UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

ESTIMATES OF UNDISCOVERED OIL AND GAS, PERMIAN BASIN, WEST TEXAS AND SOUTHEAST NEW MEXICO

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ABSTRACT

Approximately 91.6 billion barrels of oil-in-place and about 106.2 trillion cu ft of dissolved/associated and non-associated gas-in-place have been discovered in the Permian basin of western Texas and northeastern New Mexico. The objectives of this study were to estimate the in-place quantities of undiscovered oil, dissolved/associated gas, and non-associated gas in the basin and to estimate the size and number of pools in which the appraised amounts of oil and gas occur. All assessments were initially made by age-depth units; each unit consists of rocks of a specific geologic age within a specific depth interval. The age intervals used were 1) the Permian System, 2) the Carboniferous systems (Pennsylvanian and Mississippian), and 3) the older Paleozoic systems (Devonian, Silurian, Ordovician, and Cambrian); the depth intervals used were 0-10, 10-20, and 20-30 thousand feet below the surface. Assessments were made for each age-depth unit at the 5, 25, 75, and 95 percent probability levels. Statistical means for each unit were computed. By making the assessments in the small age-depth units and by utilizing Monte Carlo aggregation procedures, it was possible to determine total quantities of hydrocarbons in the entire basin at all probability levels, as well as total quantities by age and by depth.

The following table summarizes our estimates for undiscovered hydrocarbons-in-place:

Commodity	Undiscovered in-place resources		
	Probability		Mean
	0.95	0.05	
Oil (billion bbls)	3.32	10.43	6.35
Natural gas (trillion cu ft)	12.89	33.80	21.87

Our estimate of undiscovered oil-in-place at the 95 percent and 5 percent probabilities is 4 and 11 percent, respectively, of the known and produced oil-in-place. Our estimate of the total gas-in-place at the 95 percent and 5 percent probabilities is 12 and 32 percent, respectively, of the total known and produced gas in-place.

Our estimates of pool size distributions indicate that undiscovered pools in the basin will be, on the average, significantly smaller than those discovered to date.

No totally satisfactory method has been developed to determine the numbers of pools to be found, and no estimates of these numbers are presented.

INTRODUCTION

The Resource Appraisal Group, Branch of Oil and Gas Resources, U.S. Geological Survey, was assigned the responsibility for Task I of the Interagency Oil and Gas Supply Project. The assignment was to provide:

1. detailed appraisals of undiscovered oil and gas in-place by depth of occurrence and by major stratigraphic unit, and
2. estimates of the probability distributions of the size and the number of undiscovered pools of oil and gas, *regardless of economic constraints*.

These assessments were to be prepared for three pilot regions: the Permian basin of west Texas and southeast New Mexico; the offshore Gulf of Mexico, excluding the eastern carbonate province; and the Mid-Atlantic offshore province. This report is confined to the assessment of undiscovered oil and gas of the Permian basin, as of January 1, 1978.

The Permian basin, which has been producing hydrocarbons for nearly 60 years, was selected as a pilot study area so that methods for estimating undiscovered hydrocarbons in a mature onshore producing province might be developed and evaluated.

The study area (fig. 1) includes all or parts of 52 counties, approximately 82,000 sq mi., in west Texas and southeast New Mexico. Portions of Presido, Brewster, Pecos, Terrell, and Val Verde Counties, Texas, are excluded because those regions are outside the Permian basin proper.

Only negligible amounts of hydrocarbons have been found in rocks younger than Permian; consequently this assessment is concerned exclusively with the Paleozoic section. For convenience of analysis and assessment, the Paleozoic section of the Permian basin was divided into three identifiable stratigraphic units. The three units are the Permian, the Carboniferous, and the remaining older Paleozoic systems (fig. 2).

This administrative report presents results of the Permian basin study, with sections on the petroleum geology and methods of assessment of undiscovered oil and gas. Additional basic data are given in the appendix.

Previous resource estimates of this area were considerably more optimistic than the present assessment. Though comparisons are difficult because the dimensions of the previous area assessed are not identical to the areas in question, nevertheless it is clear that the present study decreases the estimate of remaining recoverable petroleum significantly; in the only previous assessment that permits comparison (Miller and others, 1975) approximately twice as much area was considered but the assessment was approximately five greater than that of this report.

The reasons for this difference are of course complex, but mostly are attributable to a significantly different data base, a more thorough assessment of petroleum exploration possibilities, and different assessment methodologies. In the Circular 725 assessment, only volumetric/yield or areal yield analytical techniques were possible. In this most recent assessment, a comprehensive field and pool data file was available, and abundant drilling and finding rate studies were conducted, along with a thorough review of the geology on a stratigraphic basis. The net result was a more in-depth perspective on the petroleum potential of this mature exploration province, and we hope a more reliable estimate.

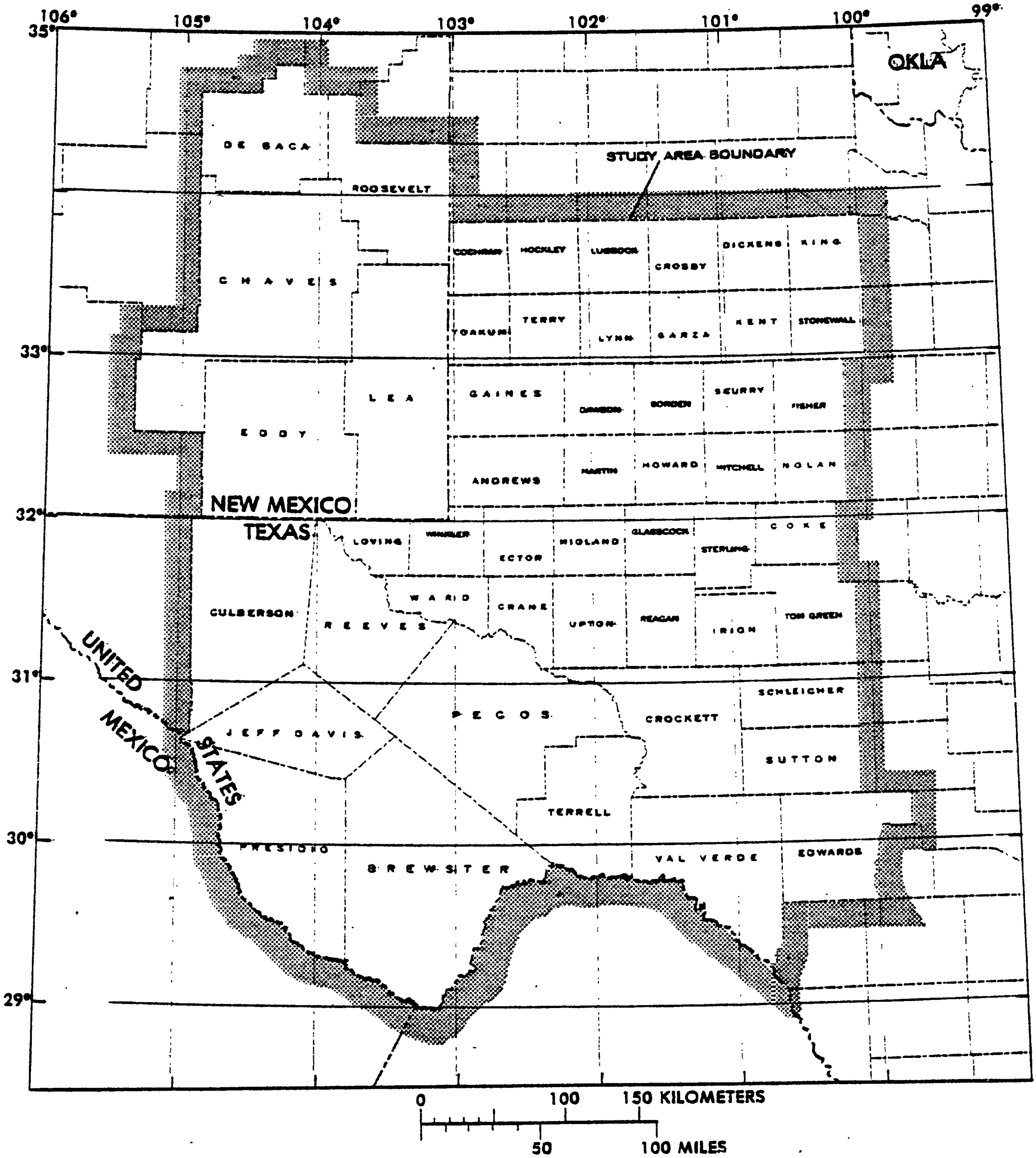

Figure 1.--Index map of the Permian basin, southeast New Mexico, and west Texas.

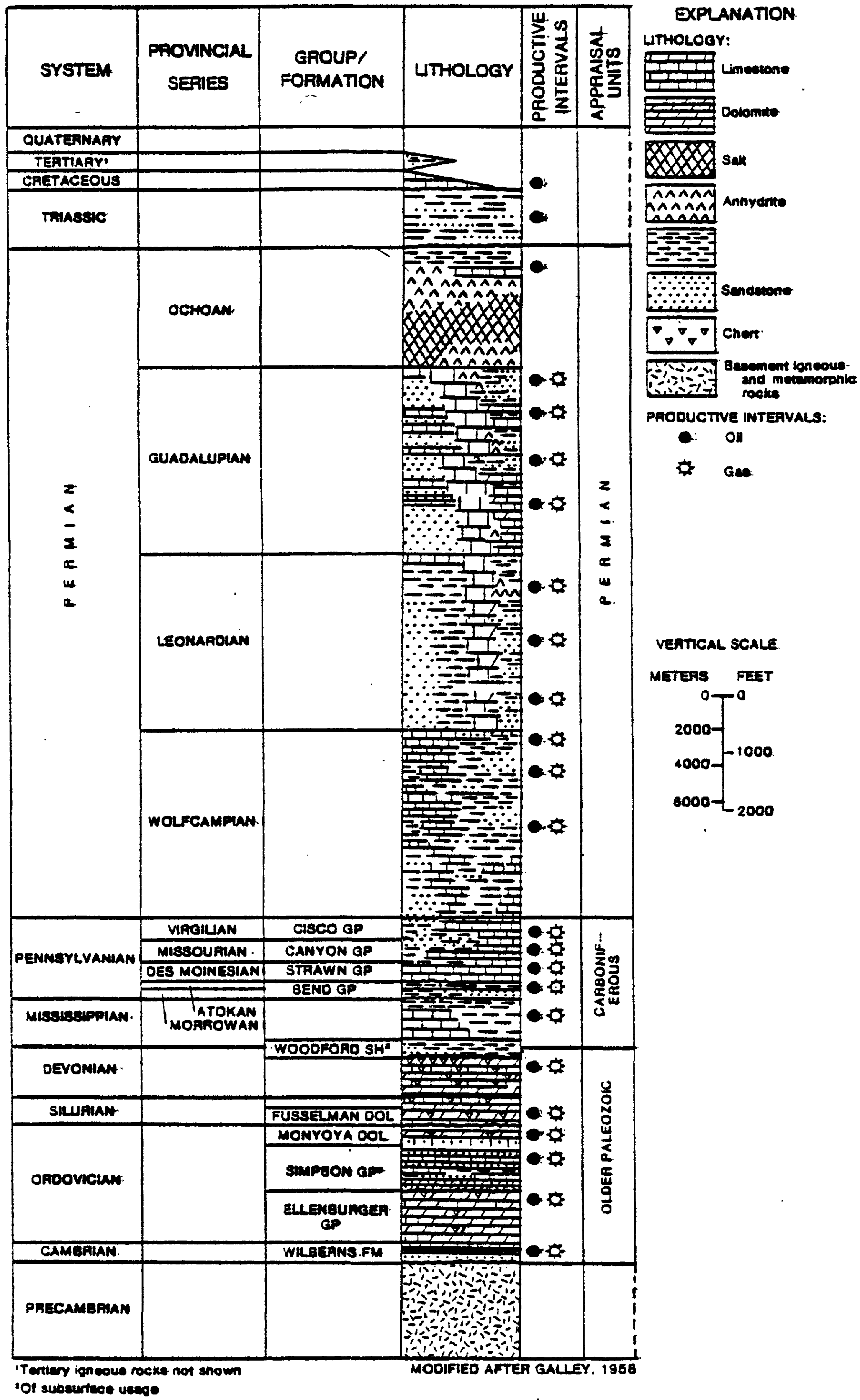

Figure 2 -- Generalized stratigraphic and lithologic column showing productive intervals.

Reassessments will always produce changes because ideas change with time, and in many areas significant new data will come to light. Those new ideas and new data, however, will not necessarily always result in decreased assessments. It is not possible, therefore, to extrapolate a reduced expectation nationwide from this single-area reassessment.

The Resource Appraisal Group reserves the right to alter any of the results in this report in the event that such modifications are considered necessary during the preparation of a manuscript for U.S. Geological Survey publication.

SOURCES OF DATA AND ACKNOWLEDGMENTS

The geologic and petroleum exploration data used in making the appraisals presented in this report were obtained from published literature, commercial sources, unpublished data, and oral communications. The literature for the area is abundant; the selected bibliography includes about 170 references ranging in scope from regional geologic studies to engineering descriptions of individual fields and pools. Published and unpublished maps, files, and correlation charts of the paleotectonic map series of the U.S. Geological Survey (Bachman, 1975; Crosby and Mapel, 1975; Mapel and others, 1979; McKee, Oriel, and others, 1967; Oriel and others, 1967) were used extensively in our study of Permian and Carboniferous rocks.

Maps of exploratory and development wells in the study area, on a scale of 1:250,000, were developed using the Petroleum Information Corporation Well History Control System. This data file also provided counts of the number of exploratory wells completed as oil or gas wells or dry holes and the exploratory footage drilled in each county. Selected production statistics from the Petroleum Data System in Norman, Oklahoma, were also used.

Field and pool data essential to the analysis were obtained from Thomas Garland, John Wood, and James Hicks of the U.S. Bureau of Mines (now of the Office of Applied Analysis, Department of Energy), Dallas, Texas. This compliation consists of 21 data items for each of 5,347 pools in the study area. Petroleum Information Corporation, through Lawrence J. Drew of the U.S. Geological Survey in Reston, Virginia, provided annual exploratory footage for 1920 through 1940. Exploratory footage for 1940 through 1974 was obtained from records published annually by International Oil Scouts Association. The authors are indebted to T. S. Dyman and R. J. Cassidy, U.S. Geological Survey, for their assistance in providing data retrievals from the computer files.

The authors wish to thank B. M. Miller and K. H. Carlson for making available computer-curve fit and Monte Carlo programs for processing the probability distributions, for programs utlized in finding-rate projections, and for their consultation during this study.

DEFINITIONS, EXCLUSIONS, AND LIMITATIONS

Commodities included in this appraisal are crude oil and natural gas. *Crude oil* is a natural mixture of hydrocarbons occurring underground in a liquid state in porous rock reservoirs and remaining in a liquid state as it is produced from wells. *Natural gas* is a mixture of gaseous hydrocarbons classified by occurrence into:

Associated gas--free natural gas, occuring as a gas cap, in contact with and above an oil deposit within the reservoir;

Dissolved gas--natural gas dissolved in crude oil within the reservoir; and

Non-associated gas--natural gas that is not associated with or in contact with significant amounts of crude oil within a reservoir.

Natural gas normally includes small quantities of various non-hydrocarbons and in the Permian basin these contaminants, particularly carbon dioxide, can run as high as 99 percent of the gas. Our estimates of undiscovered natural gas exclude carbon dioxide, except as normal background (less than 5 percent by volume). Condensate and other natural gas liquids are reported as part of the natural gas volume.

Occurrences of oil and gas specifically excluded from this study are heavy oil deposits, tar deposits, oil shale, and impermeable ("tight") gas reservoirs. All of these occurrences have characteristics that preclude the extraction of hydrocarbons by conventional methods.

The basic unit of hydrocarbon accumulation used in this report is the *pool* which is, in general, equivalent to the *reservoir*. A pool or reservoir may be defined as a porous and permeable underground rock containing an individual and separate natural accumulation of hydrocarbons. It is confined by impermeable rock or water barriers and is characterized by a single natural pressure system (American Petroleum Institute, 1976, p. 7). Pools may contain either oil or gas or both. However, for purposes of this study, any pool producing any amount of oil was considered an *oil pool*, regardless of the amount of dissolved/associated gas contained or produced.

A *field* consists of a single pool or multiple pools all grouped on, or related to, the same individual geological structural feature and (or) stratigraphic condition. In a field there may be two or more pools that are separated vertically by intervening impervious strata, or laterally by local geologic barriers, or by both (American Petroleum Institute, 1976, modified). The Texas Railroad Commission, however, defines each pool as a separate field.

A *new field* is a discovery of oil or gas with accumulation being controlled by a separate structural feature and (or) stratigraphic condition to the extent that the new discovery is not considered a new pool, or an extension of a pool, in a preexisting field (American Petroleum Institute, 1976). In the present study, undiscovered pools that occur as independent accumulations controlled by separate structural features and (or) stratigraphic conditions are considered separate fields even though they may occur at depth below preexisting fields. Such *undiscovered* accumulations are *not* considered as part of future additions to known fields (such as inferred reserves, fig. 3 and Appendix A, p. A-1), but are estimated as a part of the overall *undiscovered oil or gas in-place*.

All amounts of oil and natural gas estimated in this report are *undiscovered* hydrocarbons in-place, limited only by the arbitrary lower limits of pool size used in this study. *Oil or gas in-place* is defined to include all oil or gas in-place without qualification as to what portion, if any, may be considered either currently or potentially extractable. Amounts of known oil or gas in-place refer to the estimated number of stock tank barrels of crude oil or standard cubic feet of gas

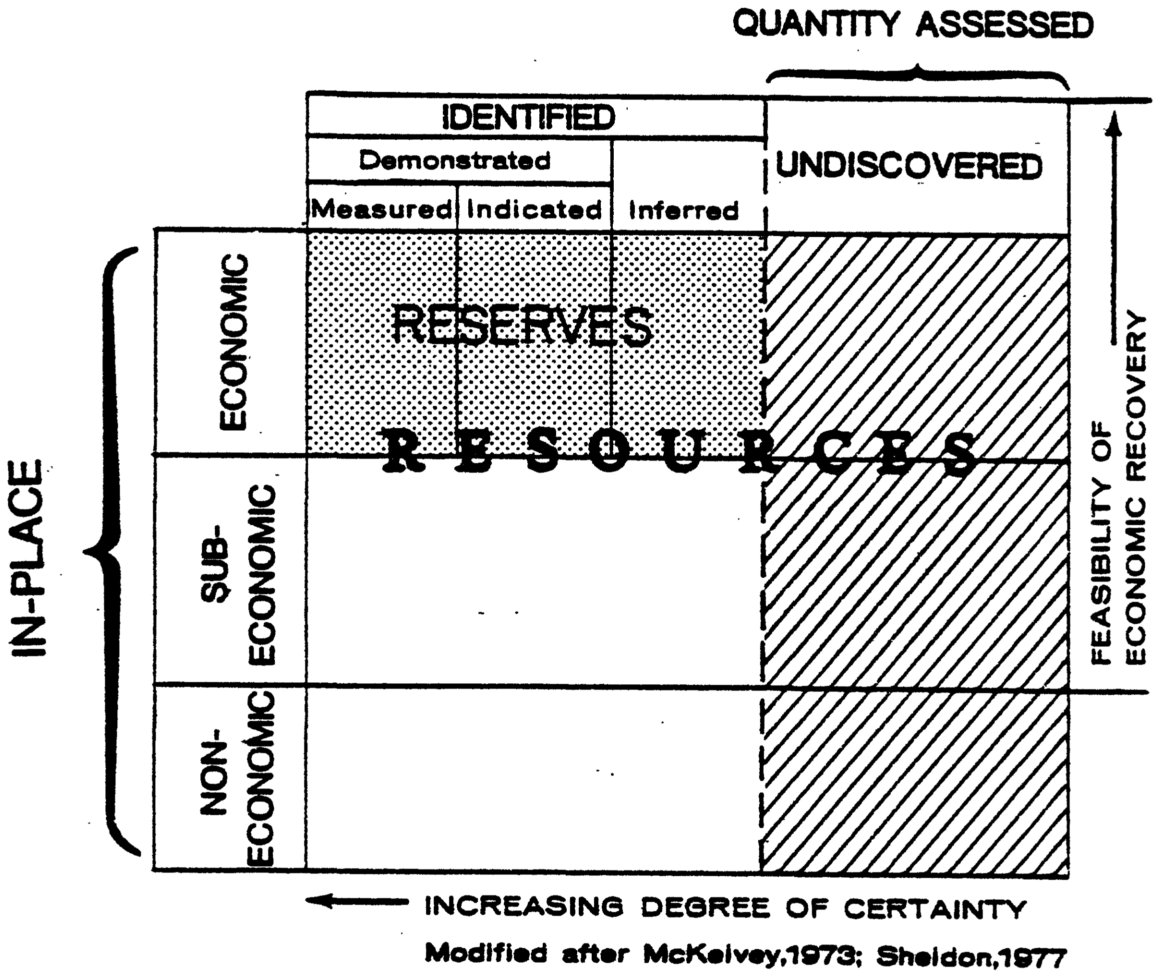

Figure 3.--General classification of remaining hydrocarbons, Permian basin, southeast New Mexico and west Texas.

(14.73 lbs. per sq. in. atmosphere-psia-and 60° F) in reservoirs prior to any production (American Petroleum Institute, 1970, pl. 19). Because our assignment was to assess the amounts of hydrocarbons remaining in the Permian basin *regardless of economic constraints*, we should, theoretically, have assessed all accumulations of oil, no matter how small. However, this is not practical because the historic data include very few accumulations below 1,000 bbls of oil although many such accumulations must exist. We arbitrarily chose 1,000 bbls of oil and 1,000,000 cu ft of gas as lower limits for our study, realizing that although such a low level may seem unrealistic, there is the historic precedent of reported pools at or near this size.

Non-associated gas is reported and assessed separately from dissolved/associated gas. Separate associated gas and dissolved gas statistics are reported for known oil pools, but are given as one quantity, dissolved/associated gas, in the assessments of undiscovered resources. Such gas is not combined with the crude oil into oil equivalents. Condensate and natural gas liquids are treated in the assessments as part of the natural gas.

Resources, (fig. 3) as defined by the U.S. Bureau of Mines and U.S. Geological Survey (1976, p. A2) are "...concentrations of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is currently or potentially feasible."[1] In-place quantities, however, may include accumulations that are either too small, dispersed or remote to be recoverable, or portions of economic deposits which are potentially or actually non-extractable in an economic or technologic sense. The assessed amounts of undiscovered oil and gas in-place fall in the right-hand hachured column of the resource diagram, figure 3.

Estimates of undiscovered crude oil and natural gas were made as of January 1, 1978.

PETROLEUM GEOLOGY OF THE PERMIAN BASIN

Geologic Framework

The Permian basin is a large asymmetric structural depression in the Precambrian basement of the southern margin of the North American craton that has been filled primarily with Paleozoic sediments. It acquired its present structural form (fig. 4) by Early Permian time although it has been modified by subsequent tectonic activity. Rocks of all Paleozoic systems are present and attain a maximum combined thickness in excess of 25,000 ft (fig. 5). Complete sequences of Paleozoic strata are not present because sedimentation was interrupted, locally and regionally, by orogenic movement and structural deformation; this was accompanied by erosion or nondeposition. A generalized stratigraphic and lithologic column is shown in figure 2.

Structurally, that part of the Permian basin included in this report is bounded on the south by the Marathon-Ouachita fold belt, on the

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[1]The other terms shown in figure 3 are not used in this report. For definitions, see Appendix A.

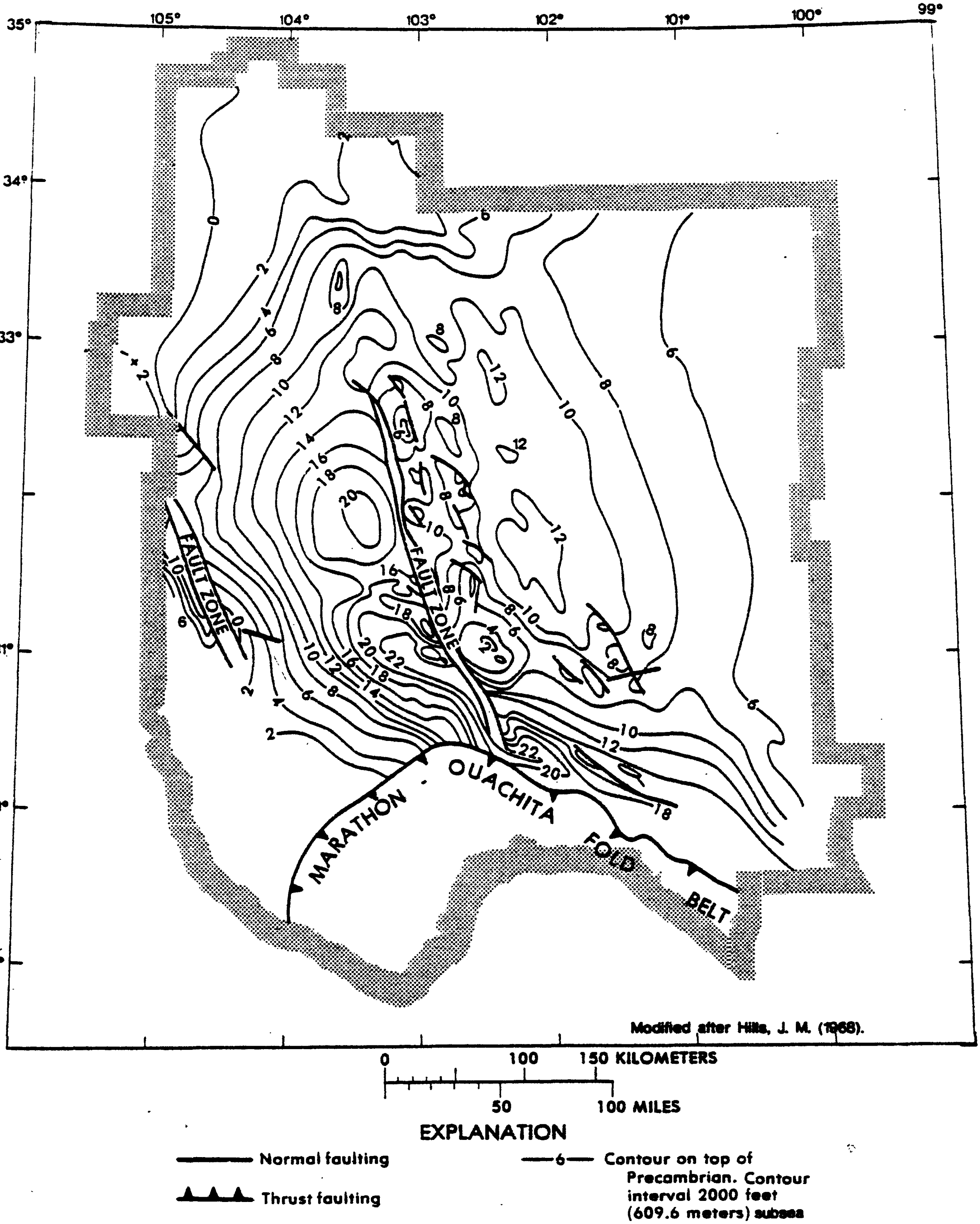


Figure 4 -- Structure contour map, top of Precambrian rocks.

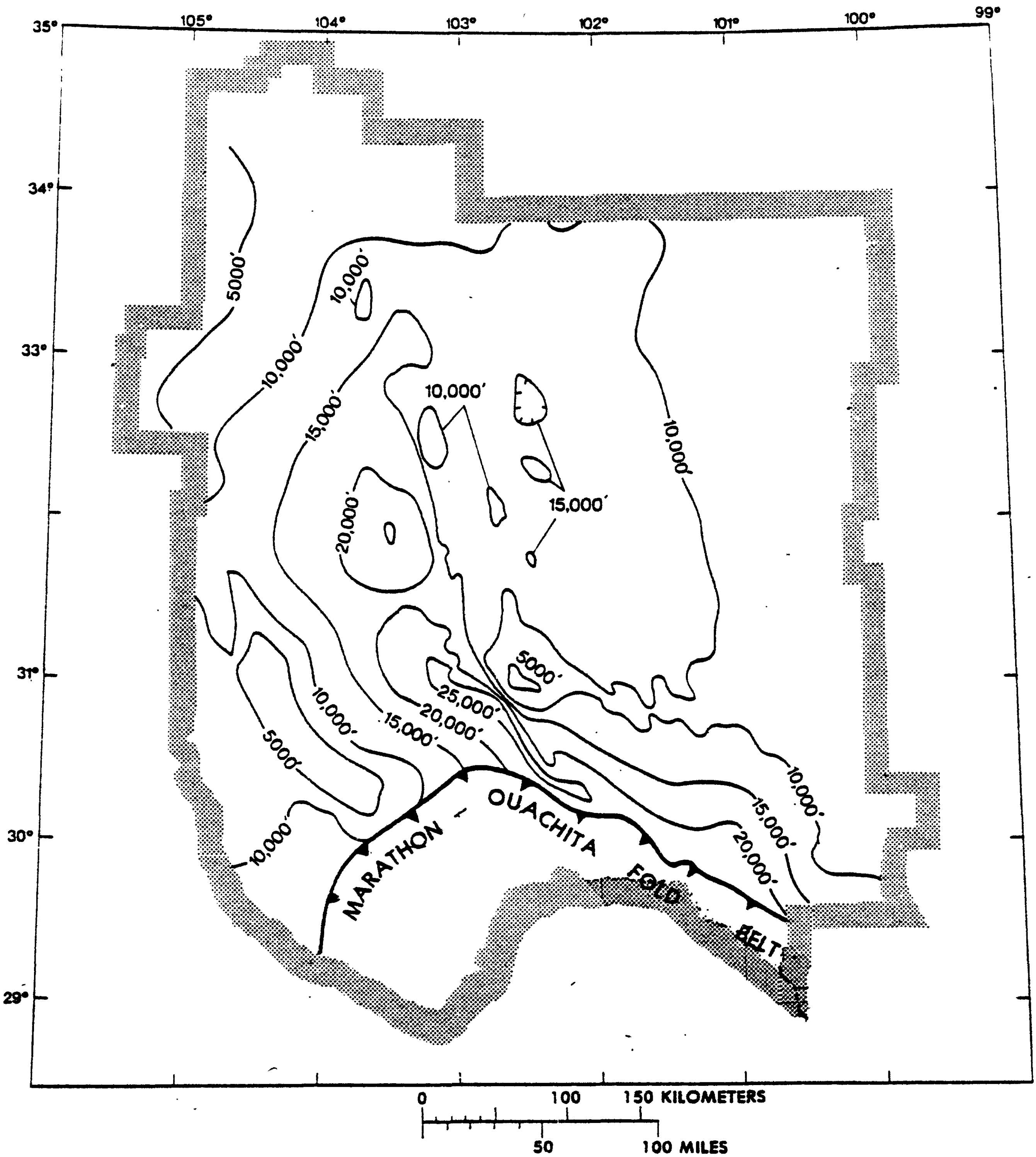


Figure 5.--Isopach of total sedimentary section, in feet. Contour interval 5,000 feet.

west by the Diablo Platform and Pedernal Uplift, on the north by the Matador Arch, and on the east by the Eastern Shelf and west flank of the Bend Arch (fig. 6). The region is readily divisible into several distinct tectonic elements. They are the Central Basin Platform and the Ozona Arch, which separate the Delaware and Val Verde Basins from the Midland Basin; the Marfa Basin, separated from the Delaware Basin by the Diablo Platform; the Northwestern Shelf; and the Eastern Shelf.

Stratigraphic and structural relationships within the Permian basin are generalized on cross-section A-A' (fig. 7). From Cambrian through Mississippian time the area was relatively stable, developing from a broad marine shelf into a marine basin with associated shelves. This basin, the Tobosa basin of Galley (1958), was the site of extensive carbonate and subordinate fine clastic sedimentation. Its deepest part was in the approximate vicinity of the present Delaware Basin. Only mild structural movement and deformation occurred during this early period, producing local unconformities and structural anomalies of low and broad relief. The deeper basins accumulated fine clastic sediments with some interbedded limestones in Mississippian time.

From Early Pennsylvanian into Early Permian time, the region was subjected to intense structural deformation and orogenic movement which culminated in the development of the present tectonic elements (fig. 6), and which provided a depositional setting totally different from the relatively stable basin that existed earlier. These tectonic elements include platforms (Diablo and Central Basin), deep basins (Delaware, Val Verde, Midland), and surrounding shelves (Northwestern and Eastern). Sedimentation varied according to the tectonic setting. In Pennsylvanian time, coarse clastic sediments were deposited near the shorelines of the basins and limestones seaward of those clastics. Reef developments make up a large percentage of the limestone. In Late Pennsylvanian only thin marine shales were deposited in the deeper basins. Pennsylvanian rocks are absent in many localities due to erosion or nondeposition, particularly along the trend of the Central Basin Platform.

In Permian time, sedimentation continued to build in the tectonic setting developed in Pennsylvanian time. Permian reefs expanded to become the most striking feature of the Permian basin. The reefs generally developed at the basin hingelines and separated the clastic and thin limestone deposition of the basins from the back-reef lagoonal deposits of interfingering layers of sandstone, mudstone, carbonate and anhydrite.

Oil and Gas Occurrence

The Permian basin, one of the most prolific petroleum provinces of North America, is now in a mature stage of petroleum exploration and development. Oil and natural gas have been found in rocks ranging in age from Cambrian to Cretaceous (table 1); however, virtually all of the known hydrocarbons have been found in rocks of Paleozoic age. The Paleozoic reservoirs here 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 (fig. 8).

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

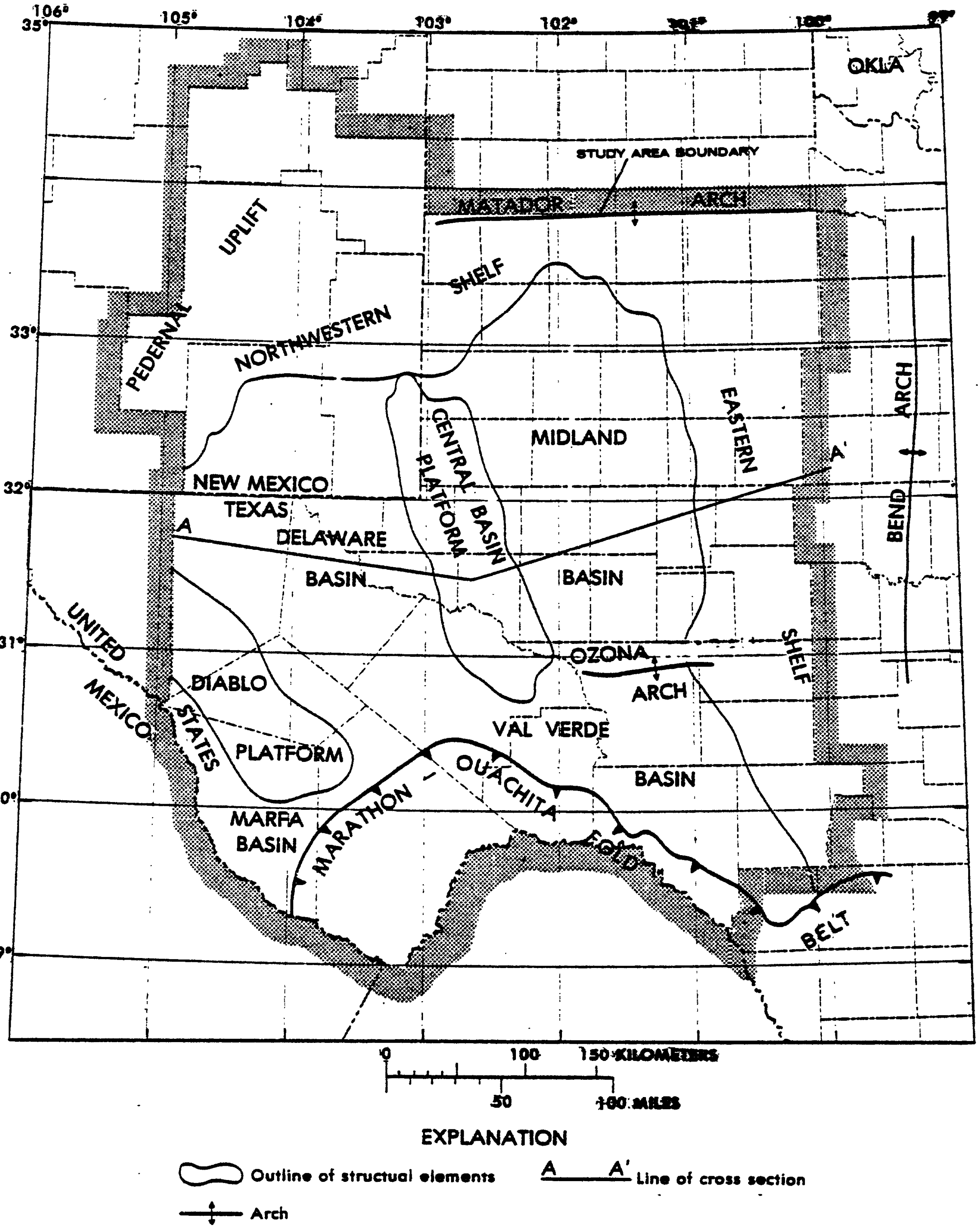


Figure 6.—Structural elements in the Permian basin.

