Geology of Part of the Horseshoe Atoll in Scurry and Kent Counties, Texas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 315-A

Prepared in cooperation with the
Bureau of Economic Geology
The University of Texas

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By PHILIP T. STAFFORD

ABSTRACT

The subsurface Horseshoe atoll is an arcuate accumulation of fossiliferous limestone 70 to 90 miles across in the northern part of the Midland basin, in western Texas. The stratigraphy, the lithologic character of the rocks, and the petroleum reservoirs of the southeastern part of the atoll in Scurry County and parts of adjacent counties are described herein.

Rocks of Strawn, Canyon, and Cisco ages, belonging to the Pennsylvanian system, and rocks of Wolfcamp age, belonging to the Permian system, form the Horseshoe atoll. Reworking of these rocks at several times during the growth of the atoll has resulted in the formation of large amounts of limestone breccia, in the mixing of the fusulinid faunas used to date the rocks, and in the complex age relations between rocks in different parts of the atoll. Thin beds of shale within this limestone mass are the only lithologic units that can be correlated for any appreciable distance in the atoll, but studies of micrologs from wells penetrating the atoll have revealed many zones of low porosity that can be correlated with reasonable certainty over much of the area described in this report.

The atoll rests on a platform of bedded limestone and shale, which has been designated as equivalent in age to the Bend and Strawn groups of the Pennsylvanian system. It is covered mainly by shale, which has been designated as equivalent in age to the Wolfcamp series of the Permian system and is partly equivalent in age to the youngest rocks within the atoll.

Reworking of the rocks, the complex distribution of rocks of different ages, the presence of thin beds of shale, and the stratification of porosity in the atoll suggest that this structure has many of the characteristics of a reef. Its growth in the Midland basin was apparently cyclic and may have been related to changes of sea level during the Late Pennsylvanian and early Permian periods.

Oil is contained in porous zones within the atoll, mainly in reservoirs in hills along the crest of the structure where the overlying shale formed an impervious cap, but some is found in the lower part of the limestone mass where the reasons for the oil traps are not as apparent. The source of the oil was probably the shale of Wolfcamp age that surrounds the atoll.

INTRODUCTION

The Horseshoe atoll, which has been identified and described by Adams and others (1951), Heck and others (1952), and Anderson (1953), is a subsurface accumulation of limestone in the northern part of the Midland basin in western Texas (fig. 1). The atoll has an east-to-west diameter of about 90 miles and a north-to-south diameter of about 70 miles. This report describes the part of the atoll and its lagoonal area that lies in Scurry and southern Kent Counties and in adjacent parts of Borden and Garza Counties.

The arcuate mass of fossiliferous limestone of Pennsylvanian and Permian ages that constitutes the Horseshoe atoll is very irregular in shape. Its surface contains buried hills, depressions, and irregular reentrants, and its flanks slope gently away from the crest on both sides. The area covered by this report includes the highest part of the atoll, the top of which is 3,738 to 5,900 feet below sea level and about 6,150 to 7,900 feet below the ground surface (pl. 1).

The terms "atoll" and "reef" have generally been applied to this subsurface accumulation of limestone, although as noted by Heck and others (1952, p. 5) the limestone does not contain large amounts of readily recognizable frame-building reef organisms. Evidence indicates that this limestone feature may have had most of the characteristics of a reef during the time of its growth, and therefore the use of the terms "atoll" and "reef" is appropriate.

This report is the result of geologic investigations made during the period from 1950 to 1953 by the U. S. Geological Survey in cooperation with the Bureau of Economic Geology of The University of Texas, as part of a regional study of the Horseshoe atoll. It summarizes the available information on the thickness, age, and characteristics of the rocks in and near the southeastern part of this limestone mass and information on the distribution of petroleum in the atoll. The report incorporates the results of studies made by Heck and others (1952), Rothrock (1952), Bergenback and Ter-

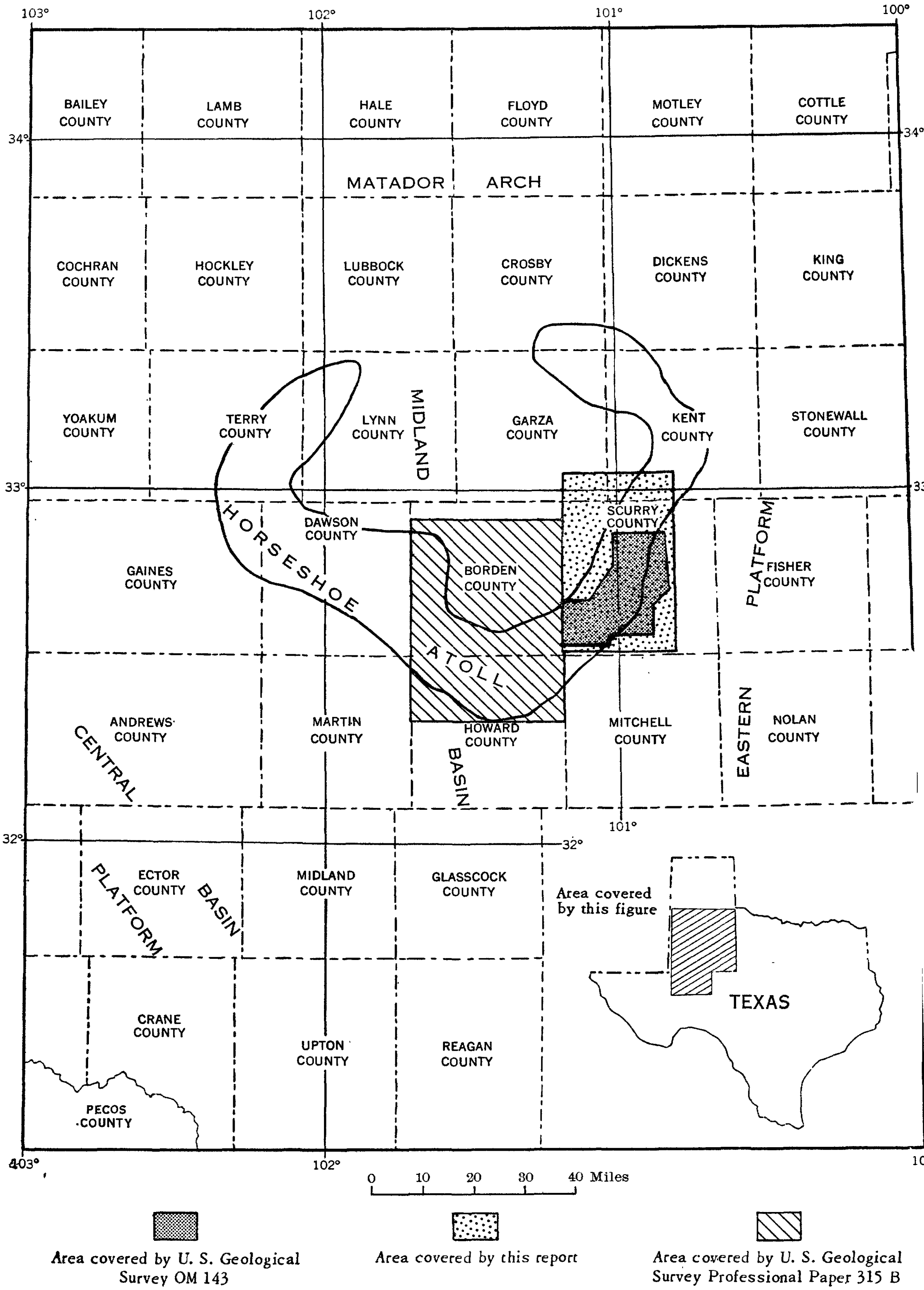


Figure 1.—Index map of part of western Texas showing the area of this report and the location of major geologic features.

riere (1953), and Rothrock and others (1953), which have dealt with some aspects of the geology of the atoll in Scurry County. It includes new information and interpretations based on additional studies of the data used for previous reports and new data acquired after the earlier reports were prepared for publication. The new information on porous zones in the atoll may be helpful in oil-recovery operations, and the new interpretations on the growth of this structure may aid in developing concepts of environmental conditions in the Midland basin during the Pennsylvanian period.

Inasmuch as the Horseshoe atoll is entirely a subsurface feature, the information and interpretations contained in this report are based entirely on the study of cores, well cuttings, radioactivity logs, and electrical logs. Detailed megascopic and petrographic descriptions were made from cores of 79 wells in the mapped area. Where cores were not available, sample logs from wells drilled by rotary methods were used to obtain lithologic data. About 2,750 electrical and radioactivity logs were studied to determine the lithologic characteristics of the atoll and the surrounding rocks and to extend the correlations of rock units into areas in which cores or samples were not available. Age determinations were based on the study of fusulinids in cores from 52 wells in the area. This report incorporates subsurface information available before August 1, 1953.

ACKNOWLEDGMENTS

This investigation was made possible by the cooperation of many organizations and individuals. Cores of wells penetrating the atoll were contributed by the following companies: Chapman & McFarlin Producing Co., Cities Service Oil Co., General Crude Oil Co., Hiawatha Oil Co., Lone Star Producing Co., Montex Drilling Co., Ohio Oil Co., Pan-American Producing Co., Phillips Petroleum Co., Slick-Moorman Oil Co., Standard Oil Co. of Texas, Stanolind Oil and Gas Co., Sun Oil Co., Sunray Oil Corp., Tidewater Oil Co., and Wilshire Oil Co.

