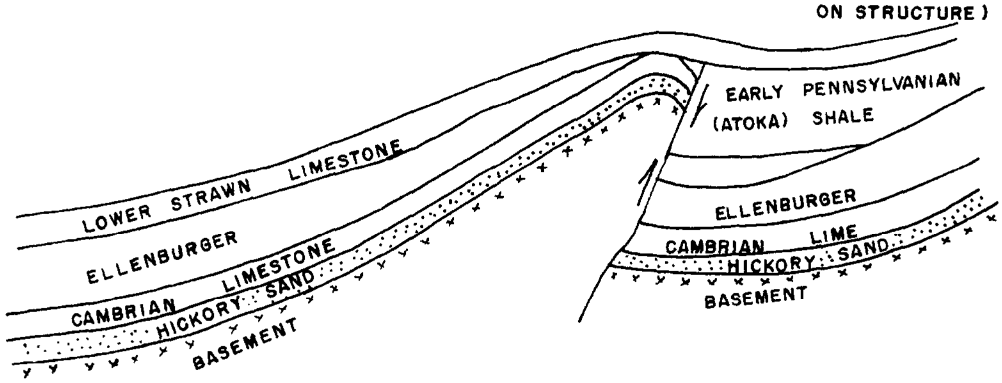
PERMIAN BASIN
CROSS SECTION WEST TO EAST
EL PASO TO FT. WORTH
SCALE APPROX. 1"=100 MILES HORIZ.
1"= 2 MILES VERT.

Figure 1



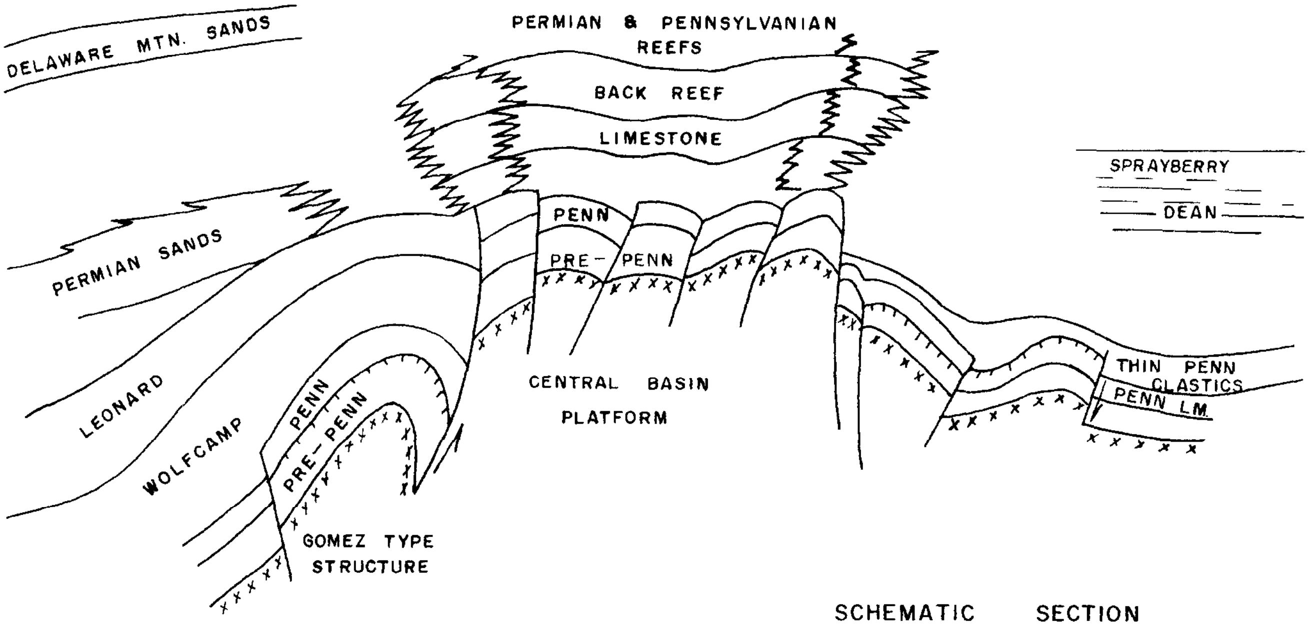
TRUE SCALE
SEA LEVEL PLOT ON EARTH'S SURFACE
(600 MILE TRAVERSE)
SCALE 1:6,336,000