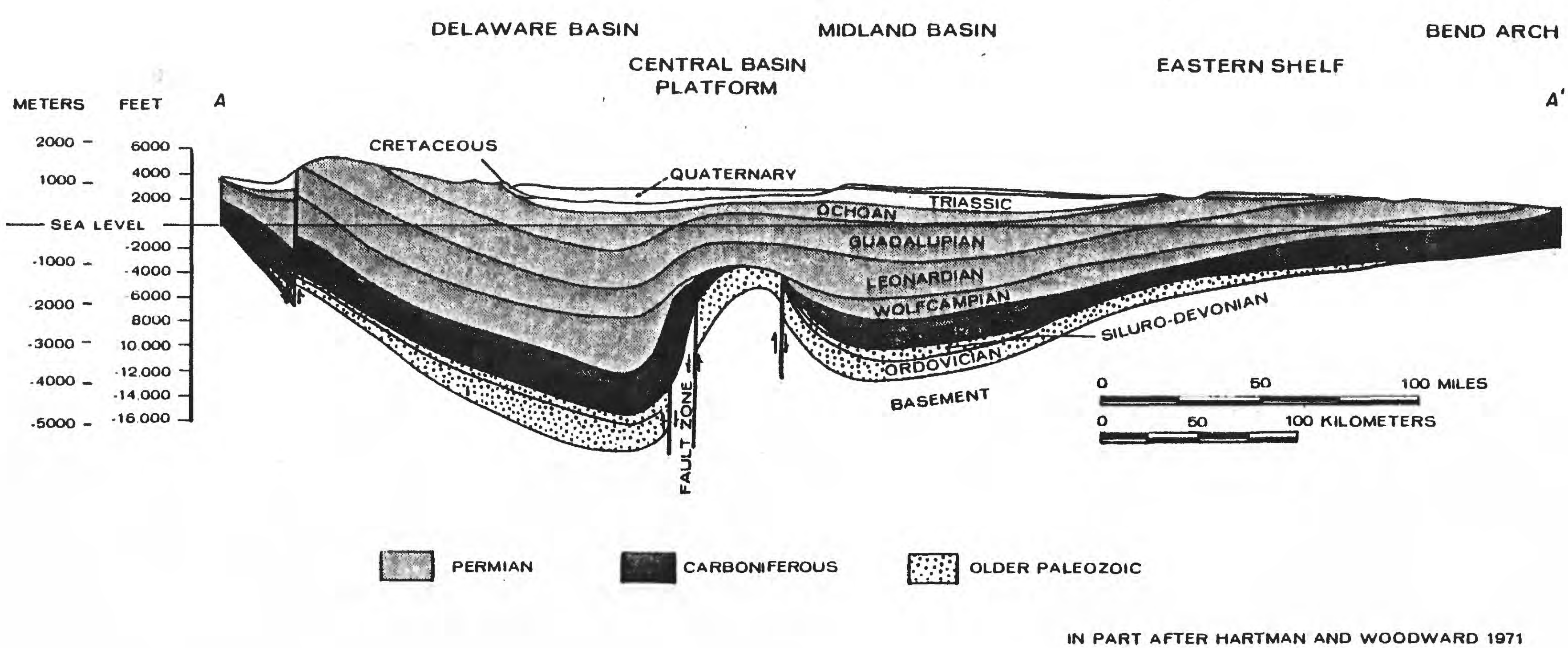


Figure 7.--Geologic cross section A-A'.

Table 1.--*Discovered oil and gas in-place, Permian basin (1921-1974)*[1]

Geologic System	Oil in-place (billions of bbls)	Associated gas in-place (trillions of cu ft)	Dissolved gas in-place (trillions of cu ft)	Non-associated gas in-place (trillions of cu ft)
Post-Permian	0.184	0	0.006	trace
Permian	65.070	2.414	30.323	6.268
Carboniferous	11.926	0.352	10.228	7.721
Older Paleozoic	14.368	1.167	16.284	[2]33.636
Undifferentiated Paleozoic	.003	0	.001	0
Total	91.551	3.933	56.842	[2]47.625

[1]Based on 1974 Bureau of Mines (now Office of Applied Analysis, Department of Energy) estimates of initial hydrocarbons-in-place, unadjusted for future growth.
[2]Includes 2.184 TCF carbon dioxide gas in natural gas fields with CO_2 concentrations greater than 5 percent.

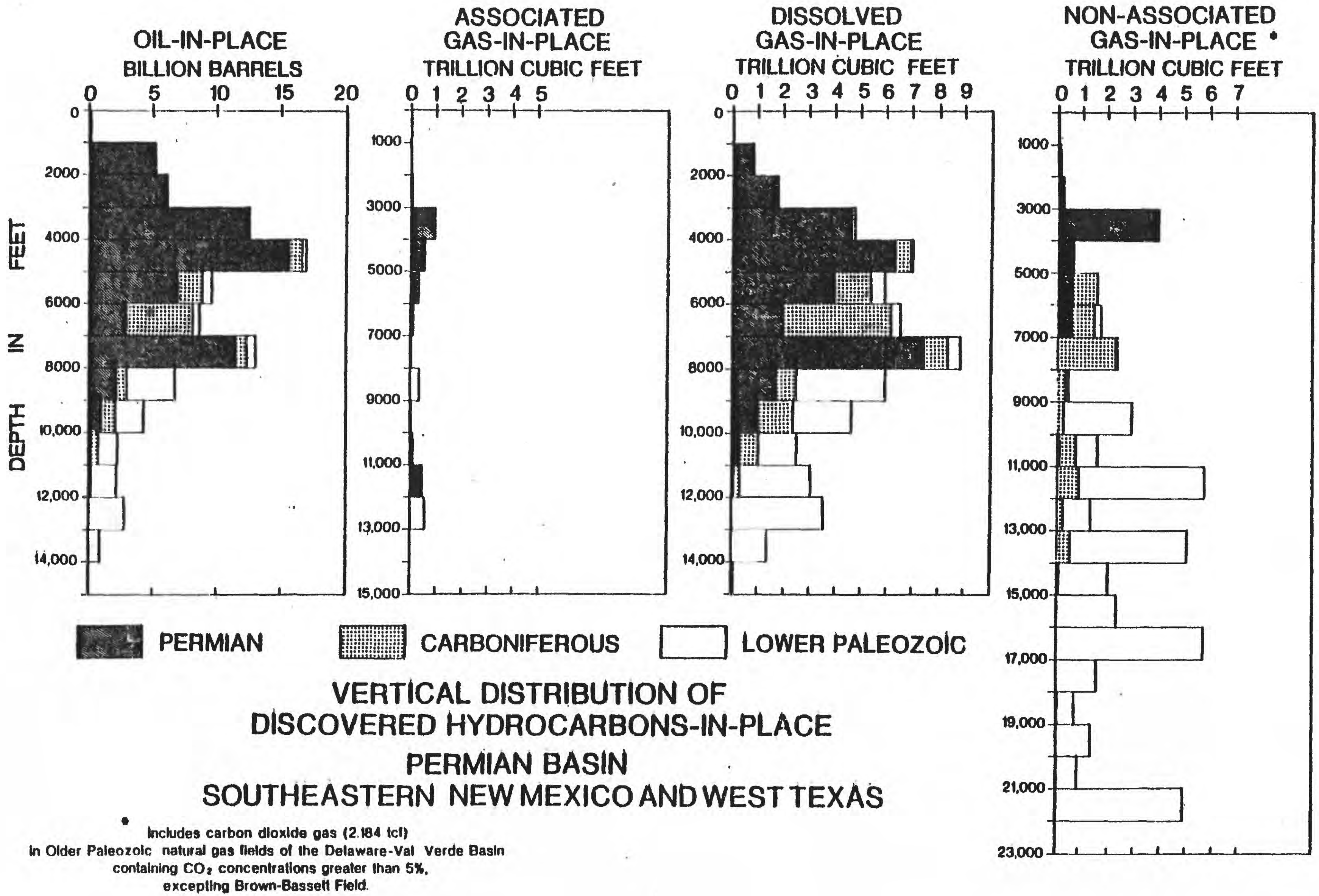


Figure 8.--Vertical distribution of occurrence of discovered hydrocarbons in-place, Permian basin.

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 Capitan 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.

The oil and gas discovered through 1974 in rocks of Paleozoic age occurred in 4,437 oil pools and 888 non-associated gas pools. The frequency distributions of these pools are shown in figures 9 and 10. Individual pools range in size from subeconomic to giant accumulations. The distributions of "fields", which group the pools into producing units, are shown in figures 11 and 12. Many of the larger fields consist of multiple pools, whose ages range from Ordovician through Permian. The maximum number of pools in a single oil field is 22 and in a single non-associated gas field is 7; however, multiple pool fields generally possess a principal reservoir from which most of the production is obtained. The average number of pools per field is 1.6 for oil, and 1.3 for non-associated gas.

Permian rocks, which account for the majority of the oil discovered in the basin, also provide some of the largest individual pools and fields. The most outstanding of these are located in the Guadalupian Capitan reef complex of the Central Basin Platform where Permian production extends over large areas. Some of these giant fields contain three or more separate Permian reservoirs. These Central Basin Platform Permian fields, which are primarily controlled by stratigraphy, locally overlie older pools which are separately trapped in deeply buried structures. The Spraberry Trend, which produces in the Midland basin from fractured siltstones of Leonardian age, is essentially independent of producing structures in underlying rocks.

The Paleozoic Systems

The Paleozoic section of the Permian basin was divided for this study into three unique and identifiable stratigraphic units (fig. 2). These three units, separated in many places by natural boundaries within the stratigraphic column, are the Permian, the Carboniferous, and the remaining older Paleozoic systems. For convenience, the Mississippian-Devonian Woodford Shale is treated as part of the older Paleozoic sequence.

Older Paleozoic Systems

The older Paleozoic pre-Carboniferous rocks occupy an area of more than 73,500 sq mi within the region of study and include Cambrian, Ordovician, Silurian, and Devonian sediments. Their combined thickness ranges from 0 to 4,700 ft and their sediment volume is about 25,000 cu mi, of which approximately 85 percent occurs between the depths of 5,000 and 20,000 ft.

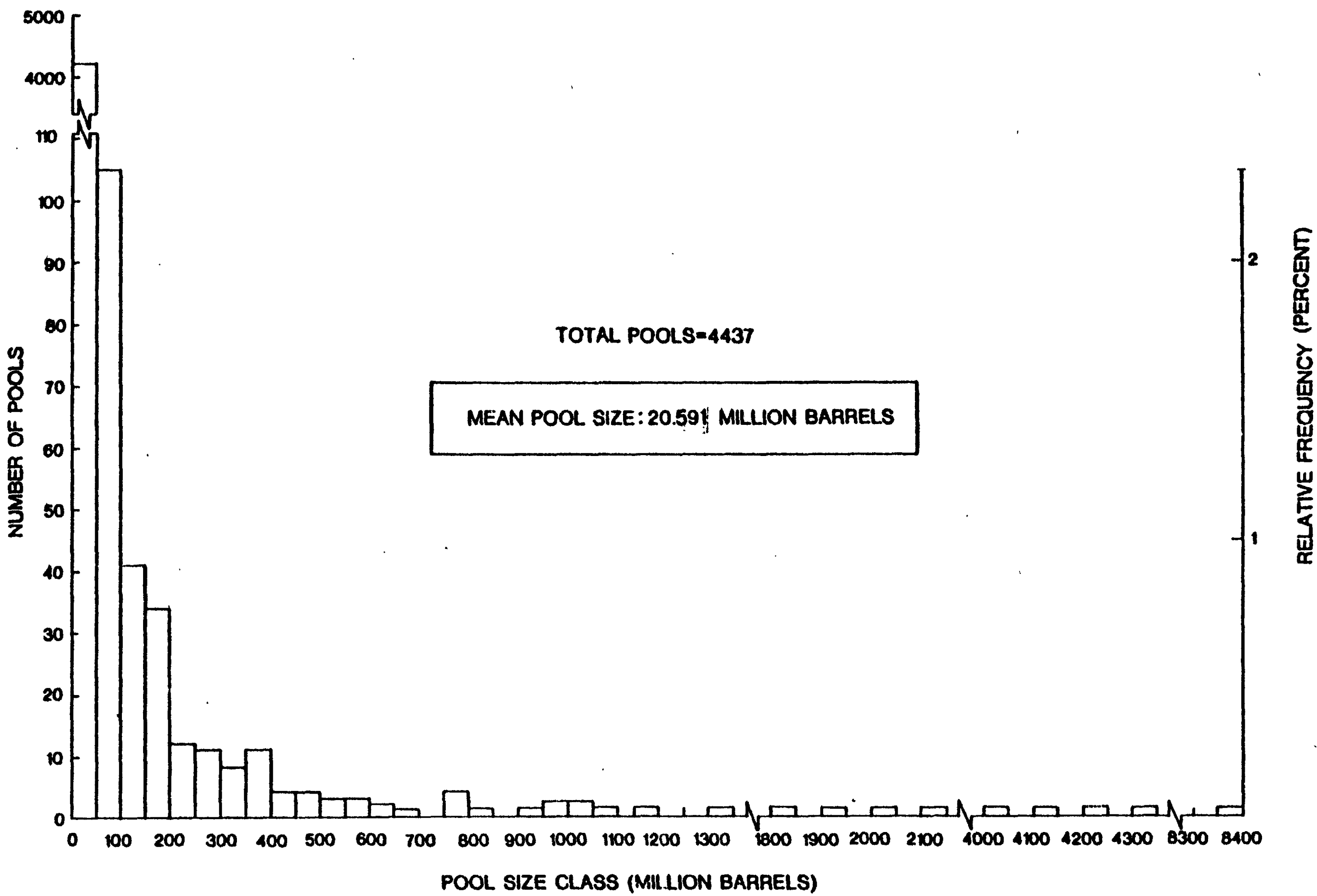


Figure 9.--Frequency distribution of Paleozoic oil pools, 1921-1974, Permian basin.

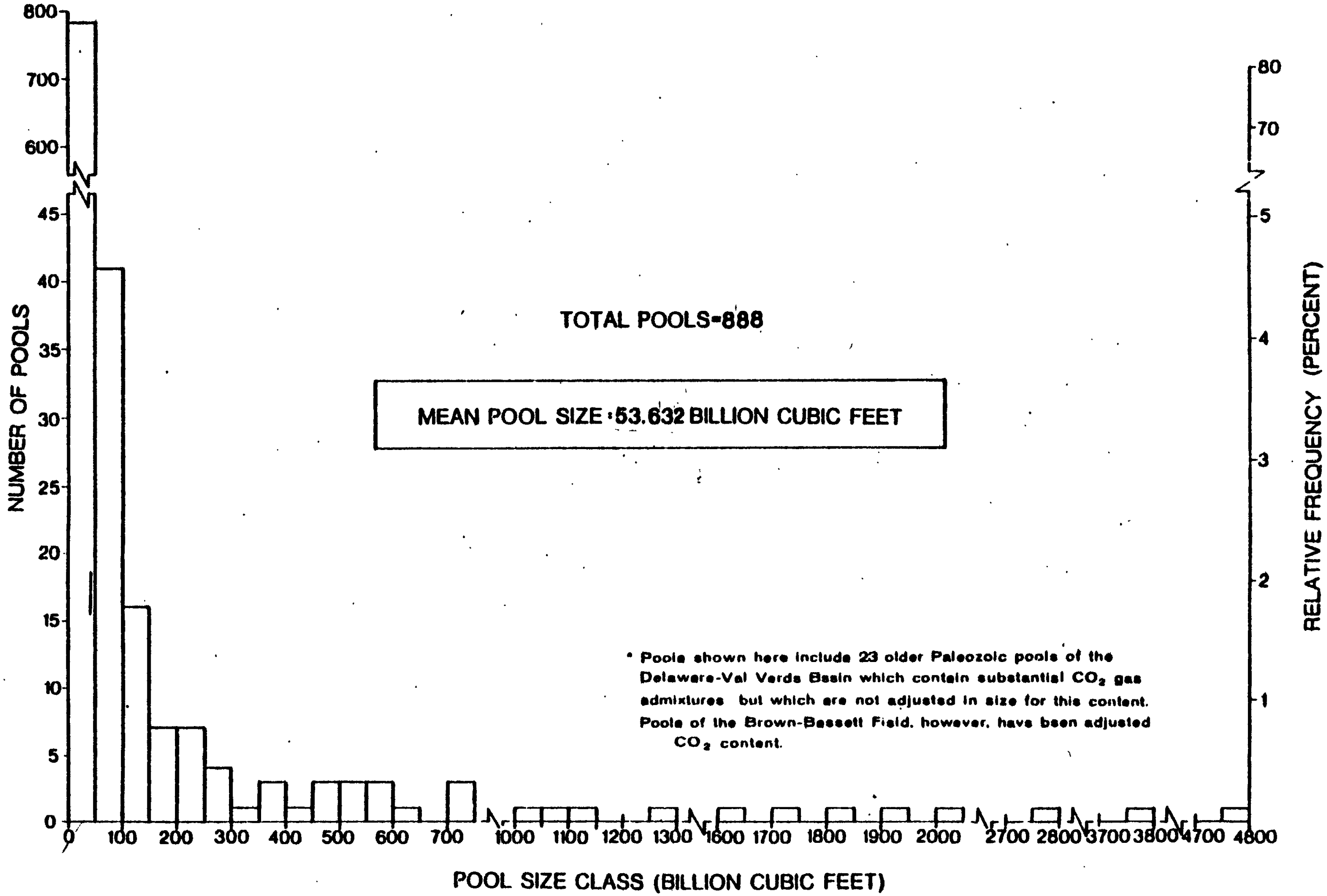


Figure 10.--Frequency distribution of Paleozoic non-associated gas pools, 1928-1974, Permian Basin.

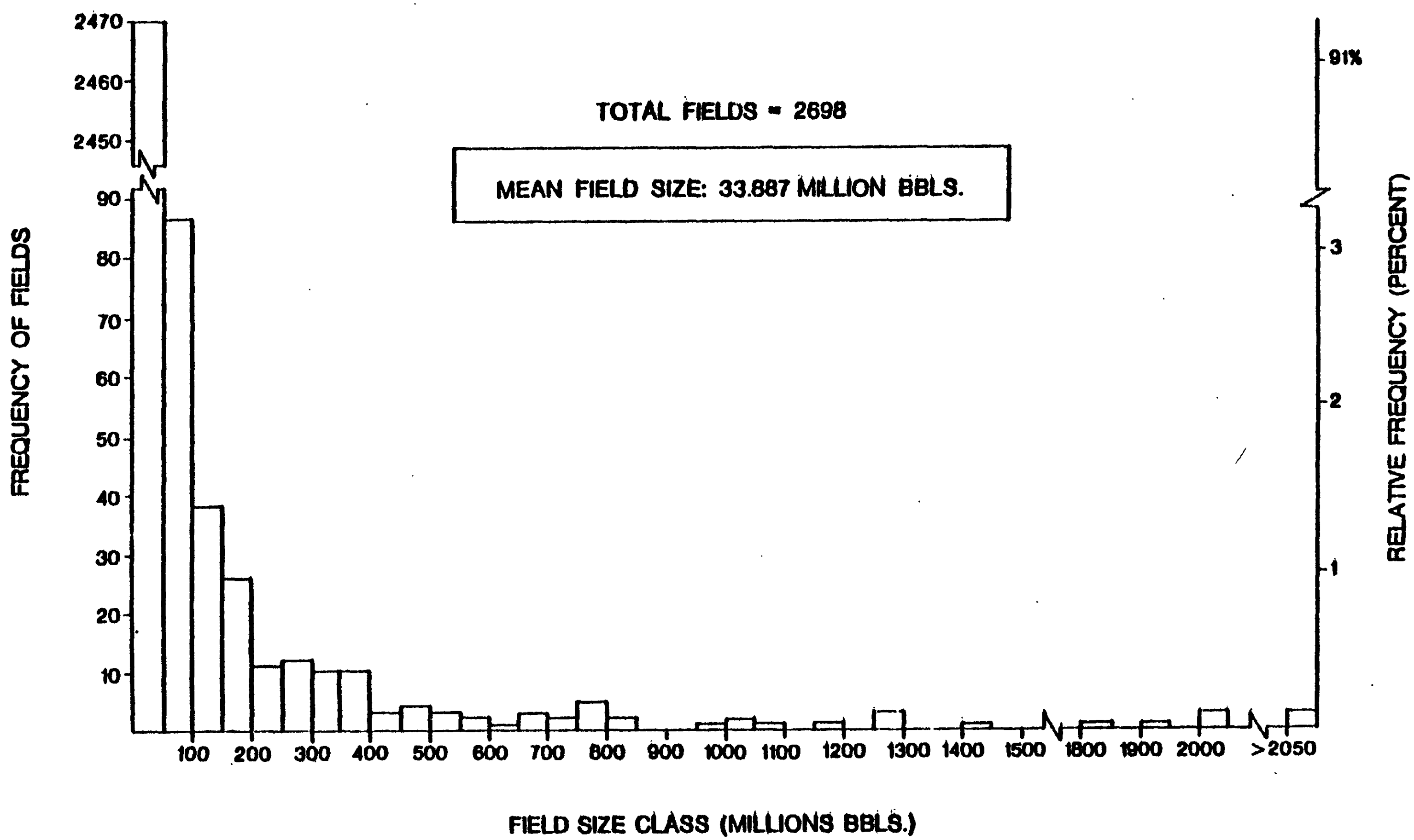


Figure 11.--Frequency distribution of total oil fields, 1921-1974, Permian Basin.

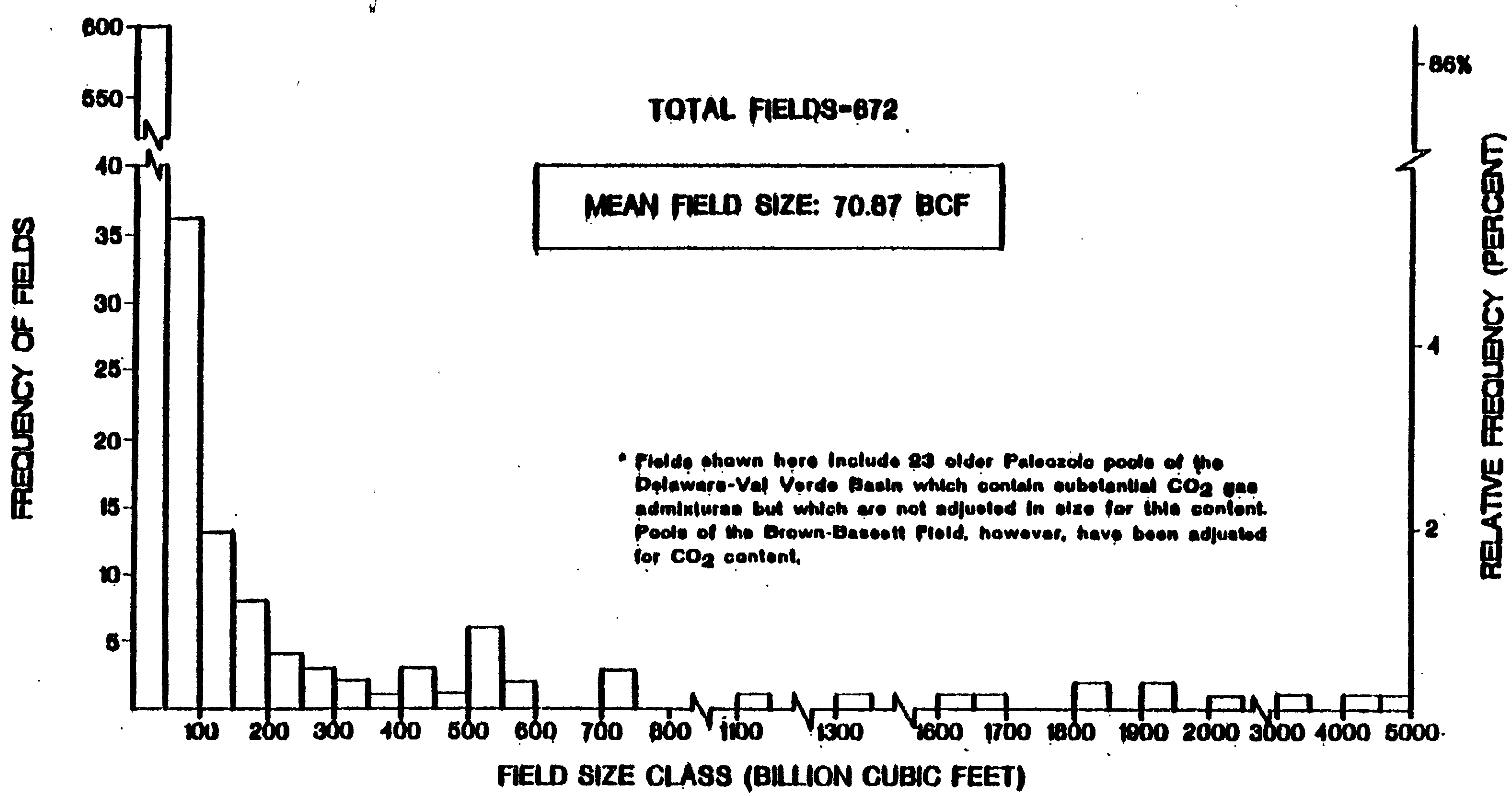


Figure 12.--Frequency distribution of total non-associated gas fields, 1928-1974, Permian basin.

With the exclusion of the Devonian-Mississippian Woodford Shale, principal lithologies in the older Paleozoic rocks are limestone (40 percent), dolomite (30 percent), shale (20 percent), and sandstone (10 percent). The sequence consists of basal Cambrian clastics unconformably deposited on the Precambrian cystalline basement, followed by Ordovician Ellenburger carbonates which were deposited on a shallow stable marine shelf, in turn followed by younger Ordovician, Silurian and Devonian carbonates and clastics deposited in the Tobosa Basin and on the surrounding shelf. The Tobosa basinal setting 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. 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).

The pre-Mississippian sequence produces oil and gas from 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 (8.6 billion bbls), 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 (27.6 trillion cu ft), 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 and Salisbury (1968) has noted an area of gas condensate or "wet" non-associated gas production in the southern Midland Basin. 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 (fig. 8).

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 from 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 also, fracturing over anticlinal structures is 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 pools, 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. 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.

Oils in the older Paleozoic rocks range from 31° to 56° API gravity; however, higher gravity condensates are found with natural gas. The crude oil tends to be napthenic to paraffinic and of low sulfur content.

Non-associated gas in the Permian basin generally increases in methane content to the south and west. Substantial CO_2 gas content is encountered in the Delaware Basin and increases to the south and west (Holmquest, 1967). This contaminant appears to be associated with known Tertiary intrusive activity, either as a product of thermal decomposition of carbonate rocks or as a late stage product of the thermal decomposition of organic material containing oxygen.

Carboniferous Systems

Carboniferous rocks (Mississippian and Pennsylvanian) occupy an area of about 74,000 sq mi within the region of study. The thickness of Mississippian rocks ranges from 0 to 2,600 ft, and that of Pennsylvanian rocks from 0 to 3,050 ft. Rock volume of the Mississippian is approximately 6,000 cu mi, and that of the Pennsylvanian is approximately 14,000 cu mi. About 85 percent of all Carboniferous rocks occur between depths of 5,000 and 15,000 ft.

Mississippian rocks consist of about 60 percent shale, 40 percent limestone, and minor amounts of chert. The shale and chert are generally confined to the southern half of the Permian basin and the limestone to the north. The authors believe that the organic-rich shales of the Upper Mississippian are probably hydrocarbon source beds. 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. Marine shales were deposited in the deeper southern part of the shelf and basin. Mississippian sediments are absent either due to non-deposition 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. Reefs make up a large percent of the limestone. The shales are important hydrocarbon source beds for Pennsylvanian accumulations.

The depositional sequence of the Pennsylvanian is strongly influenced by active tectonism that began in the Late Mississippian and continued with varying degree of intensity throughout the Pennsylvanian. This tectonism resulted in basins, shelves, and platforms that formed a depositional setting totally different from the relatively stable Tobosa Basin which existed prior to this time. Coarse sediments were confined to the peripheries of the basins. Seaward, the clastics grade into shelf limestones with active reefs on the shelf edges. Only thin marine shales were deposited in the deeper parts of the basins. Pennsylvanian rocks are absent in many localities due to erosion or non-deposition, particularly along the trends of the Central Basin and Diablo Platforms.

By the end of 1974, rocks of Carboniferous age were producing or had produced oil from 1,331 pools of Pennsylvanian age and from 50 pools of Mississippian age. At the same time, non-associated gas had been discovered in 383 pools of Pennsylvanian age, and in 10 pools of Mississippian age. The Pennsylvanian contains more than 99 percent of 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 faultbounded 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. The oils produced from Carboniferous rocks in the Permian basin include paraffinic, napthenic, and asphaltic crudes having gravities ranging from a low of 22° API to a high of 55° API. The sulfur content ranges from 0.05 to 0.5 percent. Either associated or dissolved gas is produced from 1,331 of the 1,361 oil pools. Reported gas-oil ratios range from 31:1 to 12,432:1.

Both dry and condensate-bearing non-associated gases are produced from Carboniferous rocks. All of the gases are 75 or more percent methane and low in hydrogen sulfide. Inert gases found are nitrogen, carbon dioxide, helium, and argon, in decreasing order of occurrence. They make up less than 8 percent, and in most analyses less than 5 percent, of the non-associated gas.

Permian System

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 0 to over 17,000 ft. Sediment volume is about 118,000 cu mi, of which 99 percent occurs at depths of less than 15,000 ft.

Permian rocks are extremely varied, generally grading upward from a clastic-carbonate sequence into an evaporite-red bed sequence. The combined Guadalupian, Leonardian, and Wolfcampian consist of approximately 48 percent limestone, 24 percent shale, 20 percent sandstone, and 8 percent evaporite. The Ochoan is about 65 percent evaporite with some limestone, shale, and sandstone. The organic shales and shaly limestones of the Permian are considered to be important indigenous hydrocarbon source beds (Landis, 1970, p. 329, 336). 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 shrank 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.

By the beginning of 1975, 2,188 pools in Permian rocks accounted for more than 65 billion bbls of discovered oil in-place, or 71 percent of the total oil found in the Permian basin. Oil reservoirs of Permian age also accounted for 30.3 trillion cu ft of dissolved gas in-place, which is 39 percent of all the gas found to date in the Permian basin.

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.

As the figures in table 1 indicate, 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. For many years, such gas was flared, and estimates of amounts flared are probably minimal.

The four provincial series of the Permian do not contain hydrocarbons in equal amounts. The largely evaporitic Ochoan rocks have accounted for only about 6 million bbls of discovered oil in-place, less than 0.01 percent of the Permian's 65 billion bbls. Therefore, the Ochoan rocks are not considered to have significant potential and are excluded from this analysis.

By contrast, the Guadalupian has accounted for 67 percent of all Permian oil found and 62 percent of all Permian gas. The Leonardian follows with 28 percent of the oil and 32 percent of the gas. The Wolfcampian contains 5 percent of the oil and 10 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 sealing mechanisms are porosity and permeability barriers of carbonate, evaporite or shale.

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 7.6 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.

DATA ANALYSIS

The subjective probability assessments contained in this report are based on a rigorous analysis of Permian basin data. Each major stratigraphic unit--Permian, Carboniferous, and older Paleozoic--was subjected to independent analysis by a team of geologists. Because of restrictions imposed by the physical characteristics of each unit, specific methods of data preparation and treatment in each unit varied. However, the goal of the analysis of all three units is the same, an assessment of the undiscovered in-place hydrocarbons and of the pool sizes containing these hydrocarbons; hence the methods applied to all three units are similar. Available geologic, drilling, reservoir engineering, and related physical data were entered in data forms by the three major stratigraphic units. Those compilations were basic to the estimations.

The Office of Applied Analysis, Bureau of Mines, (now the Department of Energy), supplied data concerning known oil and gas reserves, initial oil and gas in-place, estimates of ultimate recovery, amounts of associated and dissolved gas, field and pool sizes, discovery dates, age of productive units, depths of production, and general reservoir characteristics for all pools in the study area. Basic drilling information was derived from the Petroleum Information Corporation's Well History Control System and was used to establish exploratory well density, penentration depths, identification of stratigraphic units penetrated, and historical success records. Literature provided information on porosities, permeabilities, reservoir lithologies, thicknesses of net pay sections, gas-oil ratios, hydrocarbon properties, trapping mechanisms, and types of reservoir seals. Permian basin literature, as well as the files and unpublished maps of the U.S. Geological Survey, also provided isopach, lithofacies, structure, and subsurface contour maps. Geophysical investigations were not available.

Certain limitations were strictly adhered to in the analysis. Assessments of hydrocarbons were confined to in-place undiscovered amounts. Furthermore, pool sizes were restricted by the arbitrary lower limit of 1,000 bbls of oil in-place or 1 million cu ft of gas in-place, without regard to economic feasibility of extraction.

Subsurface Geologic Maps

To assist in estimating the spatial and geographic distribution of undiscovered oil and gas, geologic maps were prepared at 5,000-ft depth intervals below ground surface (figs. 13-17). These maps demonstrate the diminishing areal distribution of Paleozoic sedimentary rocks with depth in the Permian basin. Most of the sedimentary rocks are found above 15,000 ft. At 25,000 ft, only rocks of older Paleozoic age are present and these are limited to the southeastern part of the Delaware Basin. Major structural elements are clearly defined, such as the Central Basin Platform which appears as a large positive uplift beneath younger Permian rocks (fig. 13 and 14).

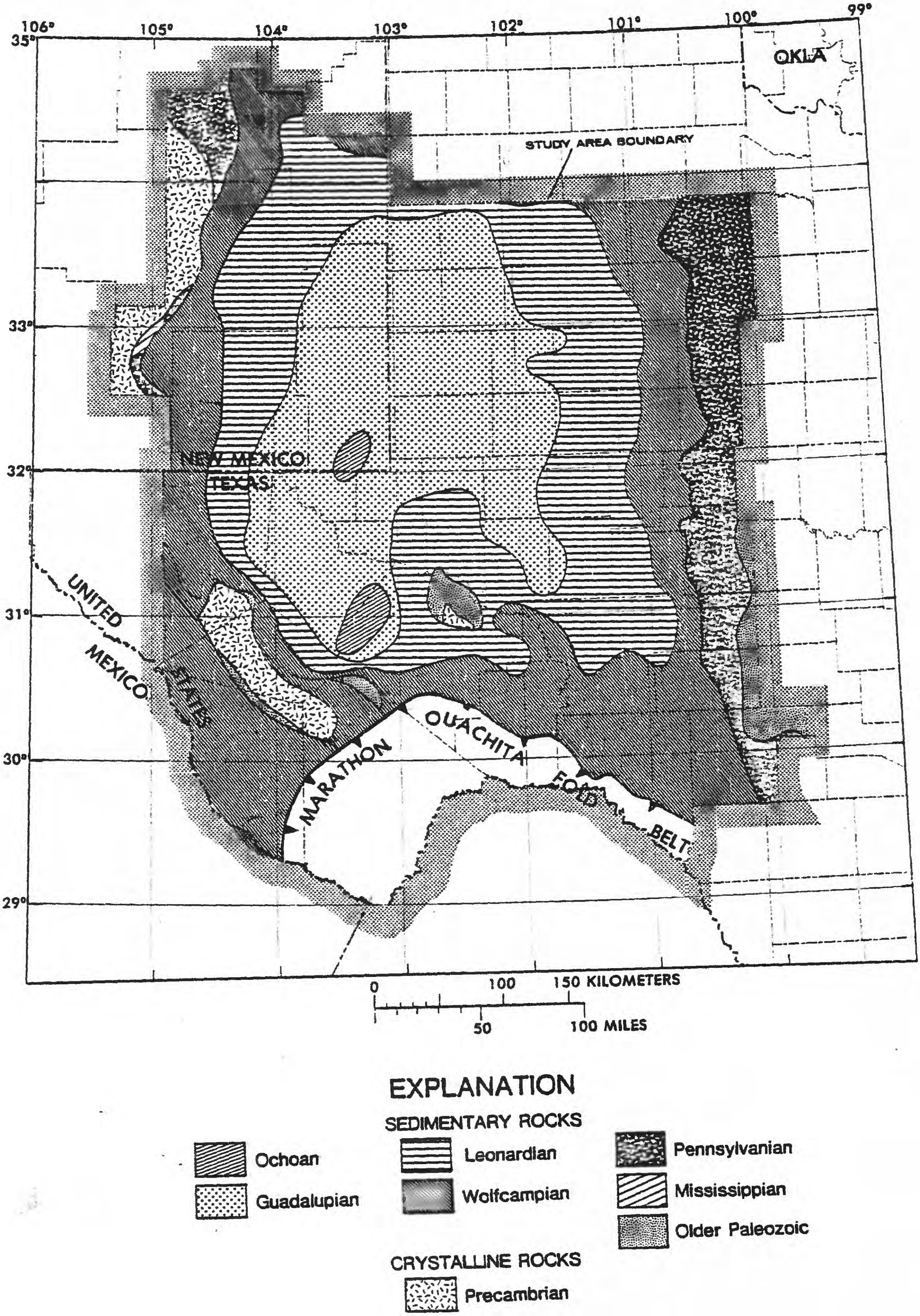


Figure 13.--Geologic map at 5,000-foot depth, Permian Basin.

