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OIL AND GEOLOGY IN THE PERMIAN BASIN OF TEXAS AND NEW MEXICO[1]

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ABSTRACT

Pre-Mississippian strata in the Permian Basin area consist chiefly of carbonate deposits of Ordovician, Silurian, and Devonian age which were produced in a marine environment probably characterized by clear, shallow seas covering a broad southward-sloping shelf. Oil accumulated in reservoirs in the carbonates, and in sandstone units of Cambrian and middle Ordovician age, the possible external sources being marine shale associated with the sandstone, a shale formation overlying the highest carbonate, and Pennsylvanian and Permian strata which lie unconformably on the older beds, as well as lower Paleozoic strata in a clastic basin south of the carbonate shelf. Mississippian strata are chiefly shale and limestone, containing probable source beds but generally poor reservoir strata.

Near the end of Mississippian time the tectonic environment changed from one of broad structures of gentle relief on a flat cratonic platform to an almost closed basin surrounded by mountain areas of high relief, the greatest of which was the Ouachita-Marathon complex.

Pennsylvanian strata, consisting of interbedded and intergrading marine shale, sandstone, and limestone, reflect the changed environment. Oil, which the author believes to be indigenous to the system, accumulated in structural, stratigraphic, and porosity traps in Pennsylvanian reservoirs.

The Permian Period was characterized by deep but areally restricted marine basins of clastic deposition, stagnant at depth and surrounded by shoal platforms on which thick masses of carbonates accumulated and shallow lagoons extended to the shorelines. Burial of earlier strata by evaporites and red beds brought the period to a close. The principal sites of oil generation probably were in the basins; reservoirs include basinal sandstone and platform carbonate and sandstone rocks. The Guadalupe Series, which is stratigraphically the youngest and highest important producing unit and was therefore among the first to be exploited, contained more than half of all the oil which to date has been found in the Permian Basin.

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[2] Senior Geologist, Shell Oil Company. The author wishes to acknowledge his gratitude for the interest and encouragement of Thomas A. Hendricks and the late John G. Bartram, who first suggested to him the presentation of this paper, and of the late E. Russell Lloyd, whose kindly criticisms and friendly advice were a constant aid during its preparation. Much of the basic material was furnished through the efforts of the author's many associates in Shell Oil Company—W. H. Ballew, E. L. Boice, R. E. Danielson, A. J. Ehlmann, R. C. Gardell, and K. W. Paul, who served admirably for various periods as assistants in the analysis and assembly of large volumes of geologic and production data; C. G. Cooper, R. L. Fay, Louise Fillman, H. E. Rankin, and J. L. Wilson, who contributed substantially to the data and interpretations. The number of other Shell geologists who aided not only in furnishing data but also in the free exchange of ideas is too great to permit individual acknowledgment, but to all of them in Midland, Abilene, Roswell, Wichita Falls, and Oklahoma City, the author is grateful. The first draft of the manuscript was read critically by John G. Bartram, John M. Hills, Theodore S. Jones, E. Russell Lloyd, and Addison Young, as well as by several of the aforementioned Shell personnel; the final draft was read by C. G. Cooper, M. King Hubbert, Theodore S. Jones, G. T. Philippi, W. A. Waldschmidt, J. L. Wilson, and Addison Young; all of these offered helpful suggestions. Fruitful and stimulating discussions also were had with John Emery Adams, Frank B. Conselman, John A. Masters, T. L. Stall, and other geologists familiar with the subject. None of the author's advisors and associates, however, should be held responsible for conclusions expressed in this paper on any controversial subjects, as the author has chosen those interpretations which in his own opinion most logically explain the observed conditions. Special gratitude is acknowledged for aid from the author's wife in the form of patience and forbearance during countless evenings and weekend days of absence while the work was in progress. Finally, sincere thanks are extended to M. S. Metz, Exploration Manager of Shell's Midland Area during work on this project, for permitting and encouraging the undertaking and for generous grants of manpower and other assistance throughout, and to Shell Oil Company for permission to publish the paper.

INTRODUCTION

Commercial accumulations of oil and gas in the Permian Basin have been discovered in all stratigraphic systems of Paleozoic age. The first discovery of oil west of the Bend arch was made in 1920 in Mitchell County, Texas. Early development was concentrated in shallow formations of Permian age on the Central Basin platform and along the marginal shelves of the Delaware and Midland basins, and in Pennsylvanian and lower Permian formations on the west flank of the Bend arch. In 1928 oil was discovered in Ordovician rocks in the south end of the Midland basin, and subsequent exploration resulted in rapid expansion of producing areas from reservoirs in almost the entire sedimentary column. By the end of 1953 cumulative production amounted to about 6 billion barrels of oil. The total amount of oil found up to that time is estimated to be about 14 billion barrels,[3] distributed stratigraphically as shown in Figure 1. Correlative data for gas production are not available. The locations of oil and gas pools producing from various stratigraphic units are shown on the maps of those intervals.

The purpose of the study reported here is to determine the geologic history of the Permian Basin, and the relation between occurrence of oil and the sedimentary and tectonic environments. It is desirable to learn the time and place of origin of the oil and its path of migration into the reservoirs in which it is now found, but in the absence of specific information such as chemical analyses or other data with which to make positive identifications of source beds such conclusions can be only tentative. The author has accepted the commonly held belief that highly organic marine argillaceous rocks, rather than pure, light-colored carbonate rocks, were the principal source beds, and in this paper he speculates about origin and migration on the basis of observations concerning the present occurrence of oil and the relations between reservoir rocks and adjacent strata of various lithologic types.

PRINCIPAL STRUCTURAL FEATURES

The Permian Basin of west Texas and southeast New Mexico occupies about 115,000 square miles, and in its shallow beds it is a structural bowl whose lowest portion, the Delaware basin,[4] lies at the southwest and is separated from the shallower Midland basin[5] by an uplift known as the Central Basin platform[6] (Fig. 2). Although not labelled or clearly shown in Figure 2, the Palo Duro basin (Gould and Lewis, 1926, pp. 10 and 13–14) at the north completes the form of the shallow Permian Basin. This simple framework is the structural picture which became outlined by early drilling in the area and is still the general concept of the shape of the Permian Basin. Deeper drilling, however, has revealed the presence of other structures within the larger framework, some of them relict, and has brought into sharper focus the elements which confine the Permian Basin (Figs. 3 and 4). It

[3] Throughout this paper, estimates of ultimate recovery refer only to oil which is recoverable by primary production methods. Estimates of secondary reserves for parts of the Permian basin have been published by Fancher, Whiting, and Cretsinger (1954).

[4] This structure was named the Delaware Mountain basin by Willis (1929b, p. 1034). In subsequent usage the word "Mountain" has been dropped.

[5] Named by Sellards (1934, p. 107).

[6] Named by Cartwright (1930, p. 970).

has also shown that the Delaware basin, which was confined by the development of marginal platforms in Permian time, extends farther north in deeper strata.

The midcontinental basin of sedimentation during the Permian Period extended from west Texas northward at least as far as Nebraska, but its deepest and most persistent expression lay in west Texas and southeast New Mexico. This "South Permian Basin", to which the name Permian Basin has become fixed by usage, reaches its northern limit at the Wichita-Amarillo uplift (Gould and Lewis, 1926, p. 8; Sellards, 1934, pp. 99, 105–106).

The Permian Basin is limited on the east by the Bend arch, a structural feature which was first shown on a map contoured on strata of Bend age by Cheney (1918, p. 75) and also on a map by Dorsey Hager (1918). Because he considered the Bend arch to be the result of successive tiltings in opposite directions rather than of uplift, Cheney (1929a, p. 558; 1929b, p. 10) later urged the substitution of the more appropriate term, Bend flexure, but the older name has persisted in general usage. Local anticlines on the Bend arch are structures of relatively low relief, in contrast to those on and adjoining the Central Basin platform. For the purpose of this paper, the boundary between the Bend arch and Midland basin tectonic provinces is arbitrarily drawn at the county boundaries nearest 99° West Longitude; no data were compiled for counties eastward.

The northwest and west flanks of the Permian Basin are formed by the Pedernal massif,[7] a broad positive area in New Mexico which was intermittently uplifted and exposed to erosion throughout the Paleozoic Era. It derives its name from the present Pedernal Hills in central New Mexico, where a small area of Pre-cambrian rocks is exposed.

The Diablo platform (King, 1942, p. 617 and Fig. 18) is treated as the south-west margin of the Permian Basin in this paper. The area of probable Permian sedimentation lying farther to the southwest, in and beyond the present Marfa basin, is not considered in this paper as part of the Permian Basin. Although it probably was active throughout lower and middle Pennsylvanian time, the Diablo platform was uplifted most strongly at the end of the Pennsylvanian Period. The unconformity at the base of the Permian System is well exposed in the local Van Horn uplift (southern Hudspeth and Culberson Counties, Texas) but the platform extends to unknown limits in the unexplored subsurface of Trans-Pecos Texas, and its outlines are obscured by Mesozoic and Cenozoic events.

Finally, the rather vaguely defined front of the Marathon folded belt (King, 1942, p. 717) marks the southern limit of the Permian Basin. The folded belt is exposed in outcrops on the Marathon dome (northern Brewster County, Texas), but eastward is recognized only in the scattered borings. Its position is suggested by the shape of an anticlinal uplift in the subsurface trending from the Marathon dome east-southeastward, which the author here names the *Devils River uplift* from the present stream which crosses it.

[7] Also referred to as the "Pedernal positive element" by Willis (1929b, p. 1034); as the "Pedernal Uplift" by Ver Wiebe (1930, p. 771); and as the "Pedernal Land Mass" by Thompson (1942, pp. 12 and 13). The present author prefers the term *massif*, because it connotes an ancient and persistent land mass.

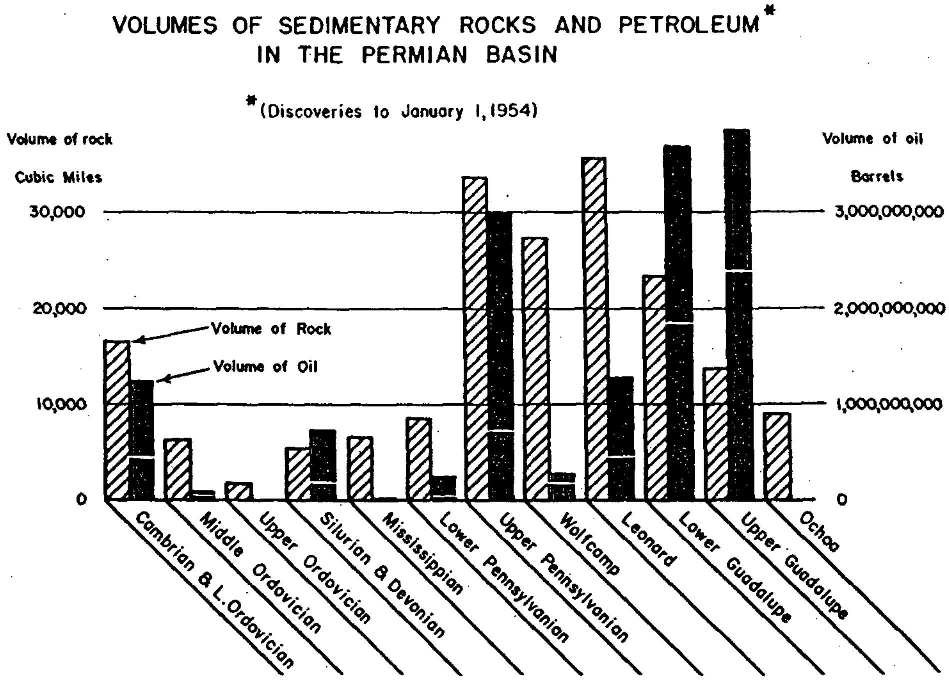

FIG. 1.—Volumes of sedimentary rocks and petroleum in the principal stratigraphic units of the Permian Basin. The horizontal white line dividing each black column separates the total volume of oil which had been produced at the end of 1953 (lower portion of column) from the volume of reserves which is believed to be recoverable by primary production methods from known pools (upper portion). Cumulative production data were compiled from Annual Report (1953) of the Oil and Gas Division, The Railroad Commission of Texas; estimates of reserves were obtained from private sources. Data on production include discoveries to Jan. 1, 1954.

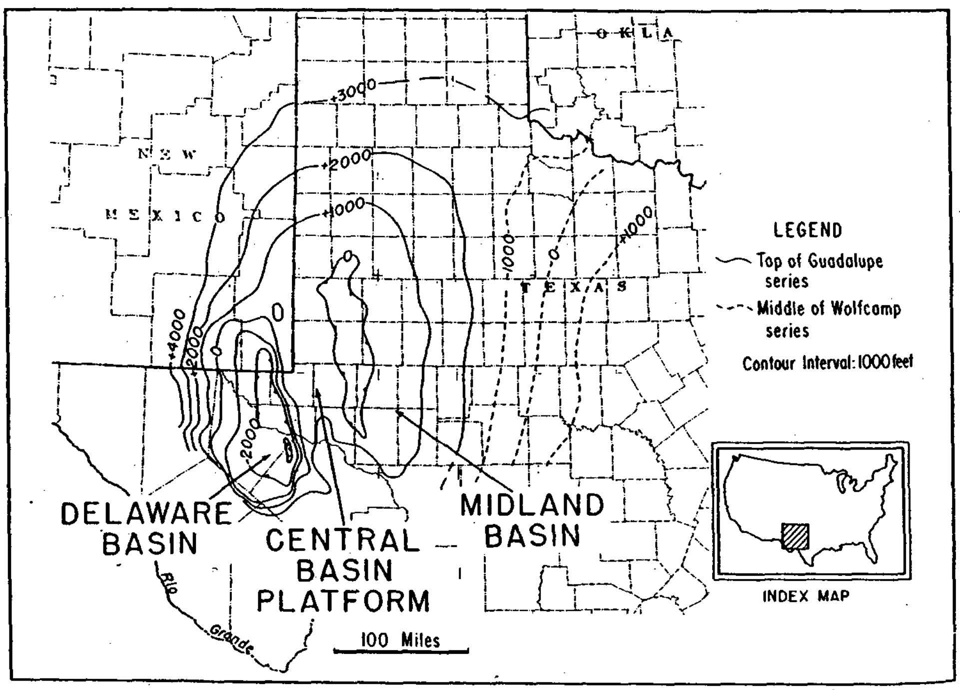

FIG. 2.—The Permian Basin in shallow strata—map showing the present structure of Permian markers in west Texas and southeast New Mexico, and the location of three principal structural divisions as revealed by shallow drilling. Compare with Fig. 4.

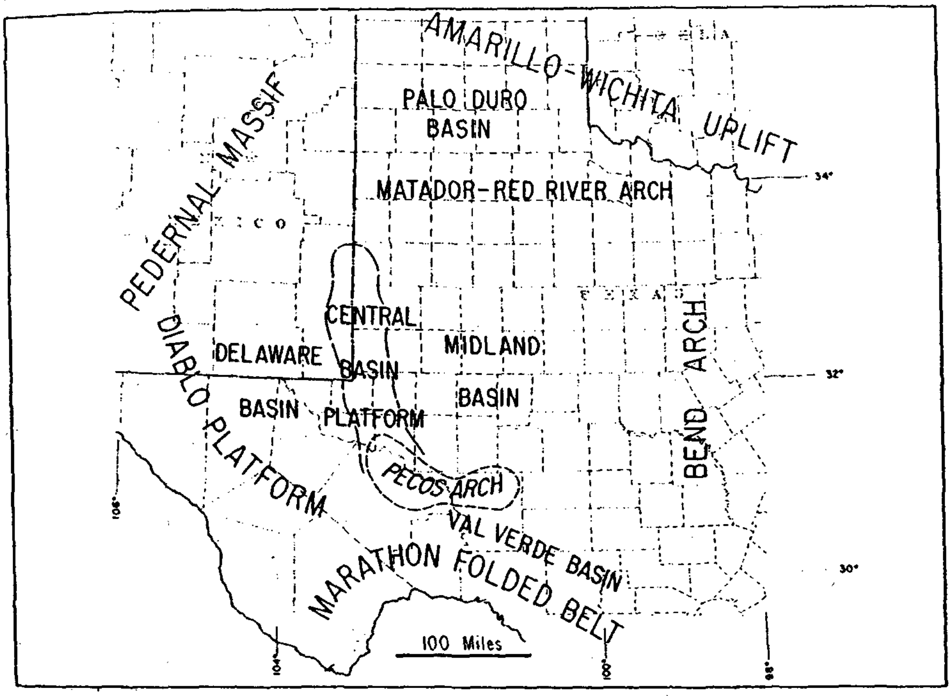

FIG. 3.—Present structural components of the Permian Basin. Relict structures such as the Concho arch and Tobosa basin are not shown.

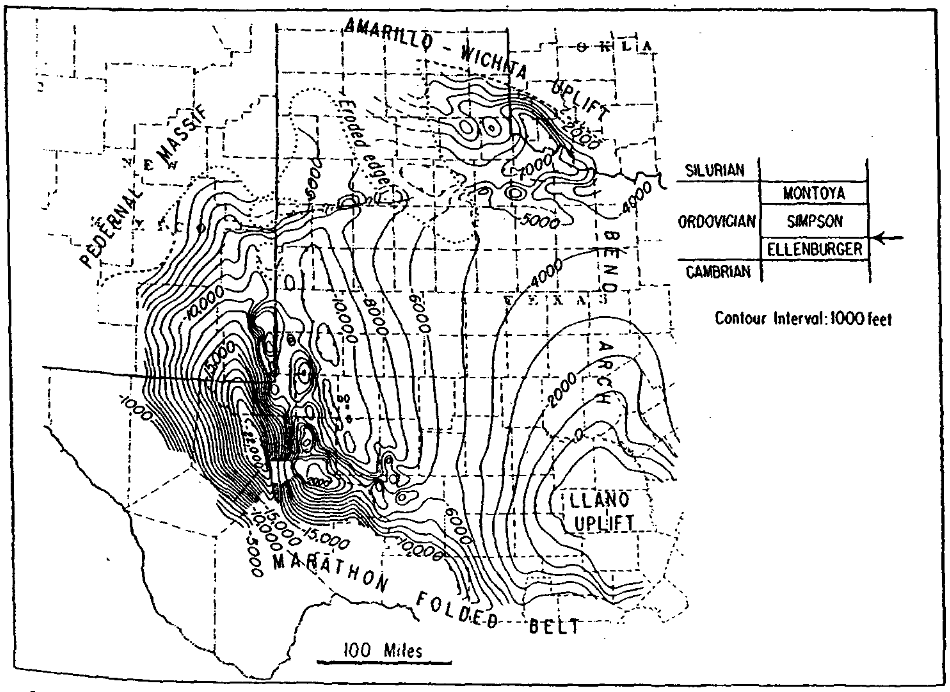

FIG. 4.—Present structure, top of Ellenburger group. The Delaware and Midland basins are more elongate in deep strata than they are in shallow (see Fig. 2).

A large anticline extends across the south ends of the Central Basin platform and Midland basin. The Fort Stockton "High" (northern Pecos County, Texas: Willis, 1929a, pp. 1026–1027; 1929b, p. 1034), where Permian strata lie on Precambrian basement, is the west half of the uplift, and the east half has sometimes been called the Ozona platform (northern Crockett County, Texas—Vertrees *et al.*, 1953, p. 1359). The uplift is older than the Central Basin platform, as will be shown in this paper. To this anticline the present author has given the name *Pecos arch*, from the river which now flows across the area. Sellards (1932, pp. 52–53) used the name Pecos uplift for the feature which Cartwright (1930) had earlier named the Central Basin platform, but because the earlier designation is now in use, the name Pecos arch is deemed by the writer to be available and appropriate for the structure which includes the Fort Stockton "High" and the Ozona platform.

The structural depression lying between the Pecos arch and the Devils River uplift is known as the Val Verde basin (Lewis, 1941, p. 78). Like the Strawn basin, east of the Bend arch, and the Kerr basin, south of the Llano uplift, the Val Verde basin is a part of the present structural expression of the late Paleozoic trough of deposition which was a foredeep in front of the Marathon-Ouachita folded belt.

The north end of the Midland basin is crossed from west to east by a narrow belt of anticlines known as the Matador arch,[8] which separates the Midland basin from the Palo Duro basin.

Extending south-southeastward across the east flank of the Midland basin is a broad, low relict anticline (Figs. 7, 9, 11, 13, 16), not recognizable in contour maps of present structure, to which the name Concho arch was applied by Cheney (1929a, p. 575 and Fig. 3; 1940, p. 99 and Fig. 7) and by Cheney and Goss (1952, p. 2262 and Fig. 10). Some Texas geologists have expressed reluctance to accept the name Concho arch for the entire uplift extending from the Texas Panhandle to the place where it disappears under the overriding Marathon-Ouachita folded belt, believing that Cheney meant to restrict its application to a local feature in the vicinity of Concho County in central Texas. However, there is no agreement regarding the location and extent of the local structure, and the references cited here make it clear to the present author that Cheney had, from the initial concept to his last description, considered the arch to be a broad regional feature, limited only by the absence of data in its distant reaches.

His first reference (1929a) states that

> A very broad, low arch seems to have been formed during Mississippian and early Pennsylvanian times, trending northwest from the present Llano-Burnet uplift and between the Ouachita-Strawn basins on the northeast and the Tesnus-Haymond basins on the southwest. This is indicated as the Concho divide in Figures 3 and 7.

In 1940 he stated that

> Loss of pre-middle Gasconade Ellenburger beds toward the Concho arch indicates that the development of this arch had begun by early Ordovician time. . . . Prior to Mississippian deposition, Cambrian and Ordovician deposits had been affected by regional uplift and trunca-

[8] Also known as Red River uplift (Lee Hager, 1919), as Electra arch, Wilbarger arch, and other names. The name "Matador archipelago" is favored by Texas Panhandle geologists (Totten, 1954, p. 2051), but is not applicable to the present structure because the feature was an archipelago during only Pennsylvanian deposition.

tion along a broad axis extending from the present Llano uplift northwestward for an undetermined distance. With extensive uplift established, this feature named from Concho County is more suitably referred to as the Concho arch rather than Concho divide.

Finally, as drilling continued to provide more subsurface data, Cheney and Goss concluded (1952)

The Llano uplift is the uptilted southeast part of a very extensive structural axis, the Concho arch. This arch extended northwest to the present Texas Panhandle region, but it has lost prominence as a result of subsidence beneath the Permian basin.

Maps accompanying the present paper, as well as that of Adams (1954, p. 71), who calls the structure the Texas arch, indicate that the Concho arch probably extended much farther south than the present Llano uplift.