Figure 2



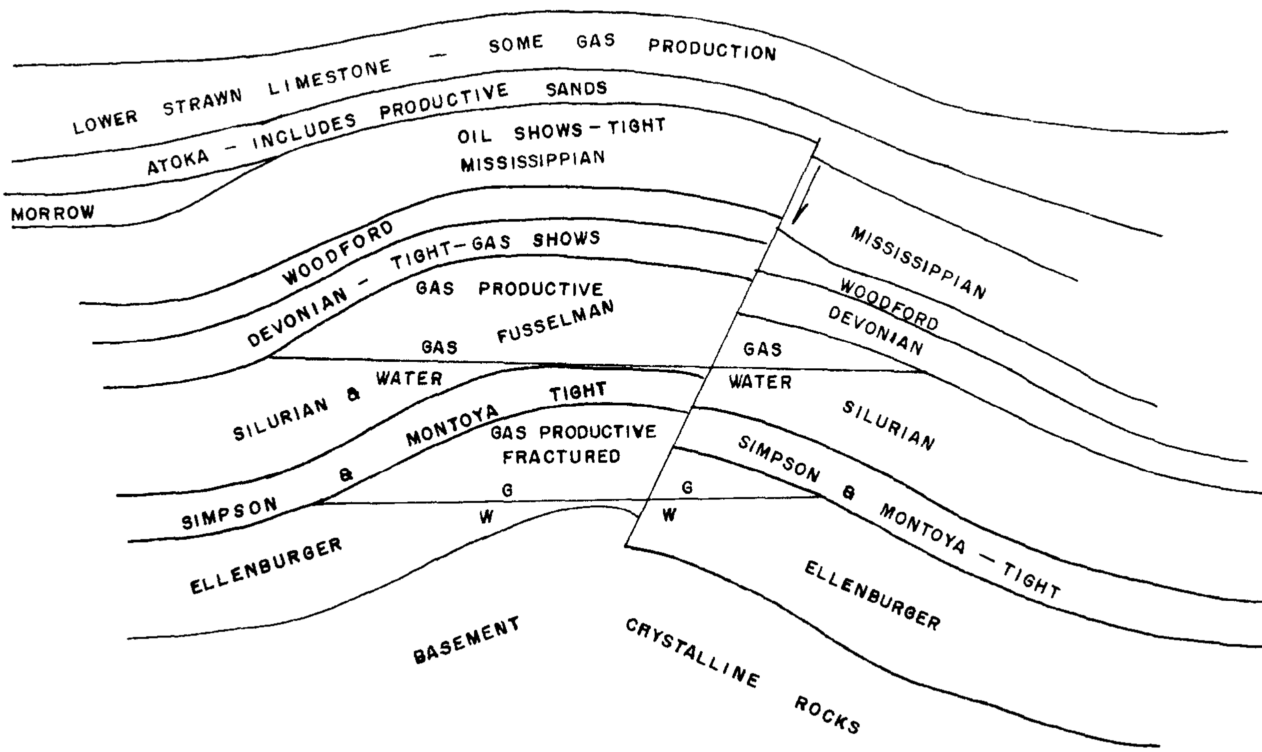
SCHEMATIC SECTION
PRE-PENNSYLVANIAN STRUCTURAL TREND
NOLAN COUNTY, TEXAS
DEMONSTRATING OIL MIGRATION FROM ATOKA SHALE INTO CAMBRIAN (HICKORY) SAND

Figure 3



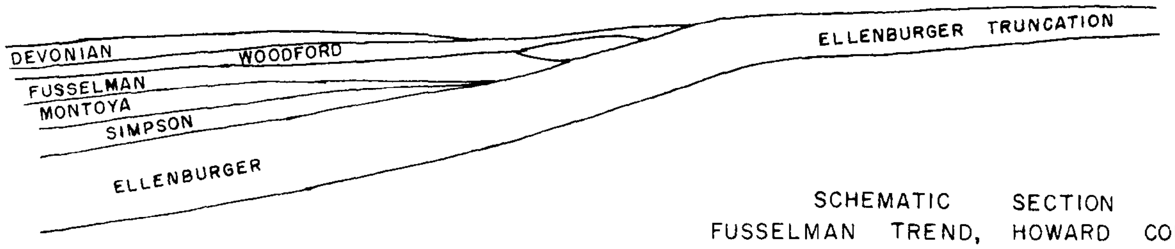
SCHEMATIC SECTION
ILLUSTRATING CENTRAL BASIN PLATFORM
STRUCTURE AND STRATIGRAPHY
& ADJACENT STRUCTURAL TRAPS
NOT TO SCALE