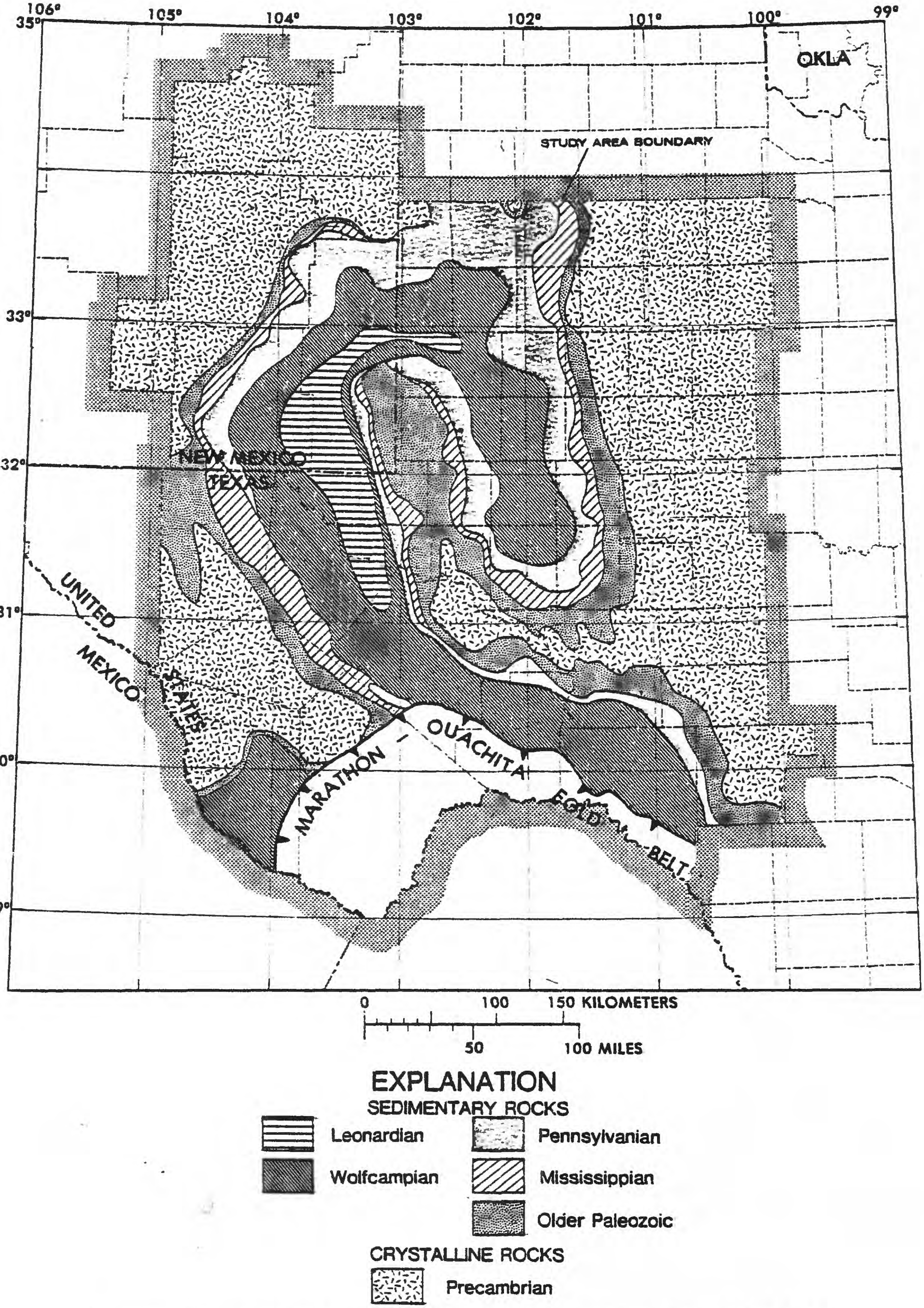


Figure 14.--Geologic map at 10,000-foot depth, Permian Basin.

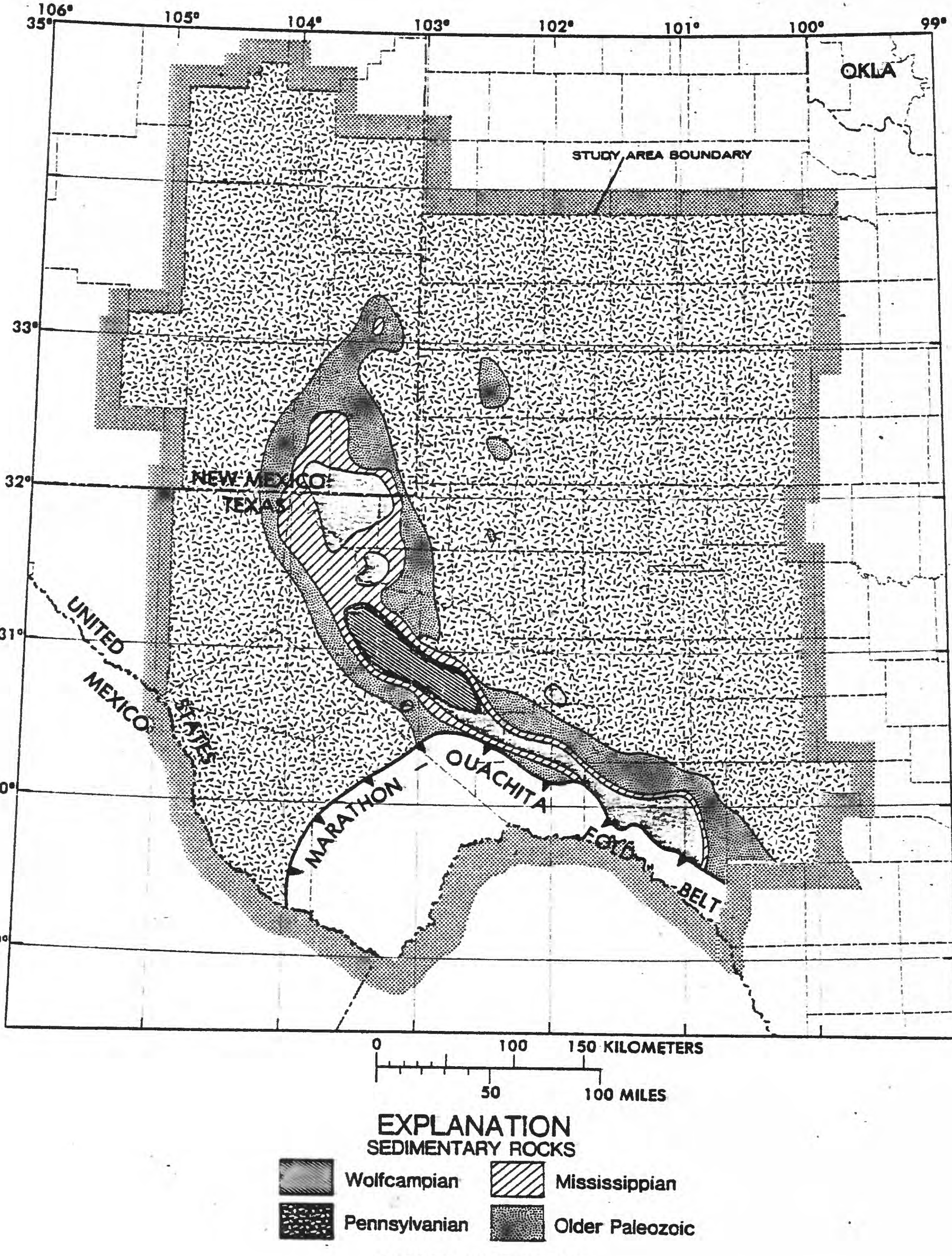


Figure 15.—Geologic map at 15,000-foot depth, Permian Basin.

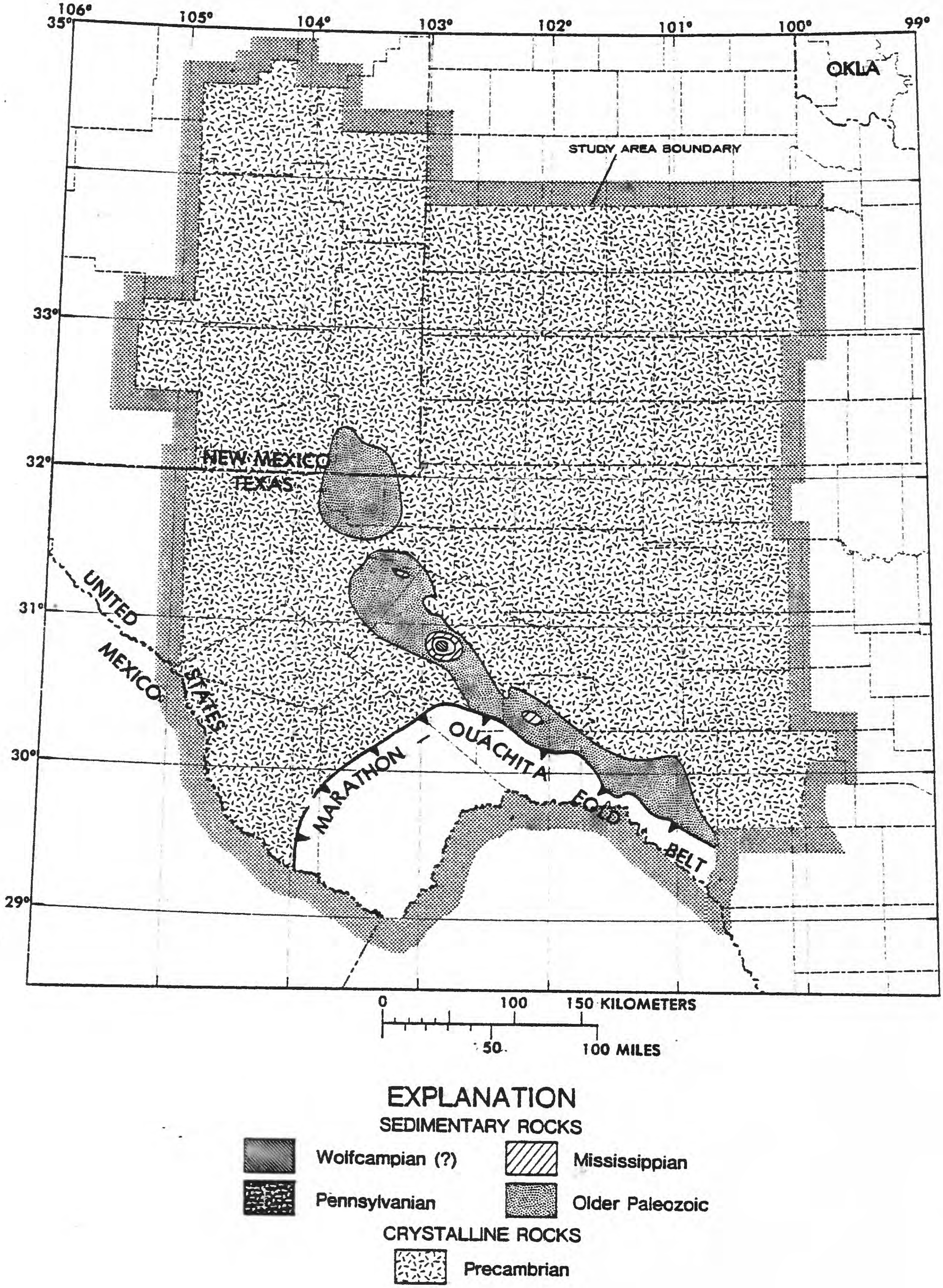
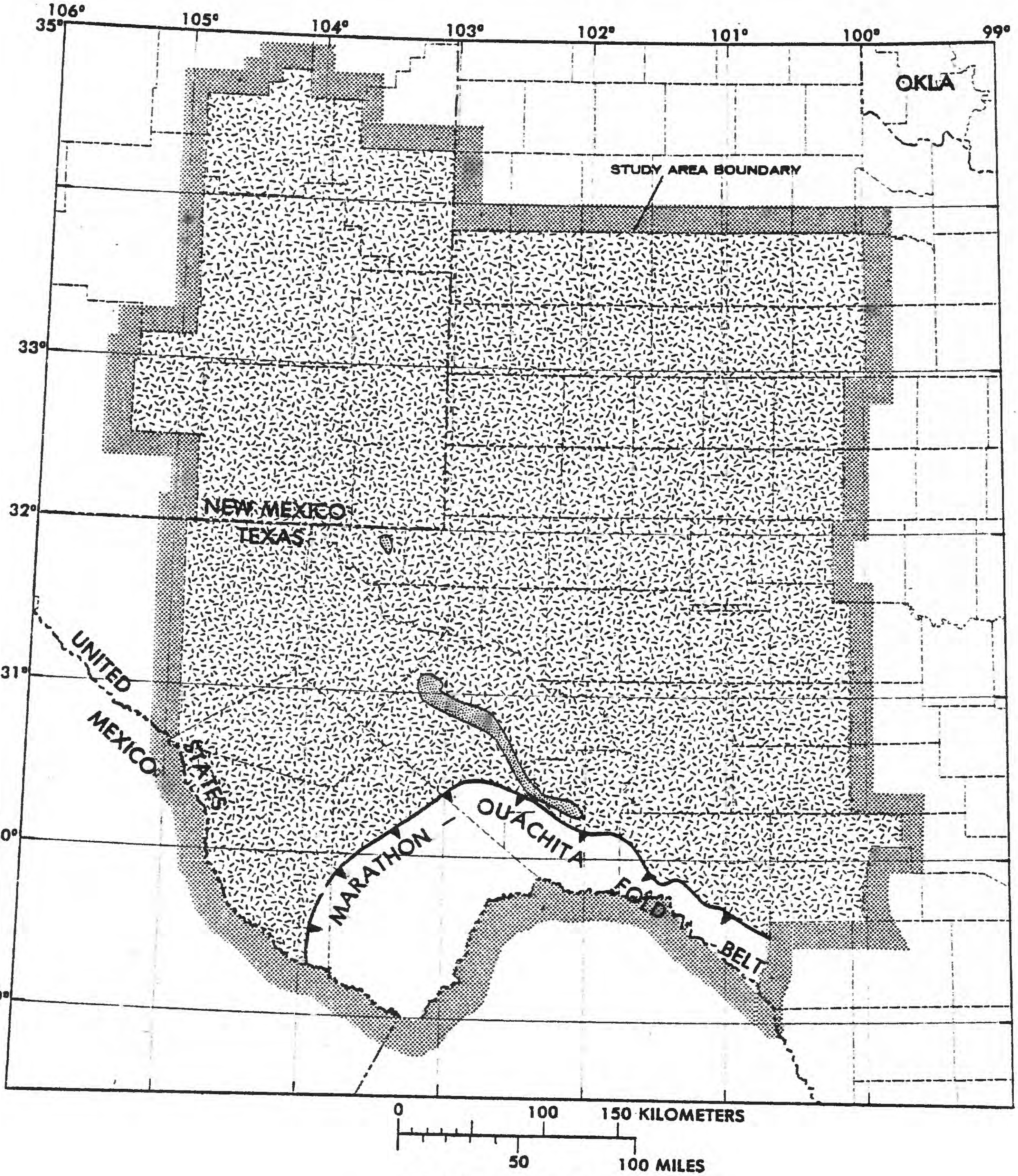


Figure 16.--Geologic map at 20,000-foot depth, Permian basin.



EXPLANATION

SEDIMENTARY ROCKS

Older Paleozoic

CRYSTALLINE ROCKS

Precambrian

Figure 17.--Geologic map at 25,000-foot depth, Permian Basin.

Areas and Volumes of Sedimentary Rocks

Areas of the various stratigraphic units were calculated by planimetric measurement of surface and subsurface geologic maps. Using these measurements in conjunction with structure and isopach maps (McKee and Oriel, 1967; Hill, 1971; Crosby and Mapel, 1975; Mapel and others, 1979), volumes of sedimentary rock were determined. In some instances, geometric models and derivatives of standard formulae were used to obtain close approximations of true volumes. Because of the overall basin configuration, rock units by depth were assumed to represent frustums of an irregular and distorted solid cone or pyramid; based on this assumption, sediment volumes can be obtained.

Total volumes of sediment in each major stratigraphic unit were partitioned on the basis of their vertical and areal distributions. Individual isopach and subsurface contour maps were used to calculate the volume of rock occurring within the depth intervals 0 to 10, 10 to 20, and 20 to 30 thousand ft. The entire areal extent of each unit was divided according to identifiable geologic trends, or into regions characterized by unique tectonic features that influenced sedimentation patterns or subsequent hydrocarbon entrapment.

Drilling Density Maps

Drilling density maps (figs. 18-21) were prepared from data in the Petroleum Information Well History Control System. The locations of exploratory wells (new field wildcats only), identified as having been drilled through or into specific stratigraphic horizons, were combined with maps of oil or gas fields producing from the same stratigraphic unit or older. The exclusion of exploratory test classes other than "new field wildcats" from these maps was mandated by the map scale and by use of pool outlines, which were assumed to include within their immediate peripheries most exploration tests of other classes. The original detailed work maps were at a scale of 1:250,000. The combined maps of exploratory wells and producing fields were then contoured on the basis of well density.

Three categories were defined for each geologic unit, *maturely drilled* areas containing 12 or more wells per 25 sq mi, *immaturely drilled* areas containing less than 12 wells per 25 sq mi, and *totally undrilled* areas. The value of 12 wells or more for every 25 sq mi (approximately 1 well per two sq mi) was assumed to be a well density representative of mature drilling in the Permian basin (Hendricks 1965, p. 7-8). However, maturity is a highly subjective and critical variable in the analysis. These maps undoubtedly under-represent the degree of drilling because of the limited exploratory well class used and data omissions resulting from unreported tests or tests that report no tops.

These maps clearly demonstrate the extent to which the younger rocks have been much more heavily explored by drilling than the deeper older rocks. For example, approximately 60 percent of the Permian rocks (fig. 18), but only 20 percent of the older Paleozoic rocks (fig. 21) are considered to be maturely drilled.

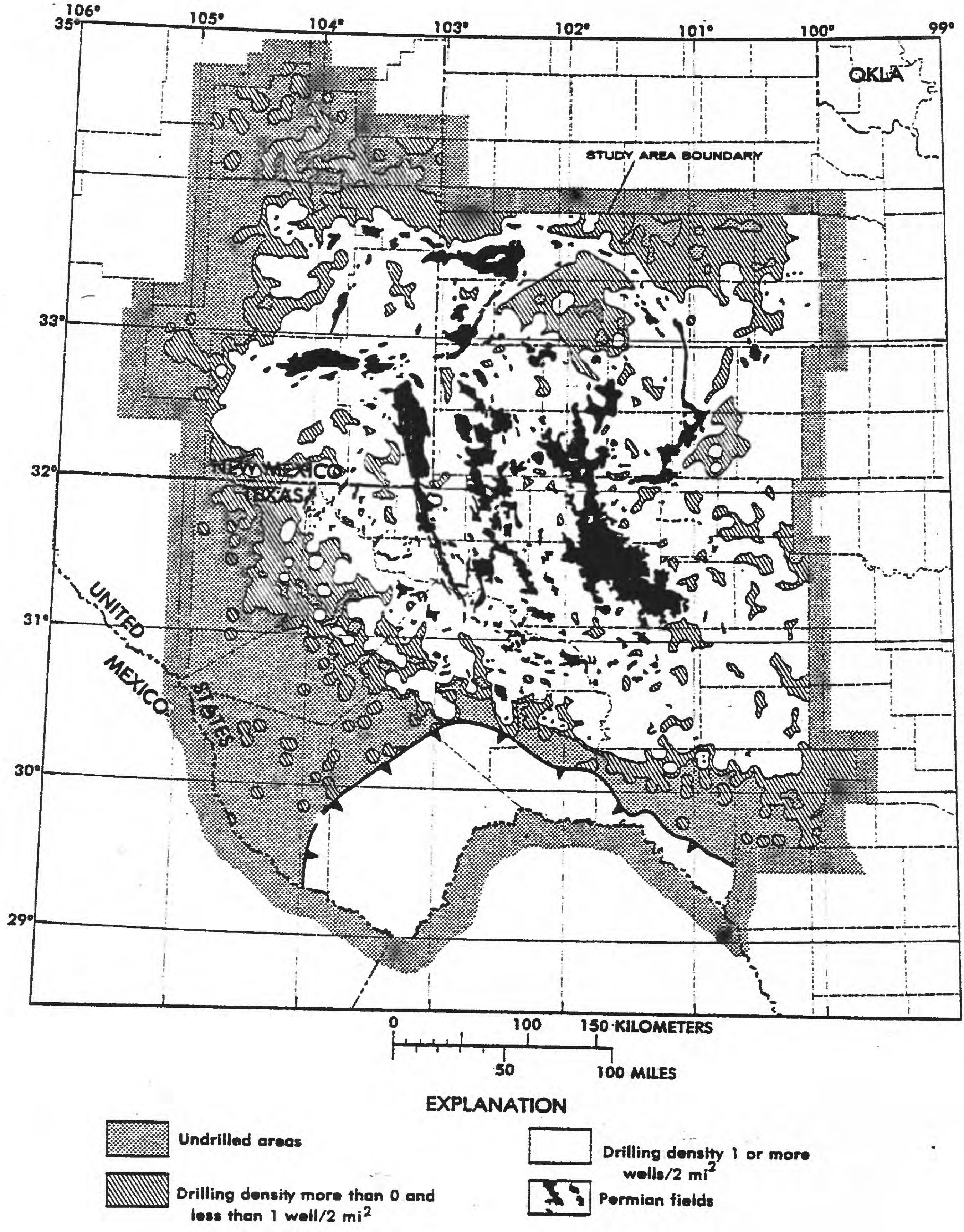


Figure 18.—Drilling density map, Permian System.

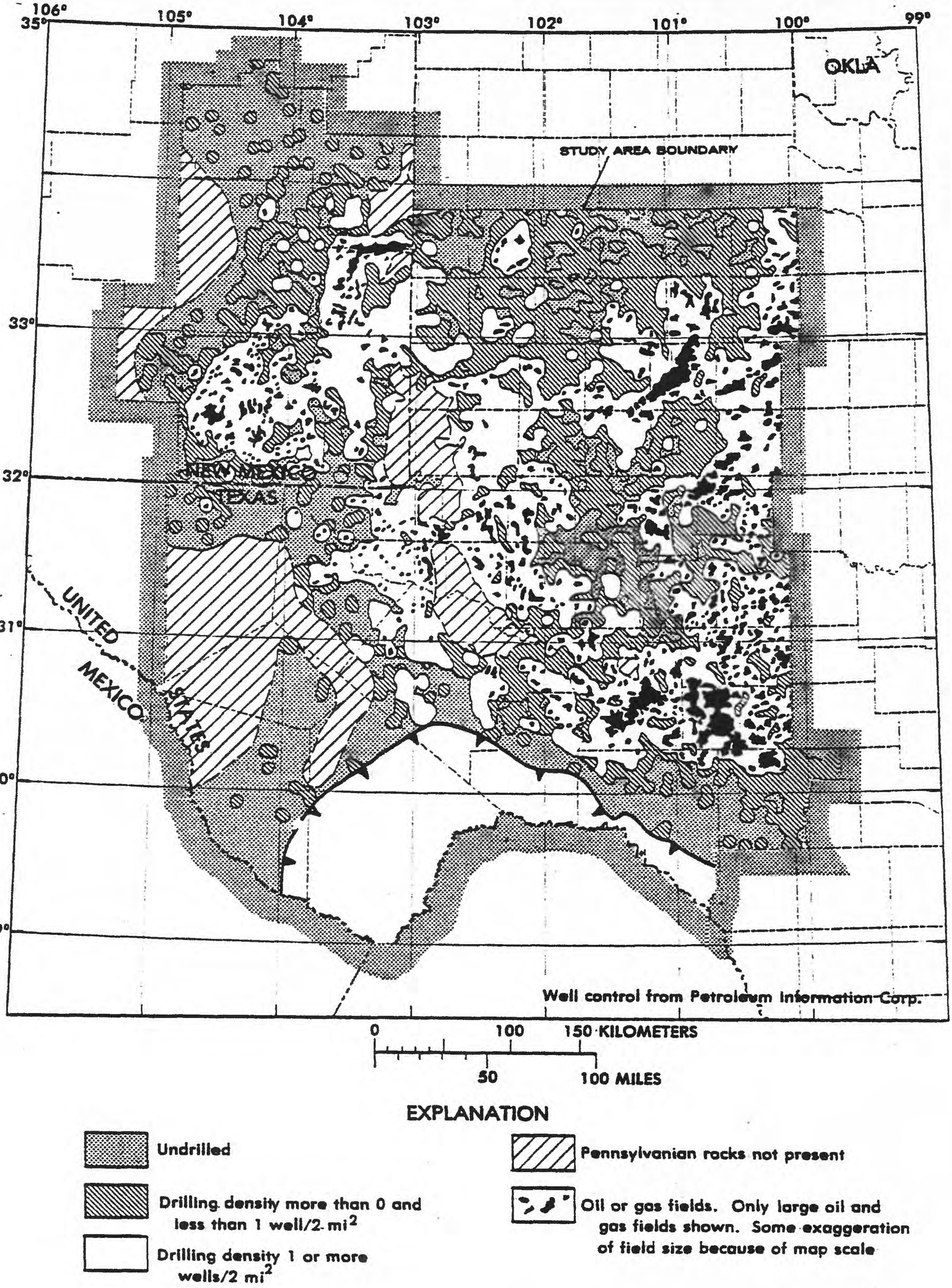
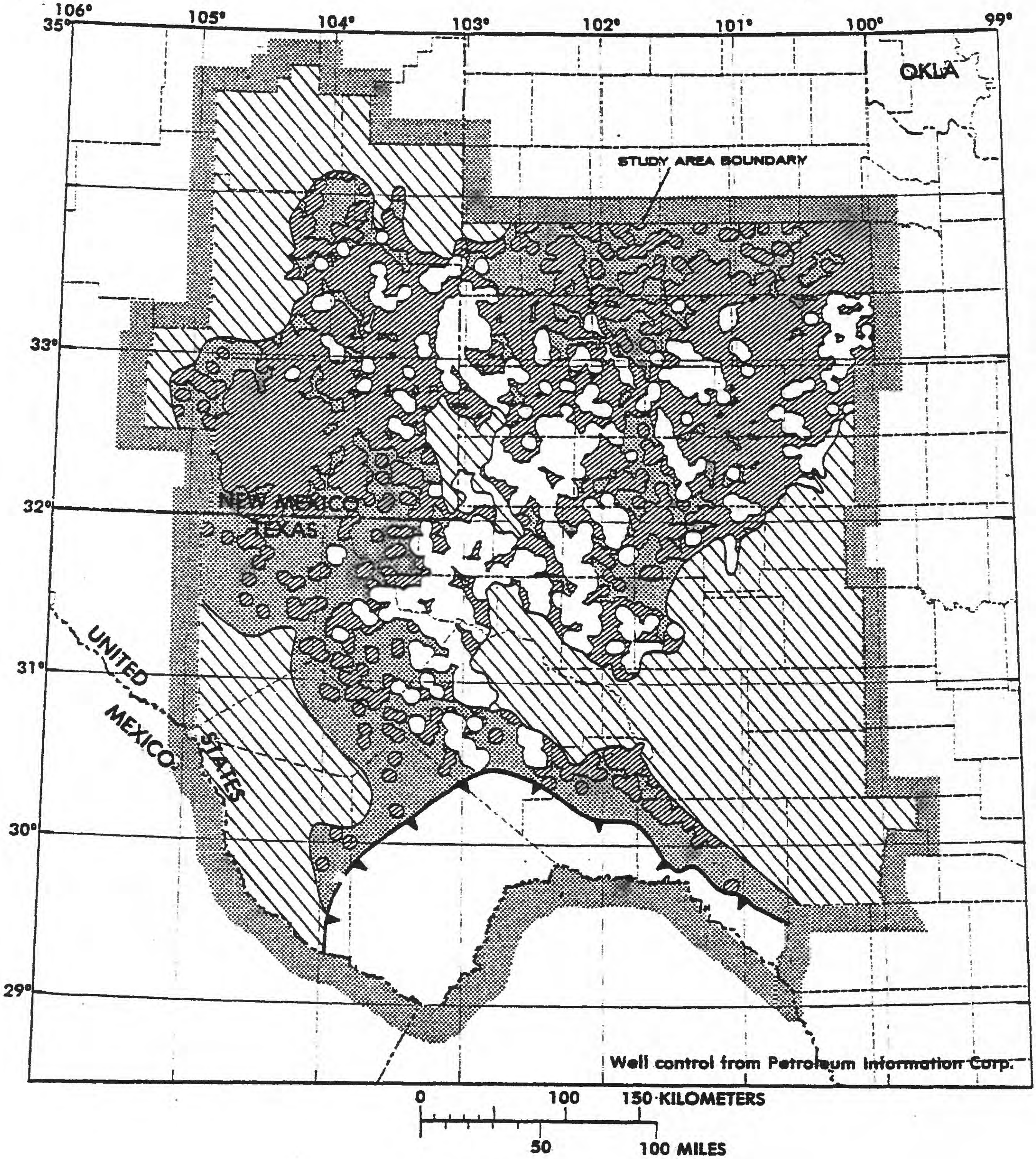


Figure 19.—Drilling density map, Pennsylvanian System.



EXPLANATION

Undrilled

Drilling density more than 0 and less than 1 well/2 mi²

Drilling density 1 or more wells/2 mi²

Mississippian rocks not present

Oil and gas fields too small to show at map scale

Figure 20.—Drilling density map, Mississippian System.

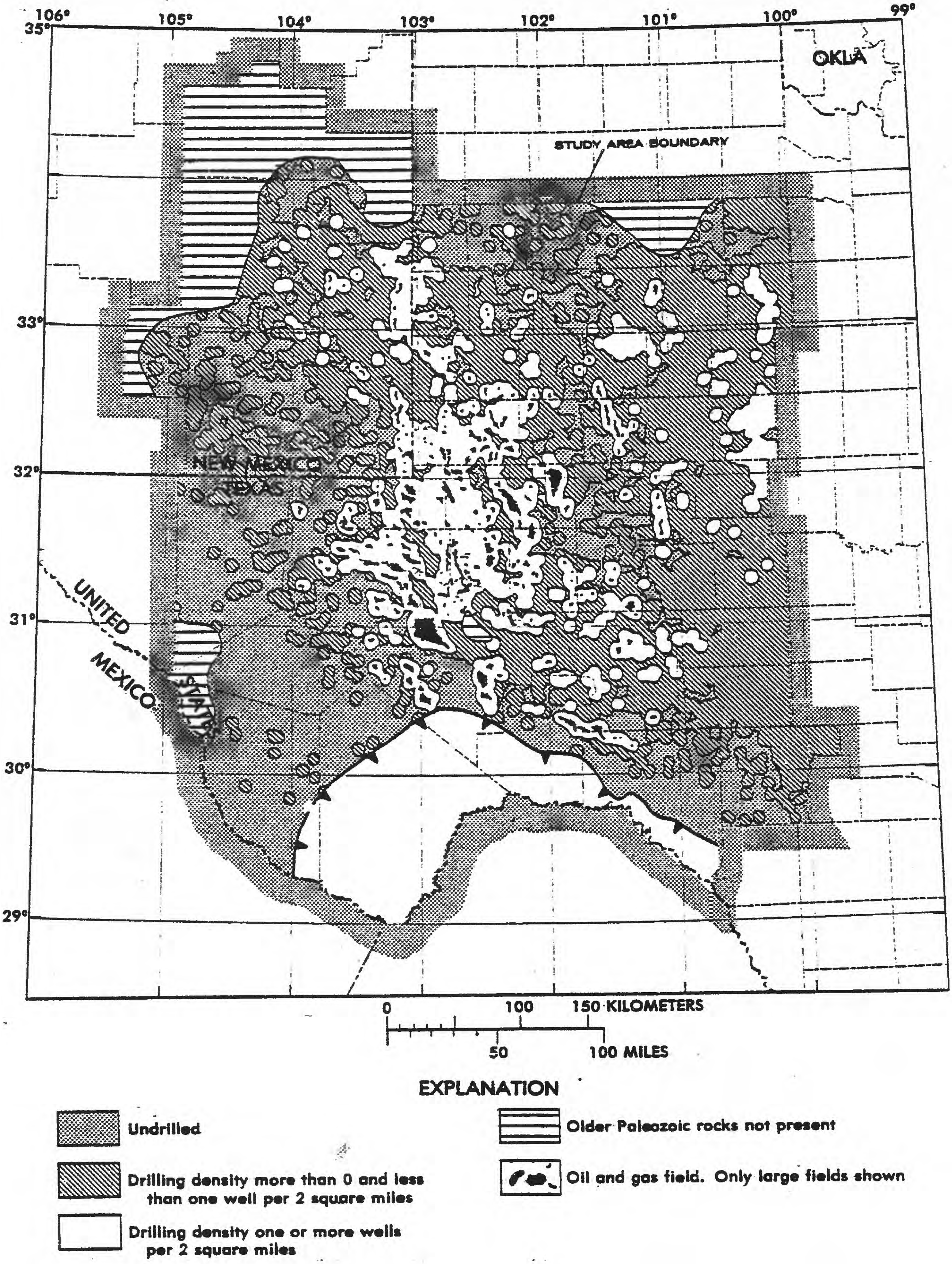


Figure 21.--Drilling density map, older Paleozoic systems.

Volumetric and Areal Yield Methods of Analysis

Information from the drilling density maps was combined with volumetric or areal data for each geologic unit. This produced a data matrix of the total sedimentary rock volume or area within a defined area or region, the amount of that rock existing within specified depth intervals, and the division of that rock volume or area into the three classes of drilling maturity.

A yield[1] factor, the amount of oil or gas *produced* per cubic mile or square mile of sedimentary rock, was calculated for each *maturely drilled* area within each depth interval for each stratigraphic or tectonically defined element.

To gain some idea of the possible range of undiscovered oil and gas-in-place, known yield factors were applied to the gross volume or area of *immaturely drilled* and *undrilled rock*. They were also applied on a smaller scale to individual tectonic elements, regions, or trends. To calculate a possible "high" amount of undiscovered oil or gas for any one area, it was assumed that geologic and reservoir conditions in the *immaturely drilled* or *undrilled* areas were similar to those existing in the *maturely drilled* producing area from which the yield factor was derived. Such conditions include lithology, porosity, permeability, trap types, sealing mechanisms, and source rocks. A "low" amount was calculated variously by: (1) reducing the total area or volume of *immaturely drilled* sedimentary rock by the quantity assumed tested by dry exploratory wells; (2) by discounting undrilled sedimentary rock in direct proportion to the success ratio established in the *maturely drilled* producing area before applying the yield factor; or (3) by discounting either the undrilled sedimentary rock volume or the historic yield factor, assuming particularly unfavorable geologic conditions. Yield factors were directly lowered in some instances to reflect a reduced probability of occurrence of additional giant fields.

The amount of undrilled sedimentary rock to be assessed depends heavily on the assumed sphere of influence of an unsuccessful exploratory well. For this analysis, we assume that a dry exploratory well has tested the rock column underlying a 2 sq mi area around the well (see p. 31). In addition, the space available for postulated undrilled traps must be taken into account. This is especially true in areas containing relatively high concentrations of exploratory dry holes.

Analog models were also applied to major tectonic elements within the Permian basin, using known hydrocarbon yields from other major elements within the basin, such as the highly productive Midland Basin or Central Basin Platform. Such analog calculations produced values of undiscovered oil and gas that were useful as scaling factors and supplemented the other analytical procedures.

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[1] *Yield*, as used in this report, applies to *in-place* rather than recoverable quantities.

Finding Rates

Finding-rate studies were informative analyses involving the relationship between discovered volume of pools and exploratory effort. Exploratory effort was measured in terms of footage drilled for exploratory wells of all classes. No statistically sound method has been devised for consistently differentiating the intent of historical exploratory drilling between oil and gas. Consequently, the aggregate exploratory drilling footage was applied to discovered volumes of both oil and non-associated gas.

The exploration footages and discovered volumes were compiled for the years following 1920, inasmuch as earlier data are incomplete and footage amounts negligible. All data were compiled on an annual basis and then combined into units of 10 million feet of exploratory effort. Source of the data for the period 1920 to 1940 was the Petroleum Information Well History Control System and that for the period 1940 to 1974 was the International Oil Scouts Assocation annual statistical summaries.

The volumes of oil or gas in-place of the discovered *pools* were classified by their discovery dates into the sequential units of exploratory effort. This linkage of discovered volumes to appropriate units of exploratory drilling effort smooths the annual and short-term fluctuations of exploration activity. The general methodology follows that developed by Miller (1976).