During all of pre-Mississippian time, when the Concho arch was more active than it was later, there lay to the west of it a basin of thicker sediments which has until now not been described or named. It included the site of the later Delaware basin, but down the middle of it lies also the post-Pennsylvanian Central Basin platform. It is not appropriate, therefore, to call it the Delaware basin. Moreover, it is not related to the entire basin of Permian deposition, the Permian Basin, its west side being the only flank which the two have in common. Acting on a suggestion by Dr. James L. Wilson[9] that this restricted early Paleozoic basin which centers around the southeast corner of New Mexico should be named, the present author calls it the *Tobosa basin,* the name being taken from Tobosa Flats (Lang, 1953) in the extreme southeast corner of the state. As seen in Figures 9, 11, 13 and 16, the south edge of the basin lay beyond the limits of our present information; or more likely there was no south boundary, the depression having been simply an embayment of a much broader basin at the south. Other boundaries are the Concho arch, the Pedernal massif, and perhaps the Diablo platform. The importance of the basin, which occupies about 40,000 square miles, will be brought out in later pages.

GEOLOGIC HISTORY, OIL SOURCES, AND RESERVOIRS

STRATIGRAPHIC COLUMN

Strata of all Paleozoic systems are represented in the Permian Basin, the maximum thickness being estimated at more than 25,000 feet of sedimentary rocks in the deepest part of the Delaware basin. The general stratigraphic column is represented graphically in Figure 5. Gross lithologic descriptions and basinwide relationships will be presented in the following pages and maps. For details of stratigraphy and lithology, the reader is referred to the excellent summary issued by West Texas Geological Society (Jones, 1953), which includes an extensive bibliography.

CAMBRIAN AND LOWER ORDOVICIAN

The first sediments deposited on the eroded surface of Precambrian rocks were laid down in late Cambrian time in the southeast part of the area by a sea which advanced from that direction, and as time progressed into early Ordovician the sea transgressed across the remainder of the area (Figs. 6 and 7). The initial deposits were sandstone and arenaceous carbonates. Shale members are thickest in

[9] Personal communication.

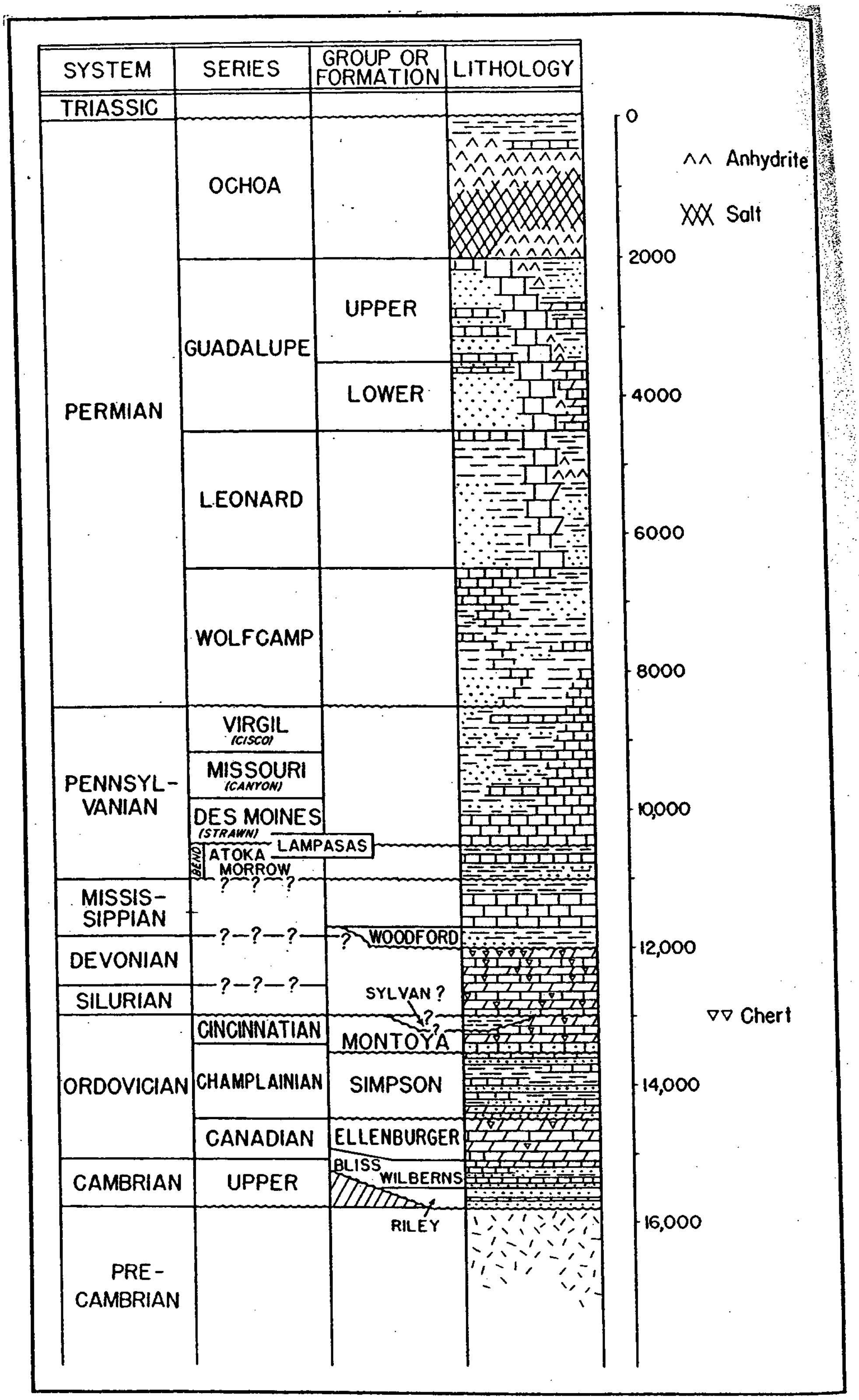

FIG. 5.—Generalized stratigraphic and lithologic column for the Permian Basin.

the southeast and nonexistent along the west side of the basin. Thicknesses of clastics in excess of 1,000 feet in the southeast contrast strongly with those generally less than 10 feet throughout most of the area, indicating the presence of a sedimentary trough at the southeast and a relatively flat area elsewhere. Thicknesses of sandstone greater than 100 feet along the west and north edges of the area indicate the existence of borderlands in those directions but beyond the present truncated edge of the strata. As a result of the transgressive nature of the deposit, the basal clastic unit is not everywhere of the same age.

Throughout the area the basal clastic rocks grade upward into the slightly cherty carbonates of the Ellenburger group which are principally finely to medium-crystalline dolomite. Small proportions of limestone occur at various places within the Permian Basin, but data are insufficient to reveal a clear-cut pattern of distribution. Principal limestone areas are at the southwest, south, and southeast.

The topmost surface of the Ellenburger group is an unconformity throughout the Permian Basin. Examination of the thickness map (Fig. 7) reveals two large anticlinal noses plunging south-southeastward from a positive area to the north, and from these features much of the original thickness has been removed by erosion as evidenced by the fact that only lowermost Ellenburger strata are present at the apices of the structures, younger beds occurring on the flanks. The structure to the west, which is covered by middle Ordovician strata, is the precursor of the late Paleozoic Central Basin platform. Local accumulations of clastics at the base of the stratigraphic column on this structure suggest the presence of high spots in the pre-Cambrian surface, but whether the highs are structural or only topographic is not known.

To the east is the feature which Cheney (1940, p. 99) called the Concho arch. Although much of the evidence for the age of this feature has been destroyed by the removal of pre-Mississippian strata, the distribution of clastics beneath the Ellenburger dolomite indicates that the north end of the arch was at least a topographic prominence during deposition of the first sediments.

A hint of thinning toward the Rio Grande at the southwest edge of the map suggests the presence of an early forerunner of the Diablo platform and thus of a primordial Delaware basin between it and the Central Basin platform.

With few exceptions, commercial amounts of oil and gas are found only in the uppermost strata beneath the unconformity, apparently regardless of the stratigraphic age of the beds, even the basal sandstone beds being productive in local anticlines on the Concho arch. Accumulation takes place in the highest porous zones, on anticlinal structures and perhaps on paleotopographic highs as well. Fractures and vugs are the principal porosity types in the carbonate reservoirs, and the thickness of the pay zone, which may be less than 100 feet or in some instances as much as 1,000 feet, is determined simply by the interval between the top of the highest porous zone and the oil-water contact. In some places this interval is the entire thickness of Ellenburger dolomite.

There are no obvious source beds in the basal clastic strata in most of the area, although thin shale intervals in the southeastern sector may have been sources for minor quantities of hydrocarbons. In rare instances oil has been found in the basal

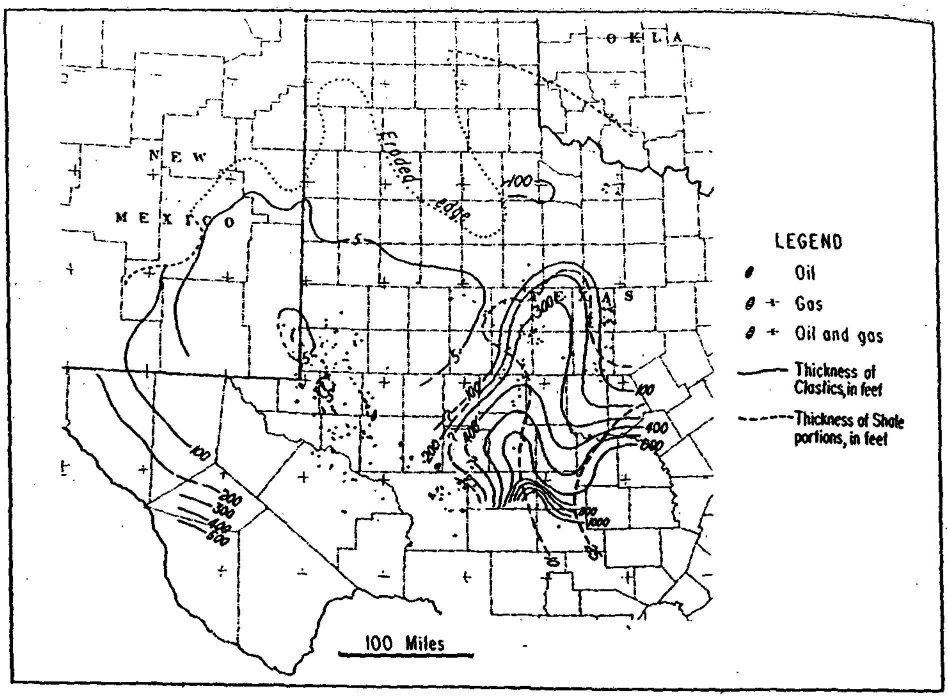

FIG. 6.—Total thickness of clastic rocks in Cambrian and lower Ordovician strata. Except locally, the clastic strata have not been subjected to erosion. Dashed contours in the southeast portion of the map represent the total thickness of shale members; the remainder of the clastic fraction is sandstone.

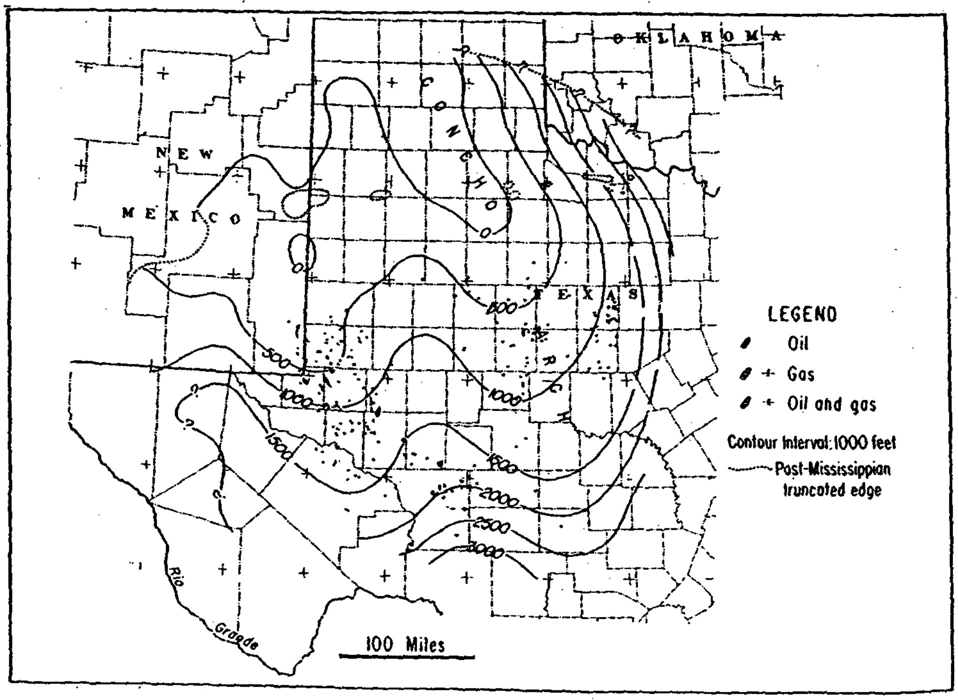

FIG. 7.—Thickness of Cambrian and lower Ordovician strata after several pre-Pennsylvanian erosion intervals. Comparison with Fig. 8 indicates the area which has not been subjected to erosion since middle Ordovician time.

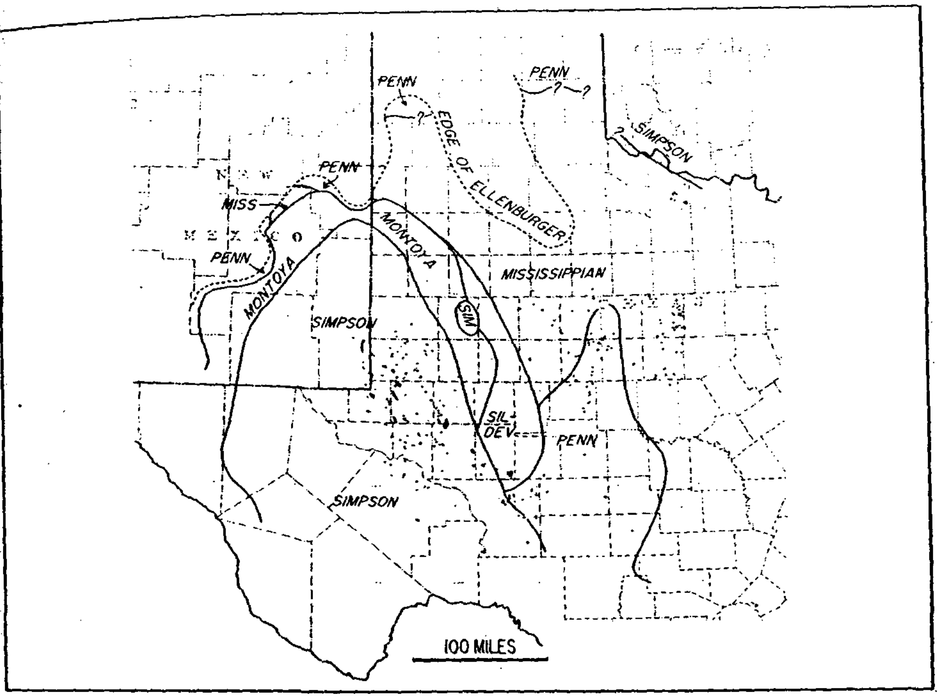

FIG. 8.—Age and distribution of strata lying on the eroded surface of the Ellenburger group.

sandstone beneath thick carbonate strata of the Ellenburger group, but the clastics have produced no oil or gas of importance except where overlain directly by post-Ordovician strata.

Evidence has been presented by Cloud and Barnes (1948, pp. 58-61) to show that the Ellenburger part of the early Ordovician sea was warm and shallow and that it contained dominantly molluscan faunas. There is no general agreement, however, regarding the potentialities of the Ellenburger carbonates as source beds for oil. The observations that oil occurs only in the interval immediately below the unconformity and that there appears to be no well substantiated record of the occurrence of oil in a lower porous zone below an upper water-bearing porous zone, suggest that the oil is not indigenous to the carbonate reservoir rock but migrated downward from overlying strata.

In general, the producing fields are found where Ellenburger dolomite or the basal clastic strata are overlain directly by either Simpson (middle Ordovician) or Pennsylvanian strata. Locally, as in many places on the Central Basin platform, Simpson beds have been removed by truncation of anticlinal structures, and the Ellenburger reservoirs lie under a cover of Pennsylvanian or lower Permian strata. High on the east flank of the Midland basin small fields have been discovered under a cover of Mississippian strata. Figure 8 shows the general areas in which these relations exist. From these observations it may be concluded that if it migrated downward from sources in overlying rocks, the oil in the upper Cambrian and

Ellenburger beds was derived from strata in the Simpson group[10] and Pennsylvanian System, along with some from lower Permian beds which are similar in lithology to those of the Pennsylvanian System. A source restricted to the east edge of the Permian Basin may be strata in the Mississippian System (Cheney, 1929b, p. 25).

A possible source of any oil which is not indigenous to the productive strata or derived from superjacent beds is postulated in the vaguely known basin of clastic deposition which lay south of the sloping platform on which the reservoir rocks were deposited. This intriguing speculation requires that migration up the slope into present reservoirs was completed prior to the late-Paleozoic Marathon orogeny.

The gravity of the oil in Ellenburger reservoirs ranges generally between 41° and 48° A.P.I. under both Simpson and Pennsylvanian covers, gravities higher than 50° occurring mainly in the deeper Midland basin fields close to the Central Basin platform. In nearly all recorded tests the oil has a low sulfur content.

The volume of oil recoverable by primary production methods, which has been found in approximately 16,500 cubic miles of lower Ordovician and upper Cambrian strata in the Permian Basin, is about 1¼ billion barrels, of which two thirds is on the Central Basin platform and one fifth in adjacent parts of the Midland basin, both largely under cover of Simpson strata.

MIDDLE ORDOVICIAN

Following withdrawal of early Ordovician seas and erosion of the surface of Ellenburger carbonates, strata of the Simpson group were deposited as sequences of sandstone, green shale, and limestone, the whole in places overlying a thin basal conglomerate which thickens toward the north. The Simpson beds were deposited in a broad sea which the author believes to have extended continuously at least from southern New Mexico and west Texas through Oklahoma and Kansas. Lithologic characteristics are uniform and persistent throughout that region, and the present restricted area (Fig. 9) of the Simpson group in the Permian Basin is more probably the result of subsequent erosion than of original depositional limits, although there undoubtedly is some depositional thinning to the northwest.

Cross sections showing well-to-well correlations of sandstone members indicate that on the flank of the Concho arch the oldest units extend farthest eastward, the younger beds being truncated so as to provide a normal sequence of subcrops under the next overlying formation. To the north and northwest, however, the individual units become indistinguishable owing to facies changes as the Simpson interval thins, although there is no evidence of any shoreline or nearshore deposit. There is, therefore, no sign of a land mass or of positive movements in the Concho arch area during Simpson deposition, but the Pedernal massif was high or emergent. Both structures were uplifted prior to deposition of the Montoya formation. The structural basin between the two uplifts persisted through subsequent events of pre-Mississippian history, and to this basin the author gives the name *Tobosa basin.* Prior to late Devonian (Woodford) time it was probably distinguished only by

[10] The possibility of source beds in Simpson strata has been suggested by various authors, among the most recent being Bartram, Imbt, and Shea (1950, p. 695).

differential erosion rather than as a separate depositional basin.

The existence of the erosional interval between Simpson beds and overlying strata is attested not only by a faunal hiatus but also by the presence of abundant grains of Simpson-type sand in the base of the next younger Montoya formation; even cobbles of sandstone having all the characteristics of Simpson sandstone are embedded in the base of Maravillas limestone (Montoya equivalent) in the Marathon area at Rock House Gap.

Figure 10, showing the total thicknesses of all sandstone and limestone components, illustrates by comparison with Figure 9 the uniform lithology of the Simpson group. The uniform texture and thickness (average 20–50 feet thick, each member) and great extent of the three main sandstone members suggest deposition in a broad basin, of clastics derived from distant sources (*cf.* Dapples, 1955). The fauna is marine and includes such forms as ostracods, trilobites, and graptolites, some of which indicate muddy bottoms.

No evidence of a positive area in the position of the Central Basin platform can be seen on the thickness and facies maps (Figs. 9 and 10), the sandstone members which together increase in total thickness toward the center of the area being relatively thin beds intercalated throughout the sequence rather than a single basal member of the group. Post-Simpson erosion, perhaps resulting partly from general regional uplift but certainly accentuated by upward growth of the Pedernal massif and Concho arch, truncated more deeply at the edges than in the center of the Tobosa basin, leaving a lens-shaped remnant of a once widespread deposit.

The sandstone members are the principal reservoirs for oil and gas. They are thin units extending for great distances between beds of shale and limestone, and each sandstone unit acts as a separate reservoir, containing oil, gas, and water in different proportions. These considerations suggest that the oil and gas being produced from Simpson strata originated within the Simpson group.

The total volume of Simpson rocks within the Permian Basin is about 6,000 cubic miles, of which about five per cent is sandstone, 55 per cent is shale, and the remainder is carbonate, principally limestone. Oil and gas production comes chiefly from structures on the Central Basin platform, in areas where the total thickness of sandstone members is nearly 100 feet or more. The amount of oil which has been found in strata of the Simpson group is estimated between 75 and 100 million barrels.

The gravity of the oil ranges from about 40° to 46°, and its sulfur content is low.

UPPER ORDOVICIAN

Like the Simpson group, the Montoya formation in the Permian Basin is a lens-shaped remnant of a once widespread deposit, its present outlines (Fig. 11) being probably the result of erosion after recurring uplift of the Pedernal massif and the Concho arch prior to Silurian time. It is a cherty carbonate deposit. Also as in the case of the Simpson group, the lithology of the Montoya formation exhibits no obvious nearshore facies; the only noncarbonate constituents, except chert, are

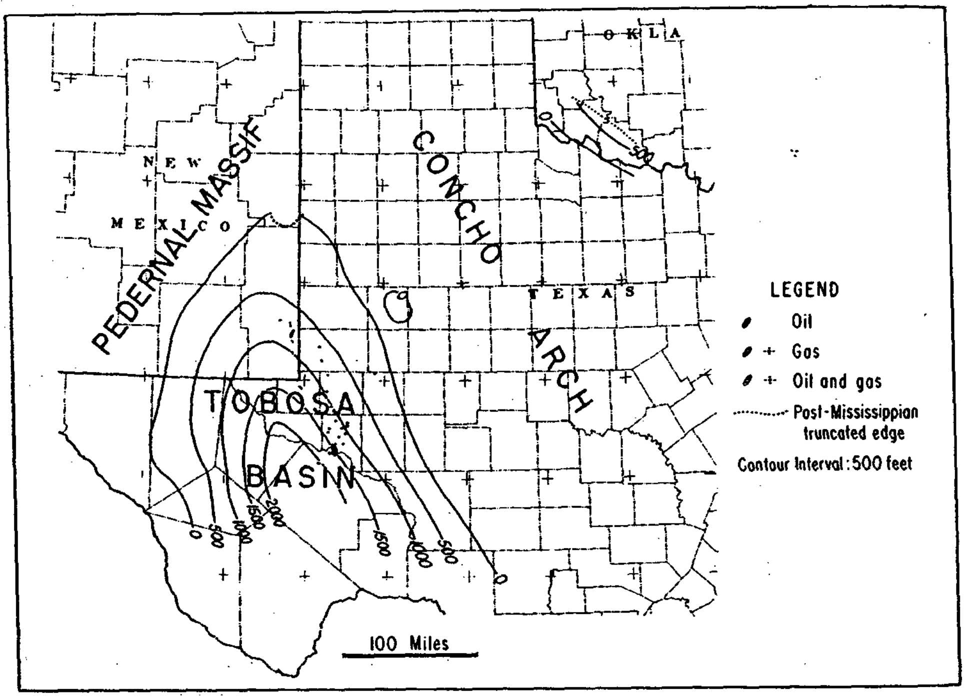

FIG. 9.—Thickness of the Simpson group (middle Ordovician) after pre-Montoya erosion. Early Paleozoic structural units are labelled.