R. V. Hollingsworth, of the Paleontological Laboratory at Midland, Tex., furnished fusulinid determinations and other data from wells in this area from which cores were not available. Without much of this data many details of the stratigraphy and geologic history could not have been worked out. Donald A. Myers and Keith A. Yenne, of the U. S. Geological Survey, identified the fusulinids from cores. The Bureau of Economic Geology of The University of Texas, John T. Lonsdale, director, provided financial assistance and laboratory space for this investigation.

METHODS OF STUDY

Initial studies of the Horseshoe atoll in Scurry County made use of standard techniques and methods of subsurface investigation. Conventional electrical and radioactivity logs, representing about 99 percent of the bore holes, were studied and correlated. For a discussion of the electrical log, see Stratton and Ford, 1950; for a discussion of the radioactivity log, see Mercier, 1950. Cores were studied both megascopically and with a microscope. Fusulinids were collected and age determinations were made. The data obtained from these studies were compiled and analyzed in an attempt to find answers to the problems of how the reef grew and why the oil is present within the atoll. This work indicated that there were no diagnostic lithologic or stratigraphic features that could be correlated over large parts of the atoll and used to reconstruct the geologic history.

The microlog, which is a resistivity curve developed primarily to determine relative permeability, was then studied to determine if it could be used to show zonation of porosity or permeability. (For a discussion of the microlog, see Doll, 1950.) An evaluation of the micrologs of wells penetrating the atoll was made by comparing them with quantitative analyses for permeability and effective porosity. These analyses, available for cores from 53 wells, confirmed the usefulness of the interpretations of the micrologs and furnished semiquantitative values for the microlog permeability classifications. The core analyses for permeability and porosity were compared with permeability classifications for corresponding intervals designated on the micrologs by the categories "good", "fair", or "broken" permeability, or with the impervious rock. The comparisons were tabulated according to both millidarcys of permeability and percentages of effective porosity. Cumulative curves were prepared to show the ranges in value of the permeability and porosity for each of the microlog classifications (fig. 2 and 3).

The comparison of the microlog permeability classifications with laboratory analyses of the effective porosity of corresponding cores showed that although each microlog classification includes a wide range of actual porosity values, most of the comparisons give actual values consistent with the terminology of the microlog categories. Thus, 89 percent of the cores of reef limestone classed as "good" on the micrologs showed effective porosity of 4 to 30 percent; whereas only 11 percent showed effective porosity of less than 4 percent. The average effective porosity of all rocks classed as "good" was 10.5 percent. In contrast to these values, 86 percent of the cores classed as "fair" and 70 percent of the cores classed as "broken", showed effective porosities ranging from 0 to 4 percent. The average effective porosities for these categories were 3.2 and 3.8 percent, respectively. In the impervious category 84

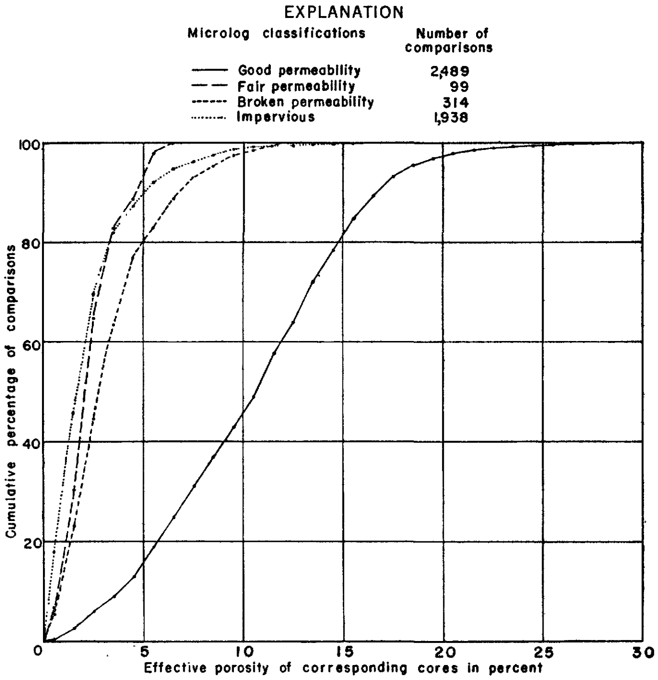


FIGURE 2.—Quantitative evaluation of microlog classifications in terms of effective porosities. Cumulative curves show the comparison of micrology classifications with laboratory analyses of the effective porosity of corresponding cores.

percent of the comparisons showed effective porosities ranging from 0 to 4 percent, and the remaining 16 percent of the comparisons ranged from 4 to 17 percent.

Comparison of the microlog categories with analyses of permeability indicates similar but less definitive results. The cumulative curves in figure 3 show that 70 percent of the rock having a microlog classification of "good" had greater than 1 millidarcy of permeability, whereas only 2 percent of the rock classed as "fair", 35 percent classed as "broken", and 23 percent classed as impervious have greater than 1 millidarcy. The difference is more marked when the high permeabilities known to be the result of cracks and fractures are eliminated, as shown in table 1.

The results of these comparative studies indicate that the microlog permeability classifications of the reef limestone can usually be considered to have semiquantitative porosity values, as shown by the averages in table 1 and the curves in figure 2. Some overlap of porosity values, however, is inherent in comparative studies of the microlog with core analysis. The microlog does not measure actual porosity; it measures the resistivity of the part of the rock invaded by the drilling mud and is therefore a function of the penetration and concentration of the mud filtrate into the rock, the resistivity of the mud, and the resistivity of the host rock.

TABLE 1.—*Quantitative comparisons of microlog classifications with laboratory analyses of effective porosity and permeability*

[For explanation of microlog classification see under "Methods of study," in text]

Microlog classification	Effective porosity		Permeability: All comparisons		Permeability: Comparisons of those permeabilities not resulting from cracks	
	Number of comparisons	Average porosity (percent)	Number of comparisons	Average permeability (millidarcys)	Number of comparisons	Average permeability (millidarcys)
"Good"	2, 489	10. 5	1, 939	19. 5	1, 689	8. 1
"Fair"	99	3. 2	74	. 1	74	. 1
"Broken"	314	3. 8	286	15. 2	240	2. 0
Impervious	1, 938	2. 8	1, 679	3. 9	1, 414	. 7

In most wells, however, these variables were of sufficient constancy so that a range of porosity values for each microlog classification could be established. The cross sections in plate 6 show correlations of porosity data taken from micrologs. The porous limestone shown on the cross sections may generally be considered to have porosity of 4.5 percent or greater.

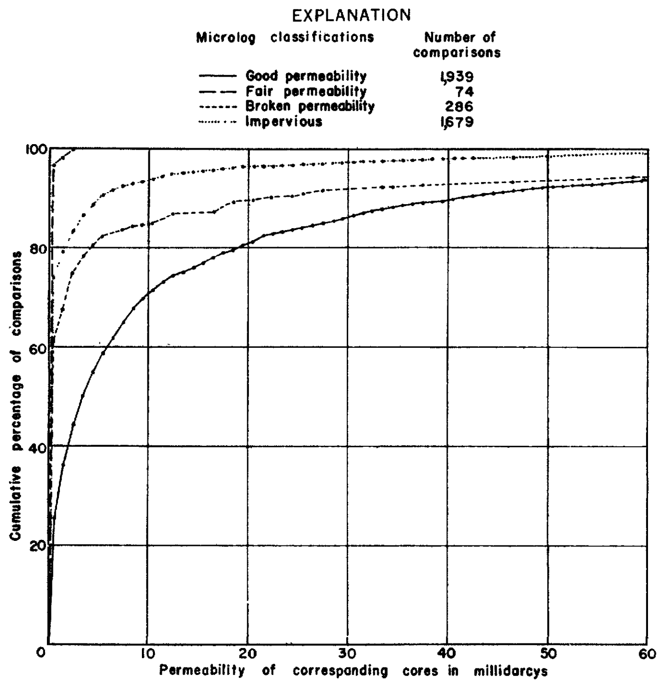


FIGURE 3.—Quantitative evaluation of microlog classifications in terms of permeabilities. Cumulative curves show the comparison of micrology classifications with laboratory analyses of the permeability of corresponding cores.

Micrologs were available for approximately four-fifths of the bore holes and radioactivity logs for approximately one-fourth of the holes. The porosity indicated by the radioactivity logs was computed by methods described by Bush (1950) and Bush and Mardock (1951). Only very slight differences in the exact position of the porous zones were found when both micrologs and radioactivity logs were available for the same bore hole.

The data obtained from study of the micrologs, radioactivity logs, fusulinids, and the lithologic character of the samples were plotted and correlated. Cross sections showing porous zones in the atoll and structure contour and thickness maps were then prepared. The correlations made possible by this technique were the only ones that gave consistent and reliable results.

STRATIGRAPHY

REGIONAL STRATIGRAPHIC RELATIONSHIPS

The Midland basin, which contains the Horseshoe atoll, is bounded on the west by the Central basin platform, on the north by the Matador arch, and on the east by the so-called Eastern platform (fig. 1). The Midland basin contains a relatively thin sequence of rocks assigned to the Pennsylvanian system and a relatively thick sequence of rocks designated as equivalent in age to the Wolfcamp series of the Permian system, as compared with the so-called Eastern platform. In most of the Midland basin, the rocks belonging to the Pennsylvanian system consist of nonfossiliferous shale and siltstone, and those equivalent to the Wolfcamp series of the Permian system consist of shale, sandstone, and fossiliferous limestone. On the Eastern platform the rocks belonging to both systems contain an abundance of fossils and consist of sandstone, shale, and limestone.