The data from the U.S. Bureau of Mines (now Office of Applied Analysis, Department of Energy) have some specific characteristics which may have had a small effect upon the finding-rate results and their interpretation. Pool volumes are not adjusted for future growth, and are therefore somewhat understated. Although pool discovery dates are used, pools might best be dated back to year of initial field discovery when this is earlier. The above limitations in these data do not significantly affect the overall finding-rate trends for the basin.

Plots of discovered volumes by unit of exploratory effort are shown in figures 22 and 23. These figures summarize historic finding rates for rocks of the three major stratigraphic units analyzed. The dramatic decline in the amount of oil discovered with progressive drilling effort is immediately apparent (fig. 22). For example, in the first 10 million ft of exploratory drilling (prior to 1941), nearly 40 billion bbls of oil in-place were discovered; this is almost half of the oil discovered through 1974. In the first 40 million ft of exploratory drilling approximately 80 percent of the total oil was discovered. In contrast, the last 10 million ft of exploratory drilling, out of a total of approximately 160 million ft, has yielded less than one-half billion bbls. Note, too, the decreasing contribution of Permian reservoirs. The crude oil finding-rate data are also plotted on a cumulative basis, (fig. 24).

Finding rates for non-associated gas present a different picture (fig. 23). No regular decline can be seen. The observed discovery rate may have been affected by economic considerations involving the exploration and marketing of natural gas. Natural gas was a commodity with little market value during early exploration in the Permian basin; however, strong demand in recent years has caused exploration to be directed

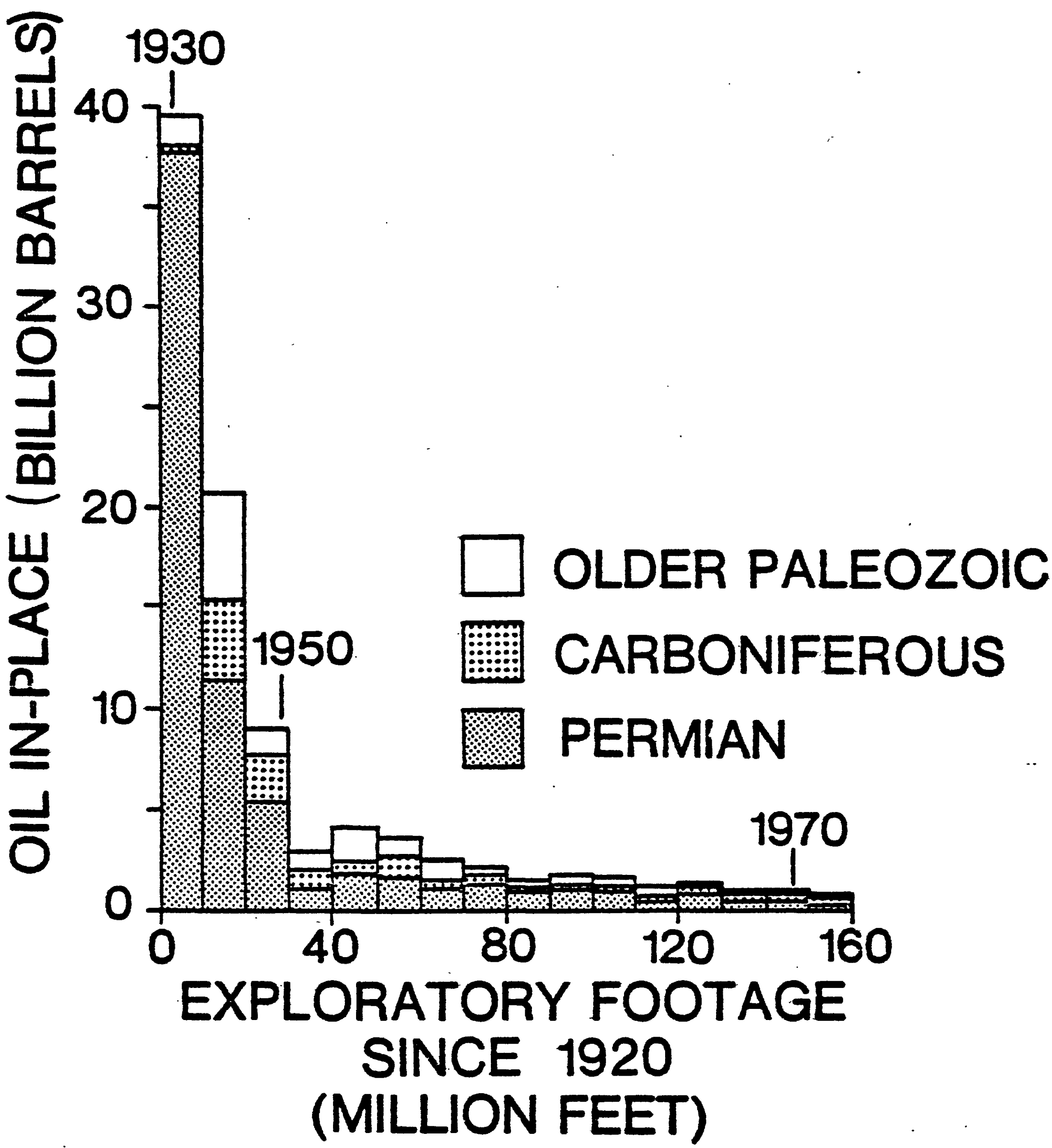

Figure 22.—Historic finding rate for oil, 1920-1974, Permian Basin.

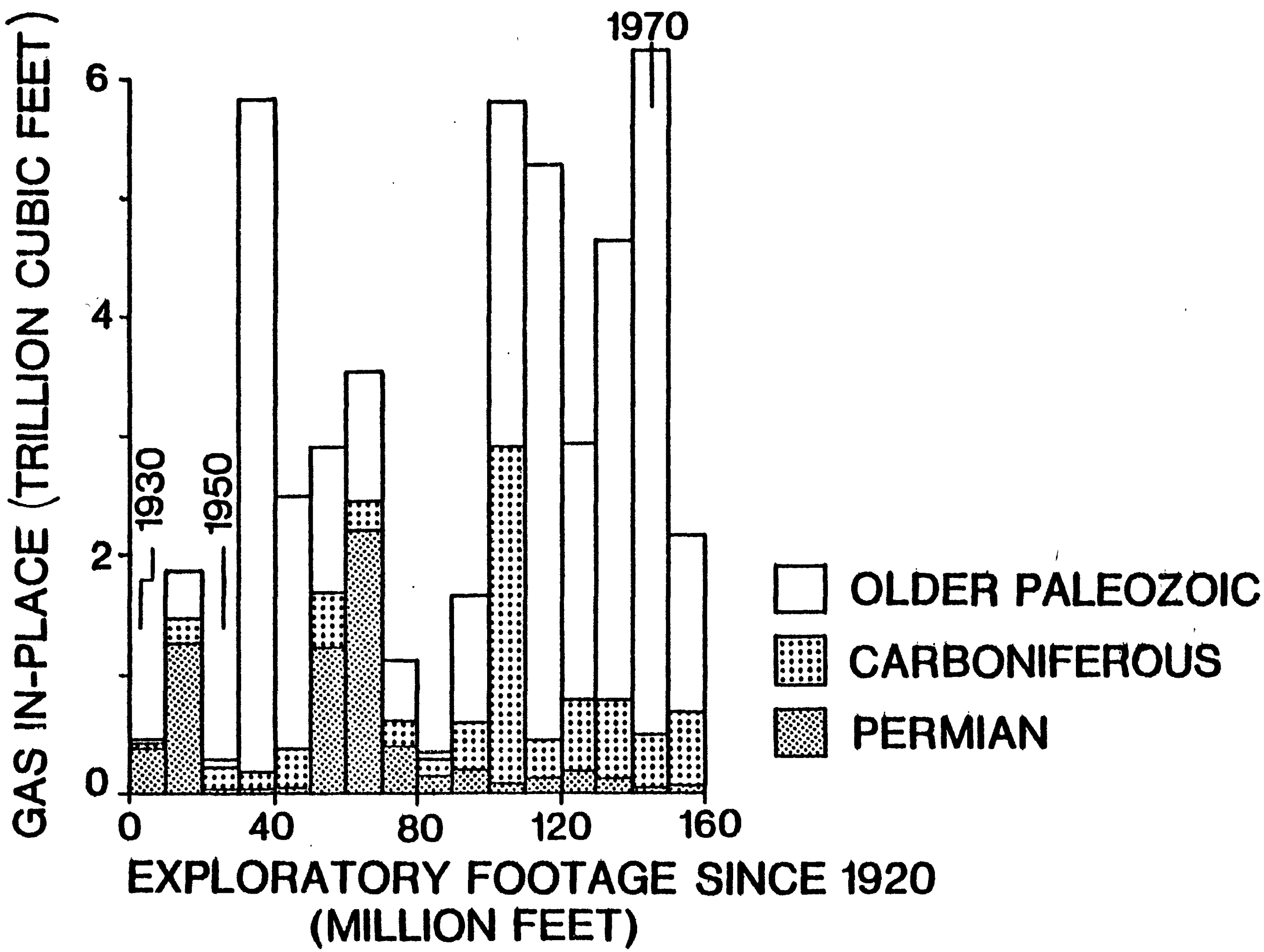

Figure 23.--Historic finding rate for non-associated gas, 1920-1974, Permian basin.

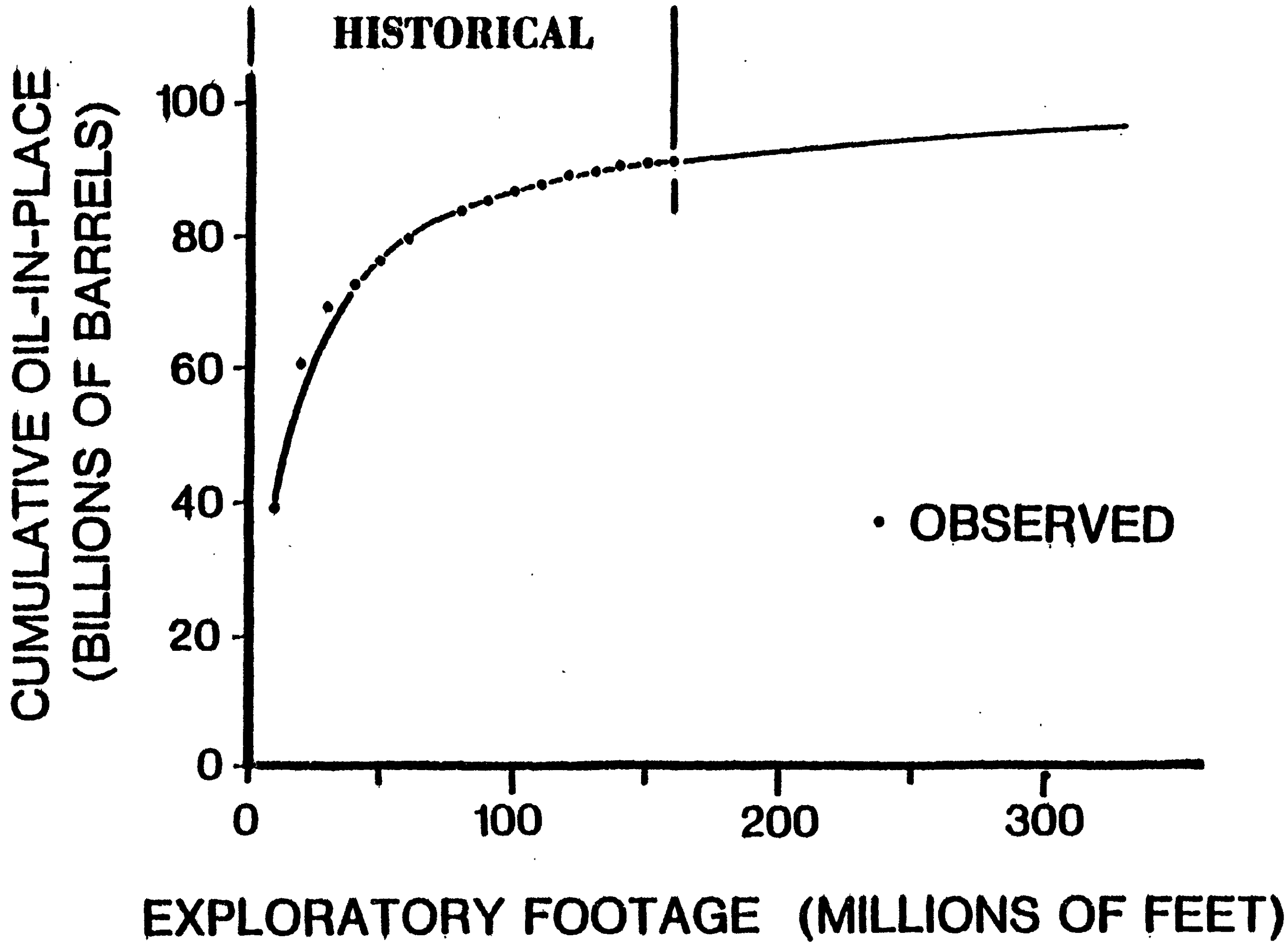

Figure 24.--Historic cumulative finding rate for oil, Permian Basin.

specifically toward the development of natural gas reserves. Finding rates show two modes: the first reflects the initial discoveries of the major deep older Paleozoic "dry" gas fields of the Delaware and Val Verde Basins in the early 1950's; and a second more recent mode reflects additional exploration in the same area. This second mode, however, does appear to decline.

Finding-rate analyses also were made for several pool-size classes in the three major stratigraphic units. These studies (not illustrated here) indicate that oil is no longer being found in the larger size classes which historically have contributed the major quantities of discovered resources. Even the larger components of the smallest size class are being found in decreasing numbers. No clear finding-rate trend can be identified for non-associated natural gas pool sizes.

SUBJECTIVE PROBABILITY ASSESSMENTS

Assessment of Undiscovered Oil and Gas

The procedures for estimating the volumes of undiscovered oil and natural gas in the Permian basin involved: (1) an intensive review and analysis of geologic and historic data by major stratigraphic unit; and (2) the application of subjective probability procedures for the actual assessments of resources in each major stratigraphic unit. The probability methods were modified from those described in Miller and others (1975).

The review of the geology, discussion of the hydrocarbon potential, and mathematical and statistical analyses of each major stratigraphic unit were presented to a committee of geologists within the Resource Appraisal Group. Following the presentation, each member of the committee individually made subjective estimates of oil in-place and non-associated gas in-place. These judgments were estimates of the *least* quantity of oil or gas associated with the 95, 75, 25, and 5 percent probabilities and a modal estimate associated with the highest probability of occurrence. Separate estimates were generated for the depth increments 0 to 10,000, 10,000 to 20,000, and 20,000 to 30,000 feet within each stratigraphic unit. The mean depths of occurrence for oil and non-associated gas were also estimated within each depth class.

Two, and in some cases three, separate iterations of the above probability procedures were made, following the introduction of new or recast data. Each repetition included an independent subjective probability assessment by each member. The estimates from the final iteration were arithmetically averaged at each probability level and at the modal estimate, and these averages[1] were statistically analyzed as described below.

Methodology for Processing Probabilistic Assessments

Statistical analsis of the average probability and modal estimates followed a modification of the procedure for computing and aggregating lognormal probability distributions developed for the United States Geological Survey by Gordon M. Kaufman of the Massachusetts Institute

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[1]These raw estimates are provided in tabular form in Appendix C and graphically in Appendix B.

of Technology, (Miller and others, 1975, p. 22). Using this procedure we computed and report lognormal probability distributions for the individual hydrocarbon assessment for each depth increment within each major stratigraphic unit.

Because of existing computer program constraints, only quantities associated with the 5 and 95 percent probability estimates and the modal values were used in developing the lognormal probability cureve fits to the original estimates. Work to date suggests that functions fit to *all* assessed probabilites should provide more representative distributions than a lognormal fit to the 5 and 95 percent fractiles and modal values. The use of functions other than lognormal will be explored in future work.

Monte Carlo aggregation techniques were applied to the above lognornal curves to derive the summary probability distributions for undiscovered oil and gas for rocks of all ages within each depth increment, for each major stratigraphic unit, and for the basin as a whole.

Descriptive statistics such as mean, mode, and standard deviation, are calculated for each lognormal probability distribution as well as for the aggregated probability distributions.

Probability Estimates of Undiscovered Pool Sizes and Statistical Methodology

Probablity distributions of the pool sizes in which the assessed undiscovered oil and gas in-place occurs were generated for each depth interval in each of the major stratigraphic units. Pool sizes were estimated as in-place quantities of oil and non-associated gas. Dissolved/associated gas occurrences were treated separately as products of the oil pools with which they are associated. Data for pool-size assessments were compiled as an integral part of the overall data collection and analysis. Particular emphasis was placed on establishing the spatial, stratigraphic, size, and discovery-time relationships of known pools.

Historic pool data were subjected to several analyses within each major stratigraphic unit.

1. Histograms were prepared for all pool-size classes by depth intervals and by sequential units of exploratory effort, each unit consisting of 40 million ft of exploratory drilling.
2. Cumulative frequency distributions were calculated and siplayed as smoothed curves for the entire historic period and for the last two 40-million-foot periods of exploratory effort. Descriptive statistic for these distributions were calculated.
3. A linear regression was fitted to the historic cumulative frequency distribution of pool size in an attempt to project cumulative frequencies of pools in the very small classes. Statistics for these distributions were calculated.
4. Finding-rate curves were calculated for various pool-size classes.

Figures 25 and 26 show pool-size finding rates for all ages and depths in the Permian Basin.

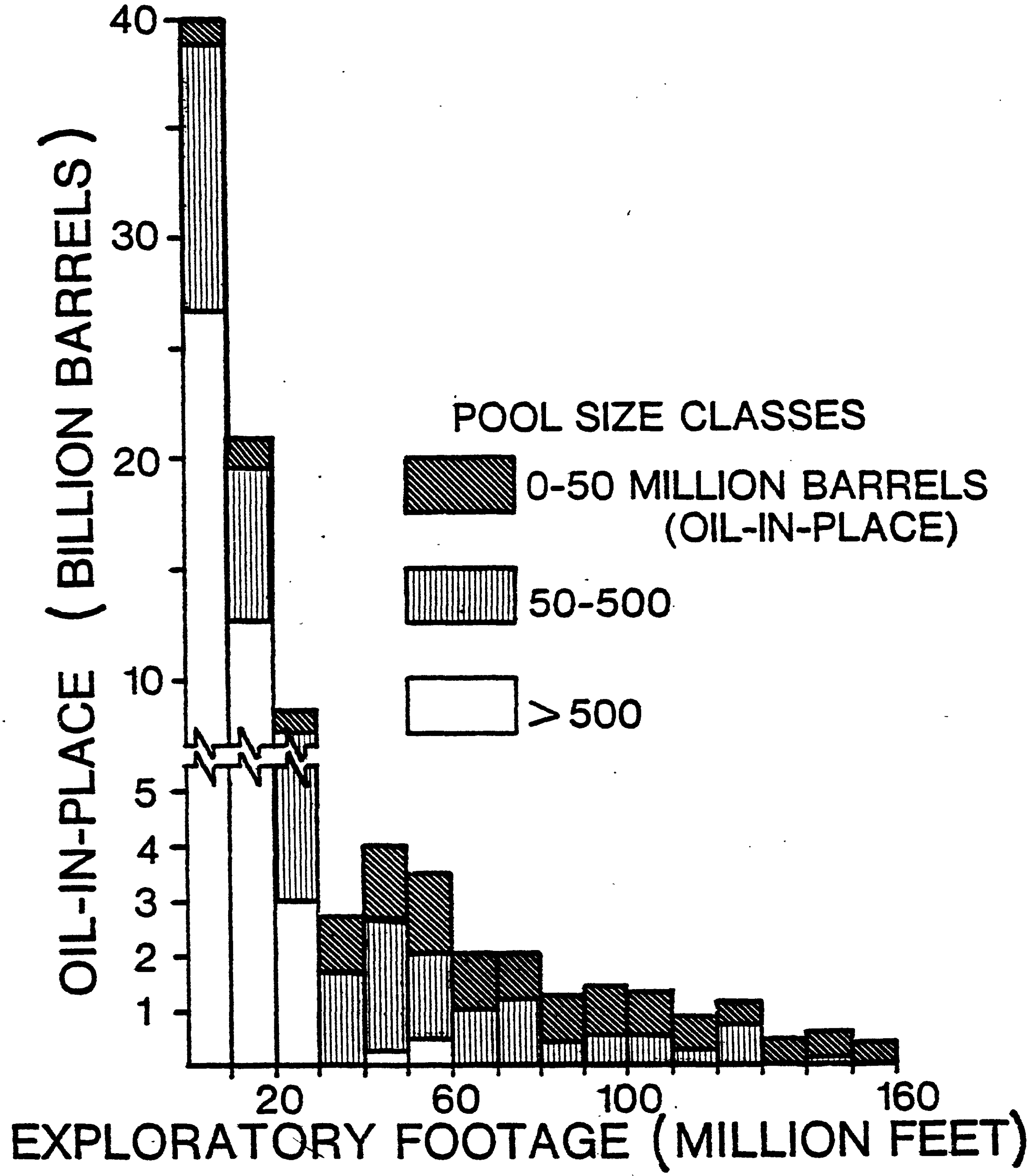

Figure 21.--Historic finding rate for oil by pool size, Permian Basin.

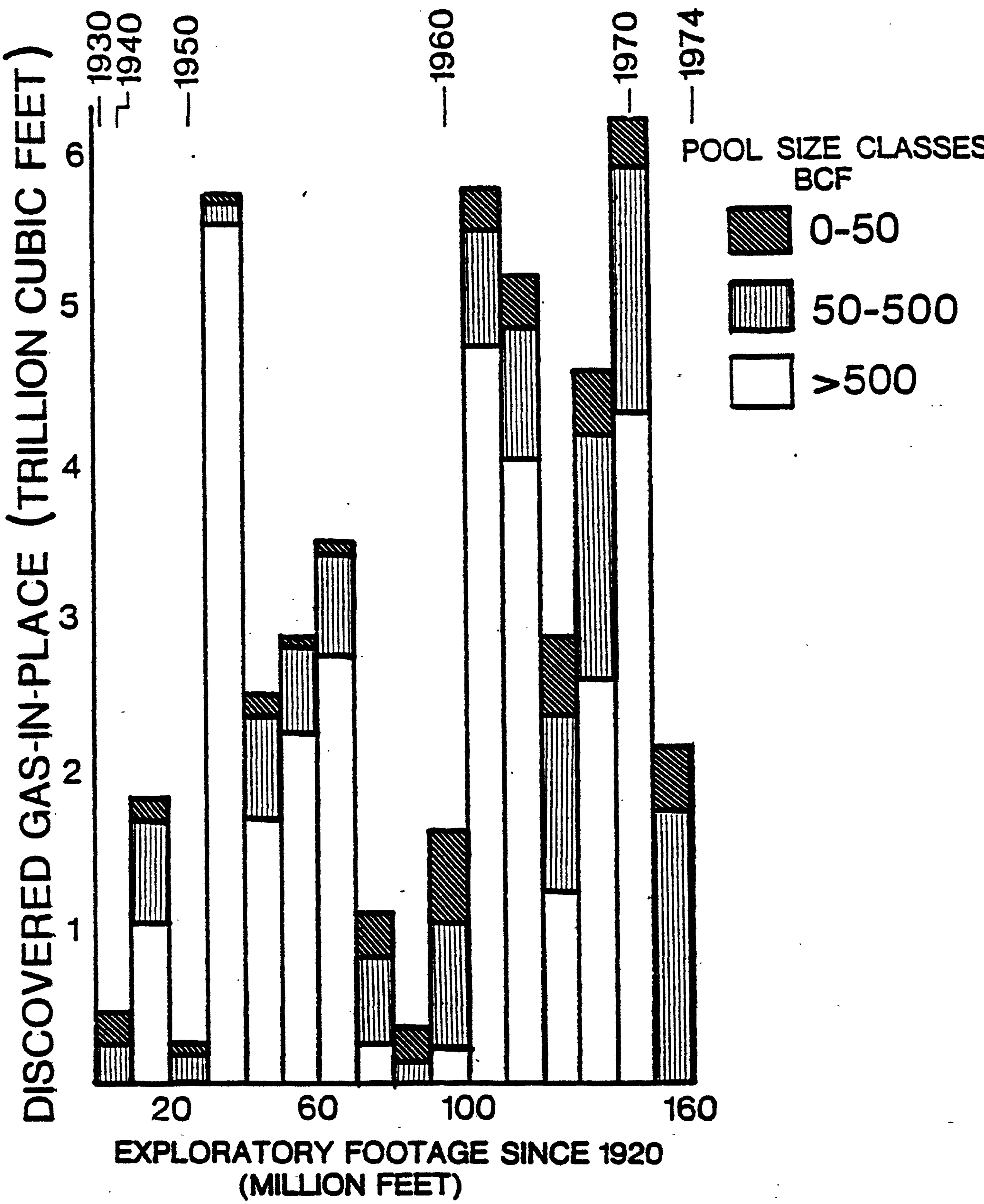

Figure 26.—Historic finding rate for non-associated gas by pool size, Permian Basin.

Pool sizes for undiscovered oil and non-associated gas were estimated by subjective probability methods. Estimates were made of *at least* a certain size of pool corresponding to the 0.95, 0.75, 0.25, and 0.05 probabilities. For example, the estimate given at the 0.05 probability represents the pool size where 5 percent of the pools are at least of that size. A modal value was also estimated. These distributions represent integrated estimates of the probability distribution of pool-sizes accompanying all ranges of undiscovered hydrocarbons previously assessed in a given unit.

Three iterations of the process for probability estimation of pool-size distributions were made and estimates of all assessors from the final iteration at each probability were arithmetically averaged.[1] A lognormal curve was fit to the averaged 95 and 5 percent probability estimates. However, the data may not be strictly lognormal in distribution, and means of lognormal curves fit to historic pool-size data are notably large when compared with the actual means calculated from those data. The lognormal distributions reported here should be viewed only as approximations of undiscovered pool size distributions.

Pool-size assessments were made by depth interval within the major stratigraphic units; however, aggregation of these distributions into a basin total or major stratigraphic unit total was not achieved. Programs for such aggregation are being developed.

Methodology for the Assessment of Dissolved/Associated Gas

Undiscovered dissolved/associated gas quantities were estimated by means of depth-related historic gas-oil ratios. Amounts of discovered in-place dissolved/associated gas and oil were assembled by 1,000 ft depth increments (fig. 8). From these data, the ratio of dissolved/associated gas to oil was established for each stratigraphic unit by depth interval (fig. 27). Substantial differences do not appear between stratigraphic units at equal depths in these plots, with the exception that the Permian System gas-oil ratios for part of the data set are somewhat low. This may be the result of an underestimation of flared gas. To derive undiscovered dissolved/associated gas quantities, the gas-oil ratios at the various mean depths of oil occurrence were applied to the assessed quantity of undiscovered oil at that depth.

UNDISCOVERED OIL AND GAS

Permian System

Only the three oldest Permian provincial series--the Wolfcampian, Leonardian, and Guadalupian--are considered significant for hydrocarbon potential, and in these over 65 billion bbls of oil and over 39 trillion cu ft of natural gas have already been discovered (table 1, p. 14).

Estimates of volumes of undiscovered hydrocarbons in-place for Permian rocks at the various depths and probability levels are shown in

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[1]These averages are shown in Appendix C, tables 16 and 17, and in Appendix B, figures 53-58.

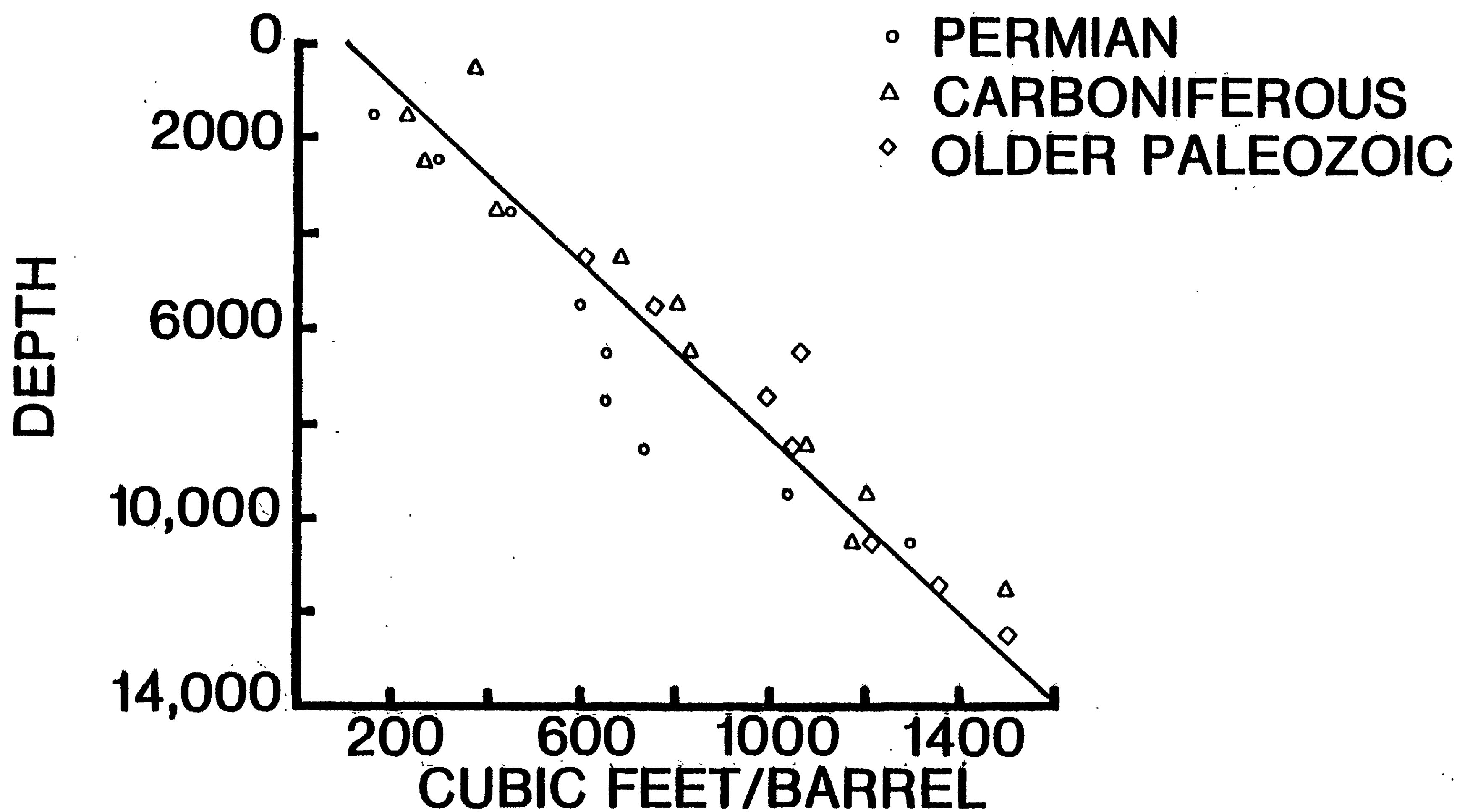

Figure 27 -- Historic dissolved/associated gas to oil ratios by depth, Permian basin.

table 2. The probability distributions for these estimates are in Appendix B, figures 28, 29, 36, 37, 44, and 45.

The estimates in table 2 indicate that at the 95 and 5 percent probabilities, 1.0 to 6.0 billion bbls of oil in-place (1.5 to 9.2 percent of the discovered Permian crude oil) remain undiscovered, while 0.7 to 4.1 trillion cu ft of dissolved/associated gas in-place (2.2 to 12.4 percent of the discovered dissolved/associated gas) remain undiscovered. Finally, 0.2 to 0.6 trillion cu ft non-associated gas in-place (3 to 21 percent of the discovered non-associated gas) remain undiscovered. Most of these undiscovered in-place hydrocarbons occur above 10,000 ft. The estimates of mean depths of occurrence of undiscovered oil and gas are shown in table 3.

These undiscovered amounts will probably occur in circumstances similar to known fields and pools with respect to reservoir characteristics, seals, source beds, and nature of the hydrocarbons. Traps will probably be predominantly stratigraphic. The undiscovered deposits are likely to be distributed in undrilled areas surrounded by or flanking known production. Such flanking areas are in the western part of the Northwestern Shelf, the western areas of the Delaware Basin, and the southern and western parts of the Val Verde Basin.

Probability distributions of pool sizes containing these appraised amounts of hydrocarbons in-place are given in table 4. The full probability distributions are shown graphically in Appendix B, figures 53 and 56.

Results indicate that undiscovered pool sizes are small; only at the 5 percent probability is there a chance of occurrence of an oil pool of 16 million bbls or larger, or a non-associated gas pool of 24 billion cu ft or larger.

Carboniferous Systems

Rocks of the Carboniferous systems account for approximately 12 billion bbls of discovered oil in-place and 18 trillion cu ft of discovered non-associated gas in-place, of which more than 99 percent has been found in Pennsylvanian rocks.

Estimates of the amounts of undiscovered in-place oil, dissolved/associated gas, and non-associated gas remaining in Carboniferous rocks are in table 5. Probability distributions for these estimates are shown graphically in Appendix B, figures 30, 31, 38, 39, 46, and 47. More than 85 percent of the undiscovered oil in-place in Carboniferous rocks is expected to occur between depths of 0 to 10,000 ft. Estimates of undiscovered non-associated gas in-place indicate that more than 70 percent will occur in the depth interval 0 to 10,000 ft, more than 27 percent in the interval 10,000 to 20,000 ft, and less than 2 percent in the interval 20,000 to 30,000 ft. The mean depths of occurrence of undiscovered oil and non-associated gas are shown in table 6. Most of the undiscovered oil and gas is anticipated to be found in the Pennsylvanian portion of the sequence.

Estimates of the probability distributions of the pool sizes likely to contain these amounts of hydrocarbons are given in table 7. Graphs of these distributions are shown in Appendix B, figures 54 and 57. The results indicate that greatest probability of large size pools occurs

Table 2.--*Estimates of undiscovered hydrocarbons, Permian System*
[The values shown are the estimates corresponding to the probability that there is at least that amount. Values shown are derived from lognormal curve fits to estimates at the 0.95 and 0.05 probability levels and the modal value. Leaders (---) indicate not calculated; negl = negligible.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05	Mean	Standard deviation
			Oil in-place (billion bbls)			
0-10,000	0.89	1.58	3.46	6.10	2.77	1.76
10,000-20,000	.06	.10	.21	.36	.17	.10
Total	1.03	1.69	3.50	6.02	2.94	1.68
			Dissolved/associated gas in-place (trillion cu ft)			
0-10,000	0.57	1.01	2.21	3.90	1.77	1.12
10,000-20,000	.07	.13	.26	.44	.21	.12
Total	.74	1.18	2.38	4.07	1.98	1.12
			Non-associated gas in-place (trillion cu ft)			
0-10,000	0.17	0.31	0.72	1.33	0.57	0.40
10,000-20,000	.01	.02	.04	.08	.03	.02
20,000-30,000	negl.	negl.	negl.	negl.	---	---
Total	.19	.33	.72	1.31	.60	.38

Table 3.--*Estimates of mean depths of undiscovered hydrocarbons, Permian system*

Depth interval (ft)	Mean depth of occurrence (ft)	
	Oil	Non-associated gas
0-10,000	5,100	4,000
10,000-20,000	10,500	10,800
20,000-30,000	None	None
Total	5,400	4,300

Table 4.—*Probability estimates of undiscovered pool sizes, Permian system*

[The values shown correspond to the probability of occurrence of a pool of at least that size. Values are derived from a log-normal curve fit to estimates at the 0.95 and 0.05 probabilities.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05
	Oil in-place (million bbls)			
0-10,000	0.002	0.027	1.08	15.48
10,000-20,000	.001	.016	.48	5.76
	Non-associated gas in-place (billion cu ft)			
0-10,000	0.003	0.044	1.72	24.04
10,000-20,000	.002	.031	1.06	13.67

Table 5.--*Estimates of undiscovered hydrocarbons, Carboniferous systems*
[The values shown are the estimates corresponding to the probability that there is at least that amount. Values shown are derived from lognormal curve fits to estimates at the 0.95 and 0.05 probability levels and modal value.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05	Mean	Standard deviation
			Oil in-place (billion bbls)			
0-10,000	0.25	0.54	1.60	3.51	1.28	1.23
10,000-20,000	.03	.07	.24	.59	.20	.23
Total	.36	.68	1.74	3.54	1.48	1.19
			Dissolved/associated gas in-place (trillion cu ft)			
0-10,000	0.20	0.43	1.29	2.82	1.03	0.99
10,000-20,000	.04	.09	.30	.74	.25	.29
Total	.33	.61	1.49	2.98	1.28	.97
			Non-associated gas in-place (trillion cu ft)			
0-10,000	0.27	0.59	1.75	3.81	1.40	1.33
10,000-20,000	.12	.25	.67	1.38	.53	.46
20,000-30,000	.01	.02	.07	.20	.06	.08
Total	.64	1.07	2.35	4.34	1.99	1.31

Table 6.--*Estimates of mean depths of undiscovered hydrocarbons, Carboniferous systems*

Depth interval (ft)	Mean depth of occurrence (ft)	
	Oil	Non-associated gas
0-10,000	6,600	7,300
10,000-20,000	10,900	12,400
20,000-30,000	None	21,200
Total	7,200	9,100

Table 7.--*Probability estimates of undiscovered pool sizes, Carboniferous systems*

[The values shown correspond to the probability of occurrence of a pool of at least that size. Values are derived from a lognormal curve fit to estimates at the 0.95 and 0.05 probabilities.]