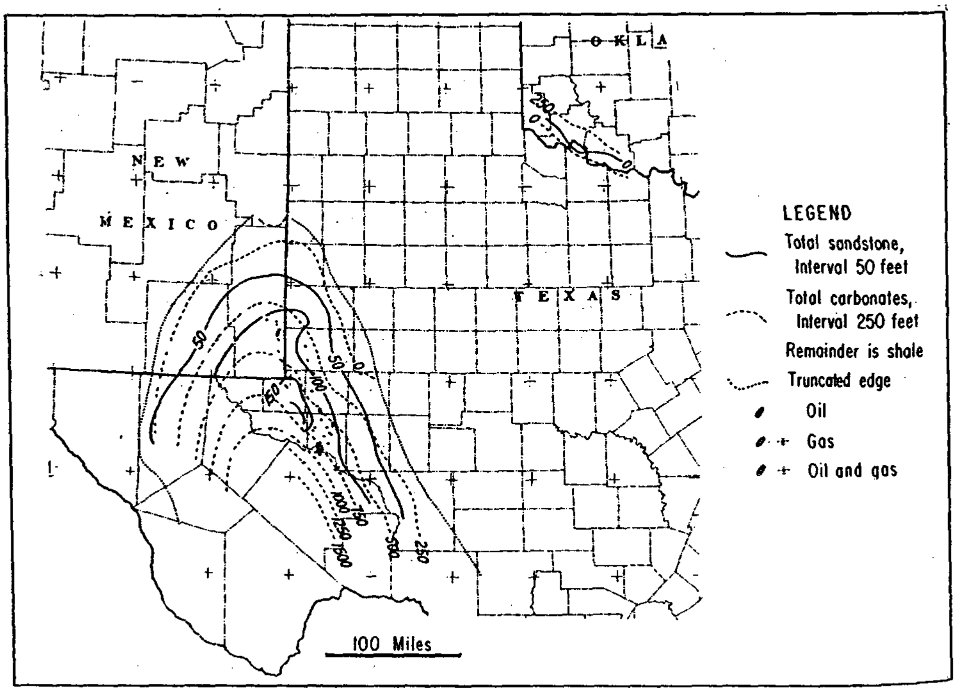

FIG. 10.—Thicknesses of the principal lithologic types in the Simpson group.

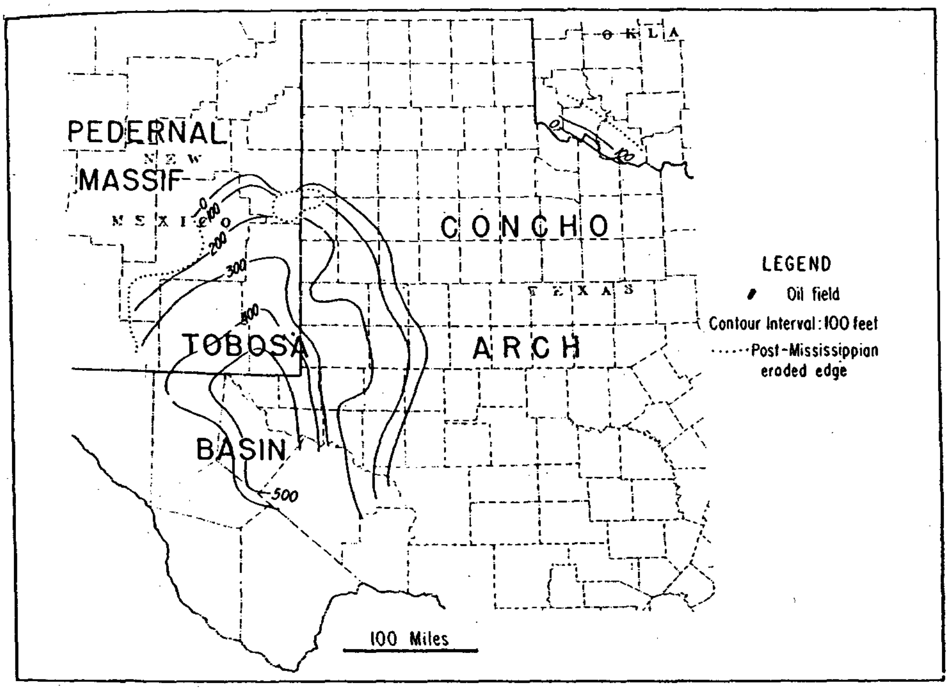

FIG. 11.—Thickness of the Montoya formation (upper Ordovician) after pre-Silurian and pre-Mississippian erosion. Early Paleozoic structural units are labelled.

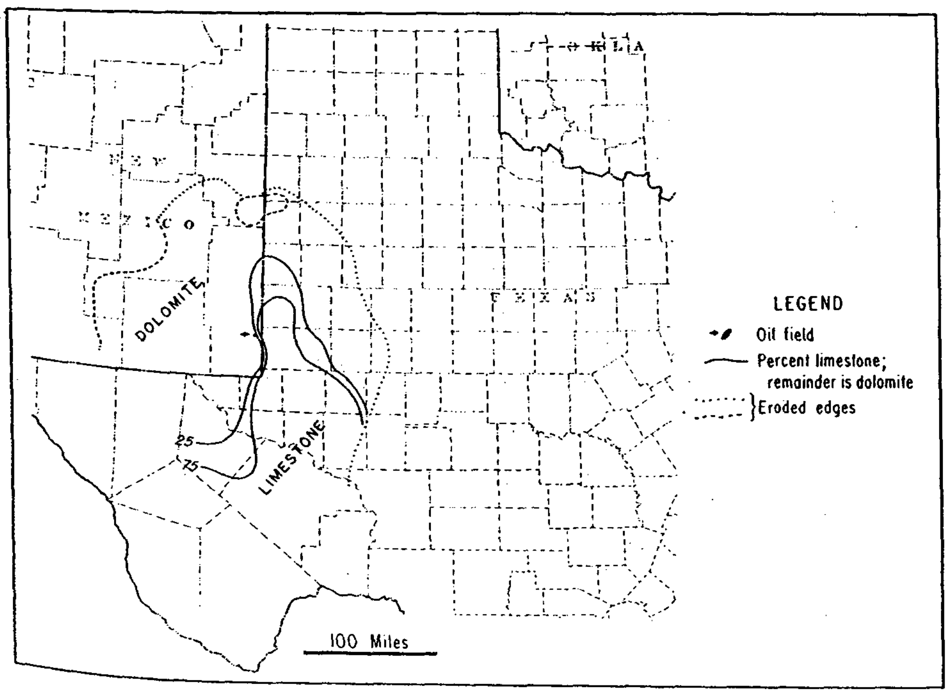

FIG. 12.—Limestone/dolomite proportions in the Montoya formation.

Simpson-derived quartz grains which are disseminated throughout the basal member. Some evidence for truncation around the edge may be seen in the thickness map (Fig. 11), which shows more abrupt thinning at the north and east edges than occurs nearer the center.

The presence of the ancestral Central Basin platform is suggested by the fact that Montoya strata thicken abruptly westward into the primordial Delaware basin at the west edge of a seemingly shelf-like area, but the position of the shelf does not coincide exactly with that of the Permian platform.

Reference to Figure 12 shows that the carbonate strata grade abruptly from limestone on the present Central Basin platform to dolomite in the Delaware basin, a relationship which occurs also in Siluro-Devonian strata and will be discussed under that heading. Abrupt termination of the dolomite-limestone boundary zone at the east edge of the area is also offered as evidence for truncation of the Montoya formation rather than depositional thinning.

Carbonates of the Montoya formation are generally finely crystalline and contain a fauna which indicates warm and shallow water during deposition, conditions over north-central and west Texas apparently having been similar to those which prevailed during deposition of the Ellenburger group. Southward lay a province of higher proportions of clastics, as shown by the lithology of strata in the Marathon folded belt. However, the original distance to this clastic province has been shortened by compression and thrusting, and it is not possible to illustrate the speculative original site on the accompanying maps (Figs. 11 and 12).

The total volume of Montoya strata in the Permian Basin is probably less than 2,000 cubic miles, and very little oil or gas production has yet been found in this formation. Because it consists of a unit of carbonate rocks underlying another unit (Silurian and Devonian) of similar lithology with an intervening stratum of impermeable rocks in restricted areas only, it is considered that there must be free movement of fluids across the plane of contact in many places as though the two carbonate units were a single reservoir. The limestone of the Montoya formation is essentially nonporous and apparently contains no fluids. In many places the dolomite has fair to good intercrystalline porosity but contains only water; any oil which may have been available to it has apparently moved upward into the overlying Silurian and Devonian dolomite.

SILURIAN AND DEVONIAN

Silurian and Devonian strata are treated here as a unit because they have not been separated or subdivided satisfactorily in much of the area in which they produce oil. Like the Simpson group and Montoya formation, they were reduced in volume to a lens-shaped remnant of a once widespread deposit by erosion and truncation prior to deposition of the next younger strata. The unit consists principally of cherty, medium to coarsely crystalline limestone and dolomite; small amounts of anhydrite have been seen in cores, but its distribution has not been studied.

Examination of the thickness map (Fig. 13) reveals, in addition to the lens-like shape of the unit, an area of thin interval at the southeast corner of New Mexico, at a position which offers evidence that at least a portion of the Central Basin platform was positive between Ordovician and Mississippian time. Likewise, an area of thin interval to the southwest suggests positive movements on or near the Diablo platform; data are insufficient to outline the area clearly. Also apparent is the continuing positive character of the Pedernal massif and the Concho arch, which form part of the rims of the Tobosa basin.

The map of limestone-dolomite proportions (Fig. 14) offers further evidence of a distinction between the areas of the Delaware basin and the Central Basin platform, for, as was observed also on the equivalent Montoya map (Fig. 12), much of the area of the present Central Basin platform is occupied chiefly by limestone, and the Delaware basin is predominantly dolomite.[11] There is striking contrast between the patterns of distribution in these early Paleozoic carbonates and those of Permian age (Figs. 26 and 31) wherein dolomite occupies the platform areas and limestone the basins, and the problem of explaining the difference is baffling. If the origins of the dolomite are similar, then the present basin areas were platforms or shelves from late Ordovician to late Devonian times, and the ancestral Central Basin platform had foundered and was the deepest part of the sea floor during deposition of the carbonates. Prior to Silurian time, however, and also after deposition of the youngest Devonian carbonate, parts of the area of the Central Basin platform seem to have been uplifted relative to the adjacent Delaware basin. If the thicker carbonates were the result of reef-like deposition on a marine shelf, one would expect to find evidence of relief on the upper surface, but such is not the case. Some of the many factors about which we know too little, but which may have been influential in producing the observed result, are time of dolomitization, natures of the original carbonates in the two areas, paleostructure controlling the movements of groundwaters at various times, possible intrasystemic unconformities, and environmental conditions of water depth, temperature, and others.

Figure 14 also provides evidence for post-Devonian truncation of the unit, by the termination of isolith contour lines against the zero-thickness line. Figure 15, showing the proportions of chert in the unit, adds possible evidence for truncation, particularly in conjunction with Figure 13, because, where the unit is thickest, the greatest concentration of chert is in the upper parts. Similarity in location of the 75-per cent contour line in Figure 14 and the 25-per cent contour line in Figure 15 have led to the suggestion that the cherty limestone in the south part of the Tobosa basin may be a younger formation which is absent farther north because of erosion, but solution of the problem of erosion *versus* lateral facies gradation in accounting for the transition in overall rock types from south to north awaits careful study of stratigraphic subdivisions within the Silurian-Devonian unit.

Environmental conditions during the Silurian and Devonian Periods must have been somewhat inconstant. During at least a portion of Silurian time the west Texas area was at the north edge of a clastic province, with the result that in the

[11] Distinctions between limestone and dolomite reported throughout this paper were based on conventional binocular microscopic examinations of cuttings using cold dilute hydrochloric acid as a test, not on precise chemical or petrographic analyses.

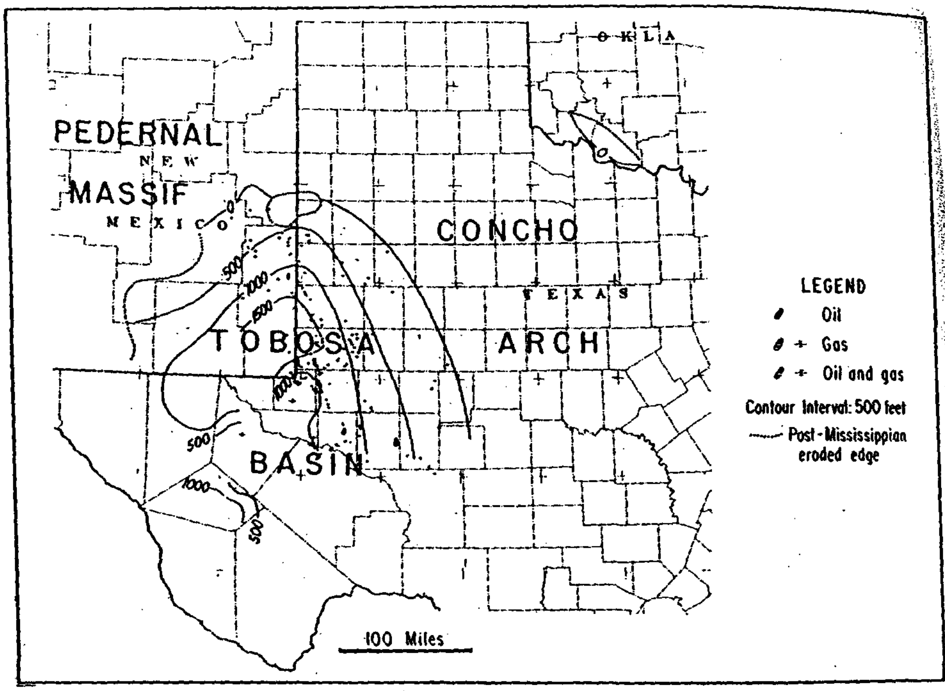

FIG. 13.—Thickness of the Silurian and Devonian Systems after pre-Mississippian erosion. Persistent early Paleozoic structural units are labelled.

more southerly counties the limestone is argillaceous and contains thin shale interbeds. During most of the remaining time, however, the water was clear, and conditions probably did not favor the preservation or slow decay of animal matter. In the limestone province, the uppermost Devonian carbonates are very cherty. At an unknown distance to the south was deposited the novaculite of Devonian and perhaps early Mississippian age which is now found exposed in parts of the Marathon folded belt.

Oil- and gas-reservoir strata within the unit of Silurian and Devonian carbonates occur at various levels in areas of interstratified limestone and dolomite members, and each reservoir has its own set of oil-water relationships. In such areas oil accumulations may be found in porous strata below other porous zones containing water. However, the lateral extent of separate reservoir strata does not appear to be great, and the degree of isolation of each from the others throughout the entire producing area is not discernible. This is particularly true at the northwest in the thick sequence of dolomite strata of monotonous uniformity in which no subdivisions have been recognized. Where such uniform lithology exists the entire Silurian-Devonian unit acts as a single reservoir, much like the Ellenburger dolomite, oil and gas occurring in the highest porous zone but no oil being found below a water-bearing reservoir. Porosity in both limestone and dolomite is dependent chiefly on vugs and intercrystalline spaces; some reservoirs in chert or in very cherty or siliceous carbonates apparently owe their porosity to the action of formation waters which have dissolved the carbonate constituents of the rock.

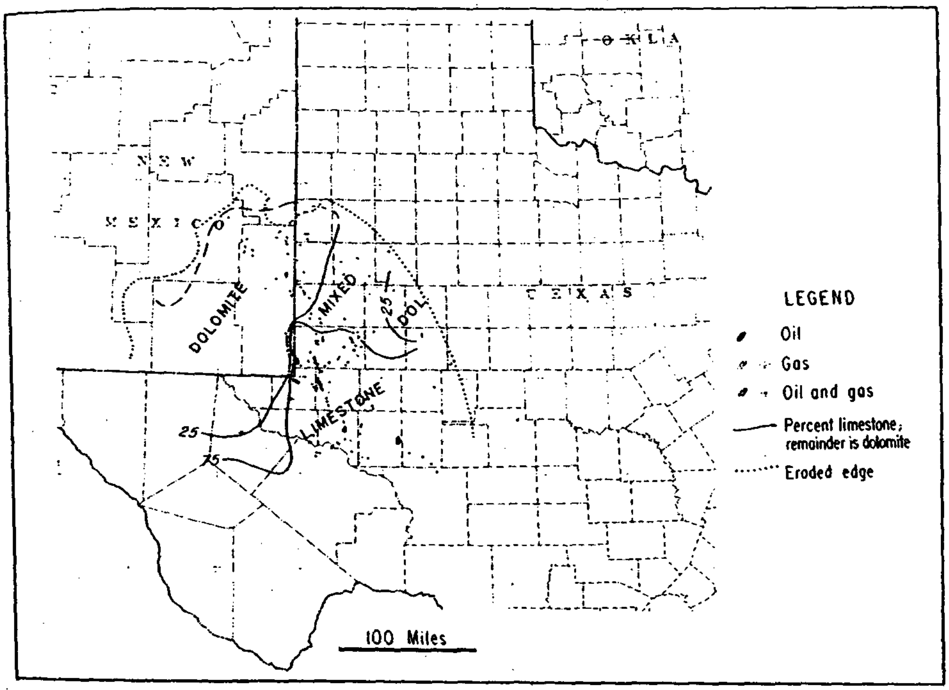

FIG. 14.—Limestone/dolomite proportions in carbonates of the Silurian and Devonian Systems.

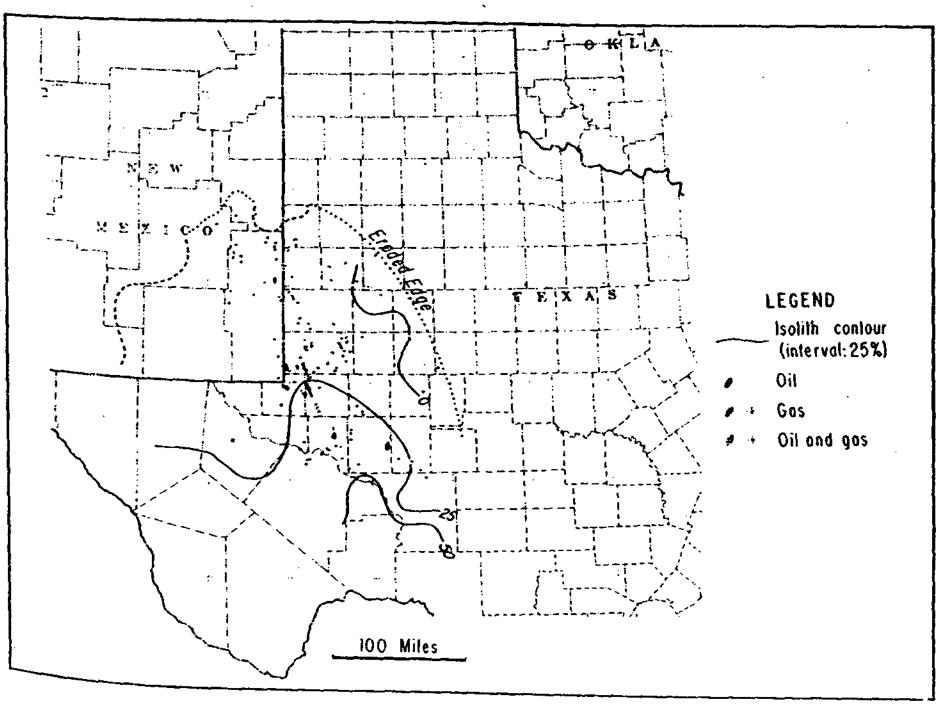

FIG. 15.—Per cent chert in the Silurian and Devonian Systems.

The source of the oil is somewhat difficult to determine from considerations of gross lithology and stratigraphic relations. In areas where the entire unit is dolomite, and oil occurs in the highest porous zone below the uppermost unconformity, sources in the overlying Woodford shale and perhaps also in the Simpson group which underlies the entire Montoya-Silurian-Devonian carbonate sequence are suggested. Where separate reservoirs exist, three possible sources are present.

1. Small amounts of shale and argillaceous material associated with the lower carbonate beds in southern areas suggest conditions favoring conversion of organic matter to hydrocarbons during deposition of these older sediments.
2. Gray-green shale, questionably of upper Ordovician age (Sylvan?), occurs locally in thicknesses generally less than 50 feet over an area of about a dozen counties on the east flank of the Tobosa basin, lying between Montoya and Siluro-Devonian strata.
3. There may have been channels of migration from Woodford and Simpson strata *via* the uniform dolomite sequence in the basin areas. Oil arriving by this route would displace formation water in different amounts in different reservoir strata, depending on the volume of flow through different parts of the dolomite facies.

Finally, as in the case of the Ellenburger group, there remains the conjecture that oil in Silurian and Devonian carbonate reservoirs, if not indigenous or derived from immediately adjacent argillaceous strata, migrated from source beds in a postulated clastic basin to the south before the occurrence of the Marathon orogeny.

Gravity of the oil in the Silurian-Devonian reservoirs extends through a wide range from about 32° to 60°, and the sulfur content is low; however, the pattern of distribution of various grades is irregular and offers no obvious clue to the source.

The total volume of oil found to the present date in Silurian and Devonian strata is close to ¾ billion barrels, although the volume of rock in these systems is only about 5,500 cubic miles, making the Silurian-Devonian strata appear to be more prolific than the Ellenburger dolomite in terms of unit volumes (Fig. 1). Local accumulations are found mainly in anticlinal traps, more than half of the total production being obtained from fields on the Central Basin platform, and the remainder chiefly in the Midland basin and north end of the Delaware basin.