The Horseshoe atoll is an accumulation mainly of fossiliferous limestone belonging to the Pennsylvanian and Permian systems in the northern part of the Midland basin. This limestone has been assigned to the Strawn, Canyon, and Cisco age units of the Pennsylvanian system and to the Wolfcamp age unit of the Permian system by Heck and others (1952), and by Rothrock and others (1953). The dominantly carbonate rocks in the atoll have an aggregate thickness of more than 1,500 feet in central Scurry County, on the east side of the atoll, and 3,000 feet in Dawson County, on the south side, as much as 15 times the aggregate thickness of the dominantly noncarbonate rocks of the same ages in adjacent parts of the Midland basin.

Correlation of the Pennsylvanian and Permian rocks in Scurry and southern Kent Counties with those of other areas is given in table 2.

STRATIGRAPHY OF ROCKS BELOW THE ATOLL

Sedimentary rocks underlying the atoll in the area included in this report have been assigned to the Ordovician, Mississippian, and Pennsylvanian systems by geologists of the petroleum industry.

The oldest sedimentary rock underlying this part of the atoll is dolomite belonging to the Ellenburger group, which has been assigned to the Ordovician system (fig. 4). This rock is overlain unconformably by limestone having a maximum thickness of 225 feet. This limestone has tentatively been assigned to the Mississippian system, but inasmuch as conclusive evidence of its age is not available, it is designated in this report as Mississippian(?). Examination of rotary well cuttings shows that this rock is mostly light-gray to light-brown finely crystalline to medium-crystalline limestone containing large amounts of chert; in part it is argillaceous and glauconitic. It is generally overlain unconformably by Pennsylvanian rocks of Bend and of Strawn age. In some places where rocks of Bend age may be absent, rocks of Strawn age may lie on the Mississippian(?).

Rocks below the atoll belonging to the Pennsylvanian system have a maximum thickness of about 1?0 feet in this area. Rocks of Bend age consist of bedded limestone and shale as much as 80 feet thick. These rocks are not everywhere present; they appear to be remnants of a once thicker and more widespread unit. Where present, they lie unconformably on rocks of the Mississippian(?) system. Lateral correlation of these rocks of Bend age is difficult because of wide spacing of bore holes penetrating the beds and because of their similarity to overlying rocks of Strawn age. Rocks of Strawn age below the atoll consist mainly of bedded limestone, but also include many thin beds of shale. This limestone ranges from 40 to 100 feet in thickness. In Scurry County and adjacent areas the bedded limestone grades upward into the reef limestone of the atoll.

STRATIGRAPHY OF ROCKS IN THE ATOLL

The rocks in the Horseshoe atoll belong to the Pennsylvanian and Permian systems, and reach a maximum thickness of approximately 1,700 feet in the area covered by this report. Most of the atoll consists of limestone, but a few thin beds of shale are present. In this paper the term "reef complex" (Henson, 1950, p. 215-216; Newell and others, 1953, p. 48) is used to refer to the entire limestone-shale mass (the Horseshoe atoll), including all detrital limestones and genetically related rocks. The term does not refer to the bedded limestone and shale of Bend and early Strawn age underlying the atoll.

TABLE 2.—*Correlation chart of Mississippian(?), Pennsylvanian, and Permian rocks in Scurry and Kent Counties, Tex.*

[Correlation of this area with other areas is based mainly on paleontological (fusilinid) data]

<table>
<tr><th colspan="2" rowspan="2">System</th><th colspan="2">Horseshoe atoll area (this report)</th><th colspan="2">North-central Texas</th><th>Ardmore basin, southern Oklahoma</th></tr>
<tr><th>Rock type</th><th>Age</th><th colspan="2">Cheney (1940); Moore and others (1944)</th><th>Moore and others (1944)</th></tr>
<tr><td colspan="2" rowspan="2">Permian</td><td rowspan="2">Bedded carbonate and terrigenous rocks</td><td>Leonard</td><td colspan="2">Leonard series</td><td rowspan="2"></td></tr>
<tr><td>Wolfcamp</td><td colspan="2">Wolfcamp series</td></tr>
<tr><td rowspan="7">CARBONIFEROUS SYSTEMS</td><td rowspan="6">Pennsylvanian</td><td rowspan="3">Reef complex (mainly nonbedded limestone)</td><td>Cisco</td><td colspan="2">Cisco series</td><td>Virgil series</td></tr>
<tr><td>Canyon</td><td colspan="2">Canyon series</td><td>Missouri series</td></tr>
<tr><td rowspan="2">Strawn</td><td colspan="2">Strawn series</td><td>Des Moines series</td></tr>
<tr><td>Bedded limestone</td><td rowspan="2">Lampasas series</td><td></td><td rowspan="2">Lampasas series</td></tr>
<tr><td rowspan="2">Limestone and shale</td><td rowspan="2">Bend</td><td rowspan="2">Bend group</td></tr>
<tr><td>Morrow series</td><td>Morrow series</td></tr>
<tr><td>Mississippian</td><td>Limestone [1]</td><td></td><td colspan="2">Mississippian(?) system</td><td>Mississippian system</td></tr>
</table>

[1] Tentatively assigned to the Mississippian system by geologists of the petroleum industry, although conclusive evidence of its age is not available.

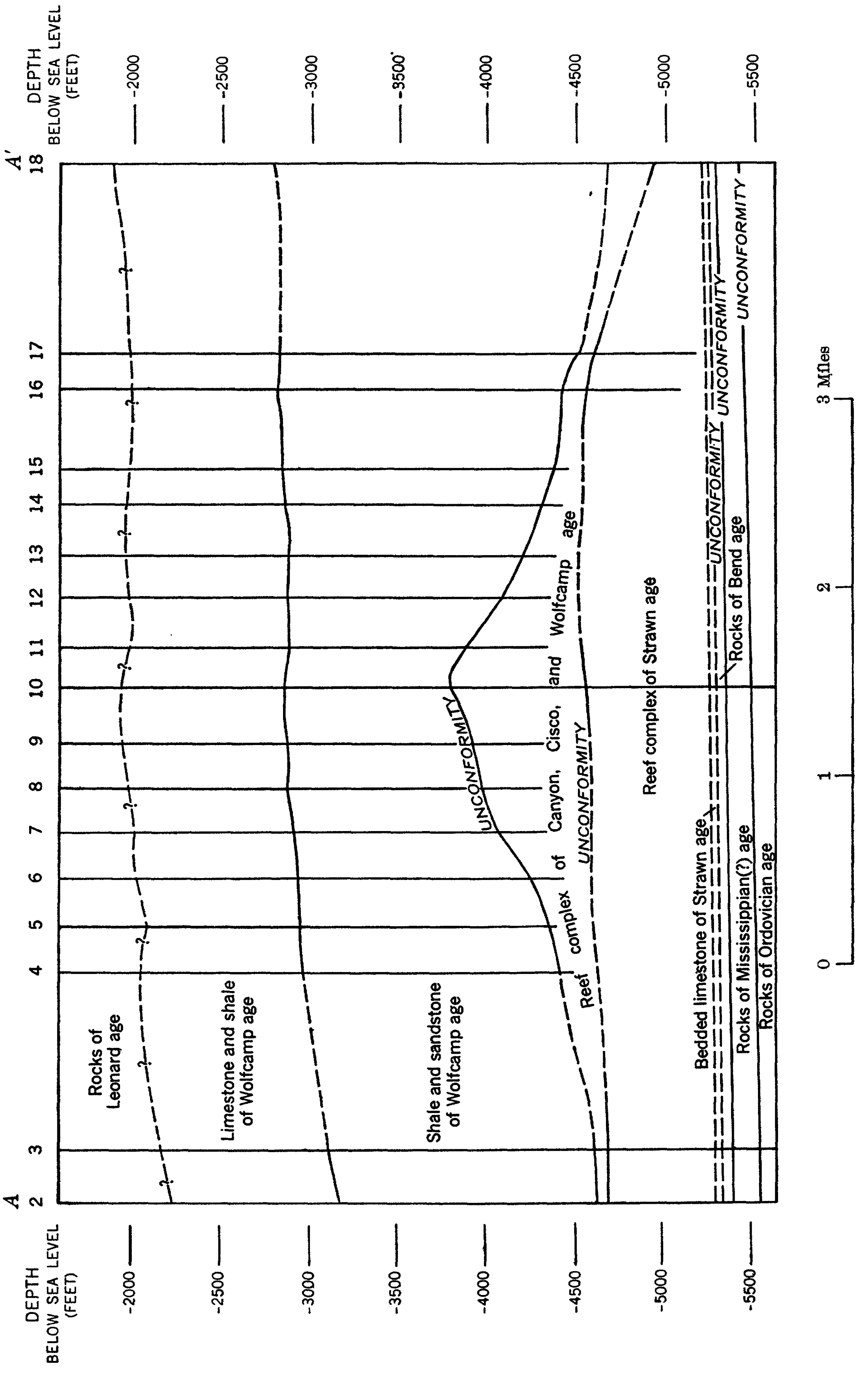


FIGURE 4.—Cross section A-A′ showing stratigraphic relationships of rocks of the Ordovician, Mississippian (?), Pennsylvanian, and Permian systems in Scurry County, Tex.