Depth interval (ft)	Probability			
	0.95	0.75	0.25	0.05
	Oil in-place (million bbls)			
0-10,000	0.002	0.024	0.84	11.12
10,000-20,000	.002	.020	.66	8.34
	Non-associated gas in-place (billion cu ft)			
0-10,000	0.003	0.057	3.02	53.08
10,000-20,000	.003	.052	2.69	46.80
20,000-30,000	.001	.027	1.65	32.11

above 10,000 ft. The average undiscovered pool size is estimated to be smaller than the average historic pool size.

The Eastern Shelf, Northwestern Shelf, and the Midland Basin, in that order, are the most favorable areas for undiscovered oil. The Northwestern Shelf, Delaware-Val Verde Basins, Eastern Shelf, and possibly the Marfa Basin, in that order, appear to be the most favorable areas for undiscovered non-associated natural gas. The Marfa Basin, a geologically complex area essentially concealed under a volcanic cover, is a high-risk area of speculative potential.

Undiscovered traps in the Carboniferous will be primarily combinations of favorable stratigraphy and structure, with stratigraphy being more important, particularly in reef developments with flanking porosity and permeability lenses. Reservoir lithology will be predominantly limestone, followed by sandstone, siltstone, and cherty conglomerate.

Older Paleozoic Systems

Rocks of early Paleozoic age, although moderately well explored, are believed to contain substantial quantities of undiscovered oil and natural gas, (table 8). Probability distributions for these estimates are shown graphically in Appendix B, figures 32, 33, 40, 41, 48, and 49.

Undiscovered oil in the older Paleozoic is estimated to be almost equally distributed above and below the 10,000 ft depth; however, approximately 74 percent of the undiscovered non-associated gas is estimated to occur in the interval 10,000 to 20,000 ft. Although significant non-associated gas occurs at depths greater than 20,000 ft, the limited distribution of rocks there is an important constraining factor. No oil is anticipated below 15,000 ft and little above 5,000 ft. The mean depths of occurrence of undiscovered oil and non-associated gas are shown in table 9.

The Midland basin and the Northwestern shelf have the greatest undiscovered oil and dissolved gas potential. Exploration on the highly productive Central Basin Platform, however, has progressed to a point where relatively few significant new accumulations can be anticipated. Remaining potential for non-associated gas is principally in the Delaware and Val Verde basins, deeper parts of the Midland basin, and portions of the Northwestern Shelf. The southwestward increase of carbon dioxide content in natural gas in the older Paleozoic reservoirs of the Delaware Basin is an important factor. The abundance of this contaminant appears to effectively limit the distribution of hydrocarbon natural gas in that direction and may preclude the occurrence of hydrocarbon gas in the Marfa Basin.

Probability distributions of pool sizes containing these assessed quantities are given in table 10 and shown graphically in Appendix B, figures 55 and 58. These indicate that undiscovered pool sizes will be smaller than historic pool sizes.

Undiscovered oil and gas pools probably occur in traps comparable to those already discovered, except that undrilled structural traps are estimated to be smaller on the average. Truncated reservoir beds along pre-Woodford, Pennsylvanian, or Permian unconformities will continue to be as important as stratigraphic traps. Traps involving possible shelf

Table 8.--*Estimates of undiscovered hydrocarbons, older Paleozoic systems*
[The values shown are the estimates corresponding to the probability that there is at least that amount. Values shown are derived from lognormal curve fits to estimates at the 0.95 and 0.05 probability levels and modal value.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05	Mean	Standard deviation
			Oil in-place (billion bbls)			
0-10,000	0.30	0.54	1.25	.29	1.00	0.68
10,000-20,000	.26	.49	1.16	2.19	.93	.67
Total	.78	1.22	2.30	3.60	1.93	.91
			Dissolved/associated gas in-place (trillion cu ft)			
0-10,000	0.30	0.54	1.26	2.30	1.00	0.68
10,000-20,000	.37	.69	1.65	3.10	1.31	.95
Total	.94	1.46	2.76	4.37	2.31	1.14
			Non-associated gas in-place (trillion cu ft)			
0-10,000	0.42	0.75	1.68	3.00	1.34	0.88
10,000-20,000	3.30	5.81	12.68	22.29	10.14	6.39
20,000-30,000	.71	1.26	2.79	4.94	2.23	1.43
Total	6.16	8.96	16.11	25.45	13.71	6.51

Table 9.--*Estimates of mean depths of undiscovered hydrocarbons, older Paleozoic systems*

Depth interval (ft)	Mean depth of occurrence (ft)	
	Oil	Non-associated gas
0-10,000	8,500	9,500
10,000-20,000	12,300	15,600
20,000-30,000	None	21,600
Total	10,300	16,000

Table 10.--*Probability estimates of undiscovered pool sizes, older Paleozoic systems*

[The values shown correspond to the probability of occurrence of a pool of at least that size. Values are derived from lognormal curves fit to estimates at the 0.95 and 0.05 probability levels.]

Depth interval (ft)	Probability			
	0.95	0.75	0.25	0.05
	Oil in-place (million bbls)			
0-10,000	0.002	0.025	1.07	16.12
10,000-20,000	.002	.025	1.04	15.46
	Non-associated gas in-place (billion cu ft)			
0-10,000	0.004	0.115	10.90	293.34
10,000-20,000	.007	.200	19.38	528.74
20,000-30,000	.005	.141	14.42	409.68

margins or biohermal buildups in Silurian and Devonian rocks may also contain hydrocarbons.

Undiscovered oil and gas pools are estimated to be in reservoirs similar to those already found. The Ordovician Ellenburger and the Devonian carbonates will continue to predominate as reservoir rocks, particularly for non-associated gas pools.

Total Undiscovered Oil and Gas

Quantities of undiscovered oil and gas for the entire Paleozoic section of the Permian basin, as distributed by depth, are given in table 11 and shown graphically in Appendix B, figures 34, 42, and 50. These amounts represent statistical aggregations of the individual stratigraphic elements discussed in the preceding section. All undiscovered oil and dissolved/associated gas is anticipated to occur at depths less than 15,000 ft, and 80 percent of it at depths less than 10,000 ft. Eighty percent of the undiscovered non-associated gas, however, is estimated to occur at depths greater than 10,000 ft, with the bulk of it between 10,000 and 20,000 ft. Mean depths of occurrence are given in table 12.

Our overall estimate of undiscovered oil in-place, 3.3 to 10.4 billion bbls at the 95 and 5 percent probability levels, is equivalent to 4 to 11 percent of the known oil in-place, with the mean of 6.4 billion bbls equal to 7 percent of that discovered. Likewise, the estimate for total gas in-place is 12.9 to 33.8 trillion cu ft at the 95 and 5 percent probability levels, 12 to 32 percent of the total discovered gas in-place.[1] Of the total gas, 8.24 to 28.3 trillion cu ft will occur as non-associated gas, 17 to 59 percent of the already discovered non-associated gas. Probability distributions for these total estimates are shown in Appendix B, figures 35, 43, 51, and 52.

Estimates of the probability distributions of undiscovered pool sizes for all Paleozoic systems are summarized in table 13. These assessments were never aggregated into basin totals. Analysis of the historic data suggests that much of the undiscovered oil and gas will occur in multiple pool deposits. The historic ratio averages 1.6 pools/field for oil and 1.3 pools/field for non-associated gas. Such fields may contain pays ranging in age from Ordovician to Permian.

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[1]Includes 2.2 trillion cu ft of carbon dioxide.

Table 11.--*Estimates of undiscovered hydrocarbons, Permian basin*
[The values shown are the estimates corresponding to the probability that there is at least that amount. Values shown are derived from aggregated lognormal probability distributions.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05	Mean	Standard deviation
Undiscovered oil in-place (billion bbls)						
0-10,000	2.31	3.37	5.91	8.87	5.05	2.18
10,000-20,000	.51	.79	1.52	2.56	1.30	.69
Total	3.32	4.53	7.22	10.43	6.35	2.29
Undiscovered dissolved/associated gas in-place (trillion cu ft)						
0-10,000	1.76	2.58	4.42	6.70	3.80	1.56
10,000-20,000	.68	1.07	2.08	3.53	1.77	.97
Total	2.99	4.06	6.31	8.83	5.57	1.85
Undiscovered non-associated gas in-place (trillion cu ft)						
0-10,000	1.43	2.16	3.83	5.98	3.31	1.52
10,000-20,000	3.73	6.17	12.74	21.90	10.70	6.15
20,000-30,000	.75	1.28	2.73	4.86	2.29	1.38
Total	8.24	11.38	18.80	28.27	16.30	6.58
Total gas in-place (trillion cu ft)						
Total	12.89	16.50	24.29	33.80	21.87	6.74

Table 12.--*Estimates of mean depths of undiscovered hydrocarbons, all Paleozoic systems*

[N.A.=not applicable.]

Depth interval (ft)	Mean depth of occurrence (ft)	
	Oil	Non-associated gas
0-10,000	6,100	7,600
10,000-20,000	11,800	15,400
20,000-30,000	N.A.	21,500
Total	7,300	14,700

Table 13.--*Estimates of probability distributions of undiscovered pool sizes, all Paleozoic systems, Permian basin*

[The values shown correspond to the probability of occurrence of a pool of at least that size. Values are derived from lognormal curves fit to estimates at the 0.95 and 0.05 probability levels.]

Depth interval (ft)	Probability 0.95	0.75	0.25	0.05
	Oil in-place (million bbls)			
Permian				
0-10,000	0.002	0.027	1.08	15.48
10,000-20,000	.001	.016	.48	5.77
Carboniferous				
0-10,000	.002	.024	.84	11.12
10,000-20,000	.002	.020	.66	8.34
Older Paleozoic				
0-10,000	.002	.025	1.07	16.12
10,000-20,000	.002	.025	1.04	15.46
	Non-associated gas in-place (billion cu ft)			
Permian				
0-10,000	0.003	0.044	1.72	24.04
10,000-20,000	.002	.031	1.06	13.67
Carboniferous				
0-10,000	.003	.057	3.02	53.08
10,000-20,000	.003	.052	2.69	46.80
20,000-30,000	.001	.027	1.65	32.11
Older Paleozoic				
0-10,000	.004	.115	10.90	293.34
10,000-20,000	.007	.200	19.38	528.74
20,000-30,000	.005	.141	14.42	409.68

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APPENDIX A

Resource Terms

The following list defines the terms used in figure 2 and used, in part, in this study. Some are modified from published definitions (Miller and others, 1975; McKelvey, 1973; U.S. Bureau of Mines and U.S. Geological Survey, 1976; Sheldon, 1976; American Petroleum Institute, 1976) in order to apply specifically to conventional hydrocarbon deposits.

Resources--Concentrations of naturally occurring solid, liquid, or gaseous materials in or on the Earth's crust in such form that economic extraction of a commodity is currently or potentially feasible.

Economic resources--Those resources, both identified and undiscovered, which are estimated to be economically recoverable.

Subeconomic resources--Identified and undiscovered resources that are not presently recoverable because of technologic and economic factors, but which may be recoverable in the future.

Identified resources--Specific accumulations of economic resources whose location, quality, and quantity are estimated from geologic evidence supported in part by engineering measurements.

Identified subeconomic resources--Known resources that may become recoverable as a result of changes in technologic and economic conditions.

Undiscovered resources--Resources estimated to exist outside of known fields on the basis of broad geologic knowledge and theory.

Reserves--That portion of the identified resource which can be economically extracted.

Measured reserves--That part of the identified resource which can be economically extracted using existing technology, and whose amount is estimated from geologic evidence supported directly by engineering measurements. In this study, they are considered to be equivalent to American Petroleum Institute-American Gas Association *proved reserves* and U.S. Bureau of Mines *proved reserves*.

Indicated reserves--Reserves that include additional recoveries in known reservoirs (in excess of the measured reserves) which engineering knowledge and judgment indicate will be economically available by application of fluid injection, whether or not such a program is currently installed. In this study, *indicated reserves* are equivalent to API *indicated additional reserves* (American Petroleum Institute, 1976).

Demonstrated reserves--A collective term for the sum of measured and indicated reserves.

Inferred reserves--Reserves in addition to demonstrated reserves eventually to be added to known fields through extensions, revisions, and new pays.

Oil or gas in-place--Concentrations or deposits of oil or natural gas which exist in nature, here defined to include all oil or gas in-place without qualification as to what portion may be considered either currently or potentially extractable as a resource. Oil or gas in-place refers to the estimated number of stock tank barrels of crude oil or standard cu ft of gas (14.73 lbs/sq in. atmosphere--psia--and 60°F) in reservoirs prior to any production (American Petroleum Institute, 1970).

Undiscovered oil or gas in-place--Undiscovered oil or gas in-place is parallel in definition to undiscovered resources; that is, it refers to quantities of oil and gas estimated to exist outside of known fields on the basis of broad geologic knowledge. In this report no qualification is made to that portion which may be considered either currently or potentially economically extractable.

Undiscovered pools that occur as independent accumulations controlled by separate geological structural features and (or) stratigraphic conditions are considered in this study as separate deposits, even though they may occur beneath or above preexisting pools. They are *not* considered as part of future additions to known fields or as inferred reserves, but are estimated as a part of the overall *undiscovered oil or gas in-place*.

Field--A field consists of a single pool (reservoir) or multiple pools (reservoirs) all grouped on, or related to, the same individual geological structural feature and(or) stratigraphic condition. There may be two or more reservoirs in a field which are separated vertically by intervening impervious strata, or laterally by local geologic barriers, or by both (modified from API, 1976).

A new field is a discovery of oil or gas with accumulation being controlled by a separate geologic structural feature and (or) stratigraphic condition to the extent that the new discovery is not considered a new pool, or an extension of a pool, in a preexisting field (API, 1976).

Pool--In general, the term "pool" is synonymous with the term "reservoir" and is so used here; however, in certain situations, a pool may consist of more than one reservoir. The Texas Railroad Commission, however, defines each pool as a separate field.

Reservoir--A reservoir is a porous and permeable underground formation containing an individual and separate natural accumulation of hydrocarbons (oil and (or) gas) which is confined by impermeable rock or water barriers and is characterized by a single natural pressure system.

APPENDIX B

Appendix B consists of the probability distribution curves for assessments reported in the text for 1) undiscovered oil and gas, and 2) pool sizes. The curves are further organized by commodity and by age as listed in the following table of contents for Appendix B.

CONTENTS--APPENDIX B

CONTENTS--APPENDIX B (Continued)

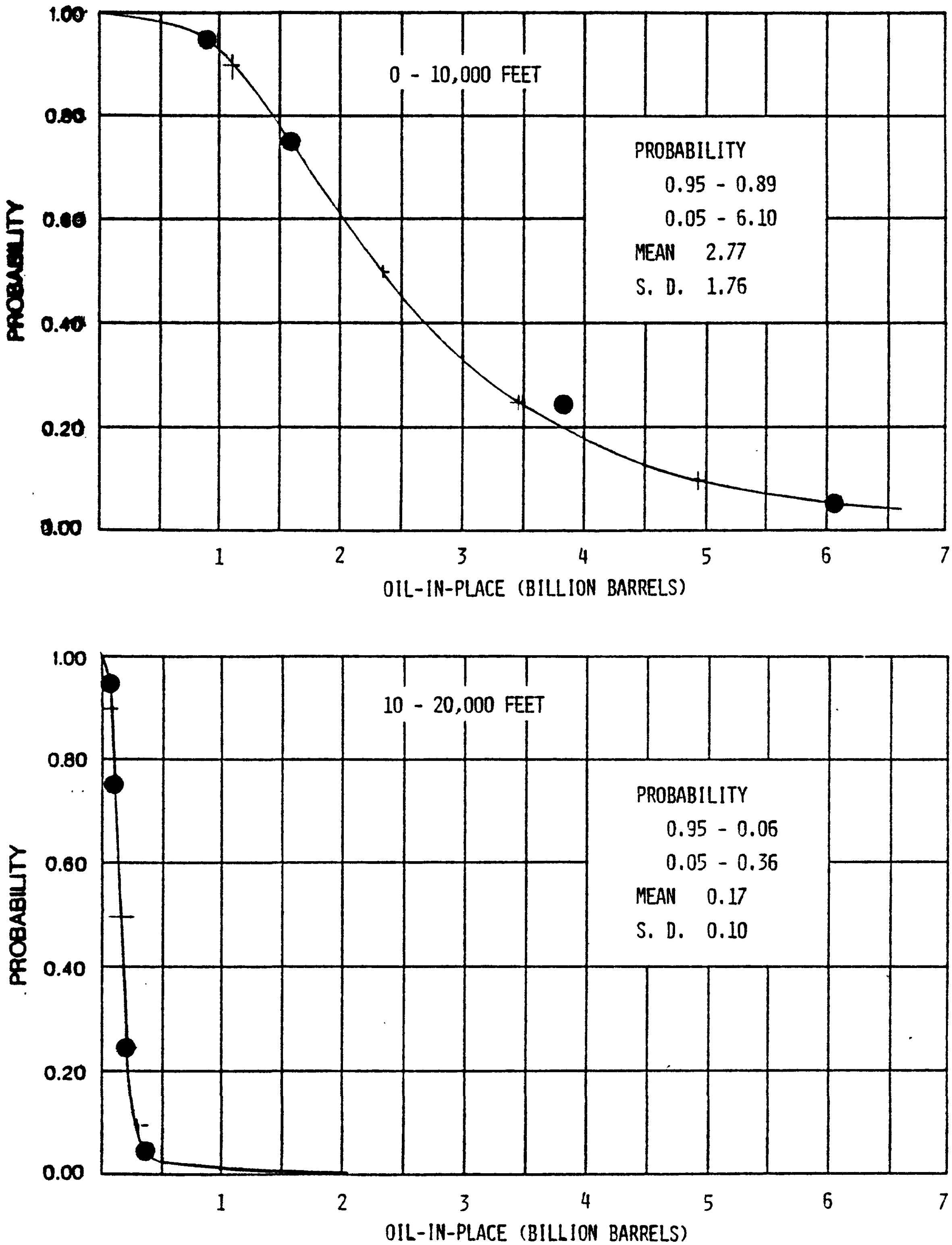


Figure 28 -- Permian undiscovered oil: lognormal probability distributions of oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

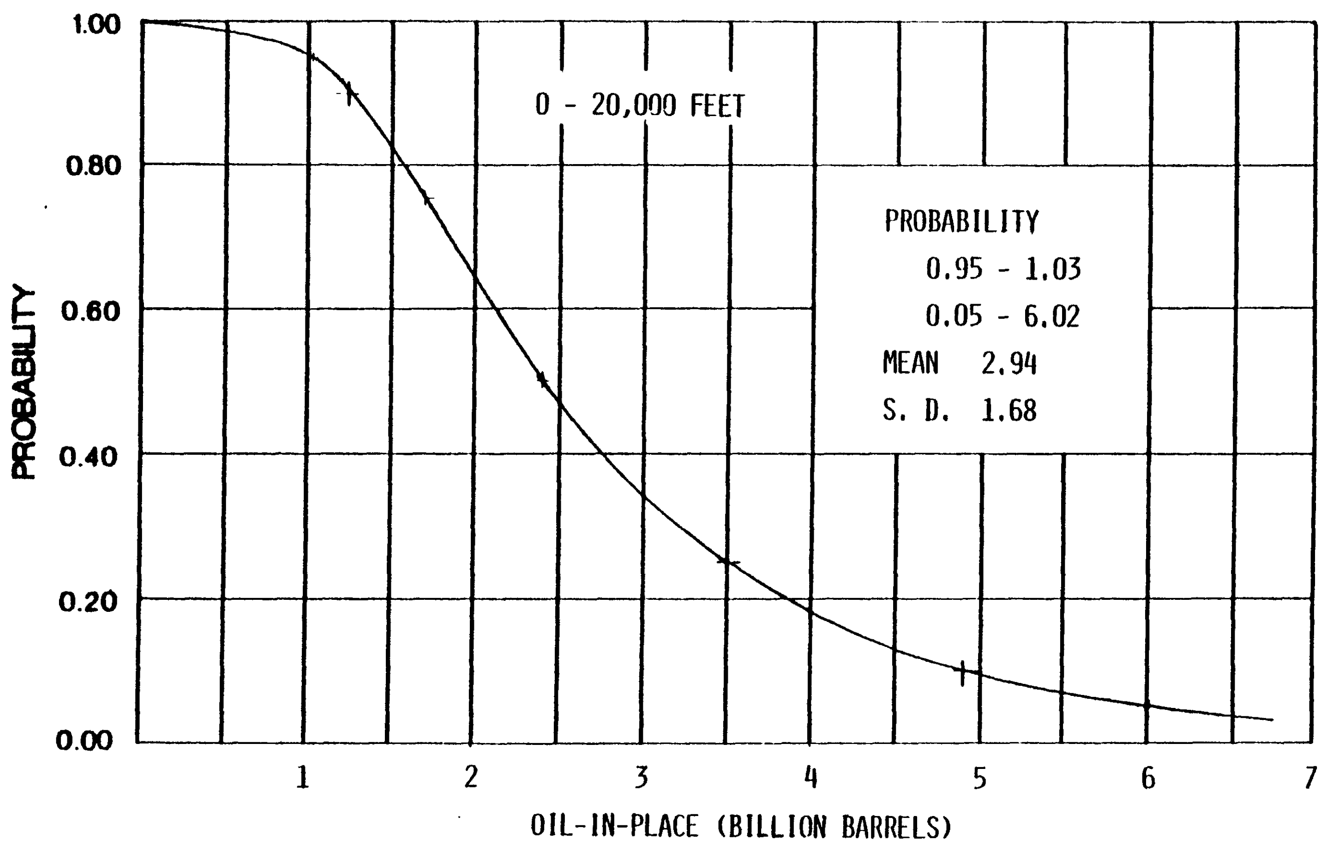


Figure 29 -- Total Permian undiscovered oil: probability distribution of oil in-place for the entire Permian.

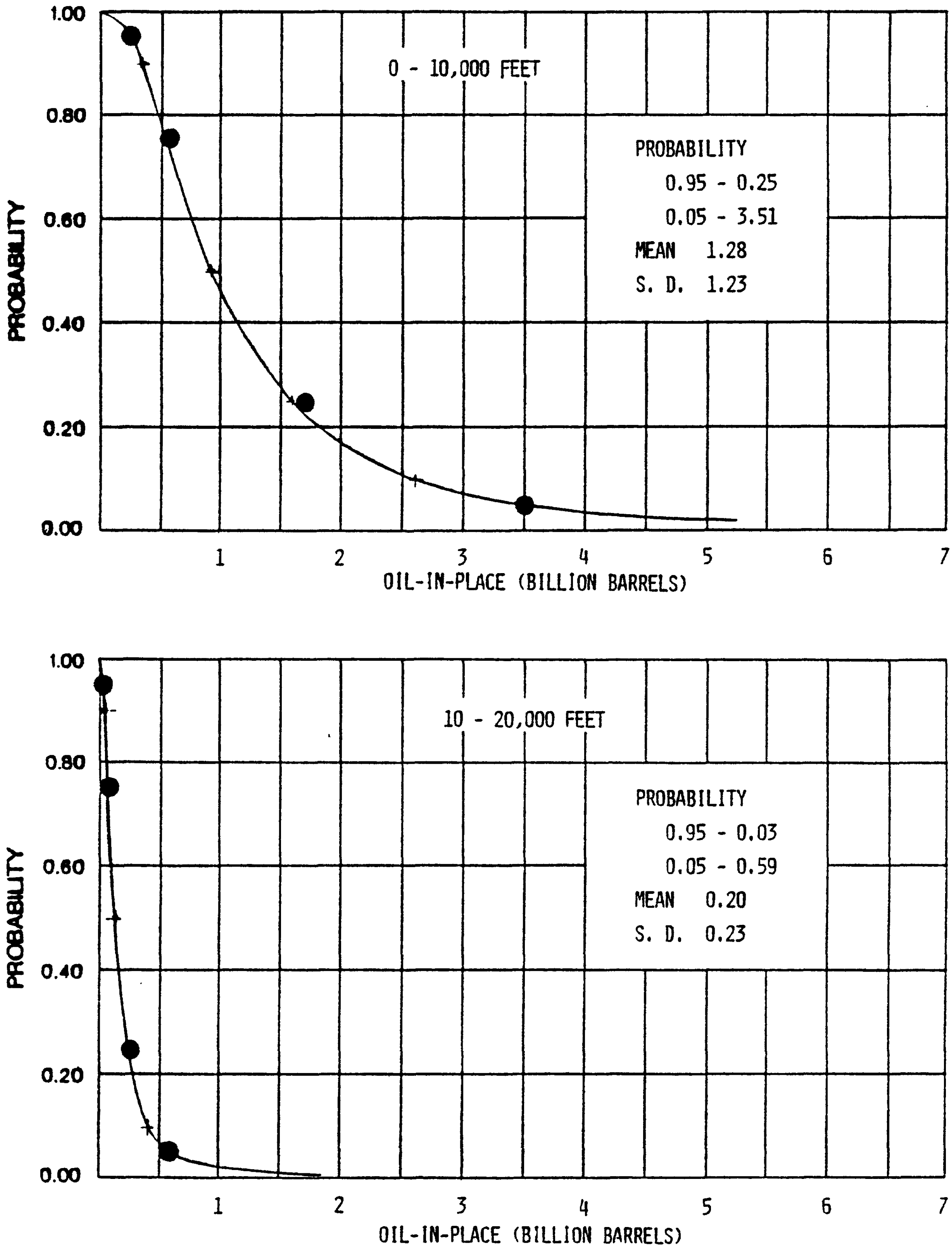


Figure 30 -- Carboniferous undiscovered oil: lognormal probability distributions of oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

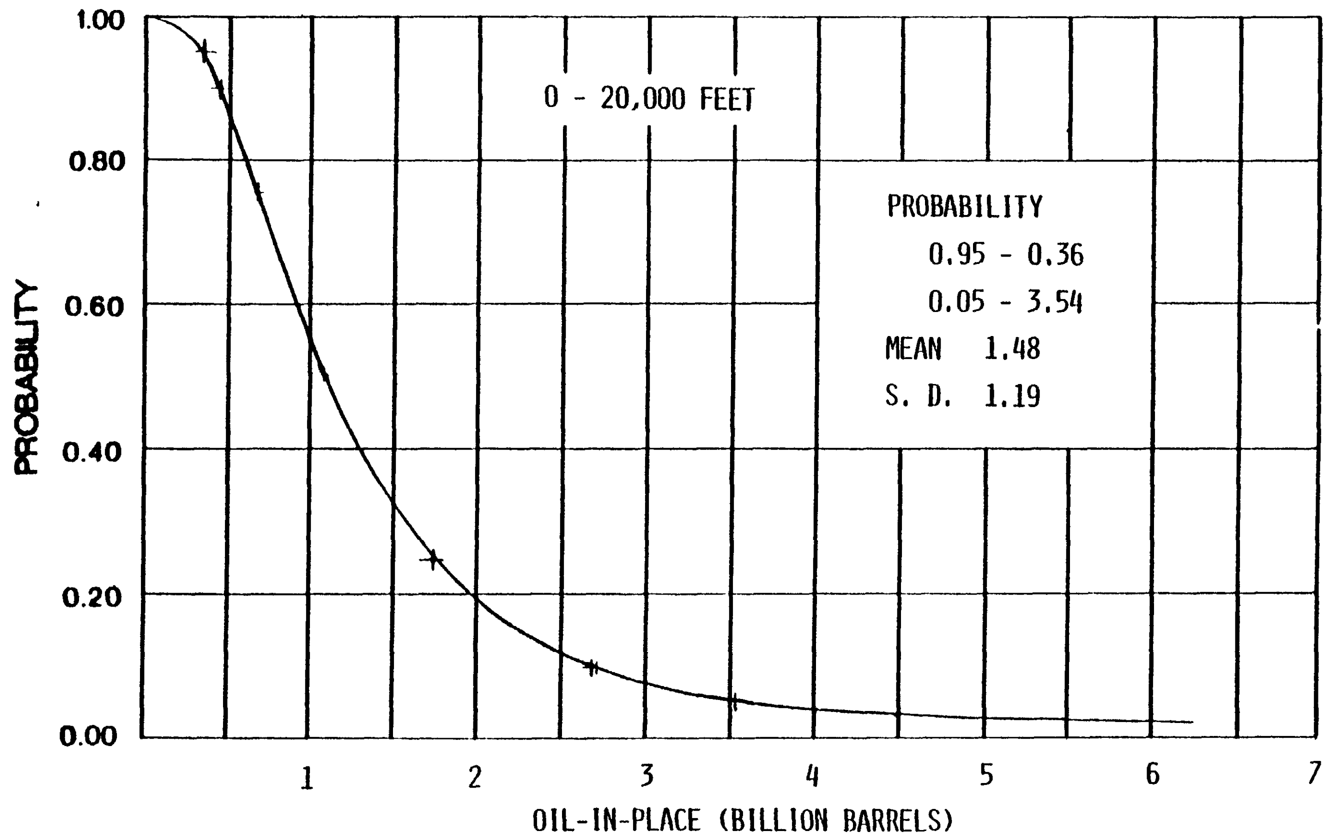
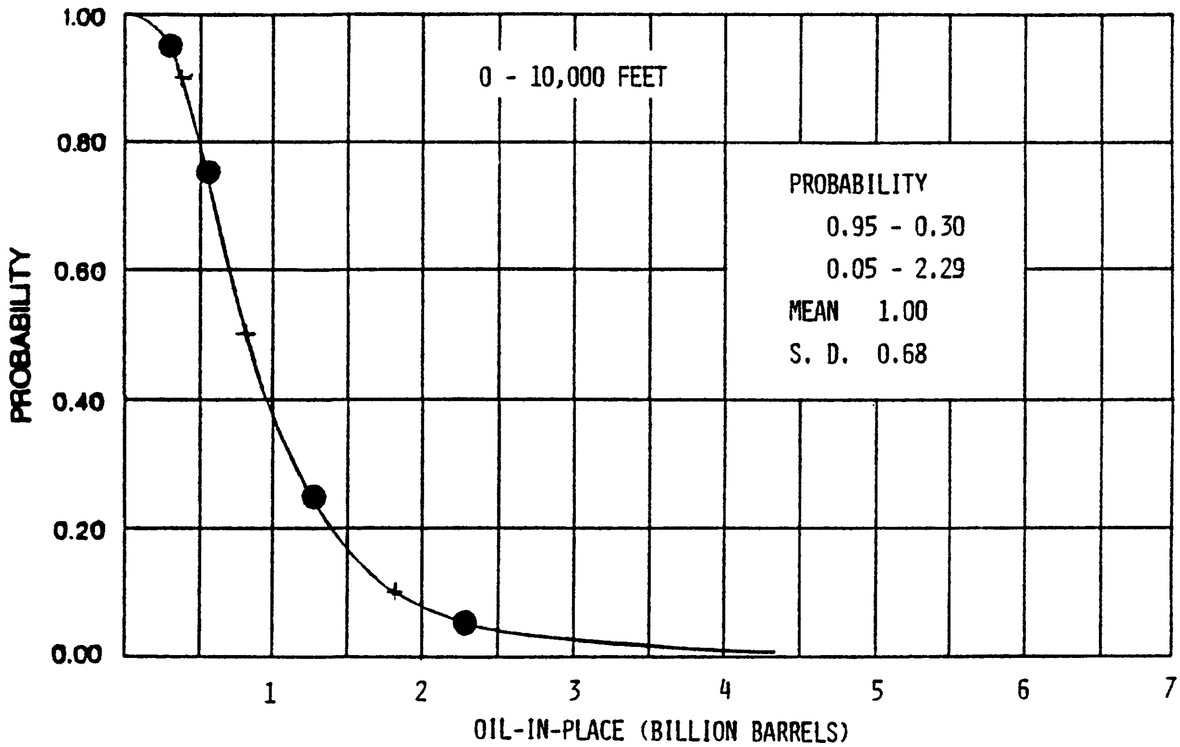


Figure 31 -- Total Carboniferous undiscovered oil: probability distribution of oil in-place for the entire Carboniferous.