PRE-MISSISSIPPIAN UNCONFORMITY

In late Devonian time widespread uplift and erosion created a surface of unconformity across the Permian Basin area, and the areal geology of that surface (Fig. 16) clearly reveals the position of the Concho arch, at the northwest end of which Precambrian rocks were exposed; Ordovician, Silurian, and Devonian strata cropped out on the northeast and southwest flanks. The Tobosa basin also is evident in the pattern of pre-Woodford outcrops.

MISSISSIPPIAN

Over the late Devonian erosion surface the next marine invasion spread a sequence of dark shale and limestone of rich organic content. As in Cambrian and lower Ordovician time, the transgressing sea deposited first a clastic unit and then carbonate sediments. The first is a body of black shale, commonly described as "bituminous," which has been correlated with the Woodford chert of Oklahoma; it contains disseminated pyrite crystals and detrital grains of various materials, and, locally at its base, a thin and patchy zone of sandstone. In northern areas it contains

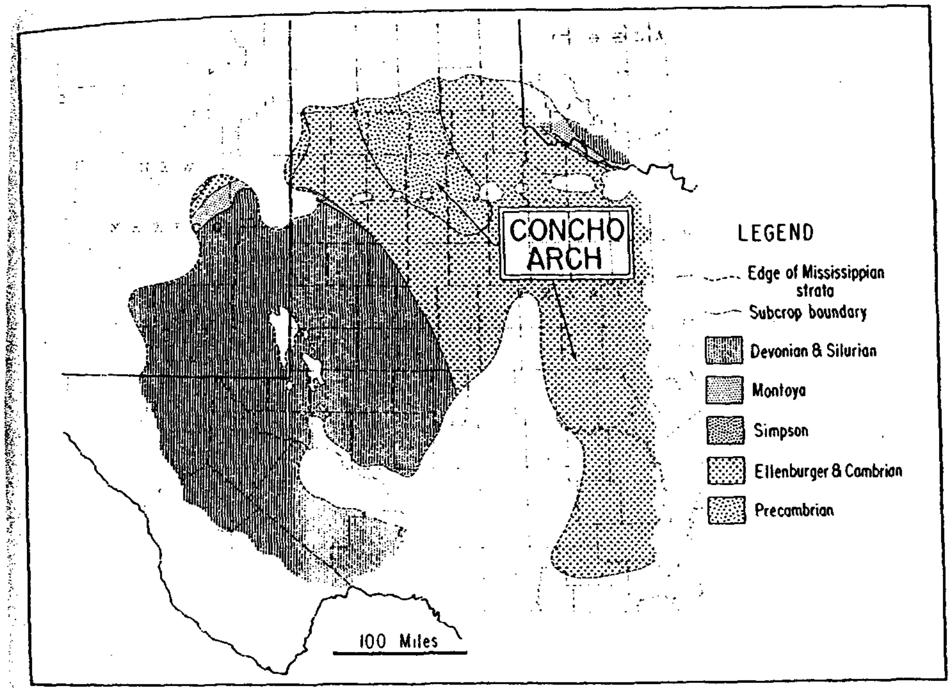

FIG. 16.—Pre-Woodford paleogeology. The map shows the age and distribution of strata immediately underlying Woodford shale and Mississippian limestone. The Concho arch is a prominent pre-Mississippian uplift.

thin interbedded siltstone and sandstone members, and at the edges it grades into a fine-grained sandstone facies of irregular distribution which the author considers to be the nearshore facies of the Woodford shale (Fig. 17). This is the earliest Paleozoic shore line which has not been removed by subsequent erosion, within the area of the Permian Basin, and its semicircular or embayment-like shape indicates the submergence of the Tobosa basin prior to later deposition across the Concho arch. However, there was contemporaneous deposition of Woodford shale northeast of the Concho arch, and probably around its southeast end as well. Deposition began in late Devonian time and, as the sea transgressed across the area, probably continued into early Mississippian. The Woodford shale, which is the product of a stagnant marine basin (Ellison, 1950, p. 15) and has an estimated present volume of about 1,300 cubic miles in the Permian Basin, is considered by many geologists, including the present author, to be a good source bed.

The remainder of the Mississippian System consists of generally finely crystalline nonporous limestone ranging from pure calcitic limestone to argillaceous and silty or to siliceous and cherty limestone in various places, interbedded with and overlain by dark-gray or brown shale. The clastic content increases generally southward, toward the clastic basin which apparently continued to exist in front of the hypothetical landmass of Llanoria.

In north-central Texas, high on the east flank of the Midland basin, the lime-

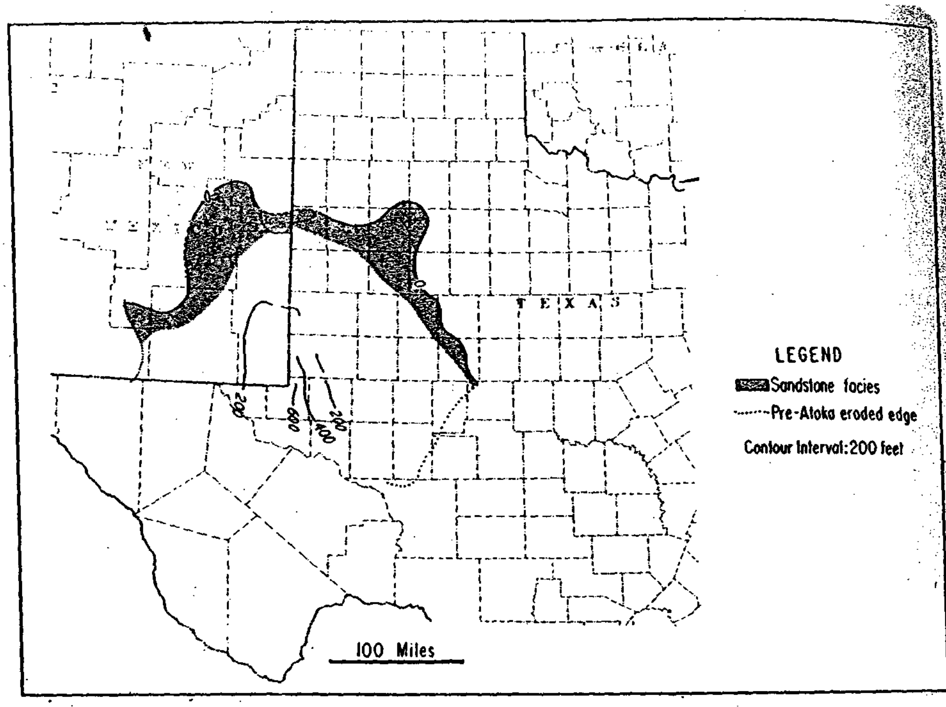

FIG. 17.—Thickness and lithofacies of the Woodford shale (Devonian-Mississippian). The shaded portion represents the approximate area of nearshore facies which are predominantly sandstone and siltstone; thinner interbeds of similar lithology extend into the unshaded area. The zero line is the position of the shoreline.

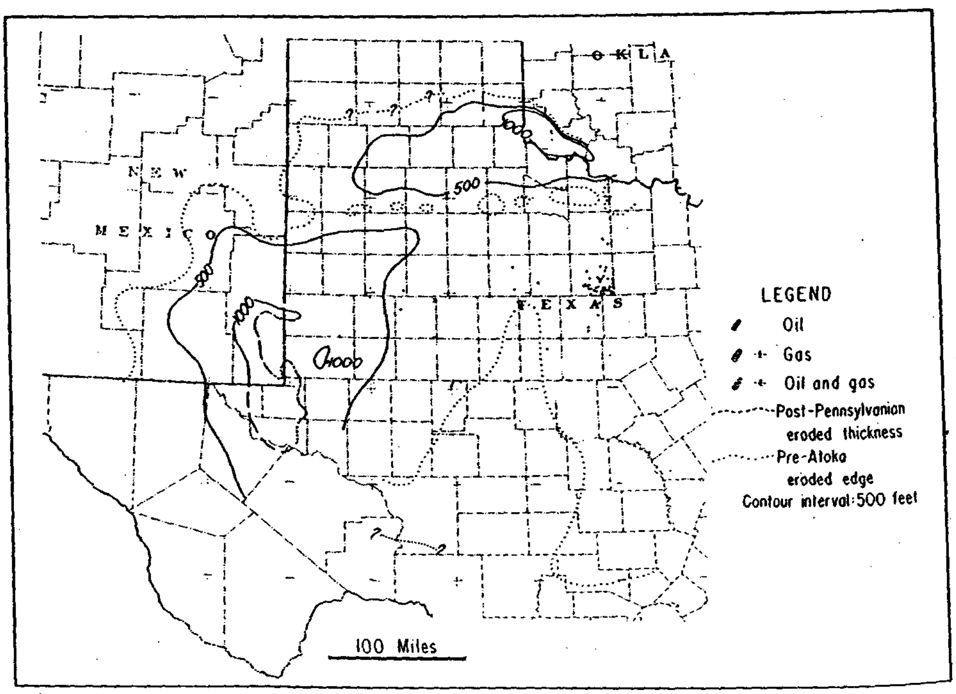

FIG. 18.—Thickness of Mississippian System after pre-Pennsylvanian erosion. The mapped interval includes Woodford shale, part of which is probably upper Devonian in age.

stone in places is crinoidal, coarsely crystalline, and porous, and is an oil reservoir of local importance; irregularly distributed porous beds produce also in a few places in the Midland basin and on the Central Basin platform. Generally, however, despite the organic richness of its dark shale and argillaceous limestone which gives them the outward aspects of source beds, the Missisipian System produces little oil or gas. Its minor role in oil production must be attributed to low permeability, for it generally yields little water when tested. Like the oil in pre-Mississippian reservoirs, the Mississippian oil is generally sweet; that is, it contains relatively small amounts of sulfur. Recorded gravities range from 34° to 44° in most fields; a few are higher.

The dark shale which overlies the Mississippian limestone has a lithologic character so nearly like that of lower Pennsylvanian shale that the position of the time boundary is obscure.

The stratigraphic interval mapped in Figure 18 extends from the base of the Woodford shale to the approximate position of the Mississippian-Pennsylvanian boundary. It is an eroded interval, within which lithologic correlations provide some evidence that original thicknesses were greatest in the center of the Tobosa basin, but minor uplift of portions of the later Central Basin platform in late Mississippian or early Pennsylvanian time is indicated by present thin areas in the center of the basin. The total volume of rocks in this interval is estimated to be about 6,000 cubic miles. The shore lines of the Mississippian sea were beyond the present limits of distribution of Mississippian beds in the Permian Basin.

PRE-PENNSYLVANIAN UNCONFORMITY

Toward the close of Mississippian time some orogenies which were the principal environmental controls of the Permian Basin area throughout the Pennsylvanian Period were initiated, and widespread withdrawals of the sea produced a broad surface of erosion in which can be seen some of the principal orogenic elements and upwarps (Fig. 19). To the south and east the mountainous lands of the Marathon and Ouachita folded belts were rising, most of their erosional debris being trapped in adjacent sinking troughs which were beyond the limits of the area with which we now are concerned. It is the writer's belief that the pear-shaped area in the southeast part of the Permian Basin from which Mississippian strata have been removed (Figs. 18 and 19) is a portion of the Concho arch which was tilted northward at the initiation of the Marathon orogeny, thus becoming exposed to denudation.

Extending eastward across the south edge of the map is an area of pre-Mississippian subcrops outlining a large anticlinal structure which merges with the north-plunging pear-shaped area of erosion on the Concho arch. The eastward-trending anticline was uplifted at some time after Mississippian limestone deposition and prior to deposition of Atoka sediments, and is the structure to which the author has applied the name *Pecos arch.*

In some portions of the later Central Basin platform from which Pennsylvanian strata have not been completely removed, thinning of the Mississippian System by

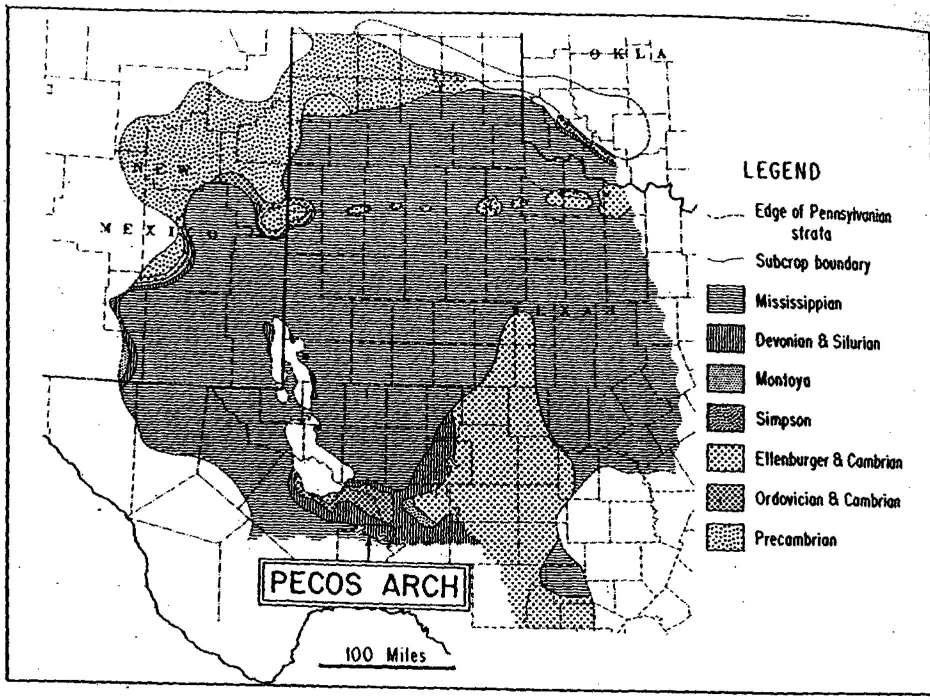

FIG. 19.—Pre-Pennsylvanian paleogeology. The map shows the age and distribution of rocks immediately underlying Morrow or Atoka strata. The position of the Pecos arch is clearly shown, except at the west end where Pennsylvanian strata are absent.

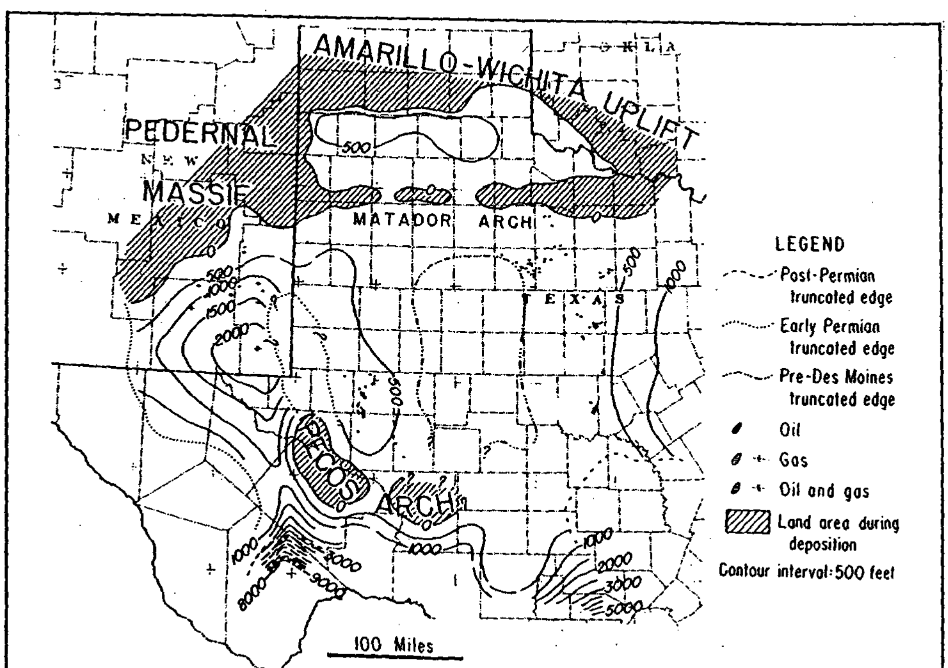

FIG. 20.—Pre-Des Moines thickness of Morrow and Atoka Series. Late-Mississippian–early-Pennsylvanian uplifts were land areas.

loss of beds at the top provides evidence of local uplifts prior to or during early Pennsylvanian deposition, but evidence is lacking to show general uplift of the entire platform area.

Areas of erosion indicated across the north part of the paleogeologic map are the result of orogenies which reached their climax at the end of Morrow time (early Pennsylvanian) and created the Amarillo-Wichita mountain system and the smaller Matador mountain system, and which rejuvenated the ancient Pedernal massif.

PENNSYLVANIAN

The Pennsylvanian sedimentary environment of the Permian Basin was characterized by an expanding sea in an intracratonic basin whose borderlands were mountainous land masses. Enormous volumes of detritus were dumped into the sedimentary catchment basin, but portions of the sea more remote from shore remained relatively free of clastics and accumulated large thicknesses of carbonate rocks. In the zones of gradation between clastics and carbonates the two types of rocks interfingered, and pulsatory crustal movements gave rise to cyclic sequences of deposition. These relationships established a sedimentary environment which produced strata of many lithologic facies, standing in strong contrast to the entire pre-Pennsylvanian history of uniform sedimentation across broad shelves having little apparent relief.

Lower Pennsylvanian (pre-Des Moines).—Because of similarities in the lithology of upper Mississippian and lower Pennsylvanian (pre-Des Moines) shale strata, the recognition of each, and their subdivision into correlatable units, have been difficult. Accordingly, the exact ages and outlines of some of the structural features formed during the time interval represented by these strata are subject to debate and revision (Fig. 20). It is not known, for example, how much thickness of rock above Mississippian limestone in the subsurface may be assigned to the Morrow Series, or what is the extent of Morrow strata. However, from regional information it is known that the principal uplift of the Amarillo-Wichita mountain system and the Matador alignment of smaller mountains occurred at the close of Morrow time (Van der Gracht, 1931, pp. 1010–11); succeeding Atoka strata contain coarse clastics derived from these areas and from the Pedernal massif, which were the principal provenance areas for clastic sediments in the north and west margins of the basin throughout Pennsylvanian time.

The greatest of the Pennsylvanian borderlands, in area and in topographic relief, undoubtedly was the Marathon-Ouachita element at the east and south rims of the basin. As the mountains rose by the action of strongly compressive forces, a narrow depositional trough sank rapidly in front of them, the waste of denudation being deposited in the trough and overflowing across the more stable sea bottom beyond. Continually reactivated forces deepened and compressed the trough and crowded it northwestward against the stable platform of the foreland as the mountains continued to rise, with the result that the thickest deposits of successively younger stratigraphic units are found at locations progressively northward in front of the Marathon belt and westward in front of the Ouachita belt. This history extended from earliest Pennsylvanian time through early Permian time and is illustrated for the area of the Permian Basin by comparing the positions of the Marathon trough on Figures 20, 21, and 24.

Atoka strata consist predominantly of dark shale, argillaceous limestone, and fine- to coarse-grained sandstone. Apparently the Marathon-Ouachita shoreline lay

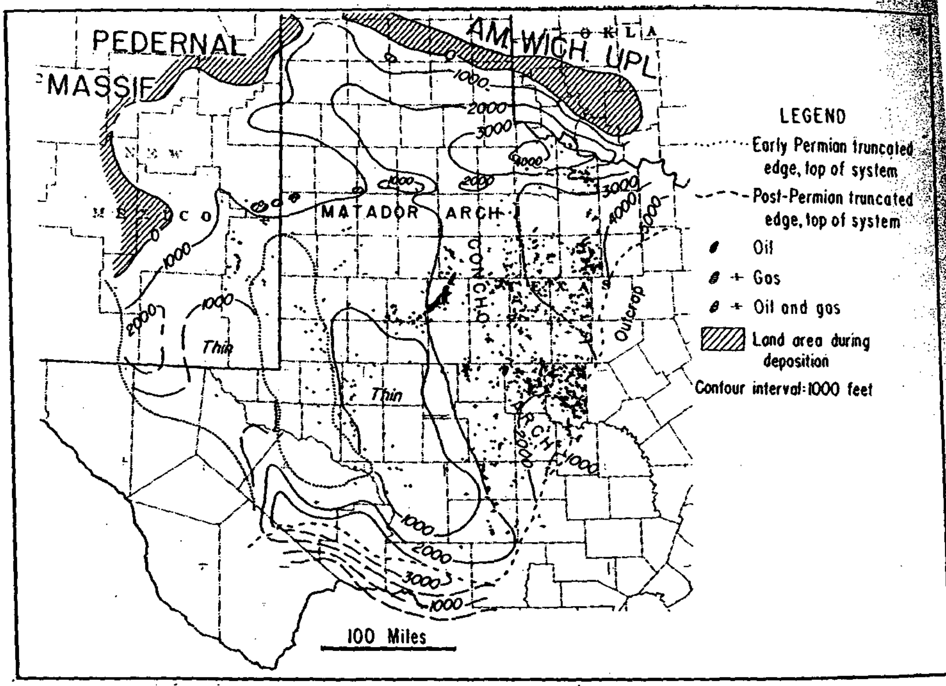

FIG. 21.—Pre-Permian thickness of Des Moines, Missouri, and Virgil Series. Principal land areas and submerged positive elements of upper Pennsylvanian time are labelled, except the Marathon-Ouachita folded belt and possible uplifts in the Diablo platform and Central Basin platform areas.

at some distance from the site of deposition, and the capacity of the intervening depositional trough was sufficient to accommodate most of the debris from that province.

The area of the Concho arch was still positive and received only a thin veneer of sediments prior to withdrawal of the Atoka sea, except at the north end where greater thicknesses were deposited in the newly formed Palo Duro basin between the rising Amarillo mountains and the archipelago of islands along the Matador arch. The Pecos arch and the northern highlands either were not completely covered or were exhumed during the period of erosion which followed Atoka sedimentation; the extent of land areas at this time is difficult to determine. The Central Basin platform probably was a relatively small positive area, and a basin lay in the present position of the Delaware basin, receiving sediments from the Pedernal massif and perhaps from an exposed Diablo platform, as well as influx from the Marathon trough.