The rocks of the atoll are considered to be equivalent in age to the Strawn, Canyon, and Cisco groups of the Pennsylvanian and to the Wolfcamp of the Permian (see table 2). Ages of different parts of the reef complex have been determined by study of the Fusulinidae, but the age relationships are complex and the rocks are difficult to correlate because fossils from older parts of the limestone mass have been reworked and incorporated into younger parts of the atoll. For example, fragments of reef limestone that contain fusulinids of Canyon age are too often found in carbonate matrices that contain fusulinids of Cisco age. Careful study of cores of limestone breccia believed to be of Cisco age shows that fusulinids of Canyon age are present only in the fragments, whereas fusulinids of Cisco age are found only in the matrix.

Fragmental debris eroded from higher and older parts of the atoll has accumulated on both flanks of this structure and has been scattered laterally for many miles from the crest of the atoll and locally incorporated into shale of Wolfcamp age adjacent to the atoll. The mixture of older and younger fusulinid faunas has resulted in difficult problems of correlation and age determination of rocks on the flanks of the reef.

Rocks of Strawn age in the atoll have a maximum thickness of 750 feet. The combined thicknesses of these rocks and rocks of Bend and Strawn age underlying the atoll are shown in plate 2. Reef rocks of Canyon age lie unconformably on rocks of Strawn age, and have a maximum thickness of 750 feet. Rocks of Cisco age in the atoll, which lie unconformably on rocks of Canyon age, are locally as much as 500 feet thick, but in many places in the atoll no reef limestone of Cisco age is present. Reef rocks of Wolfcamp age, which reach a maximum thickness of 85 feet in this area, are probably present only in a few isolated places, as indicated by the stratigraphic relations based on fusulinids and other data used for correlation and dating of the atoll.

STRATIGRAPHY OF ROCKS ABOVE THE ATOLL

Most of the rocks immediately surrounding and overlying the Horseshoe atoll are equivalent to the Wolfcamp series of the Permian system. In the eastern part of the area, however, seaward from the atoll, a few hundred feet of shale may be of Cisco age.

The rocks of Wolfcamp age overlying the atoll reach a maximum thickness of more than 3,350 feet. The lower 1,500 feet or less of these rocks consists of shale, siltstone, sandstone, and limestone (fig. 5), whereas the upper part consists entirely of limestone and shale. Lithologic units in the lower 1,500 feet of rocks of

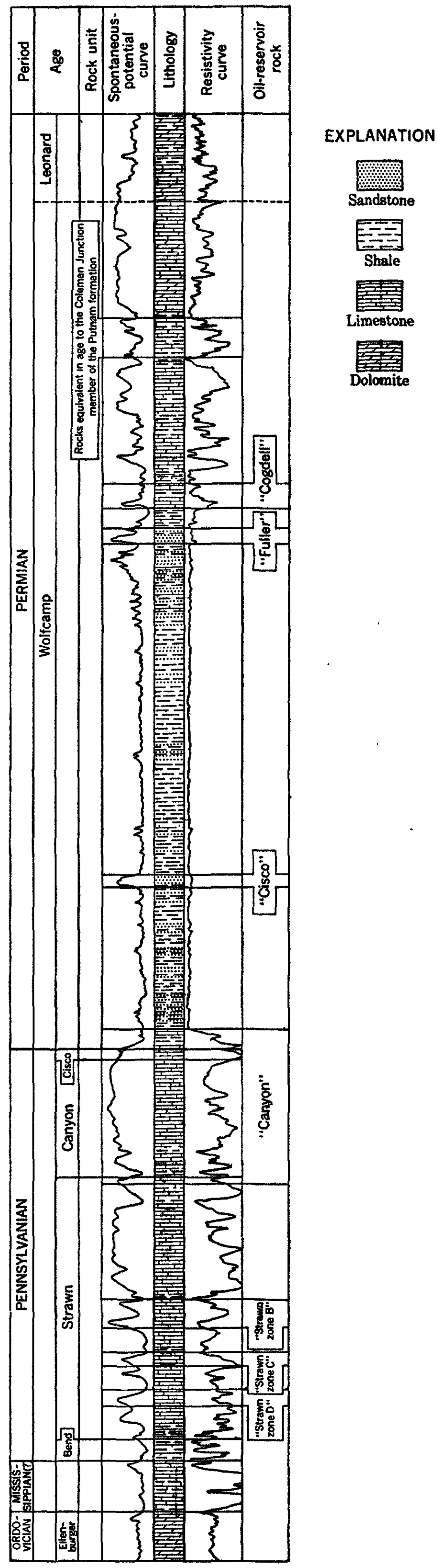


FIGURE 5.—Composite electrical and lithologic log from Scurry and Kent Counties, Tex., showing Ordovician, Mississippian(?), Pennsylvanian, and Permian rocks.

Wolfcamp age are not persistent, and because of the general lithologic characteristics, apparent primary structural features, and general stratigraphic relationships, it seems likely that these rocks were deposited as deltaic sediments. Lithologic units in the upper part are laterally more uniform in thickness and lithology and can be traced throughout the mapped area. The age of the rocks equivalent to the upper part of the Wolfcamp has been assigned by paleontologists on the basis of fusulinid determinations.

Rocks overlying the upper part of the rocks of Wolfcamp age consist of dolomite, limestone, and shale. These rocks have been designated as equivalent to the Leonard series of the Permian system on the basis of fusulinid determinations.

CHARACTERISTICS OF THE REEF ROCK

LITHOLOGIC COMPONENTS

The limestone of the Horseshoe atoll is composed of organic debris bonded by crystalline calcite and by lithified carbonate mud (Rothrock and others, 1953). The organic debris consists of the hard parts of marine animals, most of which have been broken and ground into fragments ranging in size from a few millimeters to submicroscopic particles. These lithified aggregates are classified according to grain size into three types after Grabau, as described by Pettijohn (1949, p. 300-307): calcilutite (limestone composed of particles of clay size), calcarenite (limestone composed of particles of sand size), and calcirudite (limestone composed of particles greater than sand size). Typical specimens of these three lithologic types are shown in plate 3.

The calcilutite consists mainly of submicroscopic particles but commonly contains some coarser unsorted organic debris. Some of the fine material is pulverized organic debris, some may be chemically precipitated ooze, some or most of it may have been precipitated by blue-green algae. Approximately one-third of the core examined consists of calcilutite.

The calcarenite is composed mainly of well-rounded to angular fragments 1/16 mm to 2 mm in diameter. Fragments of reef limestone larger than 2 mm, oolites, and pisolites are present in small amounts. The calcarenite grades into calcilutite and calcirudite. It makes up about one-half of the core examined.

The calcirudite is composed of angular fragments larger than 2 mm in diameter in a matrix of lime sand or lime mud. The matrix commonly contains admixed argillaceous material, and in a few places is composed almost entirely of shale. The calcirudite consists of two main types: organic fragments and fragments of older reef limestone. The finer grained calcirudite is usually composed of both organic and older reef limestone fragments in approximately equal amounts; the coarser-grained calcirudite usually contains more reef fragments than organic fragments. Fragments of reef limestone in most calcirudite are angular and undoubtedly were lithified before breakage and redeposition. Calcirudite is the least common but most distinctive of the three textural varieties of limestone. It is present in about one-sixth of the total footage of core examined.

Sorting and clearly-defined bedding planes are almost everywhere poor to lacking in the limestone. None of the calcarenite or calcilutite in the cores could be definitely traced from well to well; the calcirudite could be traced only when fusulinid and microlog determinations were made. These formal and physical characteristics are discussed in the section on zonation of the atoll.

The shale of the reef complex is dark gray to black because of a high percentage of bituminous material. Locally unsorted carbonate debris and concentrations of pyrite are common. The shale is present as tongues that project into the limestone from the shale surrounding the atoll, as thin lenses and beds which can generally be traced over widespread areas within the body of the atoll, and as stringers from a few millimeters to a few centimeters thick which cannot be traced from well to well. The thin lenses of shale within the body of the reef complex are always present in certain fairly well defined zones, which are discussed in the part of the text on zonation.

A comprehensive description of the lithology of the reef complex has been presented by Bergenback and Terriere (1953).

CHEMICAL COMPOSITION

Chemical analyses of cores from the atoll show that except for argillaceous limestone in certain well-defined zones, the limestone is almost pure calcium carbonate (pls. 4 and 5, well 1).

An average of 2.05 percent of insoluble residue is shown by 135 analyses of core taken from Chapman & McFarlin Producing Company's No. 25 Cogdell well in the reef complex. An average of considerably less than 1 percent of insoluble residue, however, is present in the more porous zones of the reef, as most of the analyses containing over 2 percent of insoluble material are in zones of relatively low porosity. These zones of relatively low porosity have time significance when correlated with paleontological data. Thus, it appears that the high amount of insoluble residue in the less porous of these zones was the result of an increase in terrigenous material coming into this area during certain times.

POROSITY AND PERMEABILITY

The effective porosity of the reef limestone, determined by core analyses, generally ranges from almost zero to 30 percent, and averages about 6 percent when viewed megascopically. Openings in cores of the limestone appear to range in size from tiny openings of pinpoint size to vugs 5 cm in diameter, but most of the openings are smaller than 3 mm in diameter.

Originally, the clastic limestone in the atoll was probably very porous. It is probable that most of the primary interstitial pore space was subsequently filled with calcium carbonate cement. Eventually, leaching formed the secondary porosity now present in the limestone. Only a relatively insignificant amount of primary porosity exists in the reef limestone, such as that found in the hollow interiors of some shells.

The permeability of the reef limestone, as determined by laboratory analyses, generally ranges from a few hundredths to 85 millidarcys with an average of about 4.5 millidarcys (measured horizontally to air). Permeability measured vertically to air has a range of values that is considerably less. This average and range of values does not include those relatively high permeabilities which are known to have been caused by open cracks, fractures, and joints in the limestone.