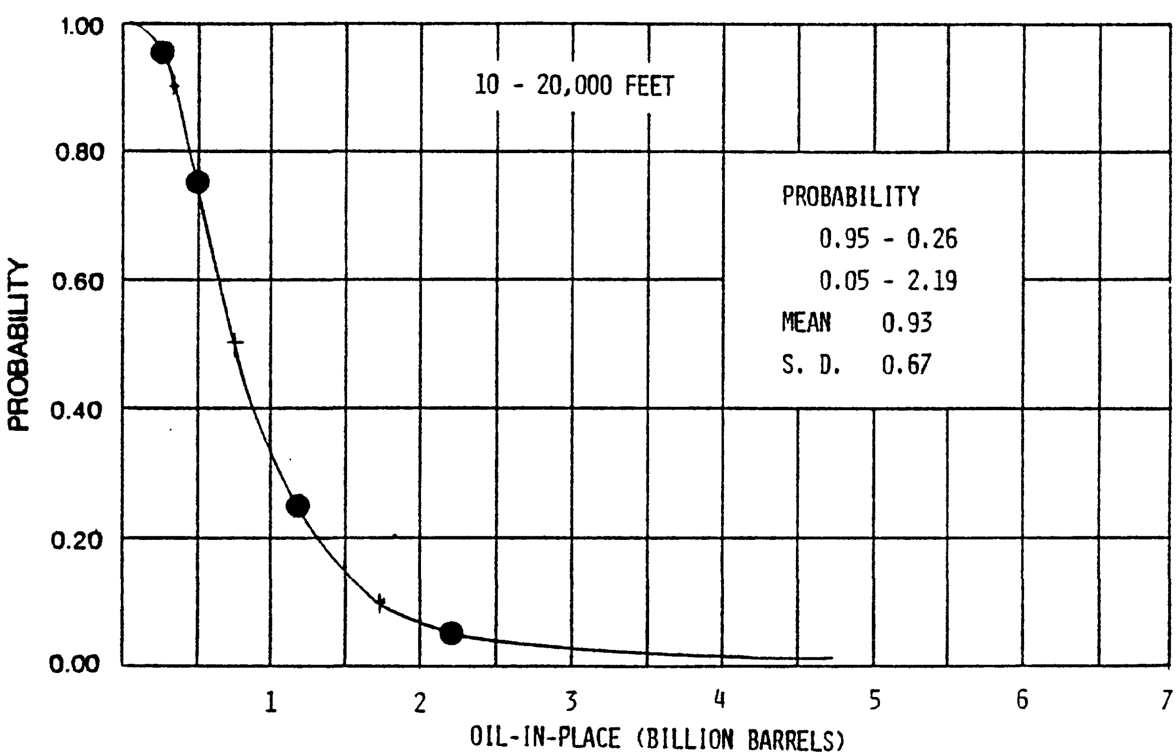


Figure 32 -- Older Paleozoic undiscovered oil: lognormal probability distributions of oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

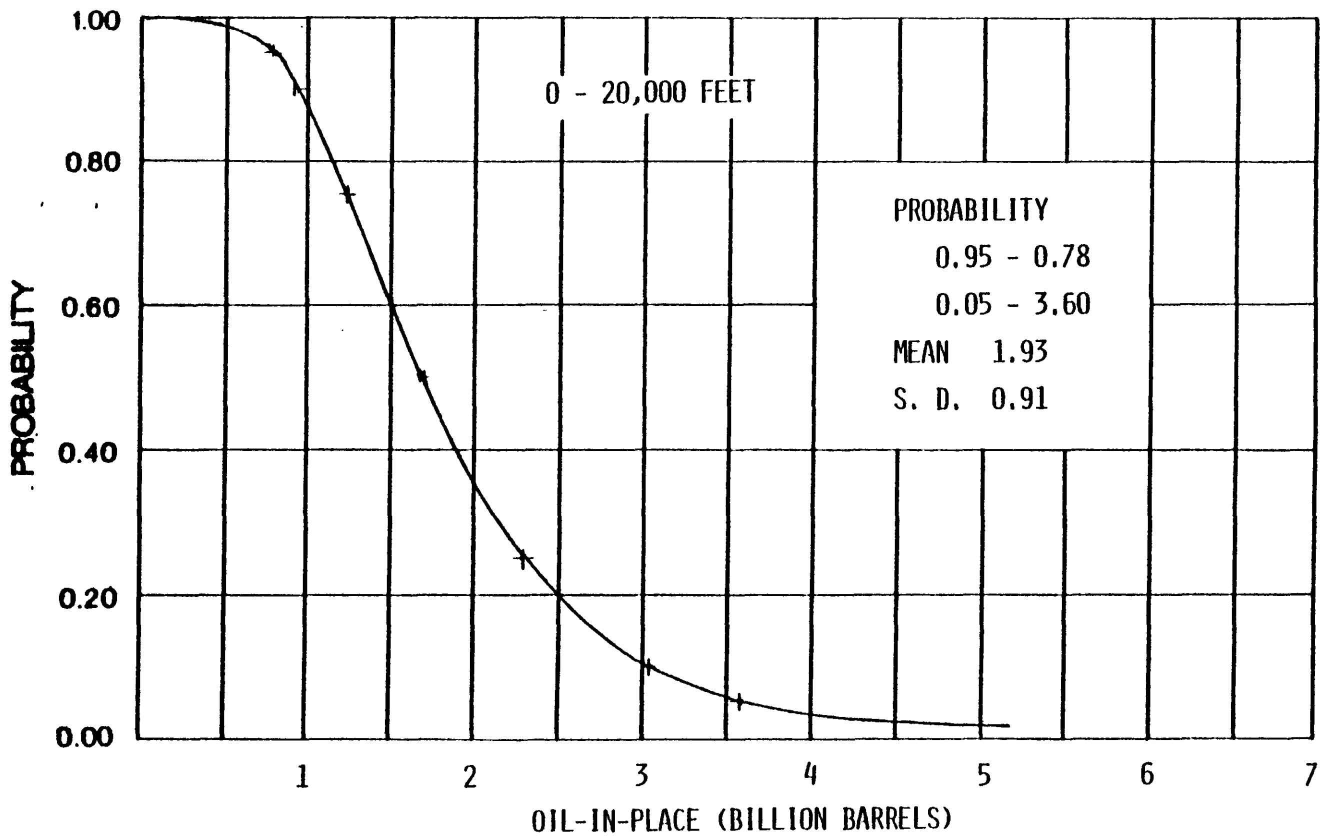
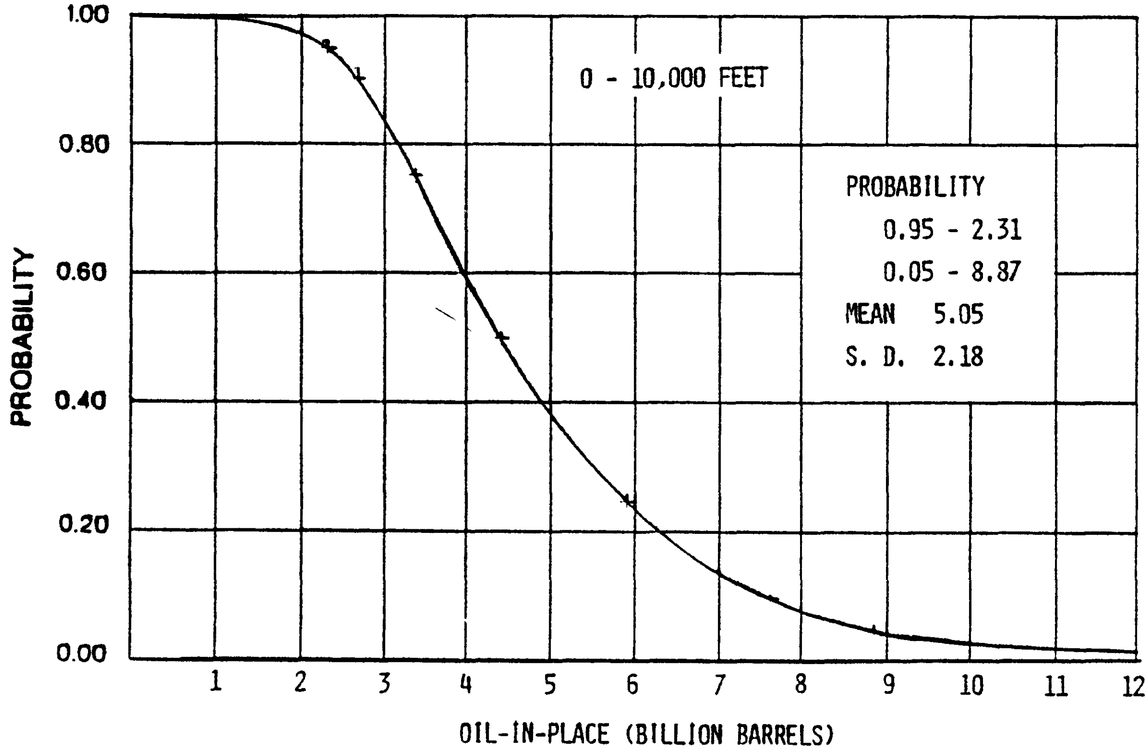


Figure 33 -- Total older Paleozoic undiscovered oil: probability distribution of oil in-place for the entire older Paleozoic.



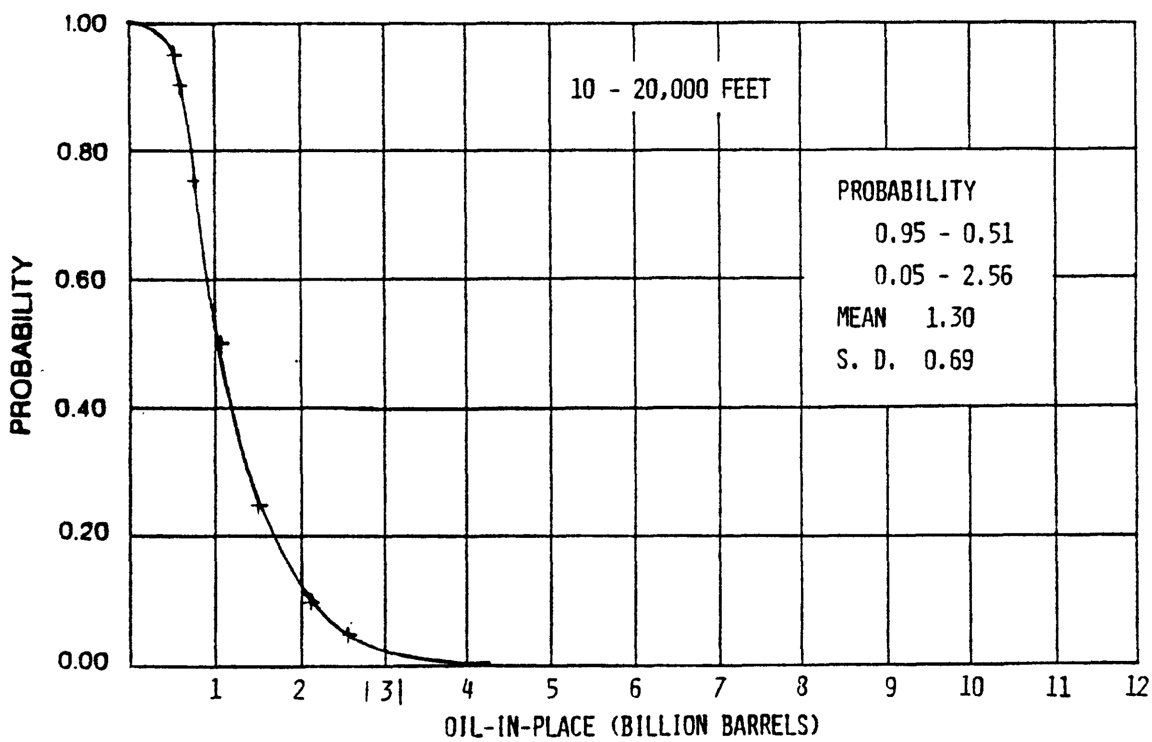


Figure 34 -- Total Paleozoic undiscovered oil: probability distributions of oil in-place for the 0-10 and 10-20 thousand foot depth intervals.

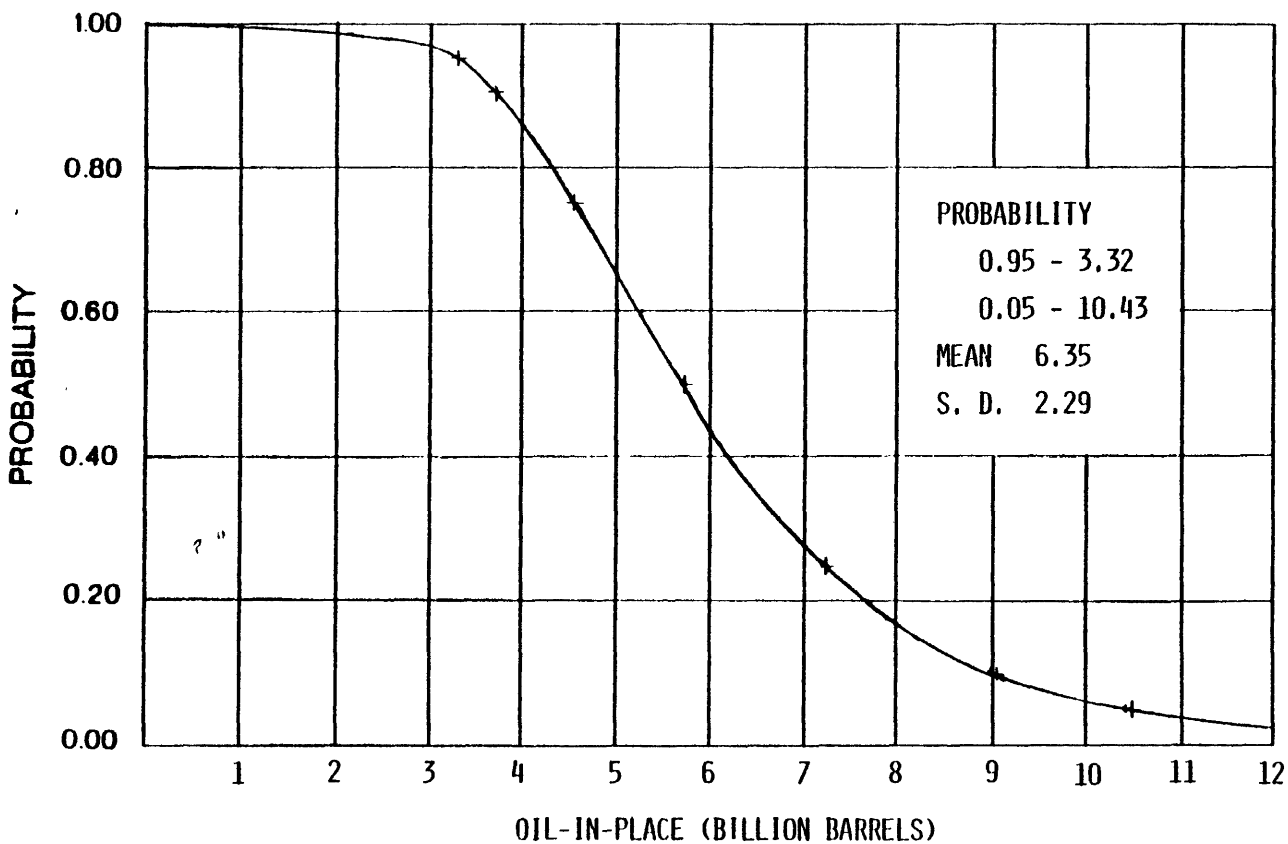
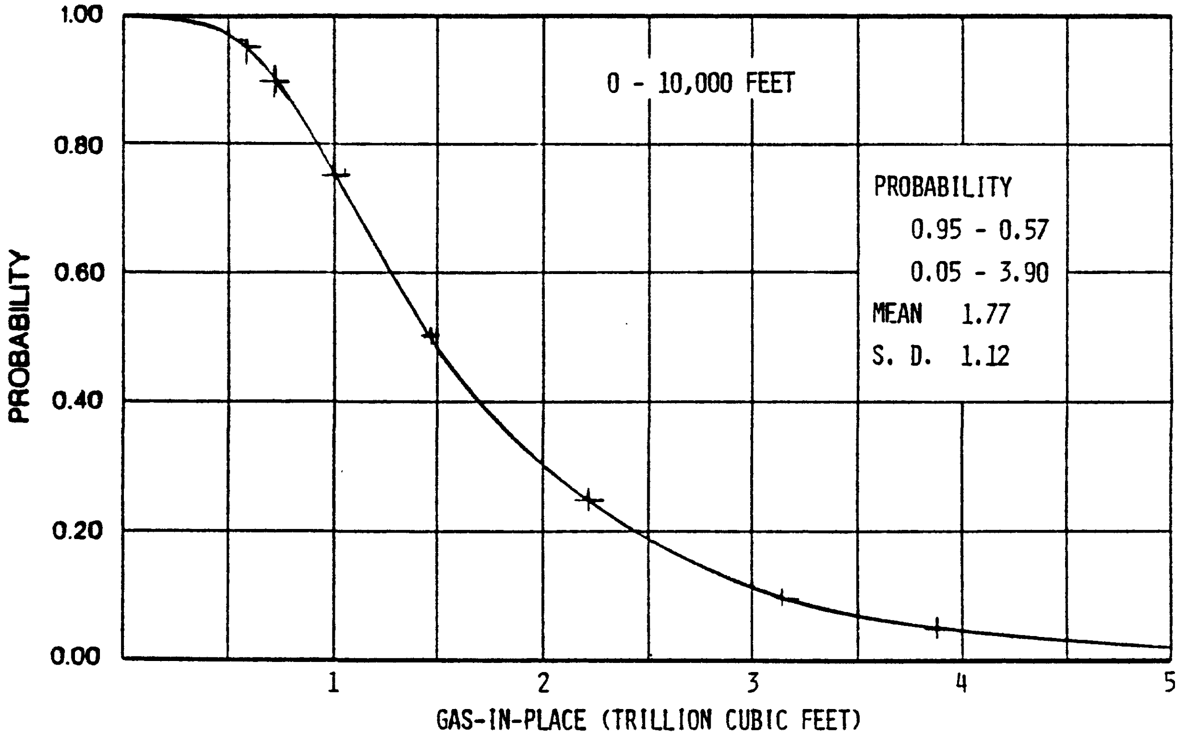


Figure 35 -- Total Paleozoic undiscovered oil: probability distribution of oil in-place for the entire Paleozoic.



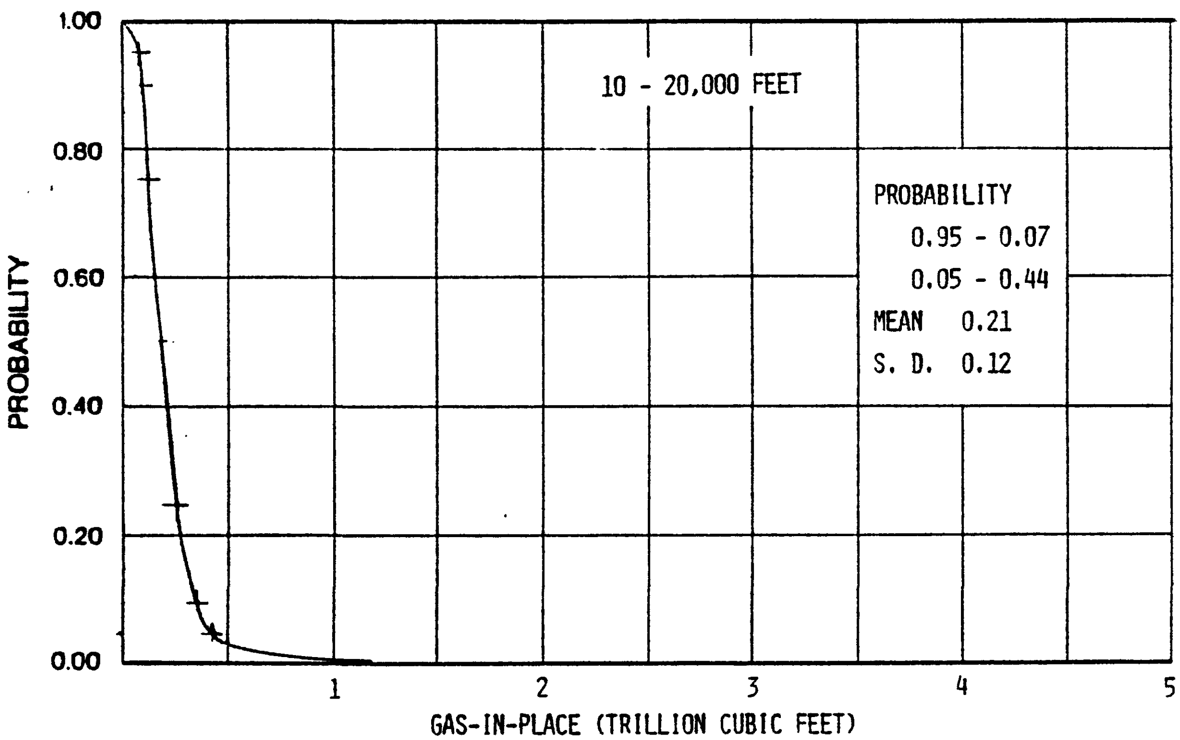


Figure 36 -- Permian undiscovered dissolved/associated gas: lognormal probability distributions of dissolved/associated gas in-place for the 0-10 and 10-20 thousand foot depth interval.

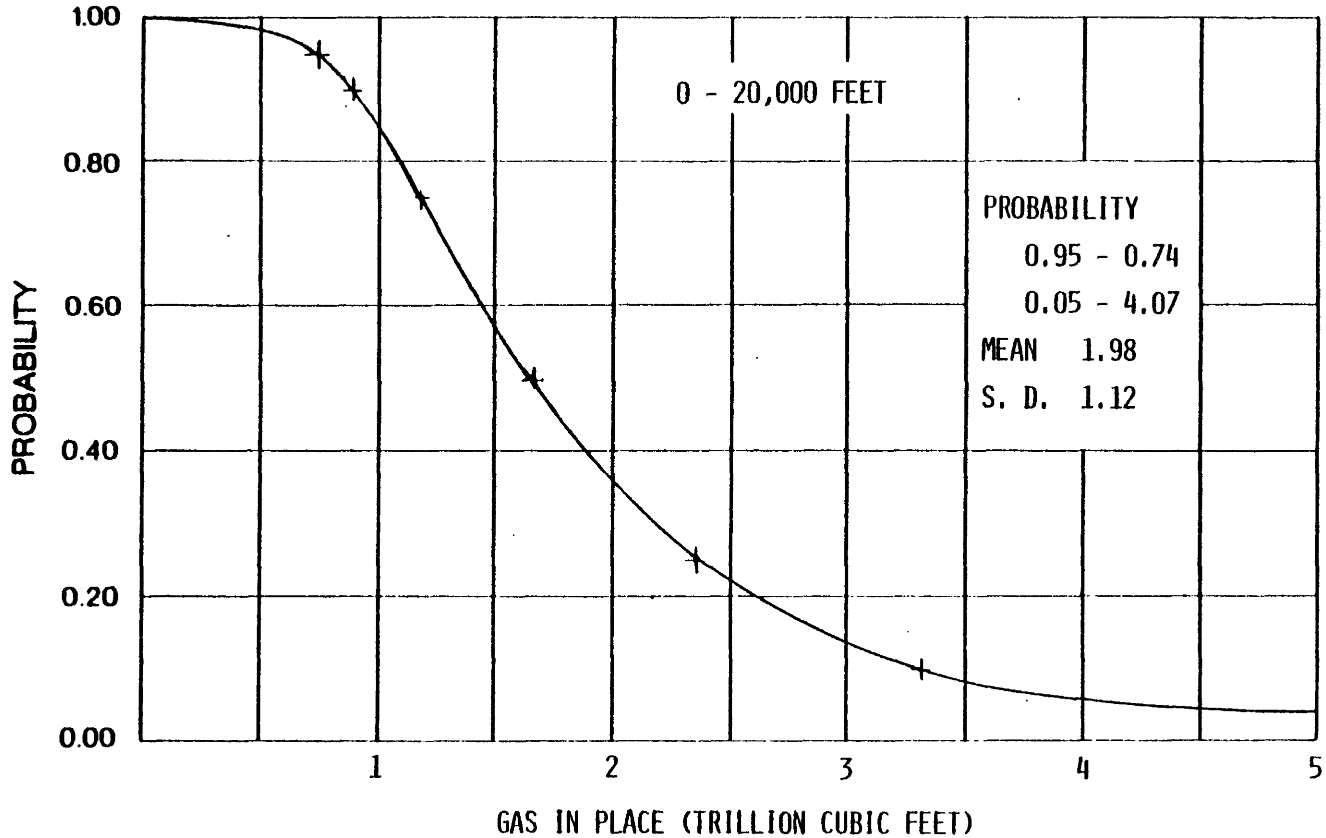
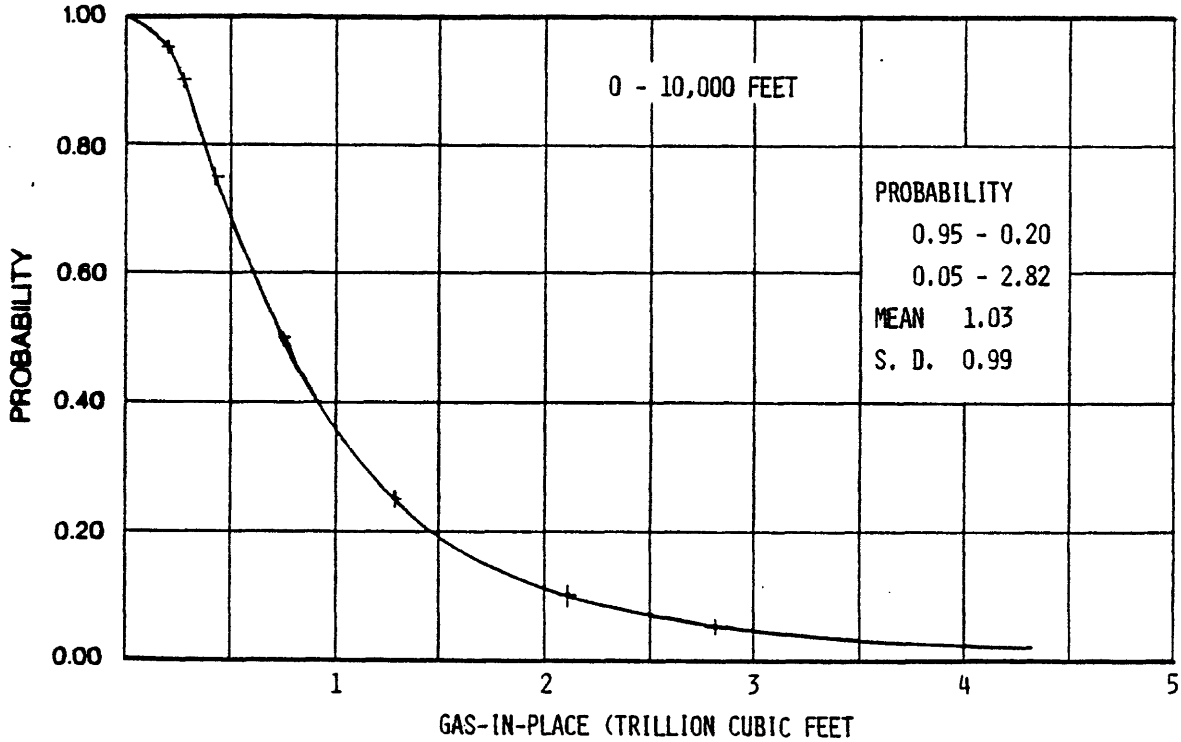


Figure 37 -- Total Permian undiscovered dissolved/associated gas: probability distribution of dissolved/associated gas in-place for the entire Permian.



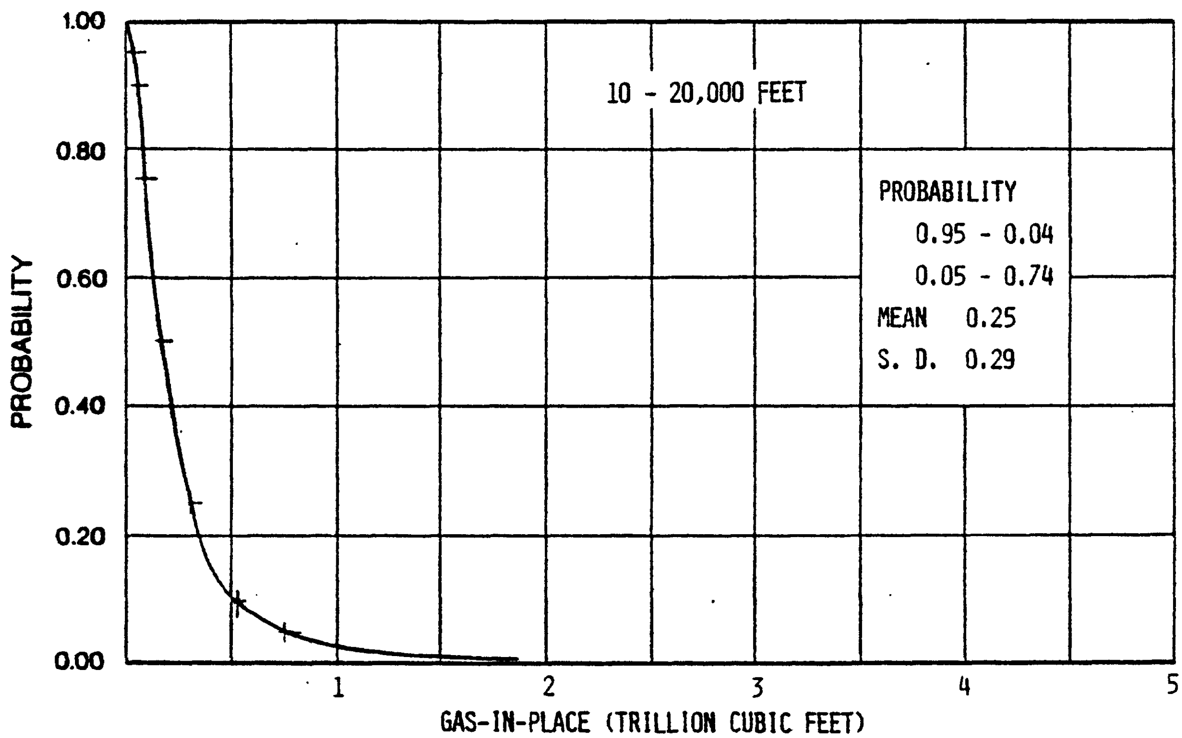


Figure 38 -- Carboniferous undiscovered dissolved/associated gas: lognormal probability distributions of dissolved/associated gas in-place for the 0-10 and 10-20 thousand foot depth intervals.

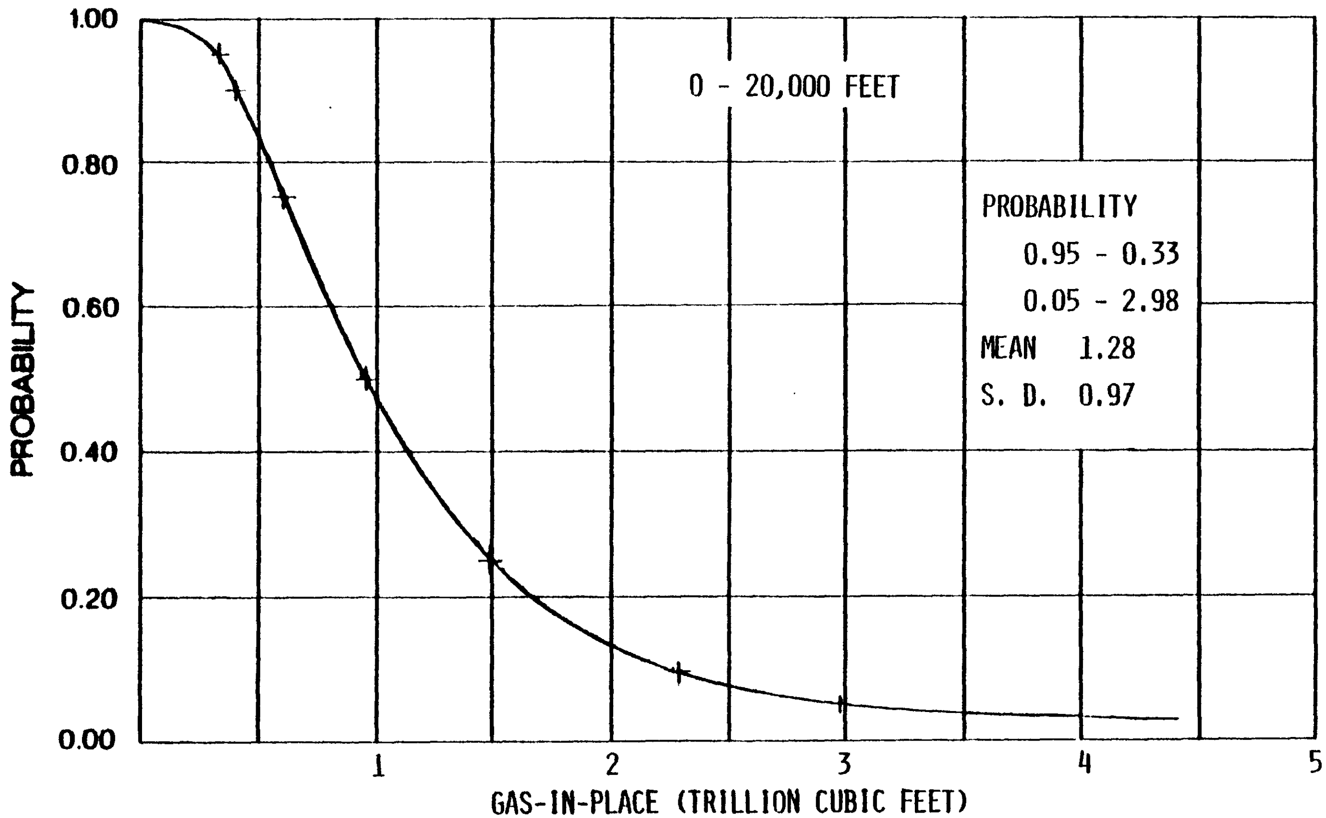
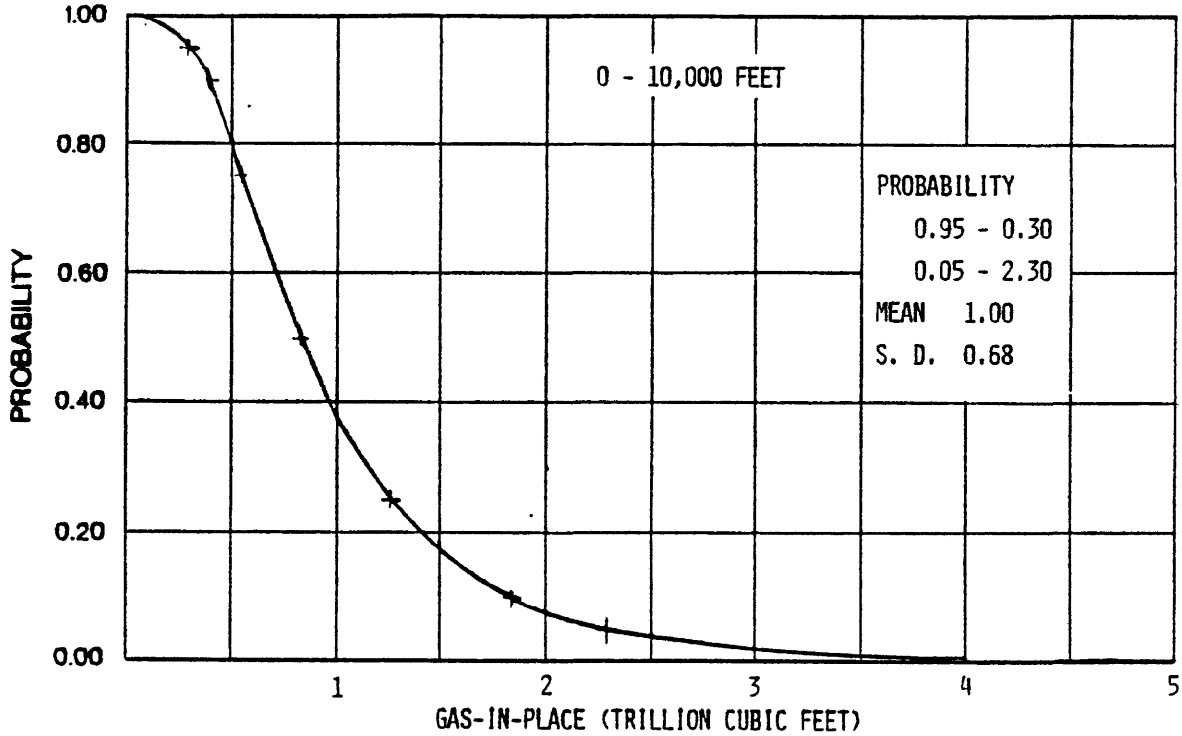


Figure 39 -- Total Carboniferous undiscovered dissolved/associated gas; probability distribution of dissolved/associated gas in-place for the entire Carboniferous.



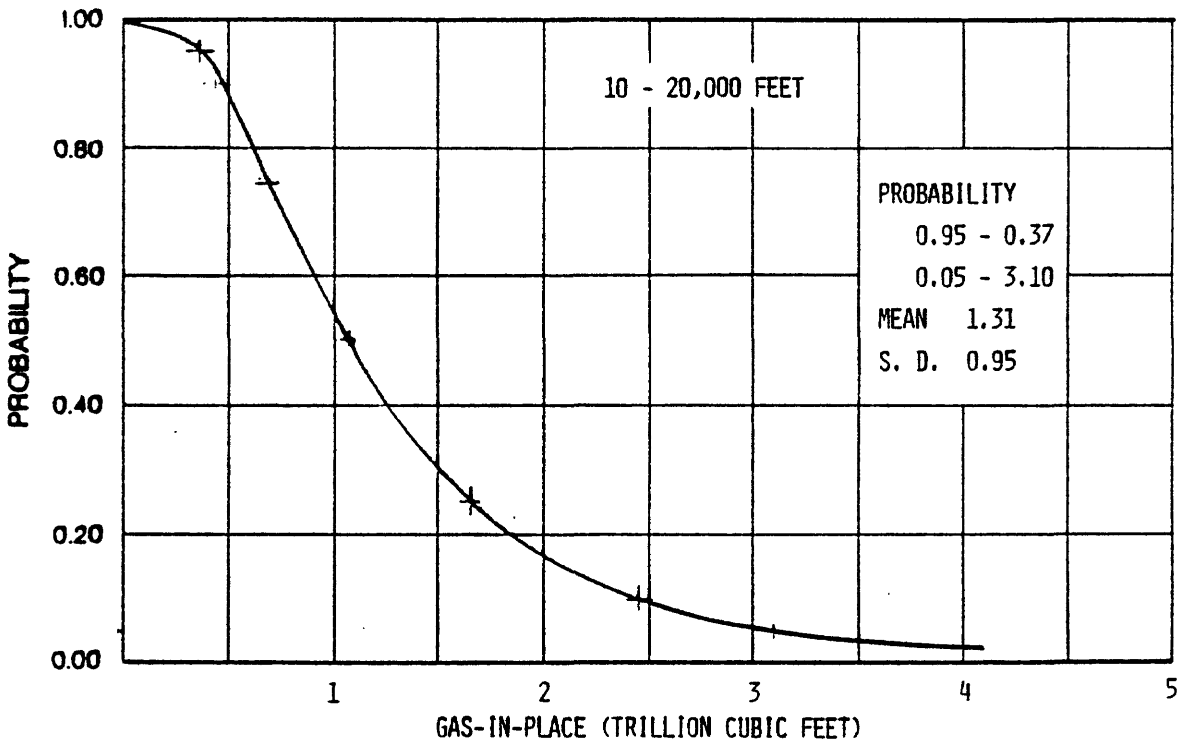


Figure 40 -- Older Paleozoic undiscovered dissolved/associated gas: lognormal probability distributions of dissolved/associated gas in-place for the 0-10 and 10-20 thousand foot depth intervals.