Figure 4



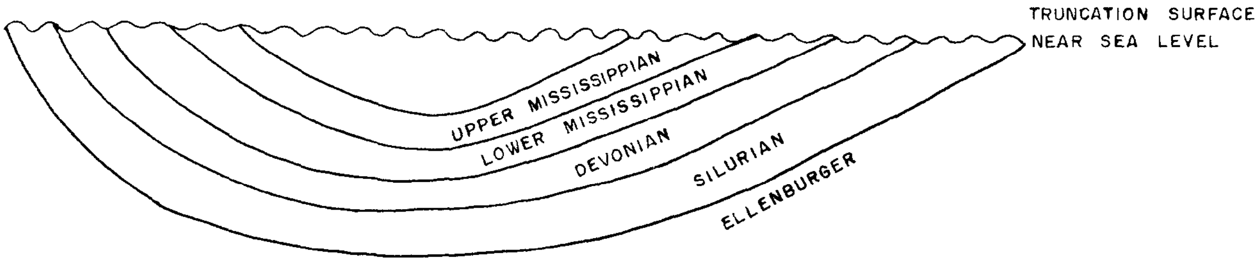
SCHEMATIC SECTION
TYPICAL PRODUCTIVE FAULTED ANTICLINE
DELAWARE BASIN
NOT TO SCALE

Figure 5



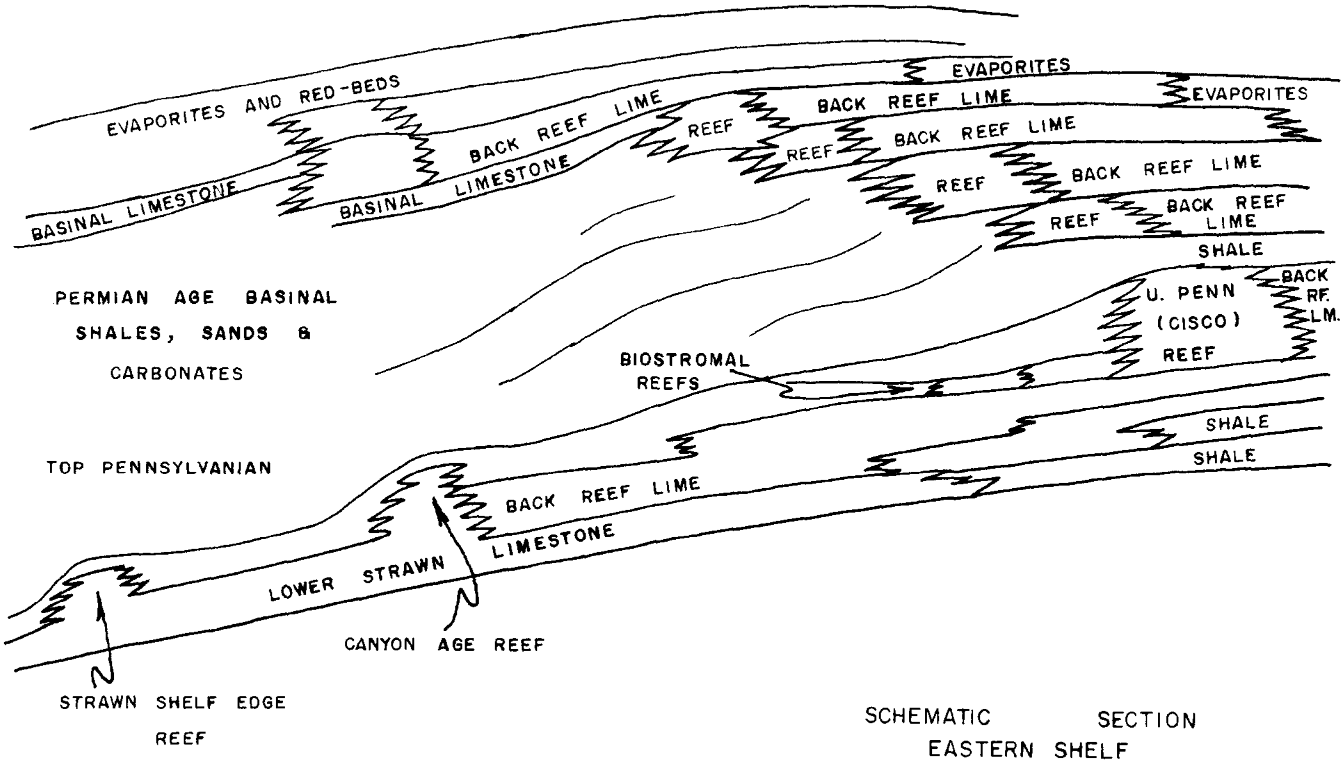
SCHEMATIC SECTION
FUSSELMAN TREND, HOWARD COUNTY
SHOWING PINCHOUT & TRUNCATION

Figure 6



SCHEMATIC SECTION
ILLUSTRATING BASIN RESTRICTION
BY TRUNCATION AFTER SEDIMENTATION
NOTE THAT MISSISSIPPIAN BASIN AREA IS
MUCH LESS THAN SILURIAN BASIN AREA
AFTER TRUNCATION.

Figure 7



SCHEMATIC SECTION
EASTERN SHELF
ILLUSTRATING PENNSYLVANIAN REEFING IN
TRANSGRESSING SEAS AND PERMIAN
REEFING IN REGRESSING SEAS.

Figure 8