ZONATION OF THE ATOLL

Rothrock and others (1953) in a discussion of the zonal arrangement of the reef complex in Scurry County presented a map showing contours on the top and the base of an "intermediate zone." This "intermediate zone" was based on differences in lithologic character and effective porosity of the reef limestone. The zone as presented in that publication was a reasonable interpretation on the basis of the data which were then available and the criteria that were used. Additional data and detailed study have indicated, however, that as many as three distinct zones of low porosity were included as part of the "intermediate zone," and that the relationships of this zone to the standard geologic time units were not entirely correct. In the following discussion, therefore, some revisions of the zonation of the reef complex have been made.

Two distinct types of zones appear to be present in the reef complex: zones consisting of relatively large amounts of rocks having low porosity and zones consisting of relatively large amounts of rocks having high porosity. Both types of zones, as shown in cross sections *B-B′* through *E-E′* (pl. 6), are based on porosity determinations from micrologs and neutron curves, the stratigraphic distribution of shale and calcirudite, and age determinations. The utility of the microlog as an indicator of semiquantitative porosity values of the reef limestone has been previously discussed in the section on methods of study.

Zones of low porosity consist mainly of reef limestone of low effective porosity (less than 4.5 percent). Study of cores and insoluble residues indicates that zones of this type contain one or more thin beds of shale and more argillaceous material than the zones of high porosity. Calcirudite consisting of older reef fragments makes up as much as 60 percent of the rock.

Zones of high porosity consist mainly of reef limestone of high effective porosity (greater than 4.5 percent). They contain neither calcirudite made of older reef fragments nor beds of shale; they have a relatively small amount of insoluble residue (usually less than 1 percent).

Faunal horizons which are plotted relative to the porosity zones show that these zones of low porosity and high porosity are definitely related to the standard units of the Pennsylvanian and Permian(?) systems. The cross sections *B-B′* through *E-E′* (pl. 6) show the relationships of effective porosity to thin beds of shale and to age. Evidence indicates that rocks containing fusulinids typical of the Canyon group have two zones of low porosity and two of high porosity, that rocks containing fusulinids typical of the Cisco group have two zones of low porosity and one zone of high porosity, and that rocks containing fusulinids typical of the Wolfcamp series have but one zone of low porosity.

Some zones can be traced throughout the area covered by this report; others have limited distribution, either having been eroded in places or never deposited. The difference in these low-porosity and high-porosity zones is the result of a varied and complex geologic history which is discussed in the section on history of the reef complex. Economic aspects of the zonation are covered in the section on oil and gas.

PALEONTOLOGY

AGE OF THE ATOLL

The presence of several species of fusulinids belonging to the genus *Fusulina* indicates that much of the reef limestone is of Strawn age. Reef limestone of Canyon age is indicated by the presence of *Triticites* cf. *T. irregularis* (Schellwein and Staff) and other species of *Triticites* which are typical of the Canyon group in outcropping rocks of north-central Texas. Fusulinids of Cisco age are represented by forms which belong to the group of *Triticites ventricosus* (Meek and

Hayden). *Dunbarinella* sp. has been found. A form of *Triticites* related to *Triticites ventricosus* (Meek and Hayden) is present in most of the cores that contain fusulinids typical of the Cisco group. This species of *Triticites* is apparently conspecific with a form that is abundant in the Wayland shale member of the Graham formation in north-central Texas.

Fusulinids of Wolfcamp age were found in cores from several wells. The diagnostic fusulinid *Schwagerina* sp. (now known as *Pseudofusulina* sp.), was reported (Heck, Yenne, and Henbest, 1952) from the Wilshire Oil Co.'s No. 8 Lunsford well (pl. 5, well 43). As previously stated, age determinations of parts of the atoll containing large amounts of calcirudite have been complicated by the presence of reworked fusulinid faunas.

FAUNAL ASSOCIATIONS

The faunal associations and ecology of the reef were determined from a megascopic study of cores from 78 wells. The major faunal groups in the atoll are echinoderms, foraminifers, brachiopods, bryozoans, coelenterates, and mollusks. The commonest group is the Echinodermata, which were noted in about 80 percent of the core footage. The echinoderms are represented by abundant crinoid columnals, by a few crinoidal calyx plates and arm segments, and by echinoid spines.

Fusulinids were observed in about 75 percent of the core footage. Foraminifera other than fusulinids were noted in about 10 percent of the footage. This figure is probably low as many of the smaller Foraminifera may have been overlooked in the methods of study that were employed. Numerous small, irregular tubelike bodies resembling *Calcitornella* have been found in the finer grained parts of the reef limestone.

Brachiopods were noted in about 50 percent of the core footage. Productidae, Athyridae, and Rhynchospirinidae are common. Discinoid brachiopods are fairly common in the argillaceous beds in the atoll, but have not been noted elsewhere. Bryozoa were found in about 25 percent of the core footage. The large amount of bryozoan debris observed in thin sections suggests that they were probably more numerous than megascopic descriptions indicate. Fenestellid bryozoans are commonest, although encrusting and ramose types are present.

Coelenterates are of minor importance in the atoll, although they were found in about 10 percent of the core footage. They are represented by tetracorals that resemble *Lophophyllidium* and colonial corals that resemble *Chaetetes*.

Mollusca were observed in about 10 percent of the core footage. Gastropods are the most common and have a random distribution. Ammonoids are most common in the shale and argillaceous limestone, but they are present also in the purer limestone. Pelecypods, represented by the Pectinacea, generally are present in the shale.

Other faunal groups were observed in less than 1 percent of the core footage. These groups consist of the arthropods, represented by ostracodes and very rarely by trilobite fragments; vertebrates, represented by fish scales; Porifera, represented by sponge spicules; and conodonts.

Algae may have been present, but only a few identifiable traces have been observed. Bergenback and Terriere (1953, p. 1017) state that no evidence of algae was found in the reef in Scurry County. However, reevaluation of the organic content of the core which they studied suggests that some of the calcareous material may be of algal origin. Elliot and Kim (1952) in a study of core from a well in Terry County, Tex., indicated algae as being the most abundant of all the organisms present in the reef complex.

STRUCTURE

The sedimentary rocks underlying the atoll in this area have a general west-southwest dip averaging about 30 feet per mile. This tilting is best portrayed by the upper surface of rocks assigned to the Mississippian (?) system (pl. 7). Structural relations of the rocks throughout the northern part of the Midland basin suggest that the time of most of the tilting was post-Paleozoic.

The structure of the rocks of the atoll is obscured by the complex distribution of rock types, resulting mainly from nontectonic processes. The progressive development of the atoll, as shown by contours on the tops of rocks of the Strawn age (pl. 2) and Canyon age (pl. 8), and on the top of the atoll (pl. 1), is mainly a result of the interaction of deposition and erosion. Each of the structure-contour maps shows a similar type of irregular surface, upon which younger sediments were deposited. A general west-southwest tilting has been superimposed upon these surfaces. The thin beds of shale within the atoll, some of which have wide lateral extent, reveal little deformation except for the effects of differential compaction and regional tilting.

The contours on the top of rocks overlying the atoll (pl. 9) show the effects of differential compaction and regional tilting of the post-reef rocks. The top of rocks approximately equivalent in age to the Coleman Junction limestone member of the Putnam formation was selected for contouring because it is the oldest postreef bed that can be traced throughout the mapped area. In the southwestern part of the area this bed dips steeply in a westerly direction and there the effects of compaction are subordinated to the effects of initial dip and westward tilting.

Anticlinal structures in the beds of sandstone and limestone, which are stratigraphically between the reef complex and the Coleman Junction limestone member, were formed by differential compaction over the Horseshoe atoll.

Structures of the rocks which are exposed at the surface do not reflect the topography of the buried atoll. Some structures in rocks of post-Wolfcamp (Permian) age in the subsurface, however, may have been partly formed by differential compaction over the atoll.

GEOLOGIC HISTORY

APPLICABILITY OF REEF DEFINITION TO THE HORSESHOE ATOLL

Because of certain characteristics of the Horseshoe atoll, applicability of the terms "reef" and "atoll" to this carbonate mass may be questioned. The relationships of the different lithologic types in the Horseshoe atoll are unlike those of any reef described in the literature. Rock composed of a growth lattice of organisms was not observed; only detrital limestone has been noted. In areas that would commonly be considered reef core, calcirudite is found. Furthermore, the slopes on the flanks of the Horseshoe atoll are generally low compared to those of the so-called Capitan reef of western Texas and New Mexico or the Quaternary reefs in the Pacific.

MacNeil (1954) has discussed the many definitions of reef and bioherm that have been proposed. He believes (p. 386) that the dictionary definition of a reef should be maintained—that is, "a rocky elevation or knoll on which there is a depth of water of 6 fathoms or less at low water." Further, MacNeil does not agree with the definitions of a reef or organic reef as proposed by Wilson (1950, p. 181), Twenhofel (1950, p. 183), Lowenstam (1950, p. 430), or Cloud (1952, p. 2125). *Bioherm* is restricted by MacNeil (1954, p. 390) to those structures which are essentially growth lattices, ancient or modern.