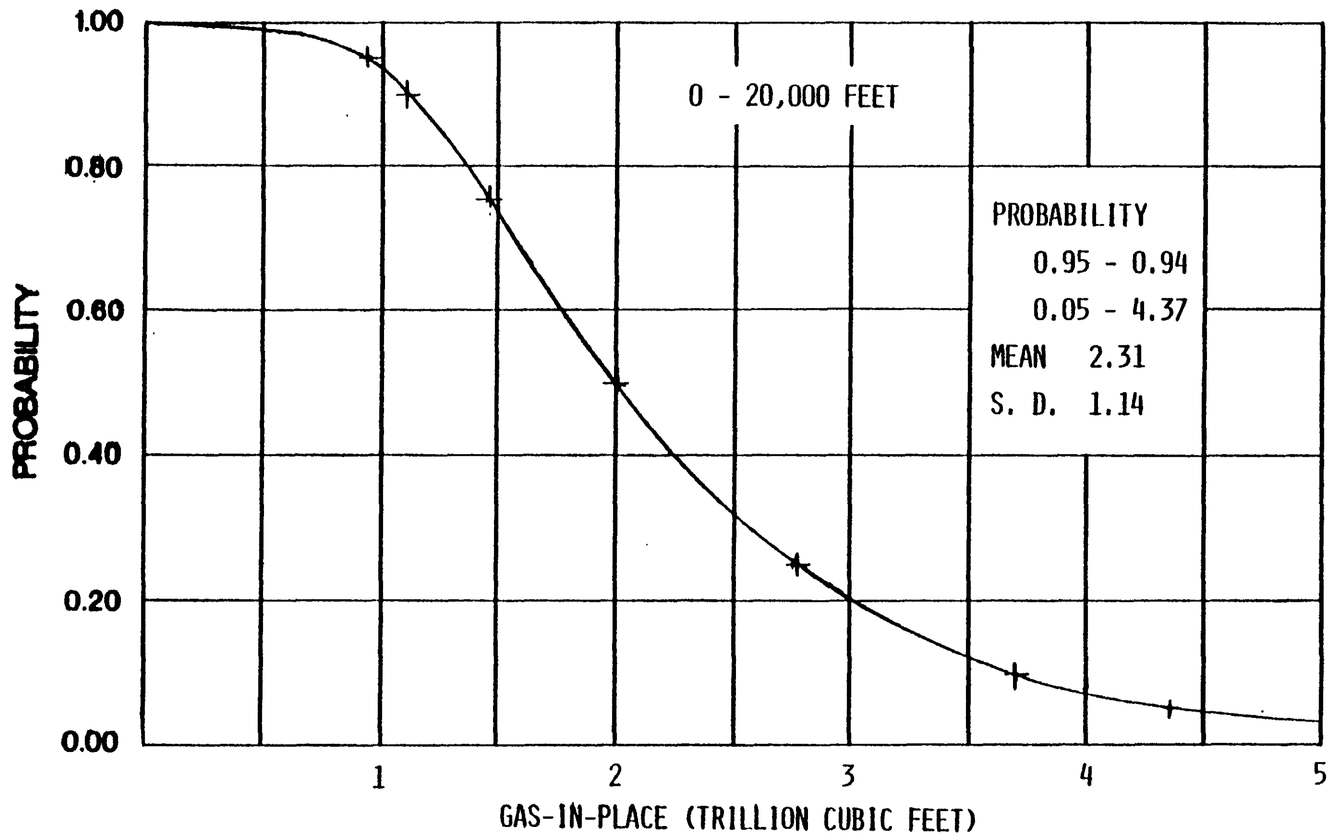
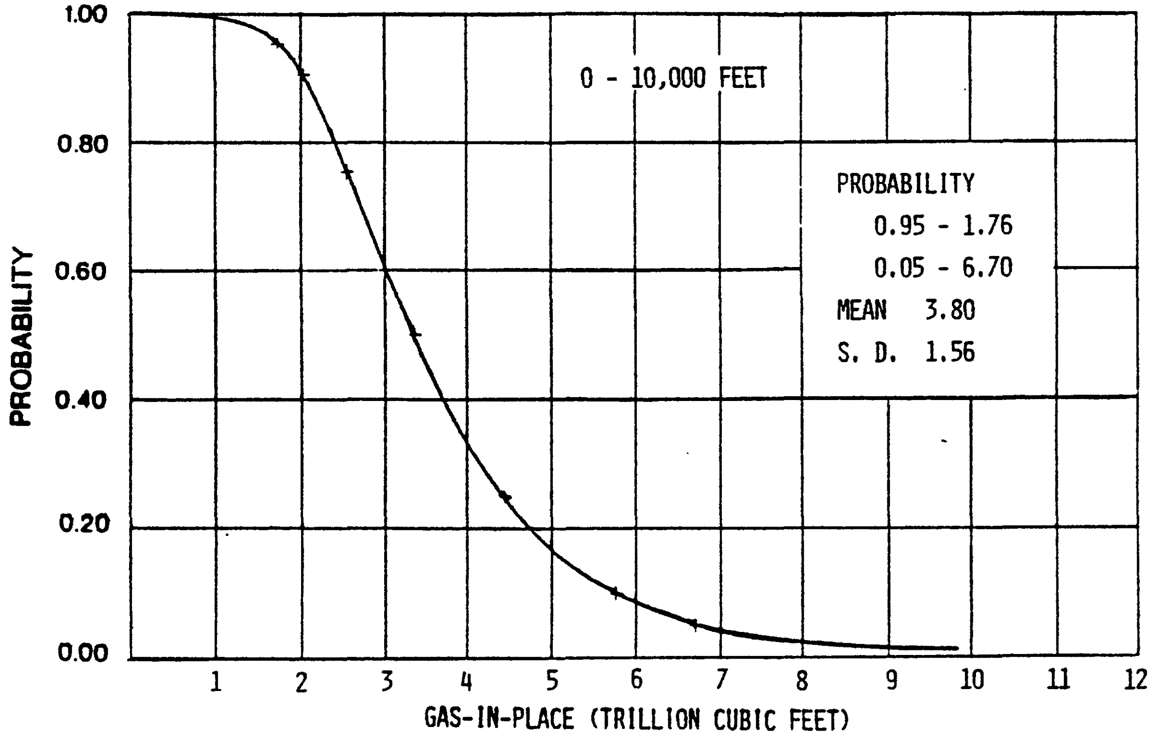


Figure 41 -- Total older Paleozoic undiscovered dissolved/associated gas: probability distribution of dissolved/associated gas in-place for the entire older Paleozoic.



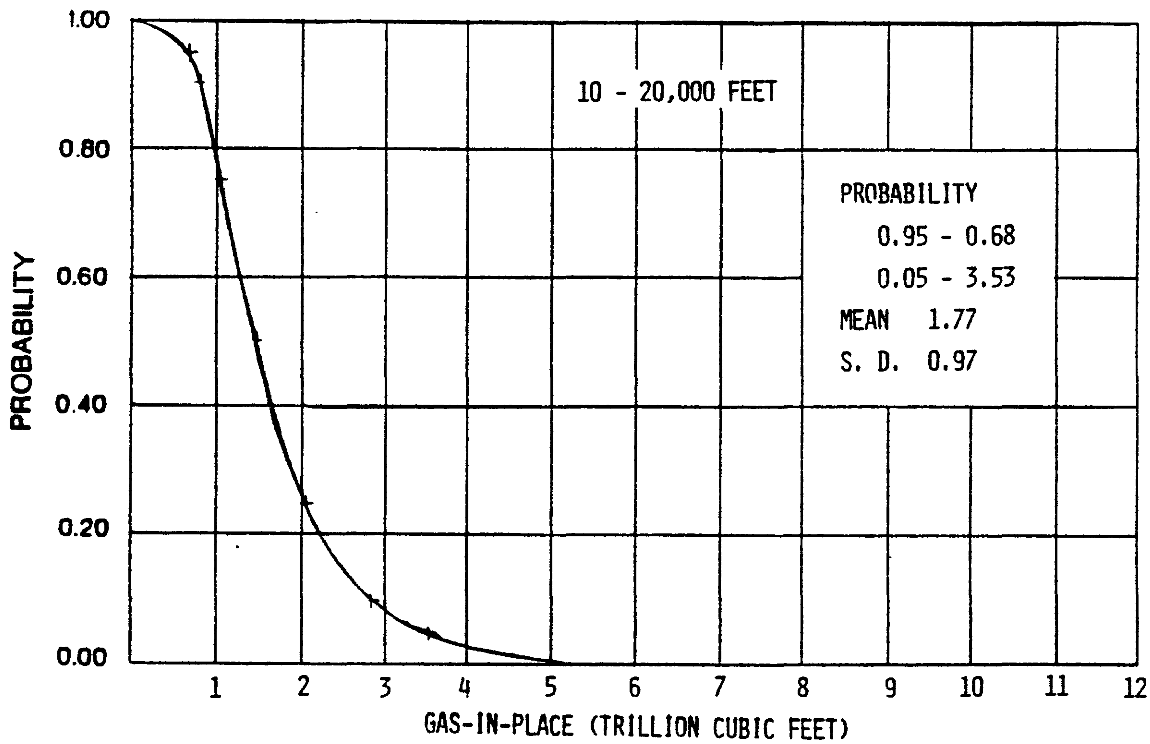


Figure 42 -- Total Paleozoic undiscovered dissolved/associated gas: probability distributions of dissolved/associated gas in-place for the 0-10 and 10-20 thousand foot depth intervals.

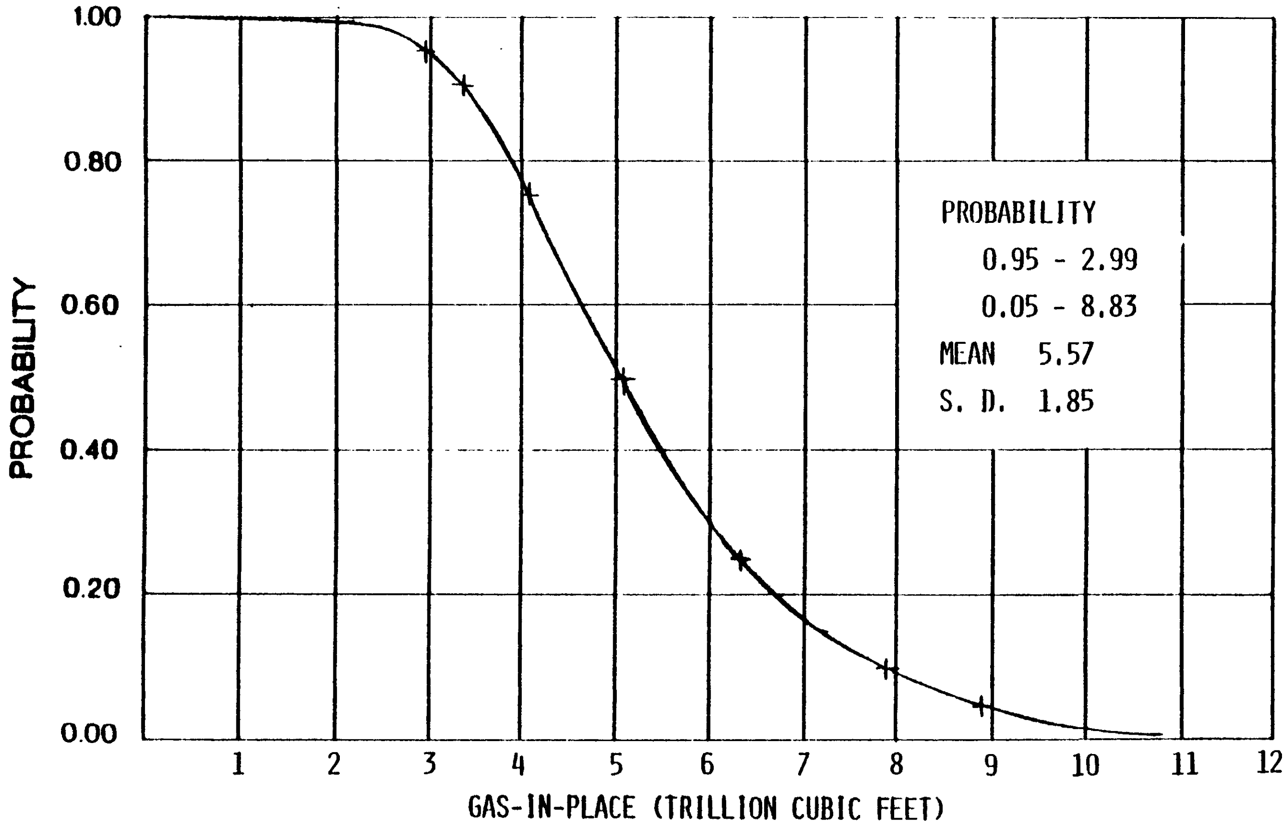
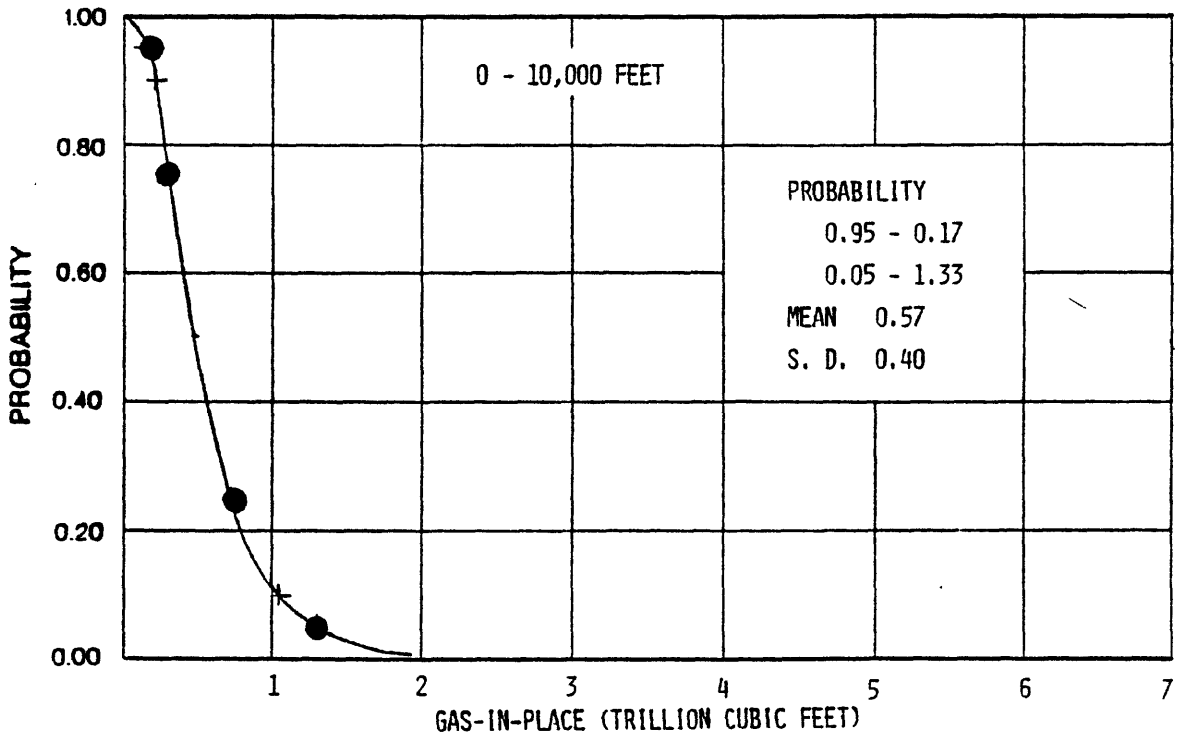


Figure 43 -- Total Paleozoic undiscovered dissolved/associated gas: probability distribution of dissolved/associated gas in-place for the entire Paleozoic.



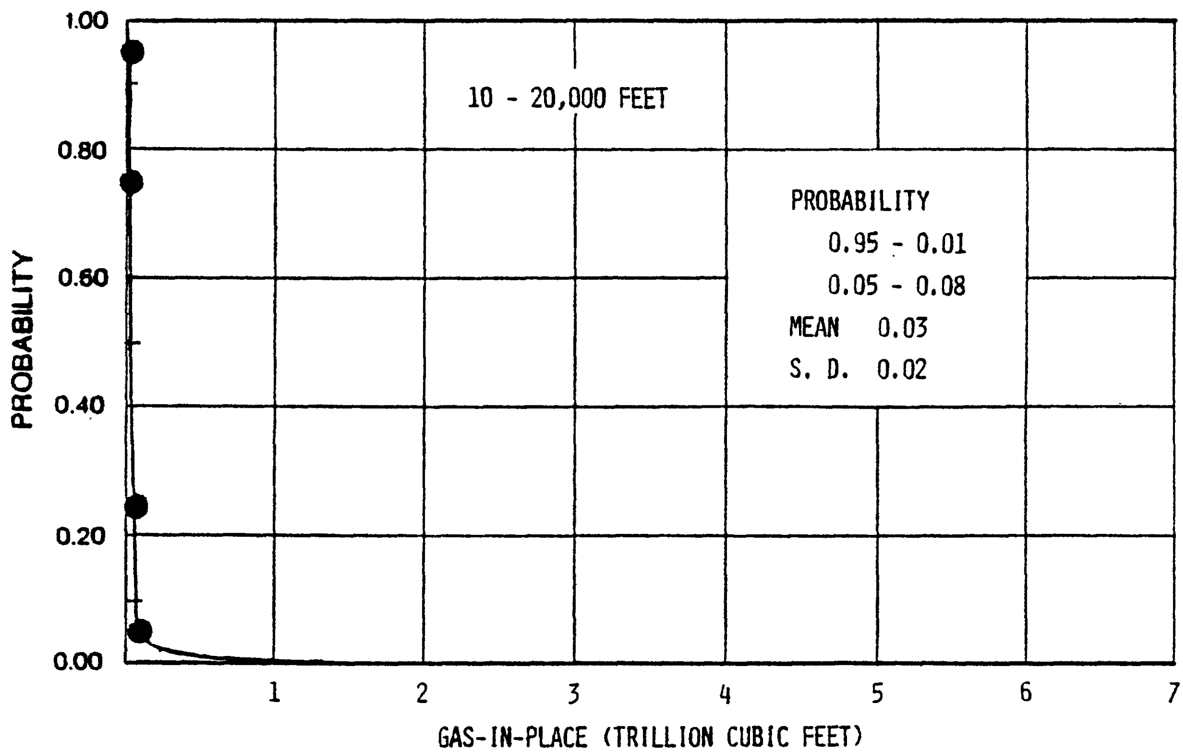


Figure 44 -- Permian undiscovered non-associated gas: lognormal probability distributions of non-associated gas in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the origional probability estimates to which the curve is fit.

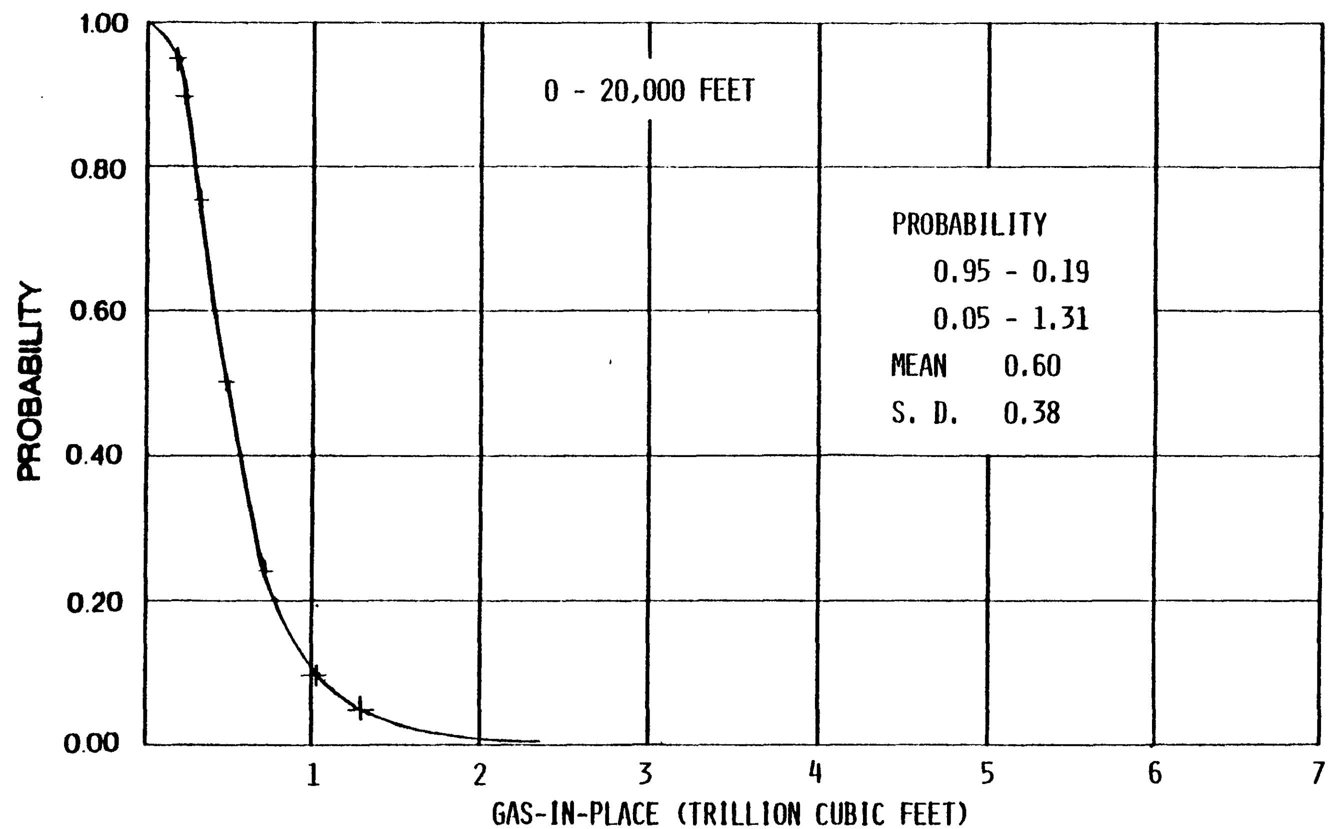


Figure 45 -- Total Permian undiscovered non-associated gas: probability distribution of non-associated gas in-place for the entire Permian.

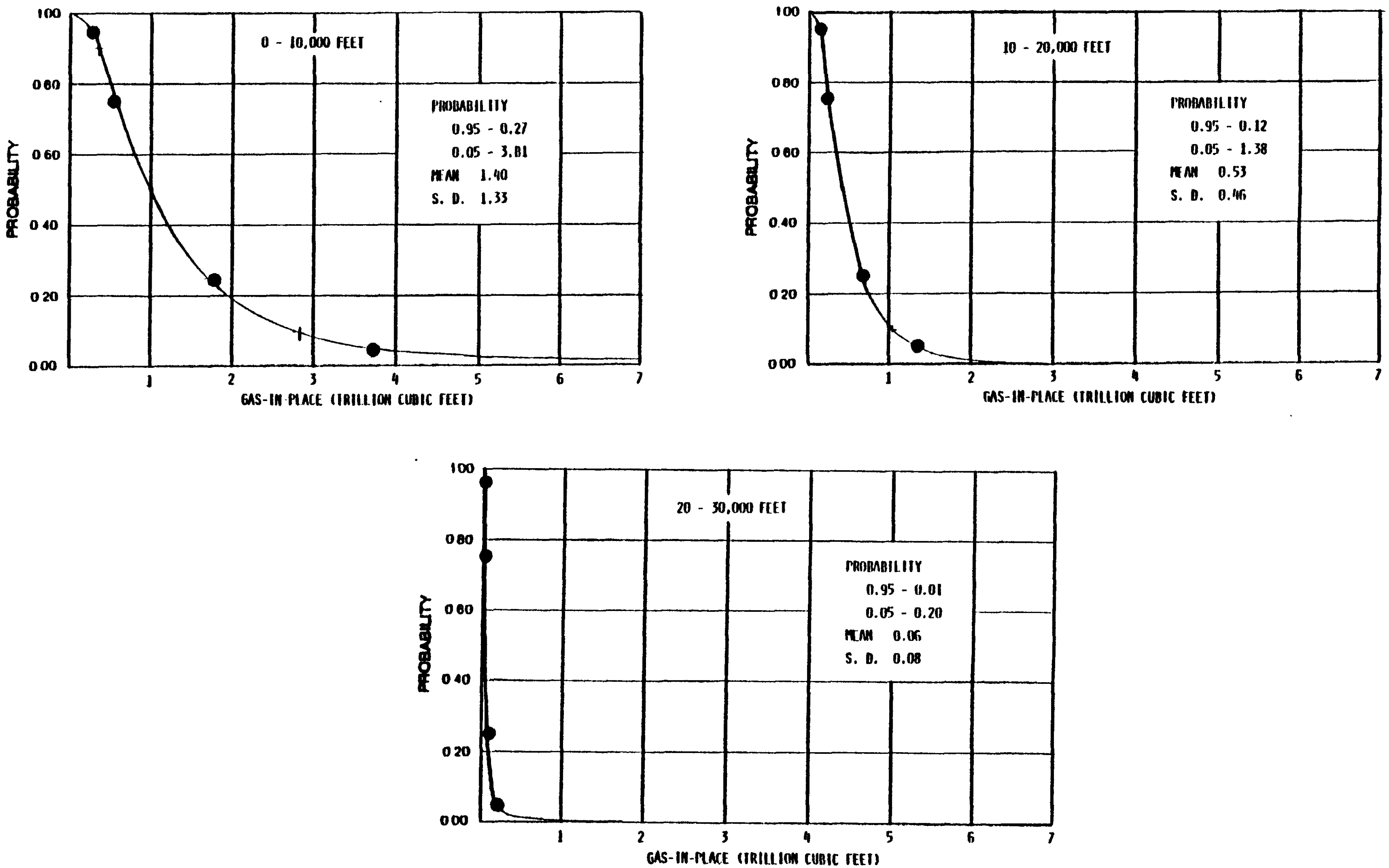


Figure 46 -- Carboniferous undiscovered non-associated gas: lognormal probability distributions of non-associated gas in-place for the 0-10, 10-20, and 20-30 thousand foot depth intervals. Dots represent the original probability estimates to which the curve was fit.

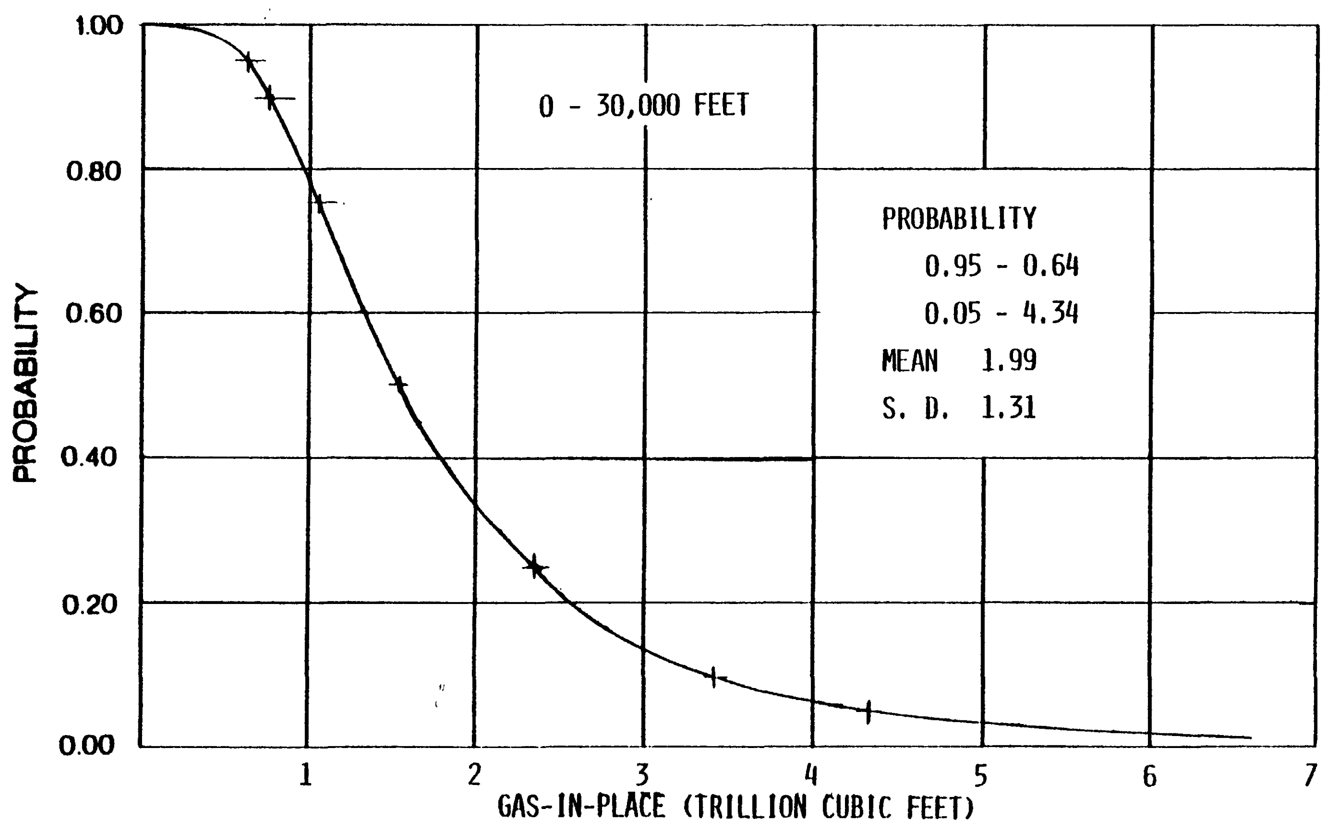


Figure 47 -- Total Carboniferous undiscovered non-associated gas: probability distribution of non-associated gas in-place for the entire Carboniferous.

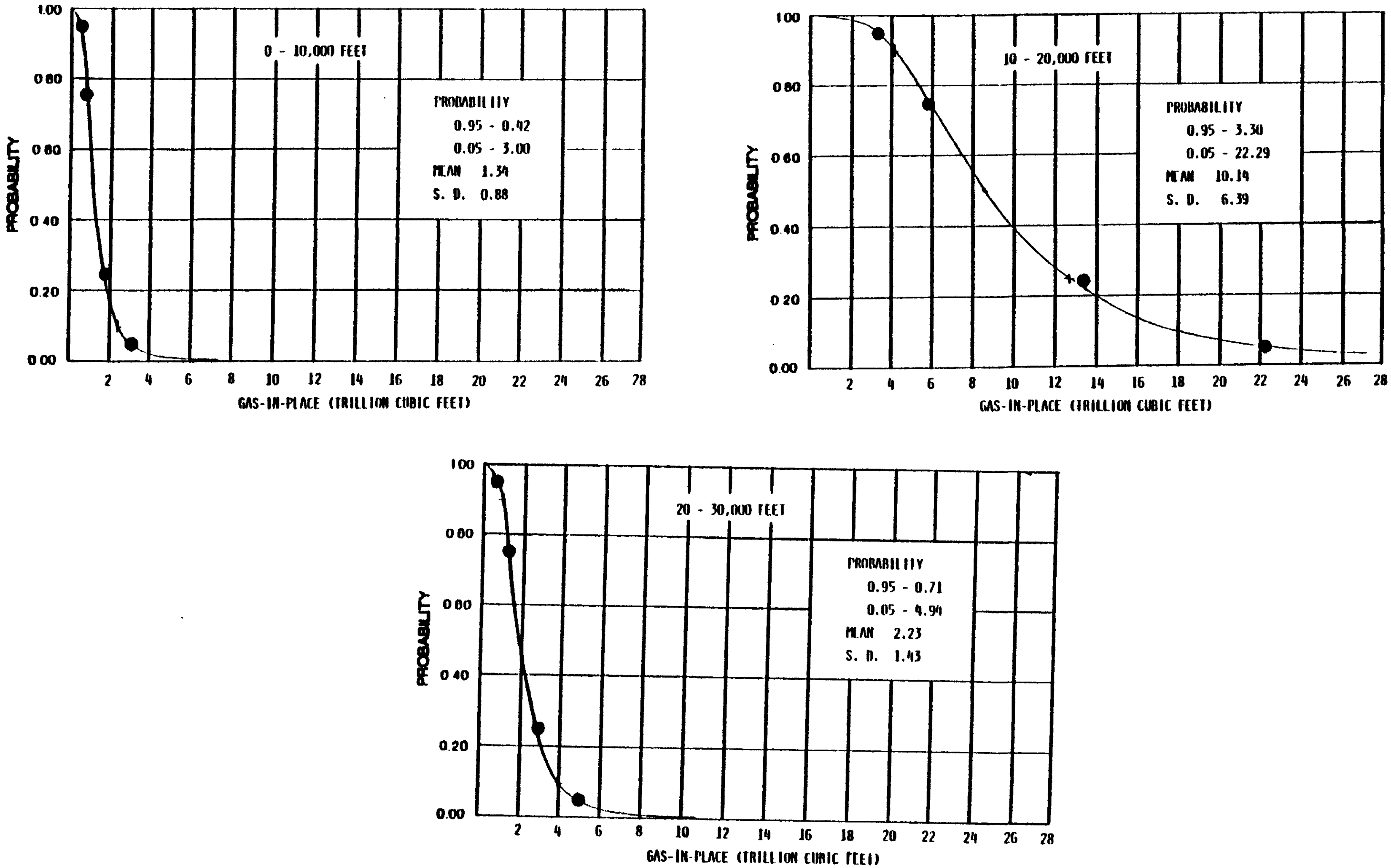


Figure 48 -- Older Paleozoic undiscovered non-associated gas: lognormal probability distributions of non-associated gas in-place for the 0-10, 10-20, and 20-30 thousand foot depth intervals. Dots represent the original probability estimates to which the curve was fit.

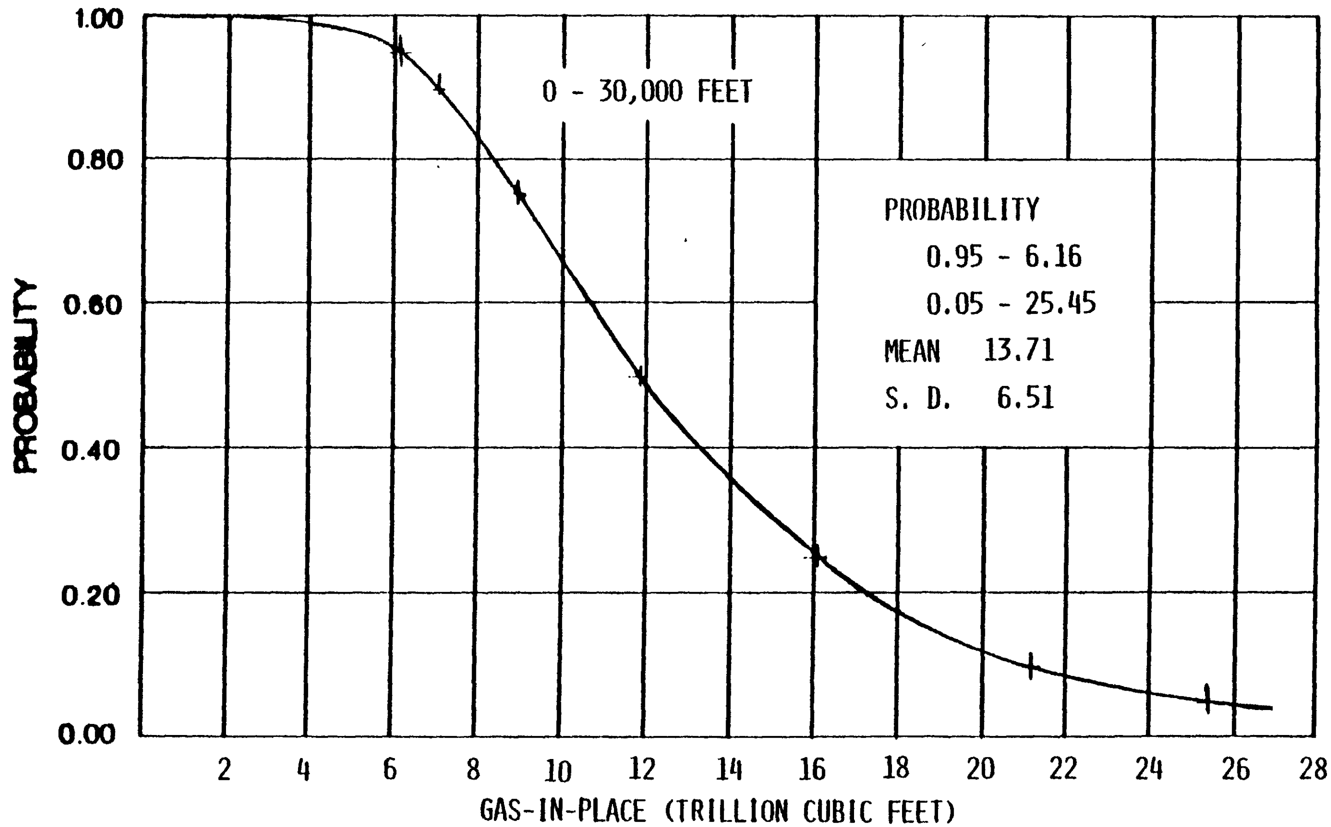


Figure 49 -- Total older Paleozoic undiscovered non-associated gas: probability distribution of non-associated gas in-place for the entire older Paleozoic.