The dark shale and argillaceous limestone of the Atoka Series are judged to have been source beds of petroleum, and enough porosity is found in some of the limestone strata as well as in coarse clastics to provide reservoirs for commercially attractive accumulations of petroleum; the total amount of discovered oil is more than 200 million barrels. Most of the production comes from limestone strata on

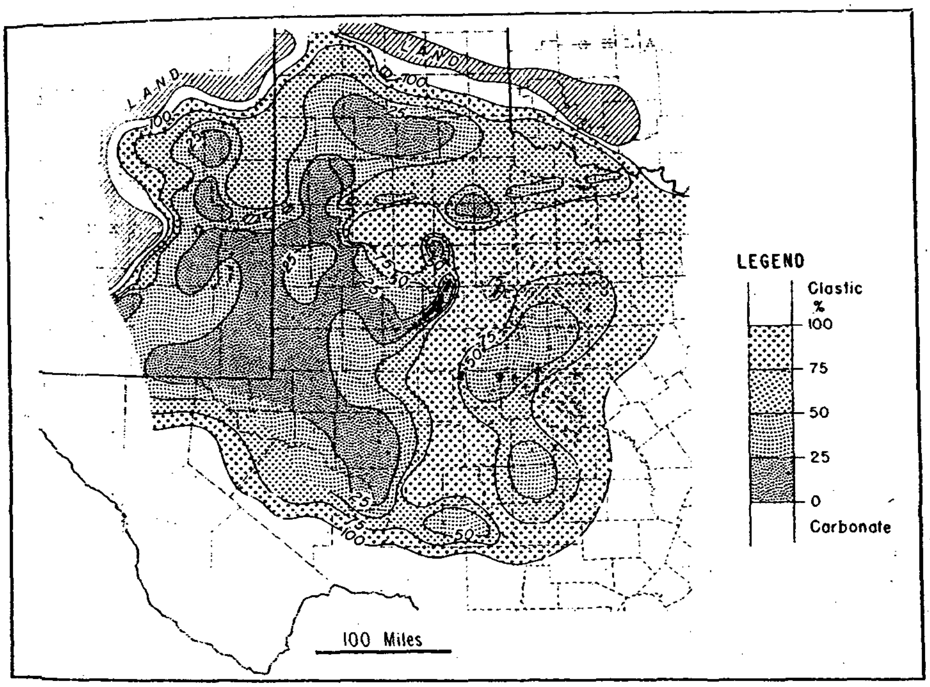

FIG. 22.—Per cent of clastic rocks in Des Moines, Missouri, and Virgil Series. The distribution pattern suggests that the principal source areas lay to the east.

anticlinal structures in the western parts of the Midland basin; a minor portion has been developed in coarse clastic strata high on the east flank of the basin, in structural and stratigraphic traps. The oil has a low sulfur content, and the gravity is generally in a range from 30° to 47°.

Gas fields are located principally in the Delaware basin and at the extreme east edge of the Midland basin.

Upper Pennsylvanian (Des Moines, Missouri, Virgil).—The post-Atoka unconformity surface was covered by sediments of the Des Moines Series, and the remainder of Pennsylvanian time is recorded by almost continuous deposition, the only breaks being chiefly of local significance. The Marathon and Ouachita troughs were filled to overflowing, and the excess of clastic material flooded half of the area of the Pennsylvanian basin; in comparison, the quantities furnished by the land areas of the foreland were minor (Figs. 21 and 22). Upper Pennsylvanian sediments were deposited in onlap relationship against the foreland prominences; the highest parts of the Pecos arch and Amarillo mountains were not covered until after early Permian time, the Matador archipelago was completely submerged by Virgil sediments, and the Pedernal massif remained as a shrinking land area of low topographic relief. The Concho arch was a positive area of low relief and relatively thin total strata, extending north-northwestward across the basin.

A suggestion of an anomaly at the location of the later Central Basin platform is indicated where remnants of upper Pennsylvanian strata thicker than 1,000 feet exist within the area of early Permian erosion; eroded thicknesses have not been contoured in Figure 21. In large areas of the Midland basin and Delaware basin the thicknesses are less than 500 feet, and much of the recognizable Pennsylvanian rock is limestone of Des Moines age; the Missouri and Virgil strata are extremely thin. Observation of these conditions led to the hypothesis of the "starved basin" by Adams and associates (1951).

The broad shelf-like area lying east of the Midland "starved basin" was called the "Concho platform" by Adams *et al.* (1951, Fig. 3); later Cheney and Goss (1952, pp. 2251–52) proposed a southeast boundary of the platform where lower Des Moines limestone grades southeastward into clastics, and described the platform as "a large region which was favorable to biostromal and biohermal developments." Thus the Concho platform, the position of which was determined by the continuing positive character of part of the Concho arch, was, in effect, the relatively stable mass which formed the northwest flank of the central Texas portion of the Marathon-Ouachita trough of clastic deposition. The excess clastic material was spread over the platform by intermittent stages, becoming interbedded with carbonates during periods of quiescence, but failing to reach the Midland "starved basin" in quantity.

Upper Pennsylvanian strata of the Permian Basin consist principally of dark- to light-gray shale, fine- to medium-grained sandstone, and light-colored limestone; dolomite is uncommon; coarse clastics occur in some areas which were adjacent to exposed land surfaces. Domal limestone masses of various sizes and outlines, either completely enclosed in shale or more commonly standing on an older limestone formation as a base, are irregularly distributed through platform areas of mixed carbonate and clastic facies. They are generally considered to be limestone reefs, but the enclosed organic remains in most cases are not those of colonial forms. Some of the masses were erected over shoals, as along the Matador alignment (Fig. 22); in other instances no evidence of local elevation of the floor is apparent. Studies of the Scurry reef by Rothrock *et al.* (1953) and by Bergenback and Terriere (1953) indicate that the reef limestone in that body is composed of organic debris bonded by crystalline calcite and by lithified lime mud.

In general the sea was probably shallow and warm except in the "starved" basins. Marine currents distributed the clastics to their sites of final deposition and in doing so regulated the mechanism or the organic activity by which carbonate masses were developed. The largest area of predominantly carbonate rocks is in the west part of the basin, well removed from the Marathon and Ouachita fronts (Fig. 22); the Scurry reef is shown as a curved finger extending northeastward and northward from the main carbonate area. It is important to note that the "starved" basins are carbonate areas by virtue of extremely thin clastic intervals rather than thick carbonate masses.

Oil production in upper Pennsylvanian strata is obtained principally from three types of traps—1. Anticlinal structures in porous reservoir strata, either limestone or sandstone; 2. Porous zones in limestone reefs; and 3. Lithologic or stratigraphic wedge edges of porous strata, either sandstone or limestone.

The oil from upper Pennsylvanian reservoirs is like that from Atoka strata, in the respect that it is sweet oil in most of the fields and has a gravity of 30° to 47°. There is no discernible pattern in the distribution of various gravities from field to field; even fields in gas-producing areas show no distinctive tendencies to either high or low gravities.

Of the estimated 3 billion barrels of oil which has been found in more than 30,000 cubic miles of upper Pennsylvanian strata, one third is expected to be produced from the Scurry reef.

The simple fact that the reservoirs in the Pennsylvanian System are isolated and separate from one another and from sources outside of the system, each having its own set of fluid and pressure levels, appears to be ample evidence that the oil is indigenous to the system. Bituminous shale is common throughout.

Most of the Pennsylvanian gas production is found in the southern and eastern parts of the Permian Basin and on the adjoining Bend arch, in localities which also have concentrations of Atoka gas fields, leading to the speculation that the Marathon and Ouachita troughs were the provinces in which conditions favored the generation of gaseous hydrocarbons.

PRE-PERMIAN UNCONFORMITY

At the close of the Pennsylvanian Period occurred the principal uplift of two subparallel features which had been intermittently but moderately positive throughout earlier Paleozoic time, the Central Basin platform and the Diablo platform (Fig. 23). The intervening Delaware basin was thereby accentuated in negative relief, and the Midland basin for the first time became clearly evident; the Delaware basin, however, remained the center of further subsidence. The area involved in the uplift of the Central Basin platform included the west part of the earlier Pecos arch and the Fort Stockton high, but the east part of the Pecos arch remained quiescent and retained its cover of upper Pennsylvanian strata, except locally. The entire extent of the Diablo platform is not yet known, but it seems perhaps to have overreached the south end of the Pedernal massif. The two new uplifts completed the framework which set the stage for all the events of Permian time.

PERMIAN

The theater of Permian sedimentation was a subsiding intracratonic basin without rising borderlands, in which occurred conspicuous carbonate build-ups on marginal platforms and contemporary deposition of fine clastics in adjacent lows, and finally the deposition of large amounts of evaporites in the shrinking sea.

The influence of the early Paleozoic Tobosa basin clearly persisted into Permian time, for the sites of the carbonate platforms, other than the Central Basin platform, appear to have been predetermined by the locations of the positive elements bounding the Tobosa basin, although admittedly the coincidences of location are not exact. The thicknesses and distribution of various rock types give evidence of the old tectonic control.

The accompanying series of thickness and facies maps (Figs. 24–49) portrays the development of contrasting environments as the separate sedimentary provinces grew into sharp focus.

Wolfcamp Series.—Except on the Central Basin platform and Diablo platform, and perhaps on some local structures, sedimentation appears to have been continuous across the Pennsylvanian-Permian time boundary. Conglomerates are not present in the basins, and they are irregularly distributed on the platforms, despite the fact that parts of the highs remained exposed until Leonard time. The Marathon trough and the Delaware basin together developed into a deep narrow basin in which Wolfcamp sediments are probably more than 8,000 feet thick (Fig. 24). The Midland basin opened at the south, like an embayment of the Marathon trough.

A few of the reefs which have their roots in Pennsylvanian strata ascend into Wolfcamp beds, but their collective volume is small. Likewise in overall facies types, the Wolfcamp Series is transitional between uppermost Pennsylvanian and middle Permian strata, partaking to some extent of the characteristics of each.

Environments of carbonate deposition predominated on the platform areas, and clastics accumulated in the basins (Fig. 25); the platforms included the Diablo platform, the Central Basin platform, and an area along the west side of the former Concho arch to which the name "Eastern shelf" is commonly applied. A vague and sprawling area across the north part of the Midland and Delaware basins also was a carbonate area; as it developed in later Permian time it became more sharply defined and is known as the "Northern shelf" or "Northwestern shelf."

Like those of Ordovician, Silurian, and Devonian strata, but unlike Mississippian and Pennsylvanian, the Wolfcamp and other Permian carbonates contain large proportions of dolomite (Fig. 26), but in contradistinction to the early Paleozoic patterns the Permian dolomites occupy platform areas and the thin basinal carbonate layers are limestone. The Wolfcamp limestones therefore are interbedded with basinal clastics, in which the proportions of sandstone and siltstone are high; the predominant clastics in association with dolomites in the platform areas are shale (Fig. 27). The Wolfcamp Series is essentially free of evaporites excepting small quantities on the east flank of the Midland basin (Fig. 28).

With two exceptions the distribution of known oil accumulations in Wolfcamp rocks is similar to that of the upper Pennsylvanian, the exceptions being—1. The fewer large oil fields in limestone reefs; and 2. The much smaller producing province on the east flank of the Midland basin, approaching the Bend arch. The accumulations occur principally in anticlinal structures and stratigraphic traps like those of the upper Pennsylvanian strata.

The range of gravity of Wolfcamp oil is generally from 33° to 44°, more restricted than that of Pennsylvanian oil, and in most cases the oil is sweet. Most of the gas fields are on the east edge of the Midland basin, the area of concentration being approximately coincident with that of Pennsylvanian gas fields.

By the same reasoning as that applied to the Pennsylvanian System, it is concluded that the oil in Wolfcamp reservoirs was derived from adjacent beds in the

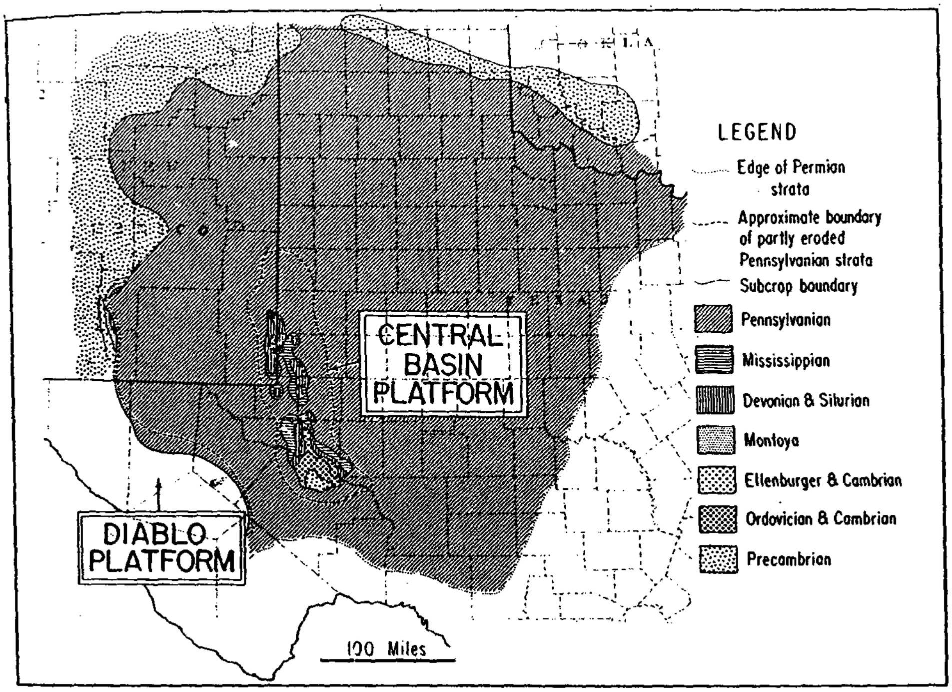

FIG. 23.—Pre-Permian paleogeology. The map shows the age and distribution of rocks immediately underlying Wolfcamp strata (or Leonard, in a few places). The outline of the Central Basin platform, distinct from that of the Pecos arch (Fig. 19), is indicated by the approximate extent of the area in which uppermost Pennsylvanian rocks were eroded prior to Permian deposition.

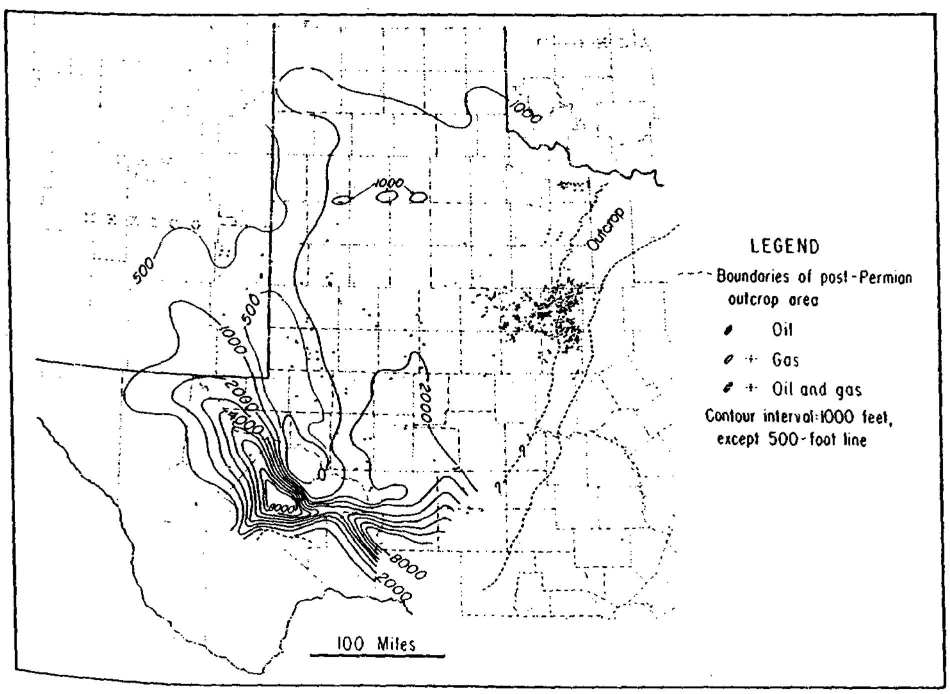

FIG. 24.—Thickness of the Wolfcamp Series.

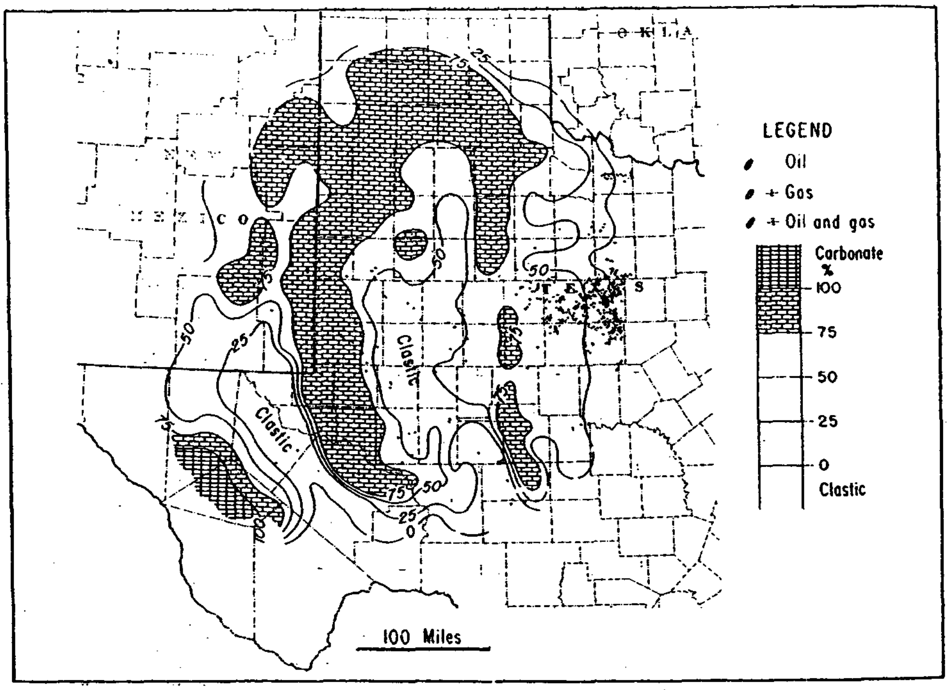

Fig. 25.—Per cent of carbonate rocks in the Wolfcamp Series; the remainder are predominantly clastic (see Fig. 28).

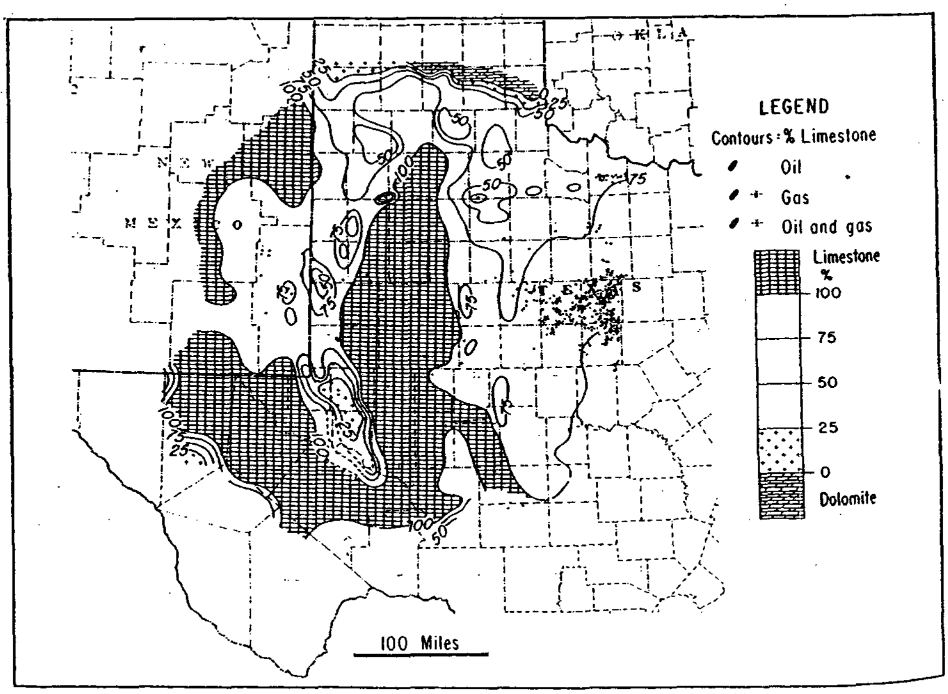

Fig. 26.—Per cent of limestone in carbonate rocks of the Wolfcamp Series; the remainder is dolomite.

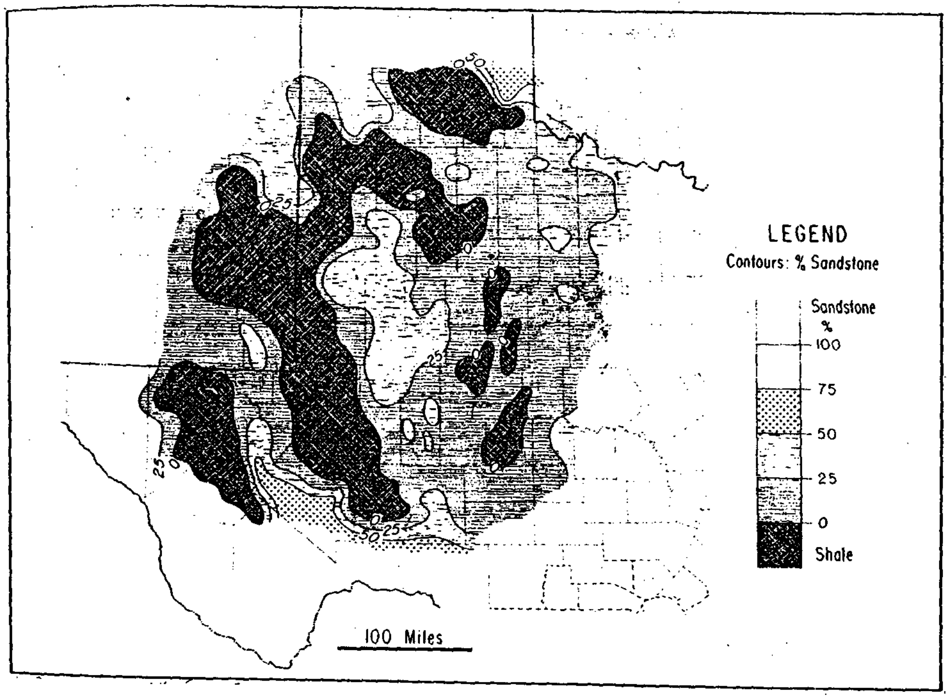

Fig. 27.—Per cent of sandstone and siltstone in clastic rocks of the Wolfcamp Series; the remainder is shale except small patches of conglomerate at the base of the series on the Central Basin platform and Diablo platform.