MacNeil (1954, p. 389) defines an organic reef as—

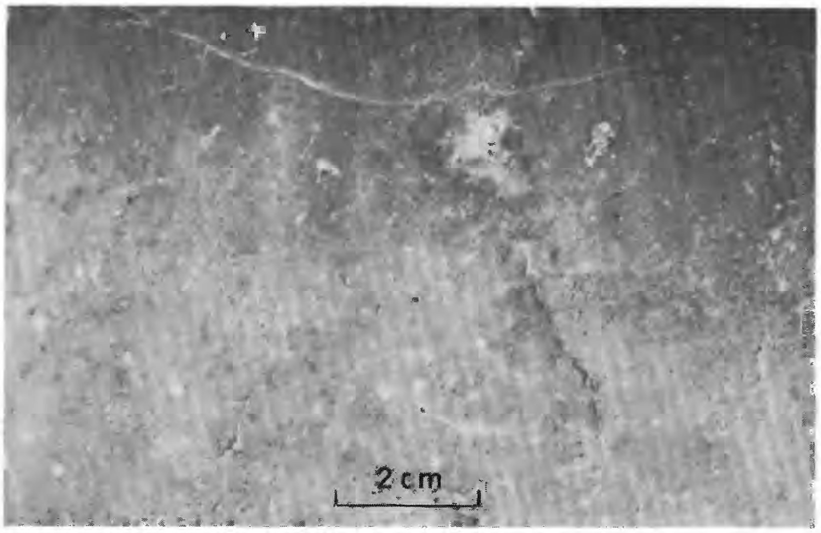
> a rigid structure—composed of the calcareous skeletons of: 1) colonial and commensal animals or plants, whether algae, corals, stromatoporoids, mollusks, bryozoa, or others, interlocked or cemented together by growth; 2) all detrital materials derived from the breaking up of the colonial organisms (which might be unconsolidated when deposited but which may become indurated later); and 3) the remains of organisms which normally live in, on, or near the organic lattice, such as foraminifers, crabs, echinoids, and other forms, which are added either to it or to the detrital deposits—which grows independently of and builds up at a rate greater than all surrounding types of sediments (except where becoming part of the reef body), and maintains its upper growing or depositional surface at or near the level of the sea (some parts of which may be exposed at low tide). During periods of emergence the upper surface of a reef may become a surface of planation due to solution and erosion. A surface of planation may result without emergence where storm-cast detritus has become cemented to the reef and has been eroded subsequently. An organic reef may thus consist of a bioherm alone, or of a bioherm and detrital materials derived from it and other organic remains normally brought to it, which together, by growth and accumulation, and without other outside assistance, maintain a prominence close to sea level. A living reef may, therefore, extend upwards far above the level of contemporaneous surrounding sediments, and a reef in the geologic column may have great vertical dimensions compared with surrounding sediments and be separated from them by nearly vertical or greater than vertical boundaries. Detrital materials derived from the biotic community, which do not contribute to the building of the near sea level component, such as those settling in the lagoon or on the steep submarine slope, though not reef in the navigator's sense, are nevertheless an important part of the reef structure, and in a buried reef would be more related in composition, texture, porosity, and genesis to the reef than to any surrounding rock.

MacNeil (1954, p. 399) in the same paper also gives a more concise definition of an organic reef:

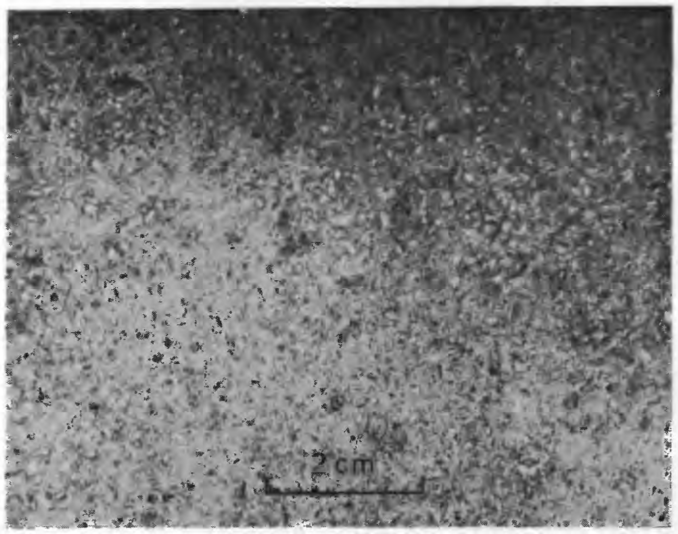
> . . . a reef formed by living organisms and their remains. An organic reef may consist of a bioherm alone, particularly if it barely reaches the surface, or if there is a broad reef flat, only the outer edge may be a bioherm, the remainder consisting of detrital materials derived from the bioherm.

It seems to this writer that the definitions of reef, bank, organic reef, organic bank, and bioherm, as given by MacNeil (1954), are the most useful definitions recently proposed for these terms. In considering whether or not the Horseshoe atoll may properly be called a "reef", it is instructive to consider the characteristics of the atoll in relation to MacNeil's criteria for an organic reef, namely: rigid structure; presence of colonial and commensal animal or plants interlocked or cemented together by growth; existence of detrital materials derived from breakup of the colonial organisms; and presence of remains of organisms which normally live in, on, or near the organic lattice.

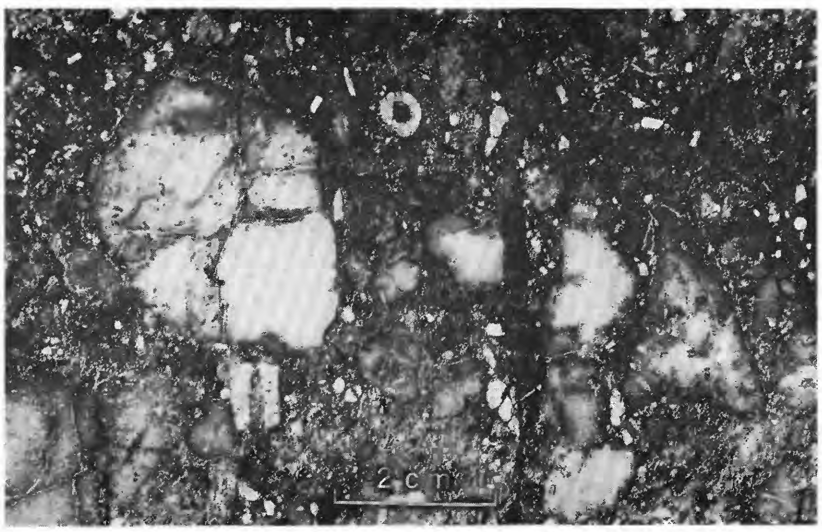
The Horseshoe atoll was most likely a rigid wave-resistant structure. During the Late Pennsylvanian and early Pérmian it was a prominent submarine feature having its crest at times as much as 1,550 feet above the surrounding floor of the Midland basin (pls. 1, 2, and 8). Thick masses of calcirudite, composed of fragments of preexisting reef rock, on the seaward or convex side of the atoll indicate that the reef complex was subjected to fragmentation by a powerful erosional agent. Inasmuch as the atoll accumulated in a marine



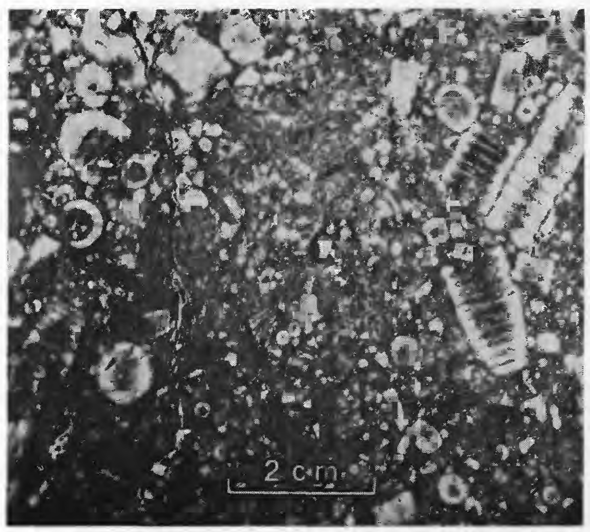
A. CALCILUTITE.



B. CALCARENITE.



C. CALCIRUDITE CONSISTING OF PREEXISTING REEF LIMESTONE FRAGMENTS.



D. CALCIRUDITE CONSISTING OF ORGANIC FRAGMENTS.

CORE FROM THE HORSESHOE ATOLL IN SCURRY COUNTY, TEX., ILLUSTRATING ROCK TYPES

environment, it seems most logical to attribute this fragmentation to the action of strong waves, and it would seem probable, therefore, that the atoll was a rigid mass of firmly-cemented rock.

The first constituent of an organic reef according to MacNeil's definition—the calcareous skeletons of colonial and commensal animals or plants—is represented in the Horseshoe atoll by crinoids, bryozoans, corals, brachiopods, mollusks, and possibly by algae. These fossil remains, however, were nowhere observed as being interlocked and cemented together by growth (unless some of the colonial corals having growth form similar to that of *Chaetetes* might be regarded as such—and these were very rare). Entire skeletons of corals (including tetracorals), brachiopods, mollusks, and individual bryozoans are present in the core. Entire skeletons of crinoids were not observed.

The second constituent of an organic reef—the detrital material derived from the breaking up of the organisms—forms most of the atoll. As previously noted, the limestone of the Horseshoe atoll is composed of organic debris bonded by crystalline calcite and by lithified carbonate mud. This organic debris, generally ranging from submicroscopic to a few millimeters in grain size, appears to be composed largely of crinoid and bryozoan fragments. Brachiopod, coral, and mollusk fragments are present in lesser amounts. However, additional petrographic study and identification of the detrital material is needed for an accurate quantitative appraisal of the organic content.