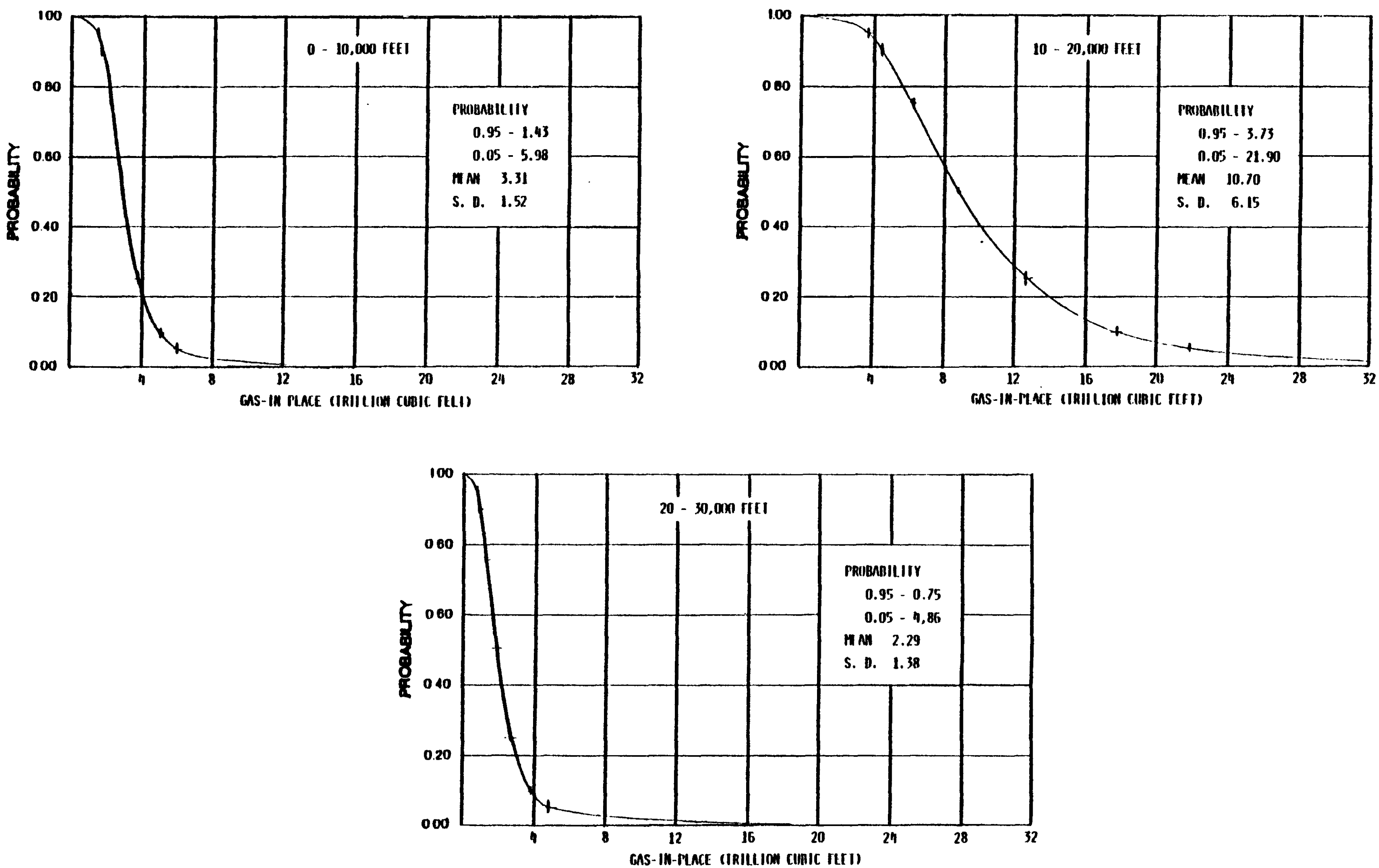


Figure 50 -- Total Paleozoic undiscovered non-associated gas: probability distributions of non-associated gas in-place for the 0-10, 10-20, and 20-30 thousand foot depth intervals.

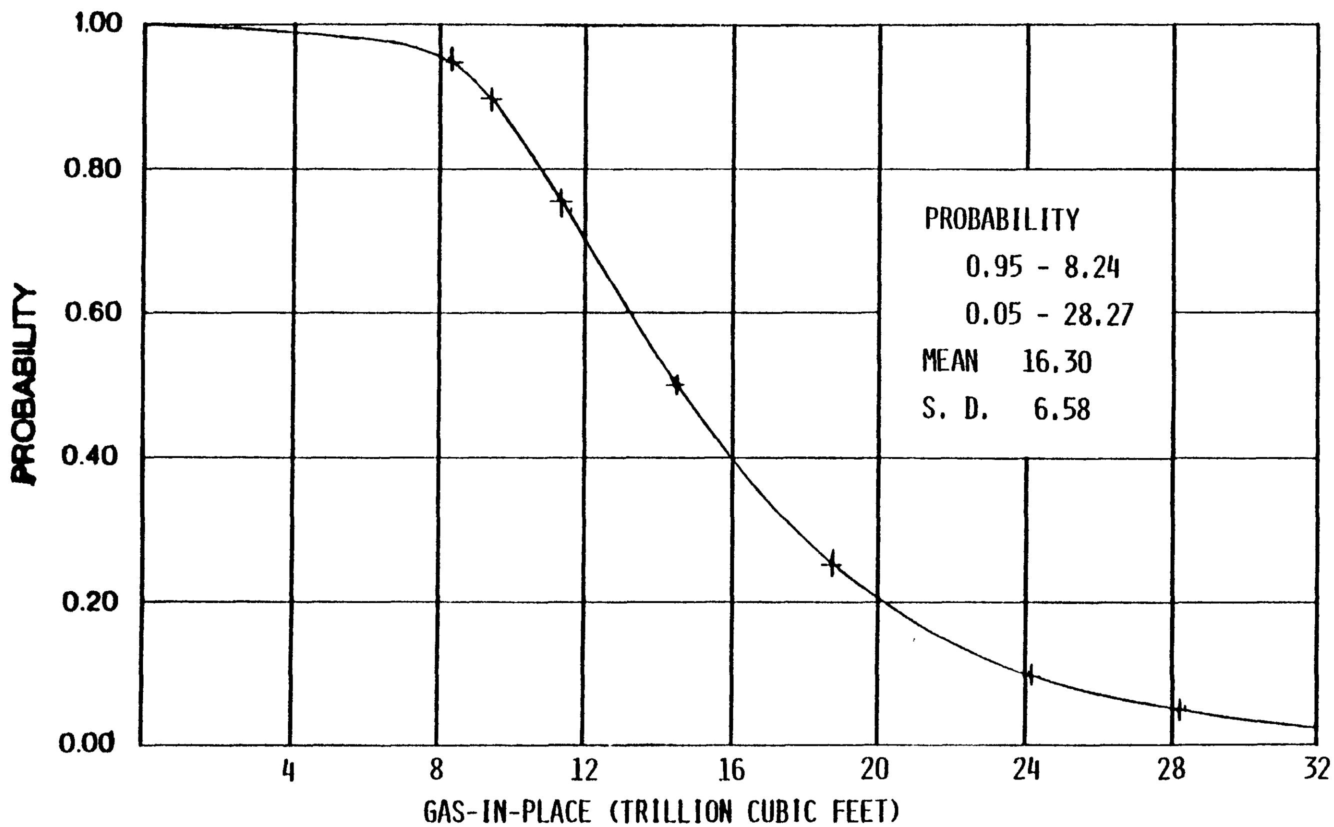


Figure 51 -- Total Paleozoic undiscovered non-associated gas: probability distribution of non-associated gas in-place for the entire Paleozoic.

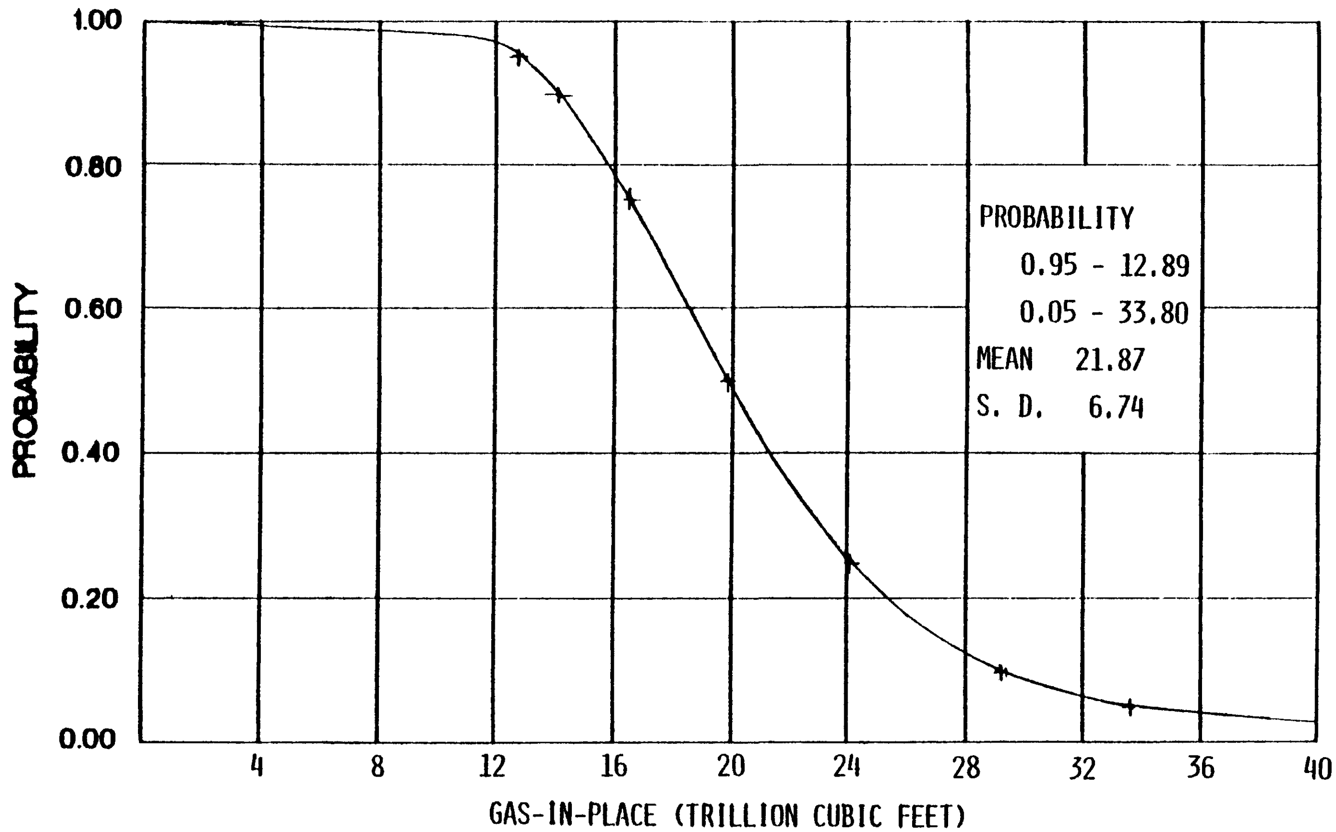


Figure 52 -- Total Paleozoic undiscovered gas: Probability distribution of total gas (dissolved / associated, and non-associated) in-place for the entire Paleozoic.

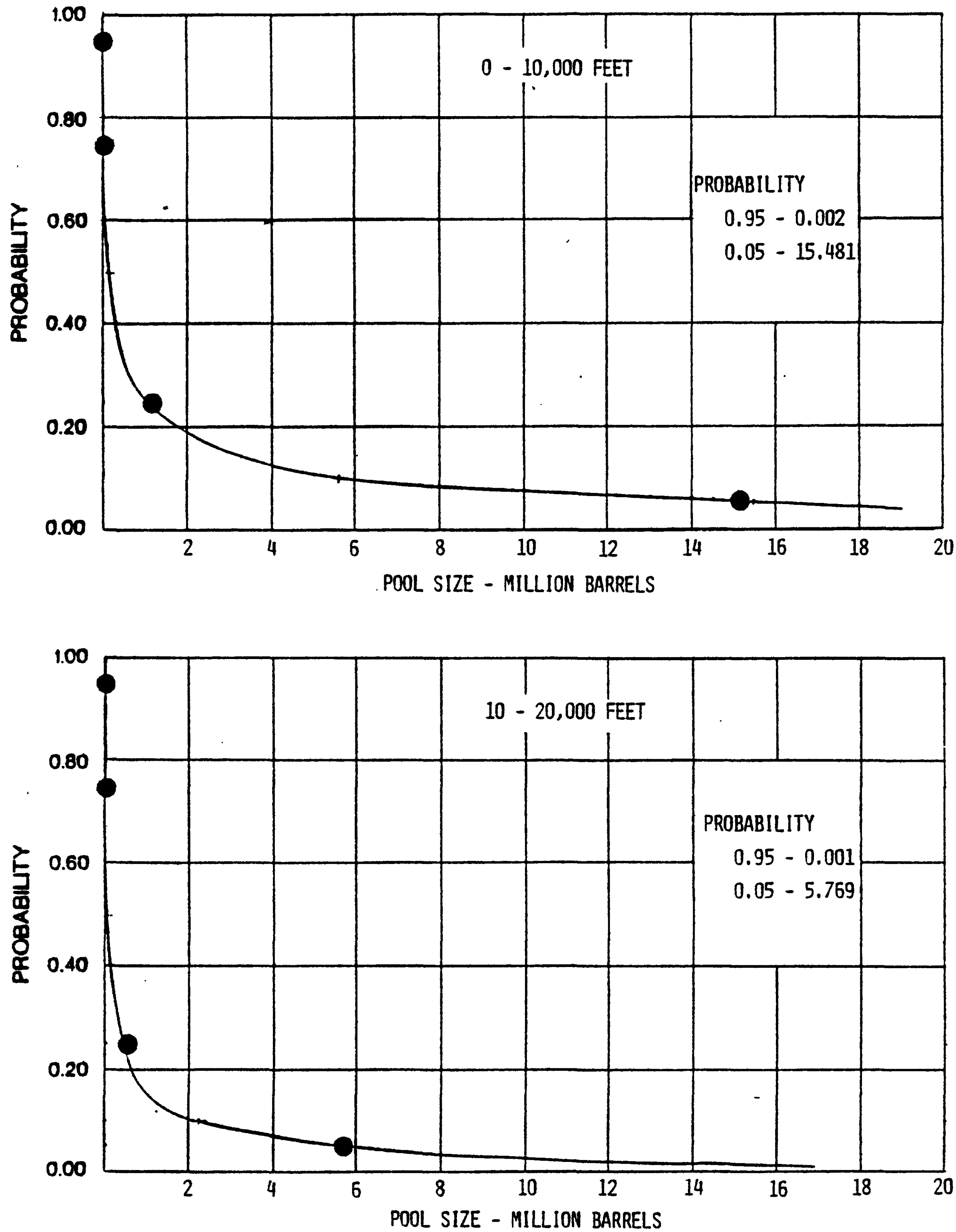


Figure 53 -- Permian oil pool-size: lognormal probability distributions of the pool-sizes of undiscovered oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

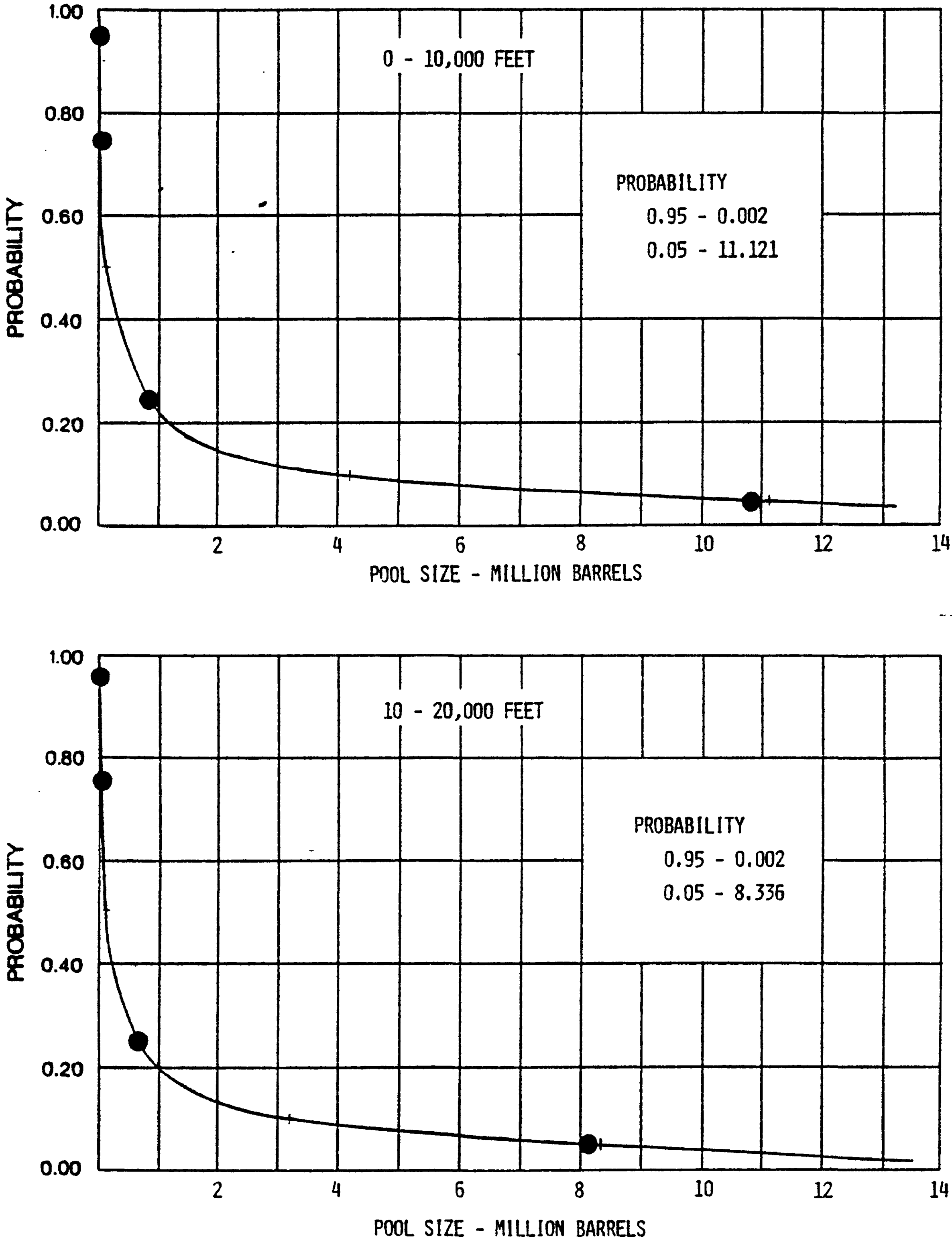


Figure 54 -- Carboniferous oil pool-size: lognormal probability distributions of the pool-sizes of undiscovered oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

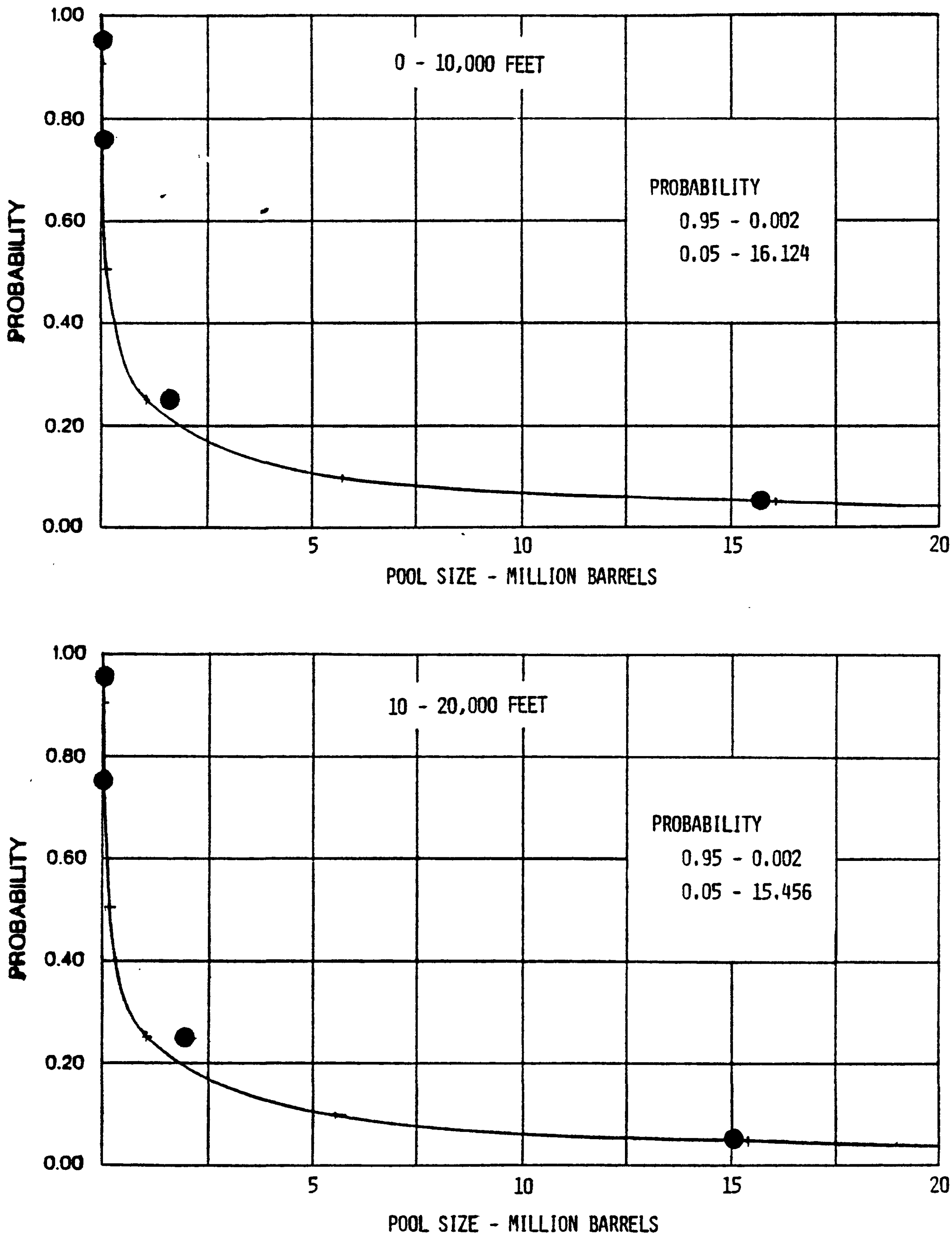


Figure 55 -- Older Paleozoic oil pool-size: lognormal probability distributions of the pool-sizes of undiscovered oil in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

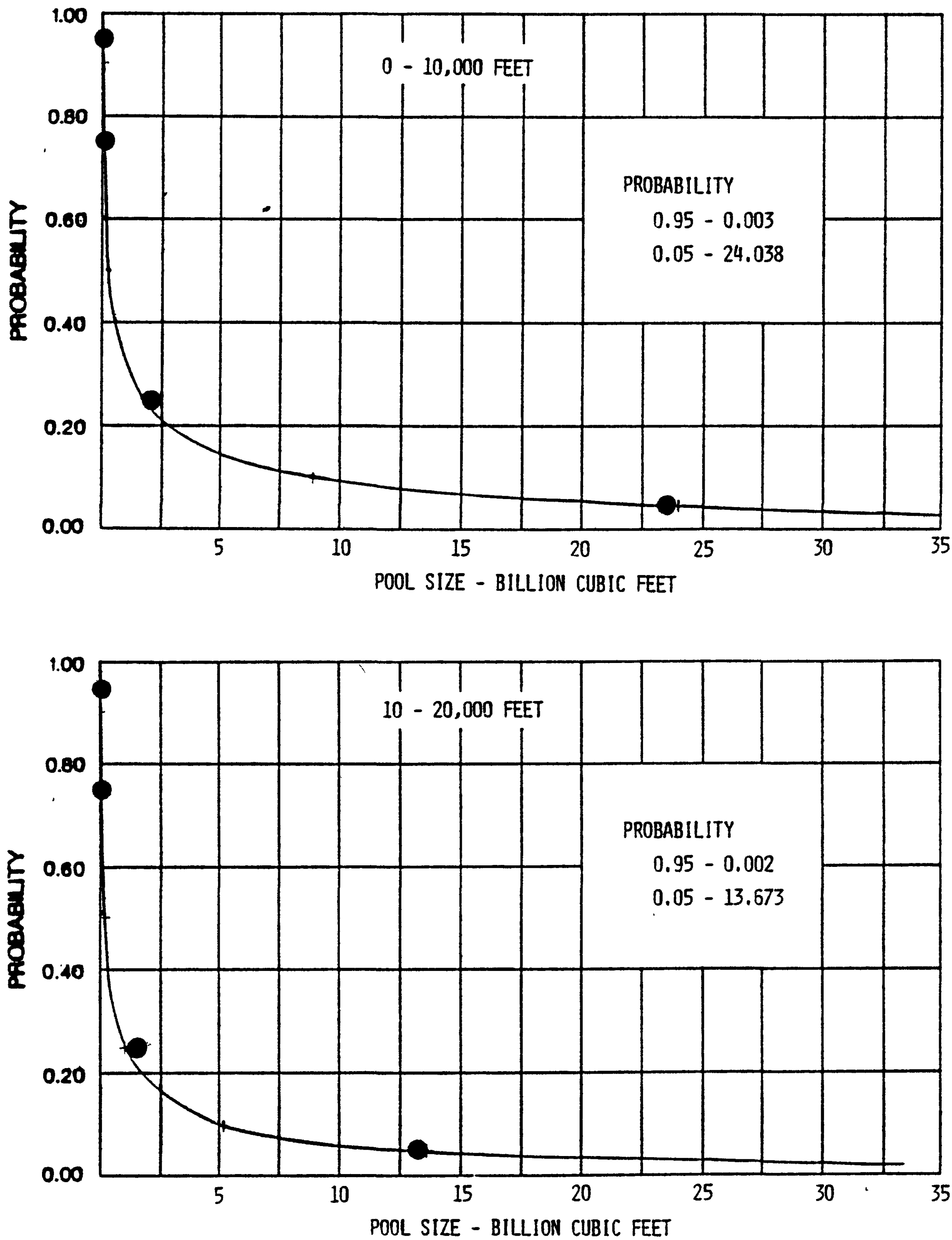


Figure 5b -- Permian non-associated gas pool-size: lognormal probability distributions of the pool-sizes of undiscovered non-associated gas in-place for the 0-10 and 10-20 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

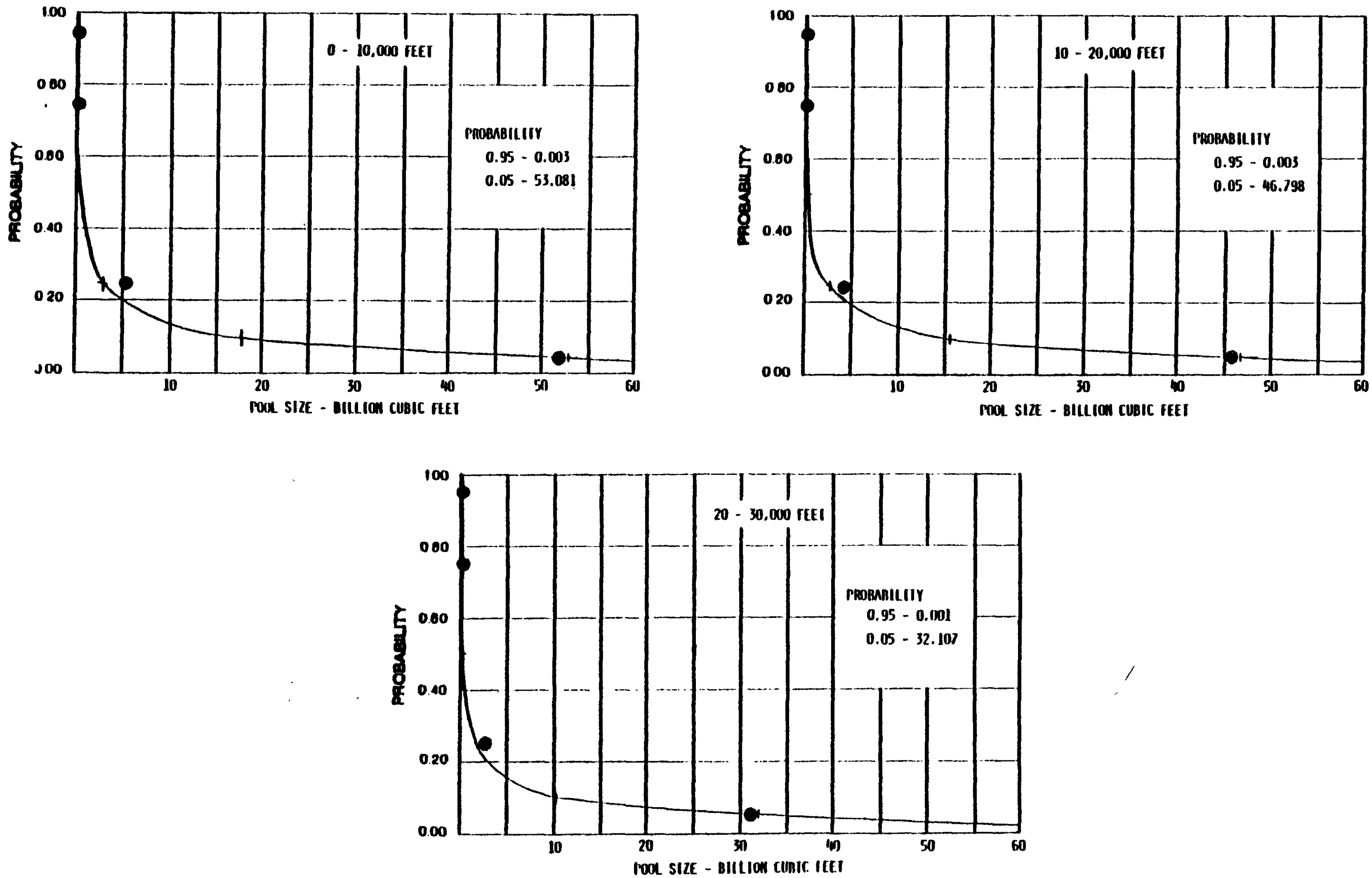


Figure 57 -- Carboniferous non-associated gas pool-size: lognormal probability distributions of the pool-sizes of undiscovered non-associated gas in-place for the 0-10, 10-20, and 20-30 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

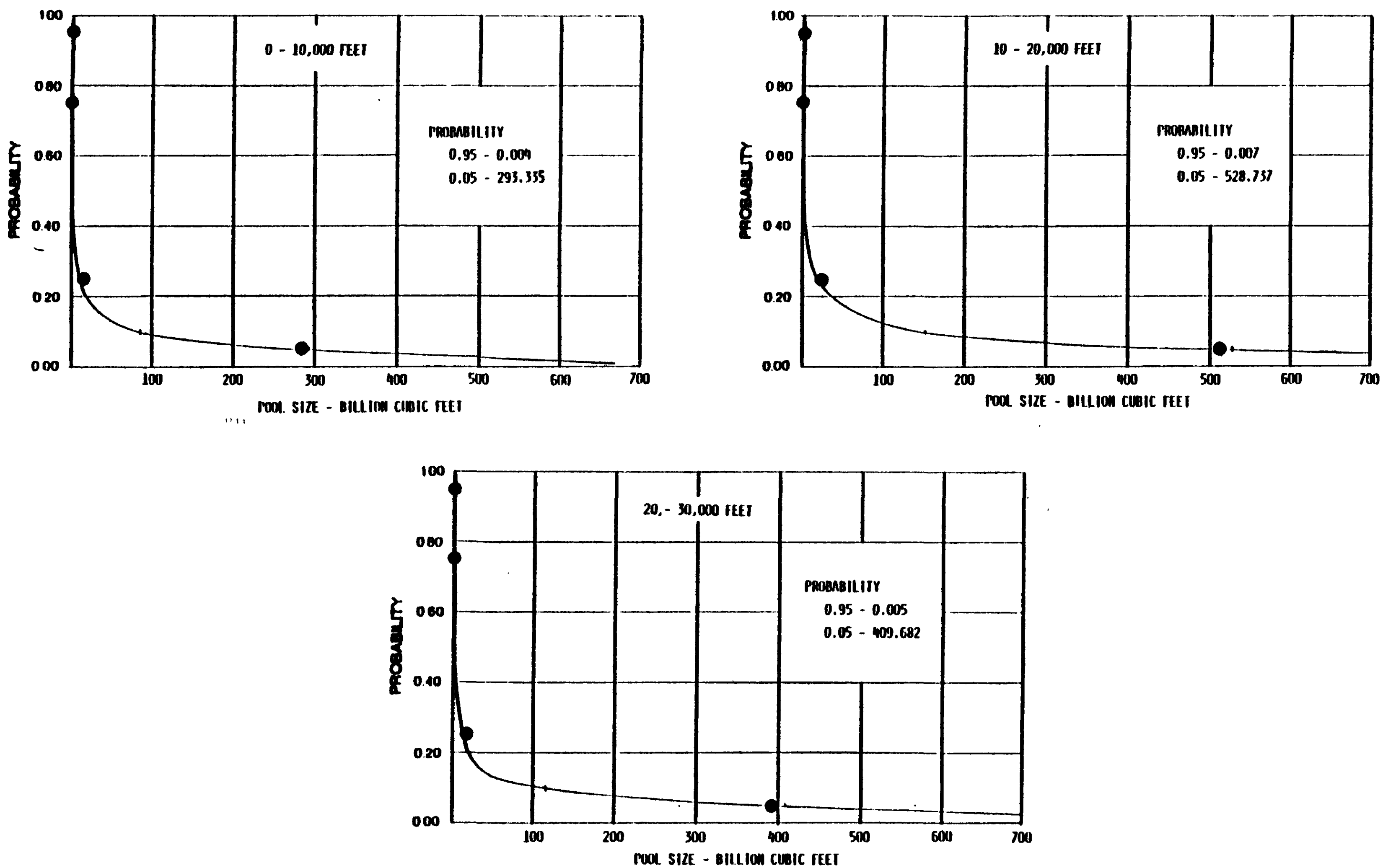


Figure 58 -- Older Paleozoic non-associated gas-pool size: lognormal probability distributions of the pool sizes of undiscovered non-associated gas in-place for the 0-10, 10-20, and 20-30 thousand foot depth intervals. Dots represent the original probability estimates to which the curve is fit.

APPENDIX C

Appendix C consists of the averaged raw probability estimates for amounts of undiscovered oil in-place and non-associated gas in-place and for pool-size distributions of oil and non-associated gas. These are the estimates to which lognormal curves were computer fitted.

The averaged raw probabilities presented in the following tables are also shown as points on the appropriate graphs in Appendix B.

Table 14.--*Original probability estimates of undiscovered oil in-place. All quantities are averages of estimates made by several people*

Age and depth (in feet)	Undiscovered oil in-place (billion barrels)			
	Probability			
	[1]0.95	0.75	0.25	[1]0.05
Permian				
0 - 10,000	0.896	1.688	3.806	6.081
10 - 20,000	.061	.090	.186	.354
Carboniferous				
0 - 10,000	.246	.462	1.693	3.492
10 - 20,000	.028	.081	.269	.584
Older Paleozoic				
0 - 10,000	.297	.552	1.340	2.277
10 - 20,000	.259	.499	1.288	2.182

[1]Estimates at the 0.95 and 0.05 probability were the quantities used to compute the lognormal probability curves (see p. 41).

Table 15.--*Original probability estimates of undiscovered non-associated gas in-place. All quantities are averages of estimates made by several people.*

Age and depth (in feet)	Non-associated gas in-place (trillion cubic feet)			
	Probability			
	[1]0.95	0.75	0.25	[1]0.05
Permian				
0 - 10,000	0.169	0.282	0.788	1.322
10 - 20,000	.011	.019	.046	.077
Carboniferous				
0 - 10,000	.272	.523	1.800	3.793
10 - 20,000	.120	.225	.683	1.369
20 - 30,000	.007	.016	.099	.197
Older Paleozoic				
0 - 10,000	.420	.701	1.808	2.993
10 - 20,000	3.312	5.717	13.467	22.216
20 - 30,000	.713	1.243	2.983	4.923

[1]Estimates at the 0.95 and 0.05 probability were the quantities used to compute the lognormal probability curves (see p. 41).

Table 16.--*Original probability estimates of the pool sizes of undiscovered oil in-place. All pool sizes are averages of estimates made by several people*

Age and depth (in feet)	Undiscovered oil pool size (million barrels)			
	Probability			
	[1]0.95	0.75	0.25	[1]0.05
Permian				
0 - 10,000	0.0019	0.021	1.120	15.130
10 - 20,000	.0013	.012	.630	5.650
Carboniferous				
0 - 10,000	.0018	.018	.850	10.880
10 - 20,000	.0016	.013	.660	8.160
Older Paleozoic				
0 - 10,000	.0017	.021	1.660	15.750
10 - 20,000	.0017	.017	1.590	25.100

[1]Estimates at the 0.95 and 0.05 probability were the pool sizes used to compute the lognormal probability curves (see p. 45).

Table 17.--*Original probability estimates of the pool sizes of undiscovered non-associated gas in-place. All pool sizes are averages of estimates made by several people*

Age and depth (in feet)	Undiscovered non-associated gas-pool size (billion cubic feet)			
	Probability			
	[1]0.95	0.75	0.25	[1]0.05
<u>Permian</u>				
0 - 10,000	0.003	0.038	2.270	23.500
10 - 20,000	.002	.026	1.620	13.380
<u>Carboniferous</u>				
0 - 10,000	.003	.062	5.380	51.750
10 - 20,000	.003	.052	4.190	45.630
20 - 30,000	.001	.020	2.590	31.260
<u>Older Paleozoic</u>				
0 - 10,000	.004	.043	14.030	284.380
10 - 20,000	.007	.145	26.130	512.500
20 - 30,000	.005	.065	20.750	396.880

[1]Estimates at the 0.95 and 0.05 probability were the pool sizes used to compute the lognormal probability curves (see p. 45).