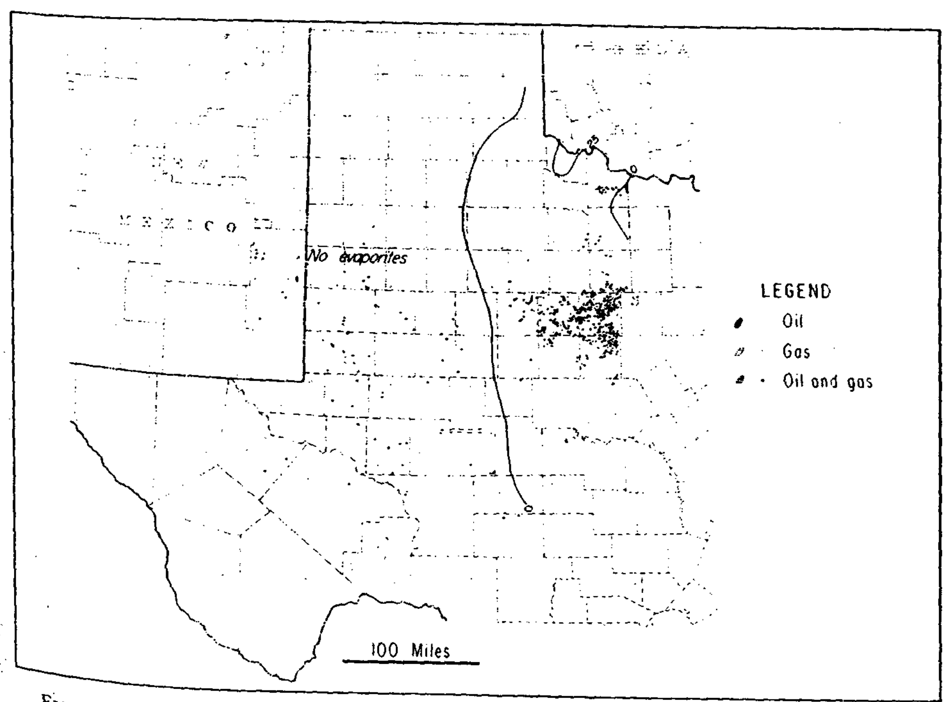

Fig. 28.—Per cent of noncarbonate evaporite rocks in the Wolfcamp Series (see Fig. 25).

same series. The shales are considered to be the most likely source beds (see following discussion of Leonard Series), the sandstones and dolomites the least likely. The Wolfcamp Series is thin or locally absent over the Central Basin platform (Fig. 24), but the author considers the small number of Wolfcamp fields in that province to be indicative of lack of migration upward or laterally across the unconformity from possible source beds in pre-Permian rocks.

A total of only ¼ billion barrels of oil has been found thus far in Wolfcamp beds, about the same amount as in the Atoka Series of Pennsylvanian age, although the volume of Wolfcamp strata is more than three times as great as that of the Morrow and Atoka Series (Fig. 1). Even if we ignore the great thicknesses of Wolfcamp strata in the Marathon trough, there is still twice as much Wolfcamp rock as Morrow and Atoka. Limestone or dolomite is the principal reservoir rock of the Wolfcamp Series, and the accumulations are generally found in anticlinal traps. Sandstone layers hold accumulations in both structural and stratigraphic traps at the east edge of the Permian Basin.

Leonard Series.—No Marathon trough is reflected in the thickness map of the Leonard Series (Fig. 29); that feature had ceased to be an active province, and the Marathon orogeny itself had drawn to a close. The influence of the Matador arch persisted through early Leonard time but is discernible only with difficulty in the lithology of younger beds. Except for its possible influence in determining the location of the Eastern shelf, the Concho arch had become a relict structure; its relief as a subsurface anticline was extinguished by westward tilting during continued subsidence of the Permian Basin. In short, the Delaware and Midland basins and their marginal platforms constituted the only control of sedimentary facies during Leonard and the remainder of Permian time.

Reference to Figure 30 shows the persistence of the pattern of carbonate deposition which was developed in Wolfcamp time, and shows also the better definition of the Northwestern shelf. In addition, a southern carbonate shelf was developing along the site of the south flank of the former Marathon trough (*cf.* Fig. 24). The Delaware and Midland basins themselves became sharply defined, and the facies transitions from dolomite on the platforms to limestone in the basins became amazingly abrupt; they mark the basin rims faithfully (Fig. 31). The basins were sinking, and the supply of clastic materials from the low-lying borderlands of the Permian Basin was insufficient to fill them completely. Consequently they were the sites of small seas of relatively great depth in which stagnant bottom conditions existed. The basin rims lay in shallow zones of clear, warm water in which lime-secreting organisms thrived.[12] The Midland basin apparently was open at the southeast, the channel (or channels) passing between carbonate shoals on which dolomitization has been extensive.

In contrast to the Wolfcamp Series, in which the largest concentration of sandstone was in the Marathon trough (Fig. 27), the Leonard Series contains broad areas of high siltstone and sandstone proportions in the Midland basin (Fig. 32);

[12] For a more complete discussion of the Permian paleoecology of the Delaware basin, including suggestions regarding dolomitization of the shelf carbonates, the reader is referred to the excellent treatise by Newell *et al.* (1953).

this facies includes the sequence of Spraberry sandstone members which are the reservoir rocks for the large oil field shown in the Midland basin on the Leonard maps.

At the north edge of the Permian Basin an evaporite environment was beginning to invade the area (Figs. 33 and 34) and before the end of Permian time would sweep across the entire basin. Anhydrite was beginning to form on the Central Basin platform as early as Leonard time.

Volumetrically the Leonard Series constitutes the second largest stratigraphic unit in the Permian basin, as the column has been subdivided for this paper; it amounts to about 35,000 cubic miles of rock. Yet its known oil content is only about equal to that of the Cambrian and lower Ordovician unit (Fig. 1), which is thought to have contained little or no source material. One quarter of the known Leonard oil is in the Spraberry-Trend field, where production is obtained from stratigraphic or porosity traps in fractured argillaceous sandstone and siltstone. Other types of traps in Leonard-producing areas include anticlines and porosity traps in sandstone and carbonate reservoirs.

While examining the distribution of oil and gas fields with respect to the sedimentary and tectonic environment, it has been observed that nearly all of the oil in pre-Permian reservoirs has a low sulfur content, and that the distribution of various crude oils by gravity distinctions has no apparent patterns. It was further noted that Wolfcamp oil is similar to pre-Pennsylvanian oil in these respects. Examination of reported data for oil produced from Leonard reservoirs provides the first contrast, for many of the pools produce sour crude oil from these strata. Of considerable interest is the fact that, almost without exception, the sour crude oils are produced from pools on the eastern and northern shelves of the Midland basin and on the Central Basin platform. Pools producing sweet crude oil lie in the Midland basin, in a few localities on the south end of the Eastern shelf, and in the east-central portion (Ector County) of the Central Basin platform. Two small pools in the Delaware basin, now depleted, produced sweet crude oil and gas.

The distribution of various gravities of the crude oils shows a range from 32° to 43° on the Central Basin platform, 34° to 41° in the Midland basin, 25° to 32° on the Eastern shelf, and 23° to 30° on the Northern shelf of the Midland basin.

Gas production is obtained chiefly along the west edge of the Central Basin platform, which is adjacent to the Delaware basin.

Sediments of the stagnant deeps in the Delaware basin are believed by Newell and associates (1953, p. 208) to have contained oil source beds which furnished petroleum to reservoirs along the margins of the basin. The bottom sediments were chiefly fine grades of clastics, and any interbedded porous limestone and sandstone layers would provide convenient reservoir space in the basin. By analogy, the present author infers that similar bituminous strata in the Midland basin were source beds, providing oil for reservoirs in the Spraberry sandstone as well as in porous carbonate and clastic beds on adjacent platforms. To what extent the shelf environments also were source areas is probably a more debatable subject, which will be mentioned again in later pages.

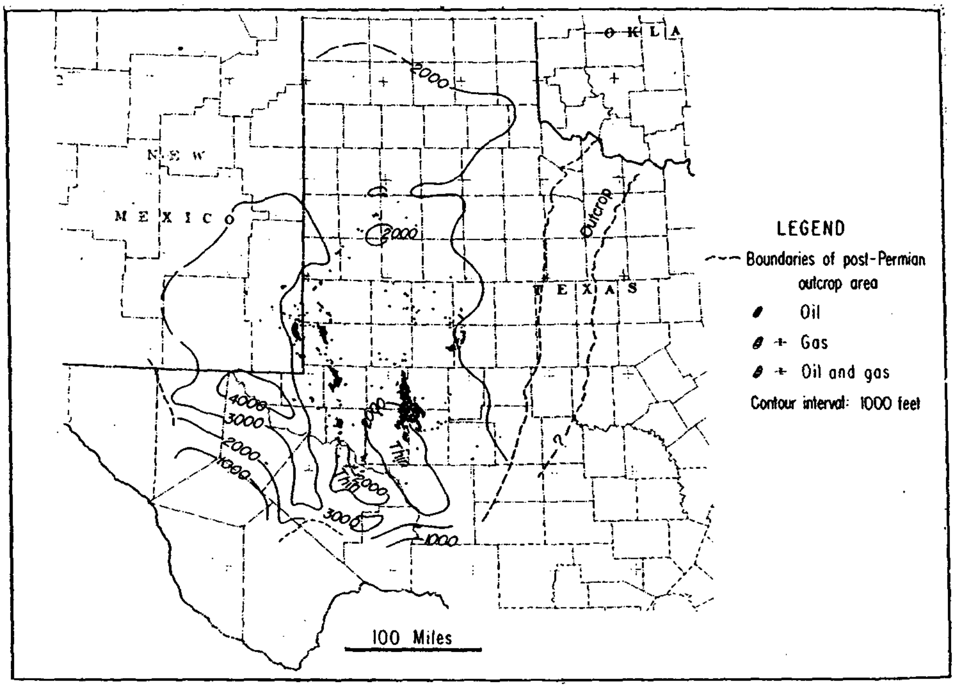

FIG. 29.—Thickness of the Leonard Series.

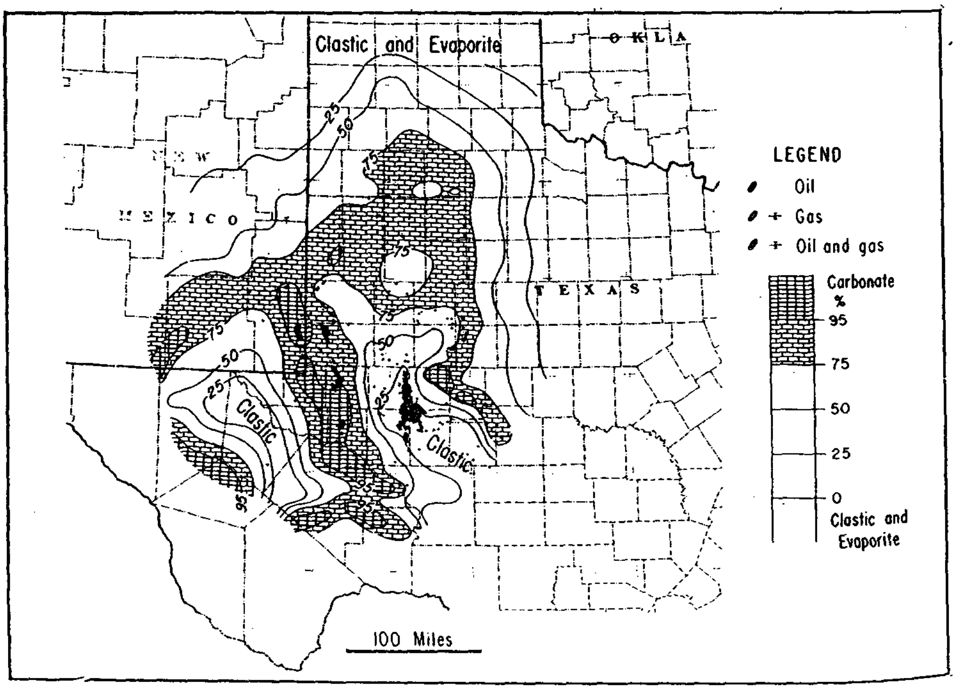

FIG. 30.—Per cent of carbonate rocks in the Leonard Series; the remainder are clastic and evaporite (see Fig. 33).

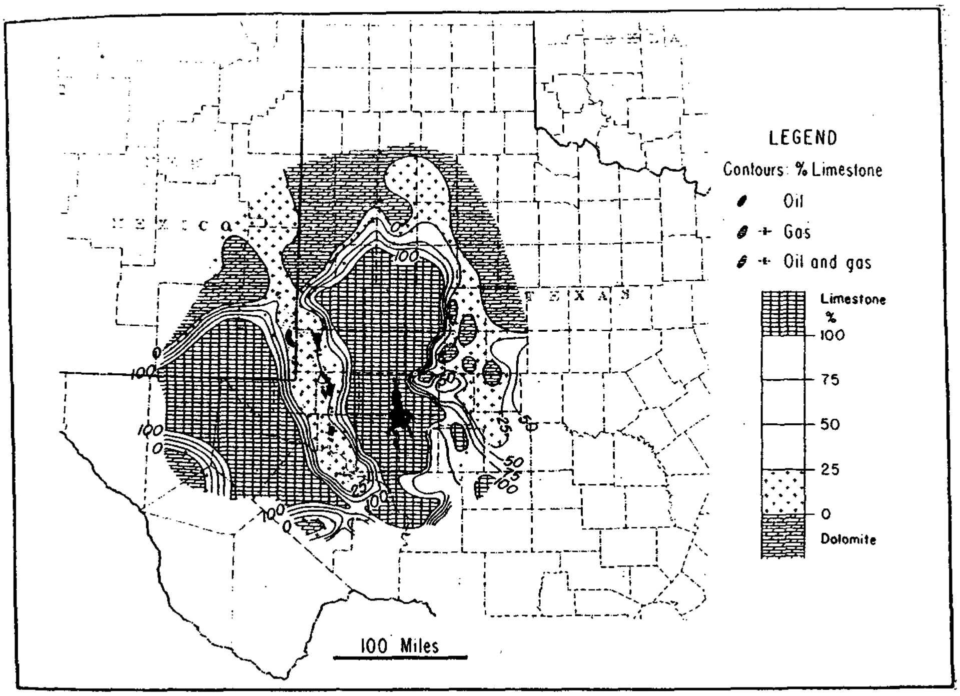

FIG. 31.—Per cent of limestone in carbonate rocks of the Leonard Series; the remainder is dolomite.

Out of a total volume of about 12,000 cubic miles of sedimentary rock in the two basins about one third is shale, and it is possibly this volume of basinal shale which accounts for most of the Leonard oil.

Guadalupe Series.—The Guadalupe Series contains at least half of all the oil which has been found in the entire Permian Basin.

In order to portray the rapid development of Guadalupe events, the series is divided in this paper into two units, the boundary being the top of the San Andres and Cherry Canyon formations and their stratigraphic equivalents. Conditions of early Guadalupe time produced results (Figs. 35-39) which differ from those of the Leonard Epoch in the following respects—1. The rocks are generally thinner, although thicknesses approaching 2,000 feet may be found in the Midland basin; 2. The Midland basin is less sharply defined; 3. Changes of facies from shelf carbonates into clastics in the Delaware basin are more abrupt; 4. Evaporite facies are more pronounced in the area north and east of the Delaware basin and Central Basin platform.

With respect to item 3, particular attention is called to the Sheffield channel, a clastic-filled strait of early Guadalupe age connecting the Delaware basin and Midland basin around the south end of the Central Basin platform and across the Pecos arch (Fig. 37). This "channel" is not to be confused with the present synclinal depression south of the Pecos arch, the Val Verde basin, which is the structural expression of a portion of the Pennsylvanian and early Permian Marathon trough.

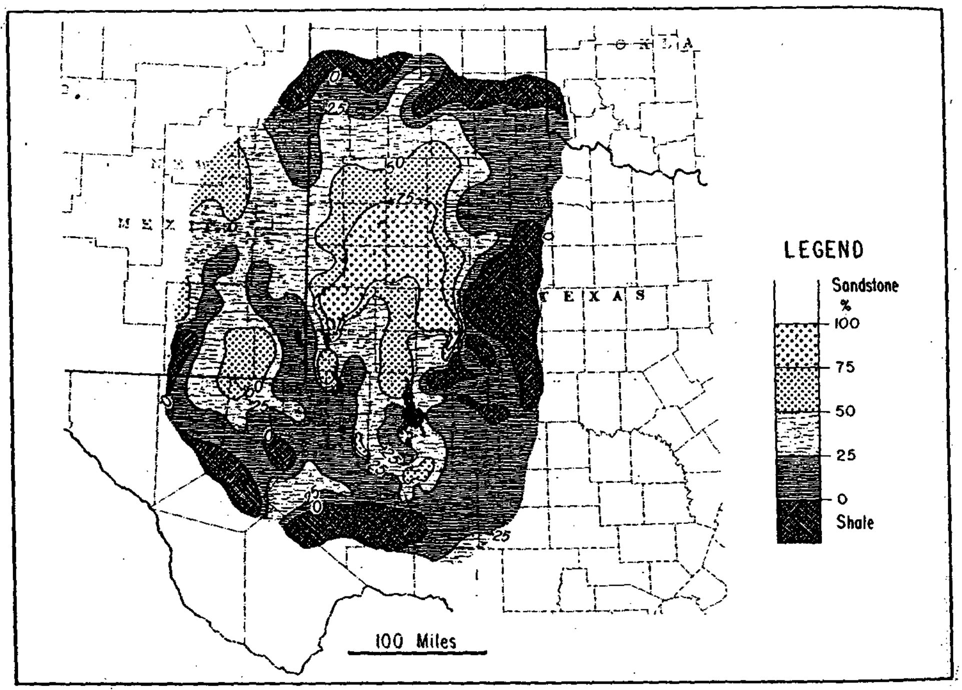

FIG. 32.—Per cent of sandstone and siltstone in clastic rocks of the Leonard Series; the remainder is shale.

The clastics of the Midland basin, Delaware basin, and Sheffield channel are predominantly sandstone.

By late Guadalupe time the Midland basin had almost disappeared as a separate lithologic province, leaving the Delaware basin and its environs as the site of principal basin and reef deposition (Fig. 40). The well-known Capitan reef was formed along the rim of the Delaware basin, growing basinward from its roots in lower Guadalupian carbonates and probably extending across the earlier Sheffield channel (Fig. 41). The deposition of sand in the stagnant deeps continued, and behind the reefs were lagoons which received layers of sand, silt, mud, dolomite, and evaporites (Figs. 42, 43 and 44). The dolomite itself is probably an evaporitic deposit.

The distribution of various types and grades of crude oils in Guadalupe rocks seems to be distinctly related to the geologic environments. For example, the oil produced in the Delaware basin, where the principal reservoir strata are sandstone formations of the Delaware Mountain group, is sweet, whereas with few exceptions the remainder of the Guadalupe fields in the Permian Basin produce sour crude oil.

Likewise, the gravity of crude oil in the Delaware basin is generally higher than that of other provinces. The gravity of crude oils in upper Guadalupe strata in the Delaware basin where the sulfur content is low, ranges from 29° to 42°; elsewhere the range is from 27° to 37°, although occasional readings above or below that range are reported. In lower Guadalupe strata, gravities ranging from 35° to

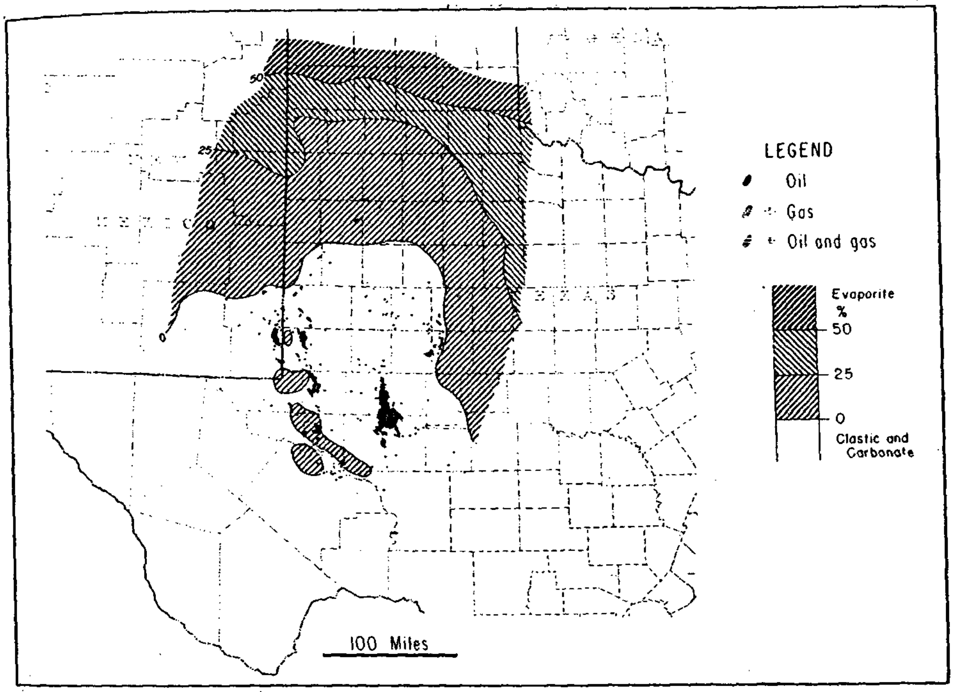

FIG. 33.—Per cent of noncarbonate evaporite rocks in the Leonard Series; the remaining rocks are clastic and carbonate (Fig. 30).

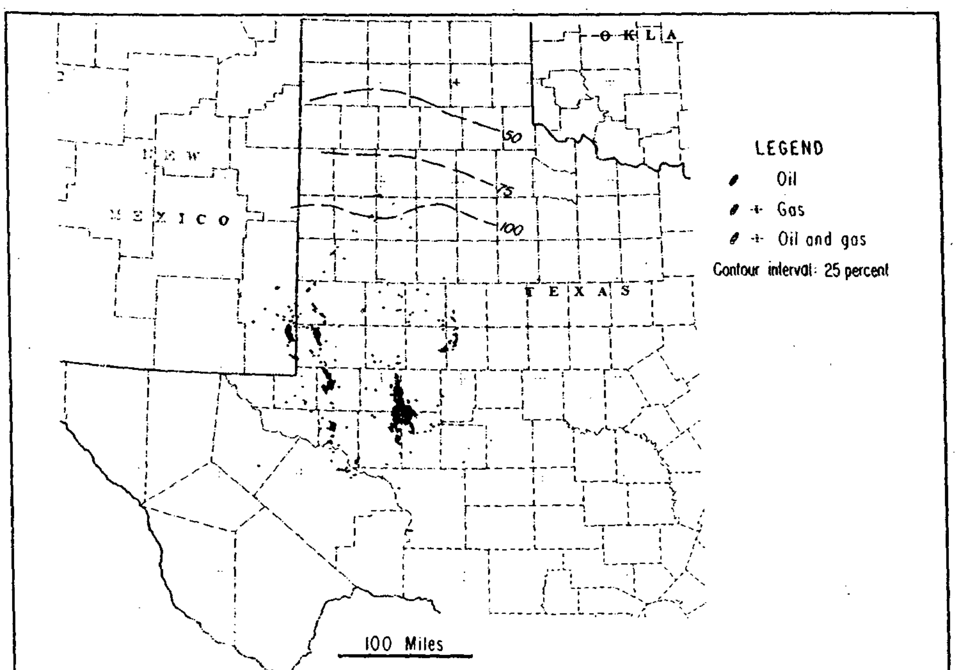

FIG. 34.—Per cent of anhydrite in evaporite rocks of the Leonard Series; the remainder is rock salt.