The third constituent of an organic reef—the remains of organisms which normally live in, on, or near the organic lattice—is represented by fusulinids and other Foraminifera, which were observed in about 75 percent of the core footage. In places, the fusulinids constitute all of the rock except for the matrix of crystalline calcite cement.

It would appear from observing the organic content of the reef complex that the requirement of a lattice or rigid organic framework is not met. MacNeil has recently noted, however, the predominance of detrital materials over growth lattice in modern atolls. He says (1954, p. 387):

> It is now known that, contrary to long-standing belief, the growth lattice of living organisms may be a subordinate constituent of atolls and other large reefs, and that detrital material derived by the forced movement and breaking up of algae and corals and the frequently more abundant skeletons of Foraminifera are a major if not a predominant part of modern reefs.

Ladd (1950, p. 204) has also called attention to the small amount of rigid framework in some larger recent reefs.

> In recent years—having examined some of the larger recent reefs and having done some diving and dredging in their lagoons and on their outer slopes—the writer has come to realize that though the rigid framework is a very essential part of a reef—like the walls and rim of a pail that holds water—it may quantitively be very unimportant and only in rare elevated reefs is it preserved and satisfactorily exposed.

Fairbridge (1950, p. 330) noted the same relationship in the reefs of Australia.

> In both living and ancient reefs the proportion of actual colonial corals grown *in situ* is extremely small in relation to the enormous quantities of "coralline" sedimentary debris.

MacNeil (1954, p. 388) notes the presence only of detrital material in raised reef platforms in the northern Marshalls.

> In the northern Marshalls there are many remnants of elevated reef flats, most of which form the cores of vegetation-covered islands. Strata of different texture, hardness, and weathering properties were observed in many of these raised reef platforms. All were composed of detrital materials.

Elsewhere, MacNeil states (1954, p. 391):

> As a result of his later work, however, Ladd became one of the first to realize that reef rock does not always contain recognizable corals or algae. Ladd and Tracey (1949) came to the conclusion that even some noncoralliferous limestones might be of reef origin and that they could have been bounded on the outer side by biohermal structures that would naturally be the first part to be eroded away on exposure.

Twenhofel noted the presence of fragmented organic material in ancient reefs. He says (1950, p. 183):

> After the deaths of the reef-builders, their constructions may be riddled by boring organisms in their search for food or to construct cavities in which to live. In this way the framework of the structure may be greatly impaired and reduced in part to calcareous sand and mud, and this destruction may be so complete that the resulting materials may show little evidence of once having been a rigid framework.

Elsewhere, Twenhofel and Shrock (1935, p. 245–247) state, concerning Bryozoa:

> In the Ordovician of some parts of the world certain genera (*Batostoma*) are responsible for the construction of low bioherms.
>
> Indirectly, the bushy zoaria must have served an important part in deposition on certain bottoms by checking the currents and causing deposition of materials in suspension or in solution. On the steep peripheral slopes of ancient coral reefs, where they appear to have grown in great profusion, they almost certainly played an important role in intercepting the reef mud and sand. . . . It is considered probable that predators and scavengers were responsible for much of the fragmentation and in some cases almost complete destruction of delicate zoaria which are apparent among fossil accumulations.

It is obvious from these statements that many modern reefs and atolls consist largely of detrital reef rock. It is believed by this writer that the Horseshoe atoll had a complex geologic history, probably involving numerous eustatic changes of sea level. If such were true, then the living bioherm would have been repeatedly destroyed, forming detritus and leaving only a fossil structure having little or no organic lattice. Further, if cores were available from every well drilled into the Horseshoe atoll, only a relatively insignificant amount of the reef rock would be represented. As it is, cores from only 78 wells in the mapped area were studied—which is approximately 70 percent of all cores taken from the Horseshoe atoll. Thus, the remains of any framework could easily have been missed because of lack of adequate sampling of the atoll.

Although no growth lattice was observed in the rocks of the Horseshoe atoll, the writer believes that the structure may be an ancient organic reef as defined by MacNeil. Organic lattices were probably present, but they were destroyed by the repeated attack of waves or other erosive agents, as a result of repeated changes of sea level, and by scavengers and boring organisms. If any growth lattice is still preserved, it forms an insignificant part of the atoll.

REEF GROWTH AND SEDIMENTATION

Any analysis of the history of the Horseshoe atoll must consider the following facts:

1. The atoll is a buried carbonate mass having hundreds of feet of relief and is surrounded and overlain by younger terrigenous rocks.
2. The reef complex consists largely of detrital reef limestone.
3. The flanks of the atoll dip more gently than those noted in most reefs.
4. Limestone debris is spread laterally at least 15 miles from the crest of the atoll into terrigenous rocks that are younger than the reef complex.
5. Fusulinid faunas indicate reworking of older rocks into younger sediments.
6. Large amounts of calcirudite, composed of fragments of older reef rock, are present at certain stratigraphic positions in parts of the atoll that would normally be considered the reef core.
7. Terrigenous rocks of Wolfcamp age lie on an irregular surface, which is developed on reef limestone of Strawn, Canyon, Cisco, and Wolfcamp age.
8. Reef limestone of Wolfcamp age in the atoll is in contact with reef rocks of Strawn, Canyon, or Cisco age at different places.

Cyclical deposition in the Pennsylvanian and early Permian has been described by many writers. Wanless and Shepard (1936), Wanless (1950), and Wanless and Patterson (1951) have interpreted these cycles as being related to eustatic changes of sea level. The rocks of Pennsylvanian and Wolfcamp age of north-central Texas exhibit similar cyclic deposition in which the marine deposits of each cycle were generally thicker and the nonmarine deposits thinner than those in eastern United States (Lee, Nickell, Williams, and Henbest, 1938).

Burnside (in press) considers the history of the Pennsylvanian and Wolfcamp in the southern part of the Horseshoe atoll as a time of cyclical growth and deposition controlled by eustatic changes of sea level. The geologic history as presented by Burnside appears to be applicable also to the eastern part of the atoll.

Two interpretations of reef growth can be postulated. The first maintains that topographic relief of the atoll was caused by rapid subsidence below the biotic zone, and thus normal reef growth was restricted to smaller areas along the crestline of the atoll. However, this interpretation does not account for these facts:

1. Large amounts of calcirudite composed of older reef rock, which are present at certain stratigraphic positions in the atoll.
2. Reworked fusulinid faunas of older reef rocks which are included with those of younger reef rocks.

The second interpretation is one which maintains that the topography of the atoll resulted from erosion, modified by reef growth, which left the present hills, depressions, and valleys on the surface of the atoll. The sequence of events appears to have been alternating submersion and exposure of the reef complex and may be summarized as follows:

1. Normal reef growth and deposition took place just below sea level.
2. Sea level was lowered and the atoll emerged.
3. The islands (emergent atoll) were subjected to wave action and subaerial erosion; large wave-cut benches and a topography of hills and valleys were formed. Leaching of the older rocks by circulating meteoric waters possibly aided by humic acids caused the development of secondary porosity. Terrigenous clay-sized materials and reef breccia were deposited on the wave-cut benches and other submarine features. Normal reef growth was limited to the flanks of the islands.
4. Sea level rose, covering most or all emergent parts of the atoll. As the water level rose, terrigenous muds and reef breccia continued to be deposited in lessening amounts on the wave-cut benches and in the low areas of the eroded surface. Normal reef growth became more widespread as marine life flourished. As much as several hundred feet of reef limestone accumulated, the most pronounced growth usually taking place on the old

hills. When all islands were below sea level, normal reef growth continued across the entire atoll.

The foregoing hypothesis appears to explain the anomalous relationships pointed out at the beginning of this section, and it seems that the Horseshoe atoll may have originated in this way.

DEVELOPMENT OF THE HORSESHOE ATOLL

The oldest known rocks of Pennsylvanian age in the area are those of Bend age. An unknown thickness of these rocks was eroded before the deposition of the rocks of Strawn age, leaving scattered patches of rocks of Bend age which formed hills having as much as 80 feet of relief. During Bend time, particles ranging from clay to pebble size and terrigenous particles of clay size were deposited as evenly bedded sediments on limestone of Mississippian (?) age. The exact time relationships between the rocks of Bend age and the rocks of pre-Strawn (Pennsylvanian) age which crop out at the surface in central Texas and elsewhere are unknown. However, they may be equivalent in age to the Lampasas series (Moore and others, 1941).

During early Strawn time, carbonate particles ranging from clay to sand size were deposited initially on rocks of Bend and Mississipian age. These nonreef sediments consist of 40 to 100 feet of bedded limestone and thin beds of shale.

Reef growth began during early Strawn time and appears to have continued cyclically throughout the remainder of the Pennsylvanian period and into the early Permian. This is indicated by the zones of low and high porosity which may have been the result of changes of sea level during Pennsylvanian and early Wolfcamp time.

In Scurry County at least four major reef cycles are indicated by rocks of Strawn age, two by rocks of Canyon age, and two by rocks of Cisco and Wolfcamp age. Undoubtedly, these major reef cycles include several minor cycles, but because of the complexity of the atoll rocks and lack of adequate information, these cycles cannot be defined. Sufficient data are not available for a detailed description of events during the time of deposition of rocks of Strawn age. However, a sequence of events probably took place similar to that occurring during later Pennsylvanian time.