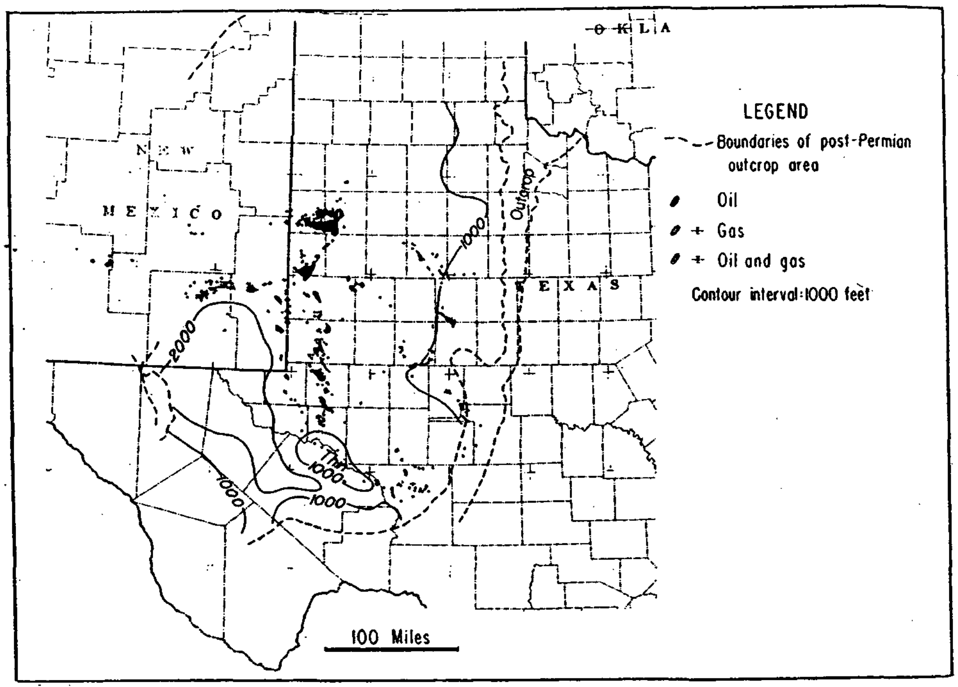

FIG. 35.—Thickness of lower Guadalupe strata.

40° are found in pools along the rim of the basin and well over toward the east side of the Central Basin platform; elsewhere in the Northern shelf adjoining the Delaware basin and along the east edge of the Central Basin platform, gravities as low as 28° are recorded. Gravities of lower Guadalupe oils in the north end of the Midland basin are about 33°, on the Northern shelf adjoining the Midland basin 24°–33°, on the Eastern shelf 26°–38°, and on the east half of the Pecos arch 18°–34°. Anomalously low gravities of 20°–29° in the westernmost pools in New Mexico are presumably the result of proximity to the outcrop.

Gas fields in both lower and upper Guadalupe strata are situated along the east and west edges of the Central Basin platform, but the upper Guadalupe fields on the west edge, rimming the Delaware basin, are by far the largest.

Oil accumulations in Guadalupe strata occur in structural traps in sandstone and carbonate reservoirs, of which many Yates-sandstone and San Andres- and Grayburg-dolomite pools are good examples, and in porosity traps as well.

The total volume of Guadalupe strata amounts to slightly more than that of the Leonard Series, and the volume of sediments filling only the two basins in Guadalupe time is about the same as that in the Leonard Epoch; the proportion which is basinal shale, however, is considerably less. At least four possible alternative reasons may be advanced to explain the great difference between the volume of oil found in Guadalupe rocks and that in the Leonard and older series (Fig. 1)—1. The Guadalupe Series, being the shallowest, was the first drilled, and more of the total oil content has already been discovered; 2. Leonard and Wolfcamp

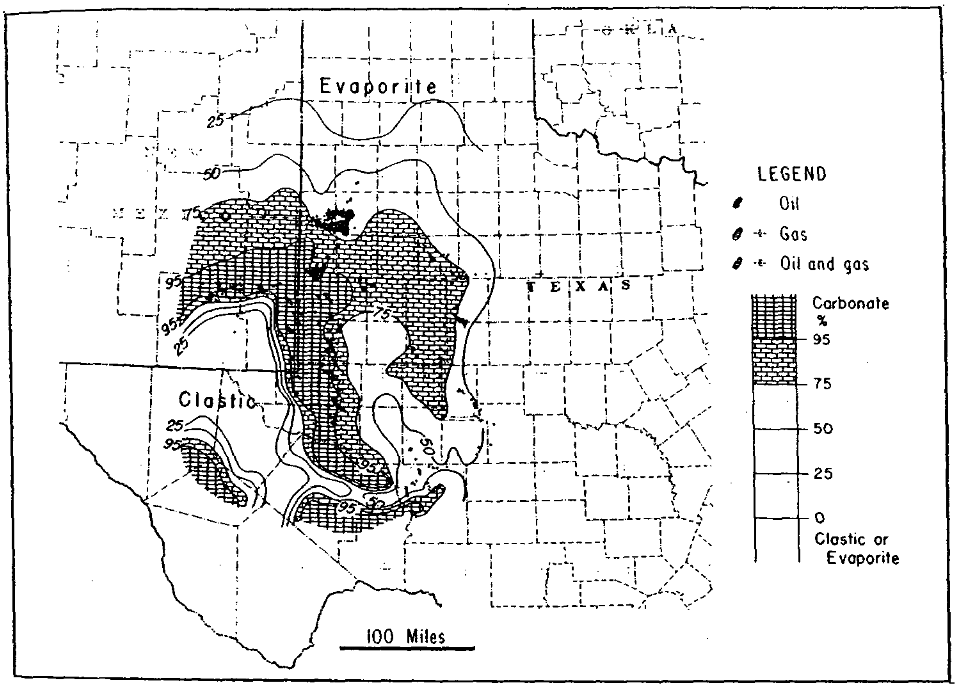

FIG. 36.—Per cent of carbonate rocks in lower Guadalupe strata; the remainder are clastic and evaporite (Figs. 37 and 38).

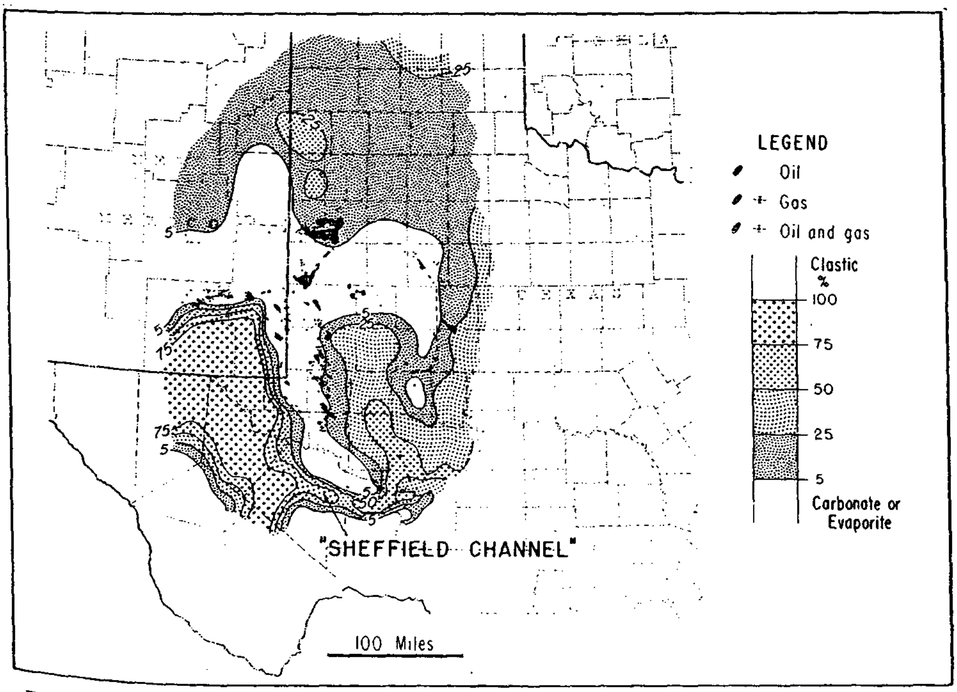

FIG. 37.—Per cent of clastic rocks in lower Guadalupe strata; the remainder are carbonate and evaporite (Figs. 36 and 38).

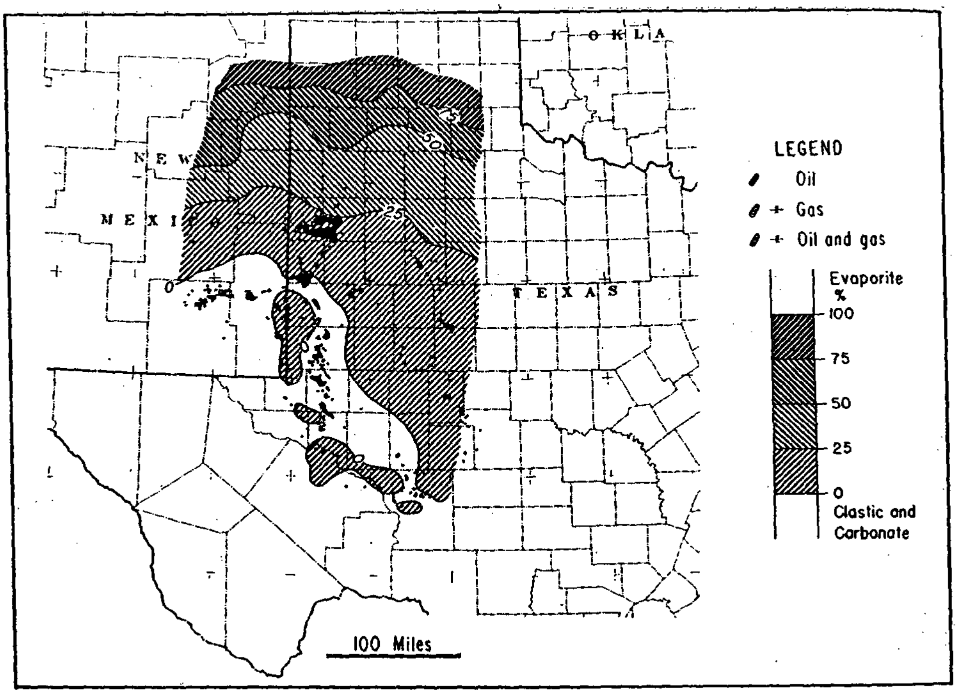

FIG. 38.—Per cent of noncarbonate evaporite rocks in lower Guadalupe strata; the remaining rocks are carbonate and clastic (Figs. 36 and 37).

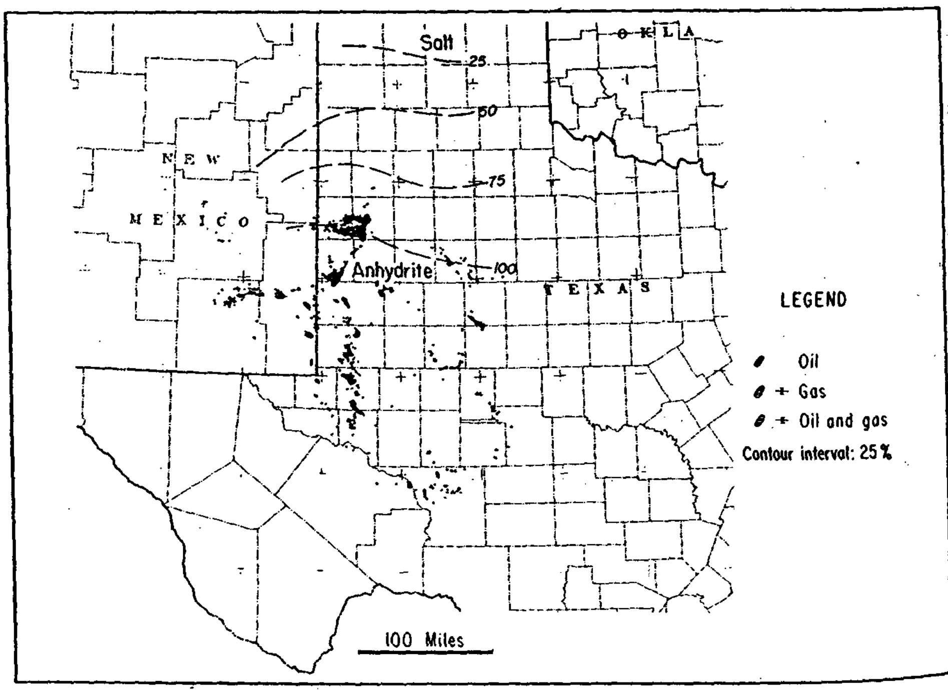

FIG. 39.—Per cent of anhydrite in evaporite rocks of lower Guadalupe strata; the remainder is rock salt.

reservoirs have smaller productive capacity; 3. There are differences in source-bed characteristics which are not apparent in gross examinations, including perhaps some attributes which are found only in the sediments of closed basins; 4. The absence of major unconformities in Guadalupe strata as contrasted with many in pre-Permian strata, prevented losses from petroliferous reservoirs.

Ochoa Series.—Deposits of the Ochoa Series are predominantly evaporites which were laid down in great thicknesses in the Delaware basin and spread more thinly over the remainder of the shrinking Permian Basin (Fig. 45). Carbonate rocks are absent in the east part of the area, and elsewhere the proportions are small (Fig. 46); except at the south edge there is no evidence of the large reefs and carbonate shelves which characterize all of earlier Permian environments. The eastern area of noncarbonate deposits contains the highest percentages of clastic strata (Fig. 47), but the volumes are small inasmuch as the total interval is relatively thin; proportions of clastics increase eastward at the expense of evaporites (Fig. 48). The Ochoa evaporites are largely rock salt, except at the southwest where anhydrite predominates (Fig. 49); much or all of the dolomite probably is evaporitic.

The overall picture of Ochoa environments is thus similar to the back-reef environments of earlier Permian epochs, the evaporite environment having by this time encroached upon the entire Permian Basin. The shapes of facies contour lines suggest that there may have been less saline conditions farther south.

Complete desiccation of the sea in the Permian Basin, probably accompanying broad regional uplift, closed the Ochoa Epoch and simultaneously the Paleozoic Era.

Small amounts of oil have been produced from three pools in Ochoa strata, two in the Delaware basin and one high on the south flank of the Central Basin platform; the ultimate recovery from these three pools may be less than ½ million barrels. The crude oil is sour, like that in back-reef reservoirs in the Guadalupe Series, and the gravities range from 18° to 28°.

The oil is presumed to have migrated into Ochoa reservoirs from underlying strata, as the Ochoa environment must have been too saline for most organisms to exist.

Source beds for Permian oil.—The problem of basin *versus* platform as source areas for the Permian oil has not been solved to the complete satisfaction of all investigators and observers. Reasonings and conclusions offered by Newell and associates (1953) to the effect that the basins were the source areas are convincing, but the present writer is inclined to suspect that some portion of the oil found in back-reef or shelf reservoirs originated in strata of lagoonal or platform environments rather than in the basin deeps. During deposition of nonevaporitic members in cyclic suites of sediments, conditions may have been suitable for the growth of organisms; such conditions were postulated by Newell and associates (1953, pp. 204–5) for lagoonal areas which were marginal to the reef.

The relative distribution of sweet and sour crude oils is of interest, but its importance as a guide to site of origin is conjectural—at least to the writer. There is a commonly accepted rule amongst oil men in west Texas that sandstone reser-

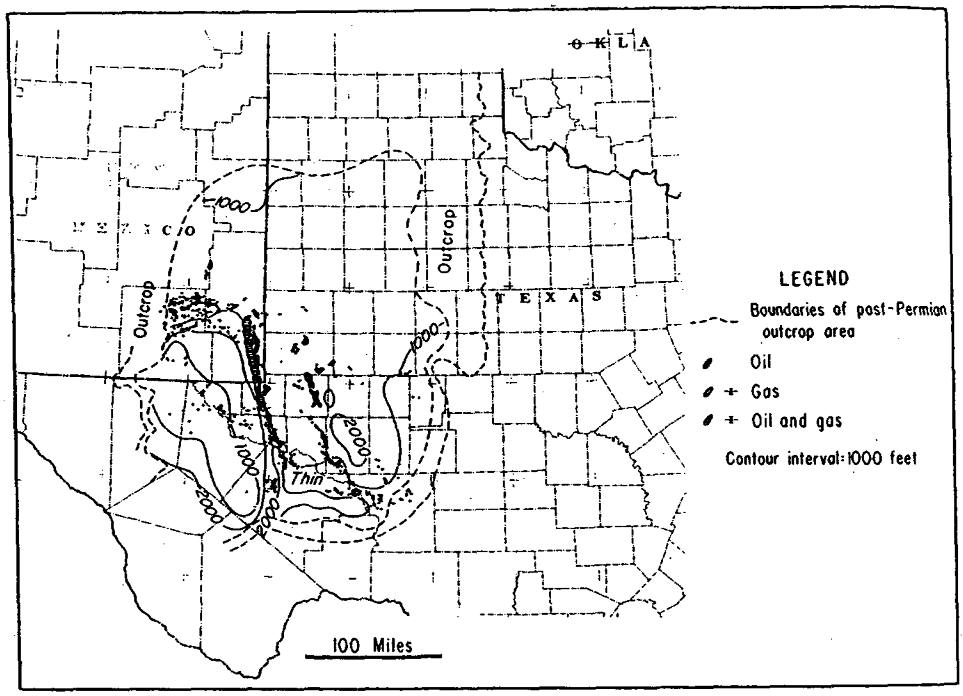

FIG. 40.—Thickness of upper Guadalupe strata.

voirs produce sweet oil and dolomite (some say limestone) reservoirs produce sour oil. The exceptions to the rule are many, notable examples being most of the dolomite or limestone reservoirs of pre-Permian, in fact pre-Leonard, age, and most of the sandstone reservoirs of Leonard and Guadalupe age, in platform provinces. A more steadfast rule is that reservoirs associated with evaporite environments produce sour crude oil and all others produce sweet. Presumably the sulfur content may be acquired by a sweet oil which migrates into an evaporitic environment, as when oil migrates from Guadalupe strata in the Delaware basin upward into Ochoa strata, but perhaps the subject merits detailed study which the author is not able to provide.

Slightly higher gravities of Leonard and Guadalupe oils in basin areas, as compared with those on the platforms may be related simply to the greater producing depths in the basins.

Although "oil in a water environment is acted upon by unbalanced forces, and will continue to move until blocked by an impermeable barrier,"[13] the fact that oil is being produced from Guadalupe reservoirs more than 40 miles behind the reef front, in beds having erratic porosity and permeability, urges consideration of the possibility of nearby source beds.

POST-PERMIAN

Events associated with Laramide and several Tertiary orogenies have broken, distorted, destroyed, submerged, or obscured various segments of Paleozoic struc-

[13] M. King Hubbert, personal communication.

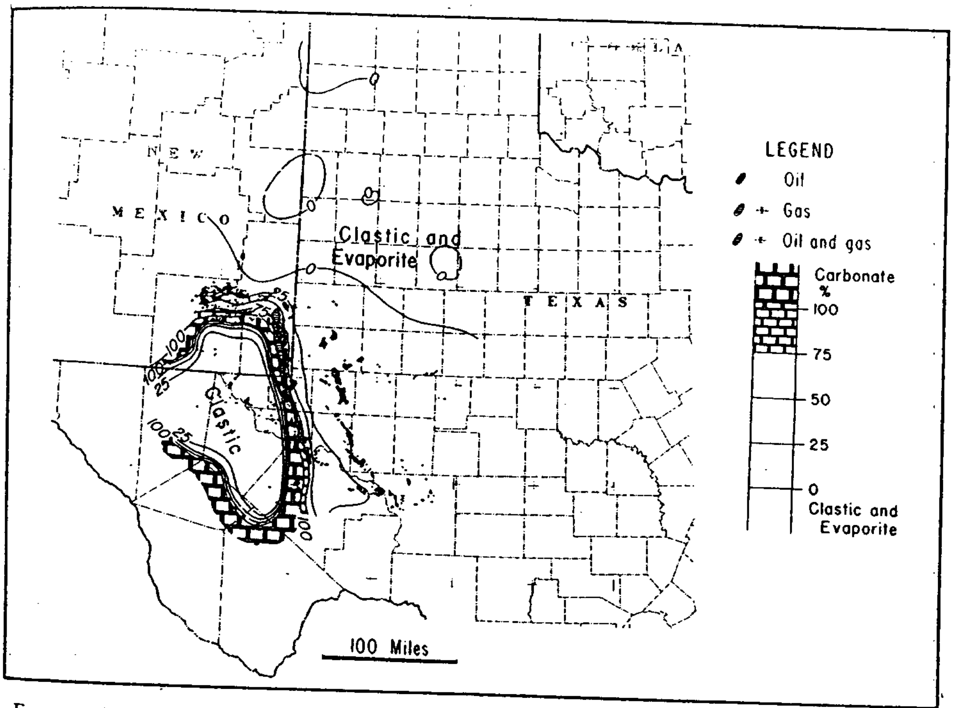

FIG. 41.—Per cent of carbonate rocks in upper Guadalupe strata; the remainder are clastic and evaporite (Figs. 42 and 43).