At the beginning of Canyon time, sea level was lowered and the atoll emerged to an unknown height. The emergent atoll was subjected to extensive wave action and subaerial erosion. Fragments were broken from the older reef rock and were distributed to the lower areas of the atoll. Terrigenous clay-sized material entered the area, probably because the lowered water level brought the continental land areas nearer to the atoll. The environment at this time was unfavorable for prolific marine life; hence, relatively little normal reef growth occurred. The rocks of Strawn age immediately underlying the eroded surface were leached by circulating meteoric waters containing humic acids from plant life on the emerged parts of the atoll. Eventually a relatively flat surface was formed along the crestline of the atoll. During early Canyon time, sea level rose and the atoll was again submerged. Terrigenous clay-sized particles entered the basin in lessening amounts. Smaller areas were subjected to wave arosion; therefore, there was less distribution of fragments from older reef rock. Soon the entire area was again below sea level and normal reef growth resumed.

A similar sequence of events appears to have occurred during late Canyon time, and twice during Cisco and early Wolfcamp time. During the time of reef accumulation, relatively little terrigenous material was being deposited in the adjacent areas of the Midland basin. In late Cisco time, however, mud and silt may have been deposited in some of the deeper parts of the sea.

During early Wolfcamp time terrigenous sediments which probably were in and near an advancing delta entered the area possibly from the northeast and progressively smothered reef growth toward the west and southwest. Many parts of the reef complex were well above the sea floor during the encroachment of the delta, as indicated by the presence of calcirudite lenses projecting from the older reef complex into the younger deltaic rocks. Eventually, these sediments covered all of the dead atoll, creating an impervious seal over the reef complex, and forming traps for oil accumulation.

During late Wolfcamp time, subsequent to the deposition of the terrigenous material, carbonate sediments containing a small amount of clay-sized terrigenous material were laid down in fairly uniform beds.

OIL AND GAS

HISTORY OF DEVELOPMENT

The first hole drilled to rocks below those of Leonard age in a test for oil in the area described in this report was Humble Oil & Refining Company's No. 1 Davis well (pl. 5, well 93). This hole was drilled to a total depth of 8,027 feet (5,614 feet below sea level) in the Ellenburger group (Ordovician) and was abandoned in January 28, 1947.

The first well in the mapped area that produced oil from the Horseshoe atoll was Sun Oil and Humble Oil and Refining Cos.' No. 1 Schattel well (pl. 5, well 94), which was completed on July 16, 1948. By the end of that year four widely separated wells were producing oil from the reef rock. Numerous other oil discoveries in the atoll were made in 1949 and subsequent years. Exploitation of the fields producing from the reef rocks continued at a rapidly increasing pace through 1950. Since 1950 the number of holes drilled each year has decreased, but exploration still remains at a high level.

On August 1, 1953, oil was being produced from 26 reservoirs at four stratigraphic positions in the atoll; one additional reservoir had been abandoned. Production of oil from the reservoirs (pl. 5) is tabulated below.

TABLE 3.—*Oil production from reef limestones*

[See pl. 5]

Year	Wells producing at end of year	Oil production (barrels)	
		Yearly	Cumulative
1948	4	24, 530	24, 530
1949	315	4, 249, 645	4, 274, 175
1950	1, 641	38, 112, 461	42, 386, 636
1951	1, 952	49, 749, 313	92, 135, 949
1952	2, 065	47, 393, 572	139, 529, 521

Oil was first produced from nonreef rocks of Wolfcamp age in April 1950. Most oil discoveries in the nonreef rocks of Wolfcamp age have resulted from studies of subsurface data obtained during development of the fields producing from the reef rocks.

On August 1, 1953, oil was being produced from eight reservoirs at four stratigraphic positions in the rocks of Wolfcamp age overlying the atoll.

Production of oil from these reservoirs (pl. 5) is tabulated below:

TABLE 4.—*Oil production from nonreef rocks of Wolfcamp age*

[See pl. 5]

Year	Wells producing at end of year	Oil production (barrels)	
		Yearly	Cumulative
1950	3	52, 060	52, 060
1951	48	467, 614	519, 674
1952	125	2, 045, 340	2, 565, 014

Free gas caps do not exist in any of the reservoirs in the atoll nor in the postreef rocks of Wolfcamp age. The only gas production has been solution gas incidental to oil production and estimates of the quantities produced are not available. Oil is also produced in this area from rocks of the Ordovician and Mississippian (?) systems and from those of Leonard and Guadalupe ages of the Permian system; discussion of the fields and reservoirs in these rocks is beyond the scope of this report. For a more comprehensive summary of the distribution and production of oil in the area, see Stafford (1957).

RESERVOIRS

Oil is produced from four stratigraphic positions within the Horseshoe atoll. These are commonly called the Canyon and Strawn zones *B*, *C*, and *D* reef-reservoir rocks (fig. 5). Production is from reef limestone of Strawn, Canyon, Cisco, and Wolfcamp age in the so-called Canyon reef reservoirs, and from reef limestone of early Strawn age in the so-called Strawn zones *B*, *C*, and *D* reservoirs. The oil in the so-called Canyon reservoirs is trapped in the higher parts of the atoll, which are overlain by impervious shale (fig. 4). The ages of the rocks in which the oil is found differ considerably from place to place, but in general the oil-water interface is in progressively older rocks to the northeast.

The reasons for most of the traps forming the so-called Strawn zones *B*, *C*, and *D* reservoirs have not been determined. Inasmuch as all oil accumulations in the lower reservoirs are in porous zones which are overlain by younger rocks of the atoll, an updip decrease in porosity and permeability is the factor controlling accumulation at some places; other traps may be a combination of porosity changes and anticlinal structures involving zones of porous and relatively nonporous reef rock.

Oil is produced from four stratigraphic positions in nonreef rocks of Wolfcamp age overlying the Horseshoe atoll. These are commonly called the Cisco, Cogdell, Fuller, and Wolfcamp reservoir rocks (fig. 5). The traps forming the so-called Cisco sandstone, Cogdell limestone, and Fuller sandstone reservoir rocks in the Wolfcamp series overlying the atoll were apparently caused by flexures resulting from differential compaction of the terrigenous deposits over the Horseshoe atoll. In the Cisco sandstone of local usage, however, some accumulation of oil was caused by the lenticular nature of some of the porous sandstones within the body of the bituminous shales of Wolfcamp age. The oil in the so-called Wolfcamp limestone reservoir accumulated in traps caused primarily by updip decrease in permeability and porosity.

SOURCE OF THE OIL

The source of the oil in the reef reservoir is a matter of much importance in the search for petroleum. The oil could not have originated within the atoll inasmuch as the porosity of the reef is almost entirely secondary (Bergenback and Terriere, 1953, p. 1023). It must, therefore, have migrated into it from an external source. In the reef reservoirs this migration must have occurred after each reservoir had been covered by an impervious seal of terrigenous sediments composed mainly of clay-sized material. The oil could not have migrated from rocks at older stratigraphic and lower structural positions because at all places impermeable and nonporous rocks separate the older nonreef rocks from the reef rocks.

According to Grout (1932, p. 337), if a shale has an initial porosity of 50 percent in the first 100 feet, an overburden of 1,000 feet will reduce that porosity to about 30 percent; 2,000 feet to about 23 percent; 3,000 feet to about 18 percent; and 8,000 feet to about 8 percent. The decrease in porosity and volume represents fluids squeezed out of the shale. The migration of the fluids from source rock to reservoir rock therefore may have been accomplished by the compaction of the source rocks with the inherent loss of fluids in the process of compaction. It is probable that both water and oil were squeezed out of the compacted shales. These fluids might have migrated into the porous parts of the leached reef rocks. Therefore, the shales in the terrigenous rocks which enclose the reef rocks are considered to be the most likely source of the oil in the reef rocks.

The process of compaction probably began during early Wolfcamp time before the dead reef was completely covered with terrigenous rocks. Differential separation of the oil and water in the reef rocks probably occurred as soon as a reservoir was effectively sealed by the covering impervious shales. The source of the oil in the postreef reservoirs of Wolfcamp age is probably also the shale that surrounds both the reef and postreef reservoir rocks.

ECONOMIC ASPECTS OF POROSITY ZONATION

The expansion of gas from solution is the main source of reservoir energy in the reef rock. Little water drive or encroachment of water is evident. Most of the oil reservoirs of the atoll are interconnected by the lower porous parts of the reef. They are connected also with the structurally high, water-saturated barren-reef hills (such as in northeastern Garza and northwestern Kent Counties north of the mapped area). A large hydrostatic head, therefore, must be present in the oil reservoirs. If the reef were homogeneous and uniformly porous, a natural water drive would be effective, but the zonation of porosity (pl. 6) indicates that this is not true. A natural water drive will be effective only in zones that have relatively high porosity and permeability and are in direct contact with the oil-water interface.

It is not known to what extent the zones of low porosity act as barriers to vertical circulation of fluids. That some of these zones are definitely impermeable is indicated by the presence of large amounts of perched water above the main oil-water interface in the south-central edge of the largest so-called Canyon reservoir in Scurry County (Rothrock and others, 1953). Burnside (in press) considers that the low porosity zones have inhibited the vertical movements of fluids in the southern part of the Horseshoe atoll as well.

Observations made on cores from wells in the Horseshoe atoll show relatively few vertical or nearly vertical open joints; calcite-filled fractures, however, are common. It is therefore probable that insufficient open joints and fractures are present to allow appreciable vertical circulation. Because the zones of relatively low porosity form partial or complete barriers to vertical circulation of fluids, it is essential that these zones be taken into account in secondary recovery in the reservoirs of the atoll.

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