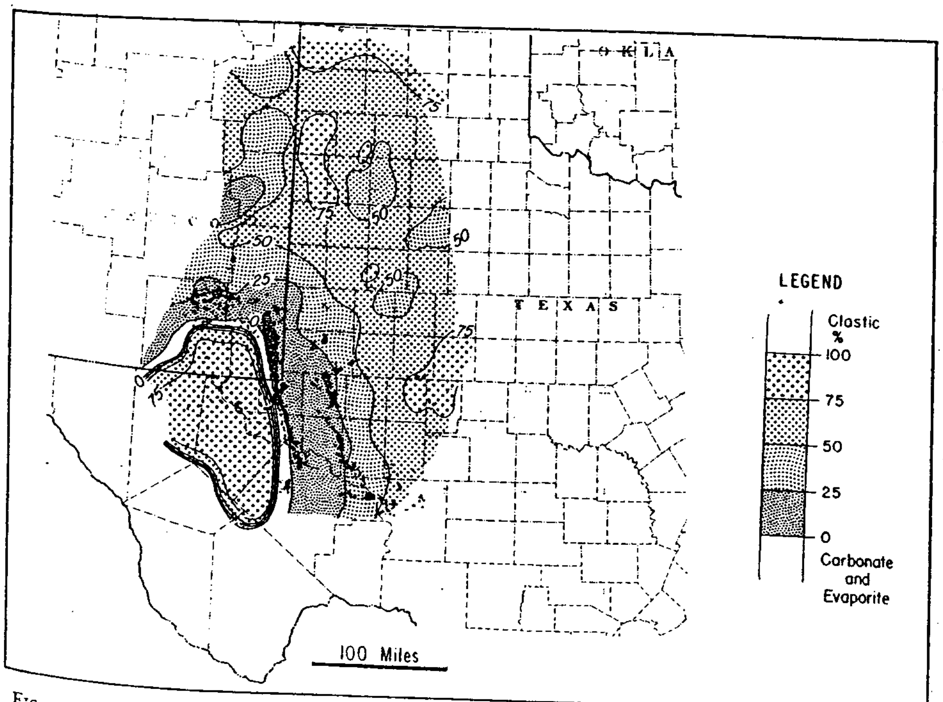

FIG. 42.—Per cent of clastic rocks in upper Guadalupe strata; the remainder are carbonate and evaporite (Figs. 41 and 43).

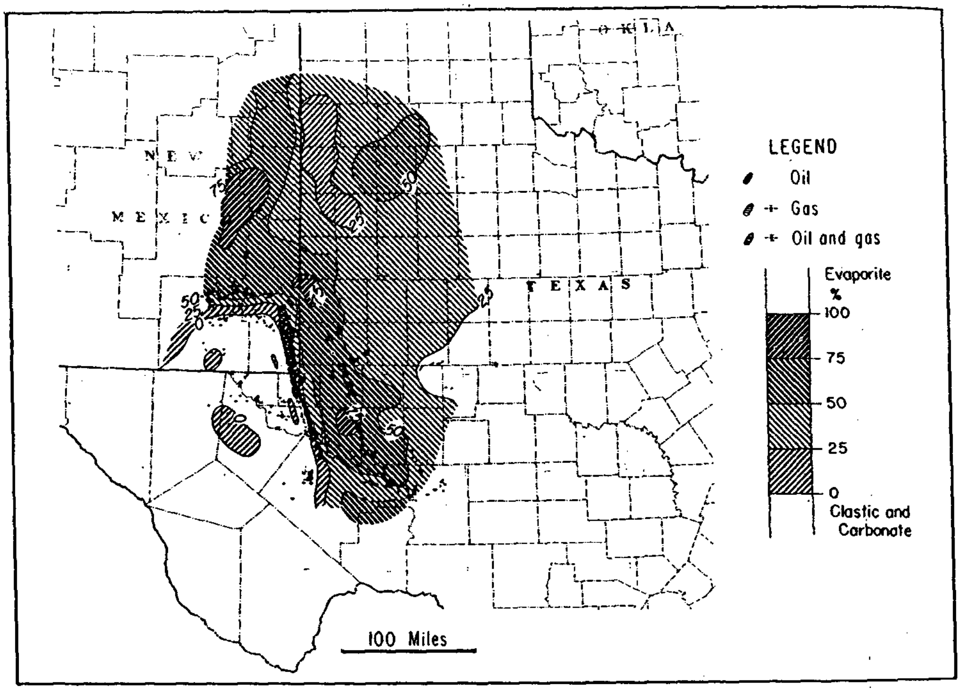

Fig. 43.—Per cent of noncarbonate evaporite rocks in upper Guadalupe strata; the remaining rocks are carbonate and clastic (Figs. 41 and 42).

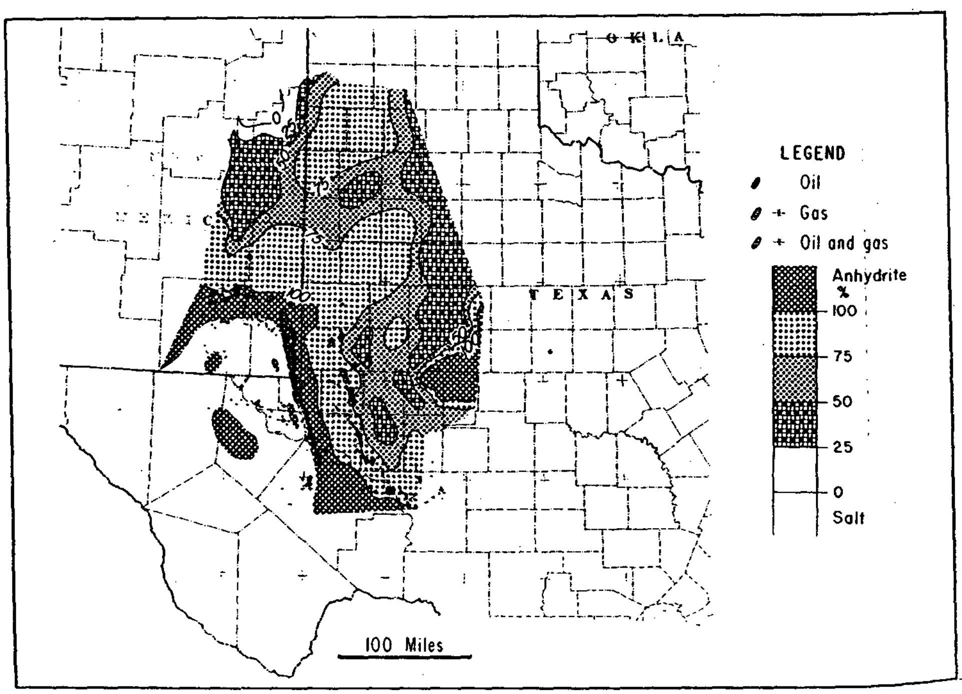

Fig. 44.—Per cent of anhydrite in evaporite rocks of upper Guadalupe strata; the remainder is rock salt.

tures at the southwest edge of the Permian Basin. Elsewhere the Paleozoic strata lie at almost the same attitudes they had attained at the close of Ochoa time, having been affected subsequently only by gentle regional tilting and local folding or faulting of small vertical displacement. Most accumulations of oil and gas, therefore, presumably were emplaced prior to Mesozoic time and have been modified only slightly by subsequent tectonic events. If any more drastic adjustments in accumulation have occurred, they are perhaps the result of changes in hydraulic gradient in response to more distant tectonisms.

SUMMARY

The foregoing text and accompanying illustrations present briefly, and with much generalization, the descriptive geology of the Permian Basin and its accumulations of oil and gas, and suggest possible origins and modes of accumulation of the hydrocarbons on the basis of observed geologic relationships.

The Permian Basin of Texas and New Mexico is a late Paleozoic structure which achieved its outline principally in early Pennsylvanian time; it was superimposed on an earlier Paleozoic shelf which sloped generally southward and which flanked a geosynclinal basin of clastic deposition lying in front of the hypothetical landmass of Llanoria. The principal structural features of the early Paleozoic shelf were two positive areas, the persistent Pedernal massif and the intermittently submerged Concho arch, and between them the Tobosa basin.

In late Mississippian time a ring of mountain uplifts began to grow, part of them rising from the Llanoria geosyncline, and within the ring smaller uplifts were created. Thus was formed the intracratonic depression which later became the Permian Basin. Deposition in an expanding mediterranean sea having mountainous shores during Pennsylvanian time, and in a shrinking sea between low land masses during Permian time resulted in the development of complex lithofacies. Carbonate platforms and great barrier reefs were developed in the Permian Period over areas of least subsidence, some of which inherited their positive tendencies from early Paleozoic uplifts.

Deposition of Cambrian and lower Ordovician strata on the early Paleozoic shelf was initiated by a transgressing sea which, entering the area from the south, laid down first a clastic sequence and then a greater thickness of carbonate strata. Oil which is produced from reservoirs in these strata, if not indigenous, may have originated in superjacent beds, or perhaps migrated out of the Llanoria geosyncline prior to the Marathon orogeny.

Middle Ordovician strata are interbedded layers of carbonate, shale, and sandstone, of which the sandstone formations provide the reservoirs. The oil is probably indigenous to the group in which it is found.

Upper Ordovician, Silurian, and Devonian strata are almost entirely carbonate and are more or less cherty or siliceous. Although separated by unconformities, they act as a single reservoir in which oil occurs near the top in areas where the unit is all dolomite, and at various levels in areas where dolomitic and calcitic carbonates are interbedded. If source beds are not to be found in these essentially

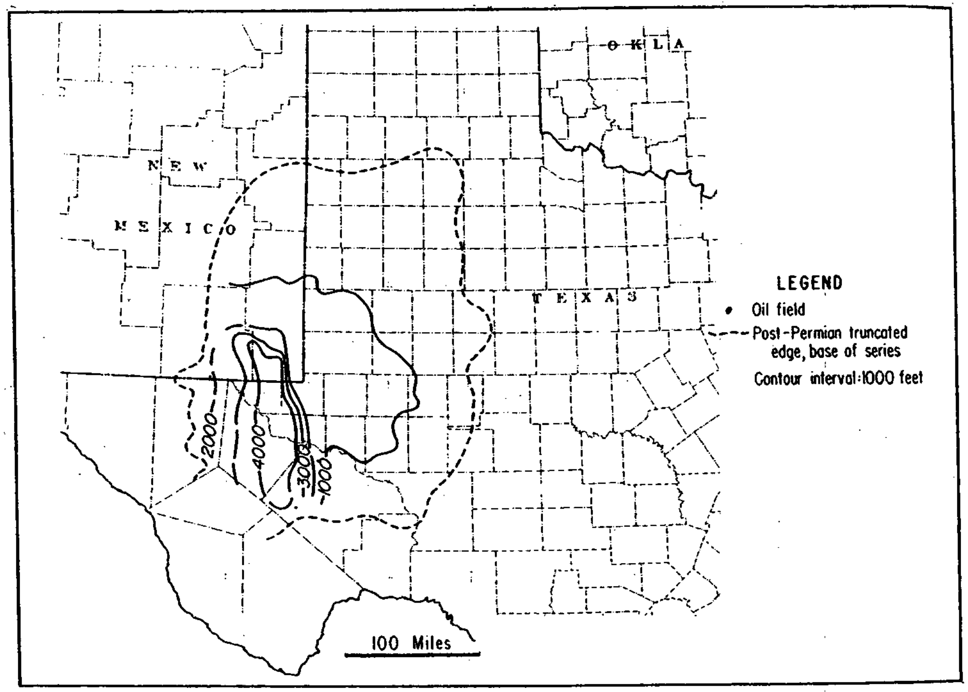

FIG. 45.—Thickness of the Ochoa Series after pre-Triassic erosion.

nonargillaceous carbonates or in closely associated argillaceous strata, the oil may have originated in the adjacent Llanoria geosyncline.

Mississippian strata are principally dark organic-rich shale and limestone which appear to have been excellent source beds but which are poor in reservoir characteristics. Likewise, lower Pennsylvanian strata, chiefly dark shale, sandstone, and argillaceous limestone, contain probable source beds, but they are favored with more porous reservoir strata.

Rocks of upper Pennsylvanian age have less total volume in the Permian Basin than the aggregate volumes of all older sedimentary rocks, but the amount of oil which has been found in upper Pennsylvanian strata exceeds that in all older reservoirs. The reason for the difference is probably the combination of good source beds and excellent reservoirs, for upper Pennsylvanian strata consist primarily of dark-gray shale, sandstone, and large volumes of pure calcitic limestone which forms many large and porous reefoid masses.

The Wolfcamp Series of early Permian age is transitional in character between upper Pennsylvanian and middle Permian strata. It contains dark-gray shale like that of the Pennsylvanian System, but the volume of limestone in reefoid masses is small. It contains broad limestone areas on carbonate shelves like those of later Permian series, but the volume of dolomite in the shelf carbonates is relatively small. The amount of oil which has been found in Wolfcamp reservoirs is accordingly much smaller than in those of upper Pennsylvanian strata, and it likewise is less than that in overlying Leonard reservoirs.

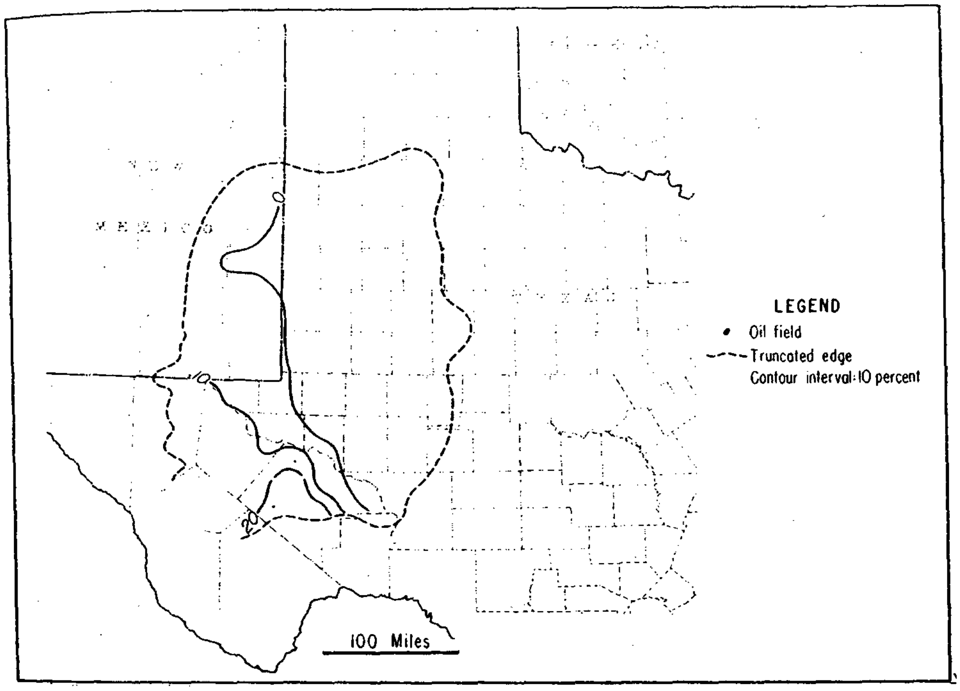

FIG. 46.—Per cent of carbonate rocks in the Ochoa Series; the remainder are clastic and evaporite (Figs. 47 and 48).

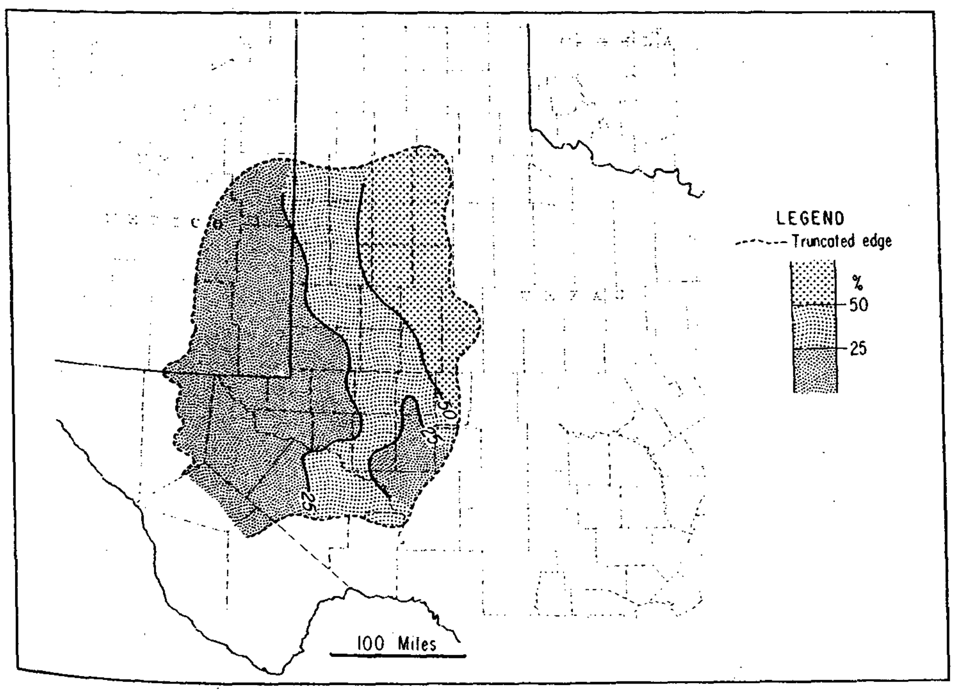

FIG. 47.—Per cent of clastic rocks in the Ochoa Series; the remainder are carbonate and evaporite (Figs. 46 and 48).

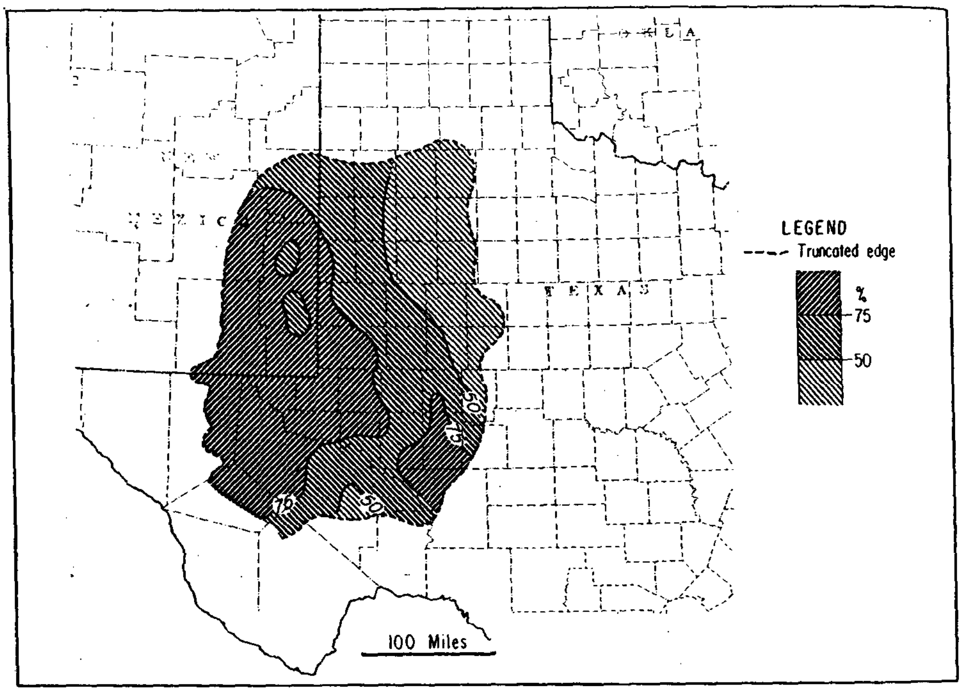

FIG. 48.—Per cent of noncarbonate evaporite rocks in the Ochoa Series; the remaining rocks are carbonate and clastic (Figs. 46 and 47).

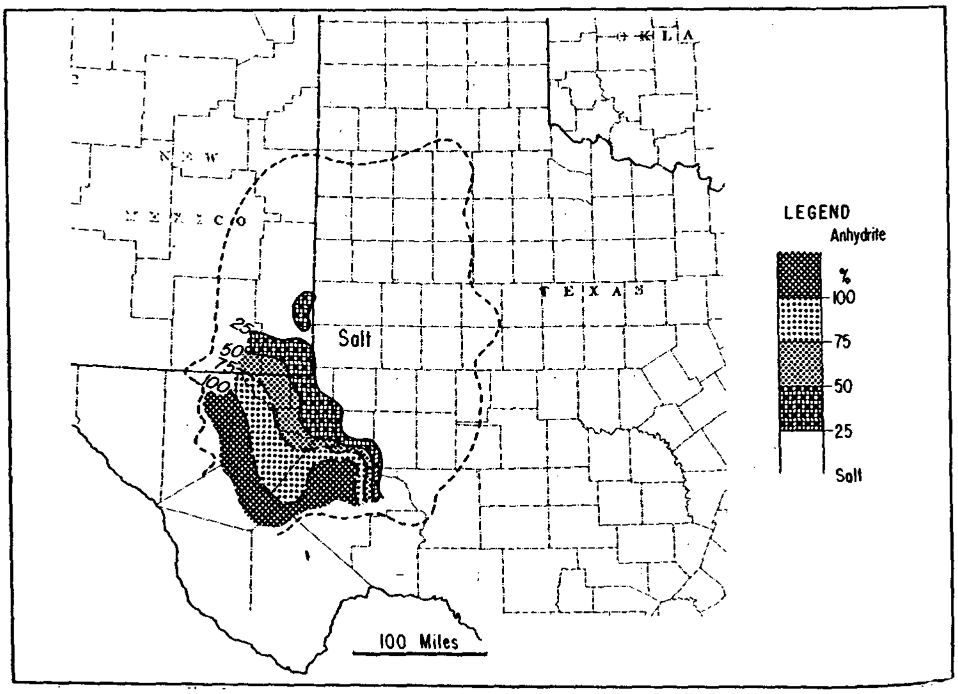

FIG. 49.—Per cent of anhydrite in evaporite rocks of the Ochoa Series; the remainder is rock salt.

The oil in Pennsylvanian and Wolfcamp reservoirs is believed by the author to have originated in rocks of the same age, probably the adjacent dark shale and other argillaceous strata.

Leonard and Guadalupe strata were deposited in deep basins and on shallow submerged shelves marginal to them, and consist of contrasting facies of basinal shale, sandstone, and limestone; platform and barrier-reef carbonates; and lagoonal complexes of carbonates, evaporites and red beds. The basin deposits are dark and richly organic and are believed to have been source beds for oil that is found in basin reservoirs and in some if not all of the platform strata. The merits of the platform, reef, and lagoonal deposits as source beds are debatable. The Leonard reservoirs have produced more oil than has been found in Wolfcamp strata, but more oil has been found in Guadalupe strata than in all older rocks combined.

Youngest Permian rocks are the evaporites and red beds of the Ochoa Series, in which only very minor amounts of oil have been found.

From the geologic history of the Permian Basin it is concluded that most of the oil accumulations were completed prior to Mesozoic time.

CONCLUDING REMARKS

The foregoing text and accompanying generalized maps present to the reader merely a brief geologic description of the Permian Basin, together with some observations on its content of oil and gas. This is only the first step in reaching a clear understanding of the relationships between the sources, migration, and accumulation of oil and gas on the one hand, and the environments of deposition and the diagenetic and tectonic history of the rocks on the other. To gain that ultimate objective would require minutely detailed, discriminating, and accurate studies of the lithology and paleontology of the rocks; thorough and enlightened interpretations of paleogeography and paleoecology; complete analyses of the fluids in the rocks; and discerning recognition of the various changes through which the rocks and the fluids have passed in geologic history. The author hopes that this presentation of the elementary geology of the Permian Basin will stimulate at least a few of his readers to undertake the advanced studies that will lead to the knowledge we all desire.

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