Geology of part of the Horseshoe Atoll in Borden and Howard Counties, Texas

GEOLOGICAL SURVEY PROFESSIONAL PAPER 315-B

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

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By R. J. BURNSIDE

PENNSYLVANIAN AND LOWER PERMIAN ROCKS OF PARTS OF WEST AND CENTRAL TEXAS

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GEOLOGY OF PART OF THE HORSESHOE ATOLL IN BORDEN AND HOWARD COUNTIES, TEXAS

By R. J. Burnside

ABSTRACT

The Horseshoe atoll is an arcuate mass of deeply buried fossiliferous limestone of Pennsylvanian and early Permian age in the Midland basin of west Texas. The southern part of the atoll is in southern Borden and northern Howard Counties. From early Strawn until early Wolfcamp time this atoll, which had some of the characteristics of a reef, was a prominent feature on the floor of the Midland basin. The crest of the atoll is a series of buried hills and saddles. In the area of this report, 10 oil fields have been found in the hills along the crest, 2 on spurs on the flank of the atoll, 2 in the distant seaward area, and 2 on the seaward flank occupied by the central lagoon.

Calcilutite, calcarenite, and calcirudite comprise most of the reef rock, but there are a few thin beds of shale. The complex facies relations and stratigraphy of this reef are best explained as effects of oscillation of sea level during the time of reef growth. The cementation of the reef and subsequent development of porosity can be explained by the same oscillations of sea level, plus leaching by ground water during the periods of emergence. Reef growth was terminated in early Wolfcamp time when large volumes of fine-grained terrigenous sediments were deposited in the area.

The oil probably accumulated during Wolfcamp time shortly after the atoll was covered by black shale. Some peculiarities in the observed distribution of oil in the atoll may be explained by the apparent stratification of porosity.

INTRODUCTION

The Horseshoe atoll, as identified by Adams and others (1951), is a large curvilinear subsurface accumulation of limestone in the northern part of the Midland basin. The northern side of the atoll is open, as shown in figure 6. The east-west diameter is about 90 miles and the north-south diameter about 70 miles. This study covers the southern part of the atoll in southern Borden and northern Howard Counties, where it curves from a north-northeasterly trend on the east to a northwesterly trend on the west. The southeastern part of the Horseshoe atoll, which is known as the "Scurry Reef", has been described by Rothrock and others (1953). It is a northeastern extension of the area included in the present report.

Fossiliferous limestone of Pennsylvanian and early Permian age forms the Horseshoe atoll. This limestone is surrounded and overlain by shale of early Permian age. The crest of the limestone mass, which ranges from about 4,200 feet to more than 6,000 feet below sea level in the mapped area, is a series of irregular buried hills and saddles (pl. 10). The reservoirs of oil fields in the atoll are on the hills; oil and gas are not produced from the saddles. Ridges and valleys on the flanks of the atoll merge with the hills and saddles on the crest.

The terms "atoll" and "reef" have generally been applied to this subsurface accumulation of limestone; however, as noted by Heck and others (1952, p. 5), the limestone does not contain large amounts of recognizable frame-building reef organisms. Probably this limestone mass had some of the characteristics of a reef during the time of its growth, however, and therefore the terms "atoll" and "reef" will be used in this report. Because of uncertainty as to whether the Horseshoe atoll ever contained a rigid actively growing organic core, regarded by most geologists as an essential characteristic of a reef, this atoll might be called a "bioherm" in accordance with the definition proposed by Cloud (1952, p. 2128), who suggested that "ancient reef-like masses of uncertain potential or doubtfully wave-resistant nature may be termed bioherms."

Data for cross sections prepared to accompany this report were obtained from studies of micrologs, electrical logs, and radioactivity logs. The contour map of the reef (pl. 10) is based on interpretations of electrical and radioactivity logs. On these logs the top of the reef is indicated by strong increases in resistivity and usually in self-potential. At the top of the reef, gamma-ray curves show a marked lessening in intensity of radioactivity whereas neutron curves show a sharp increase. Cores from 12 wells were studied for their lithologic character and fossil content.

ACKNOWLEDGMENTS

This investigation was aided by the generous cooperation of many organizations. Cores were contributed by

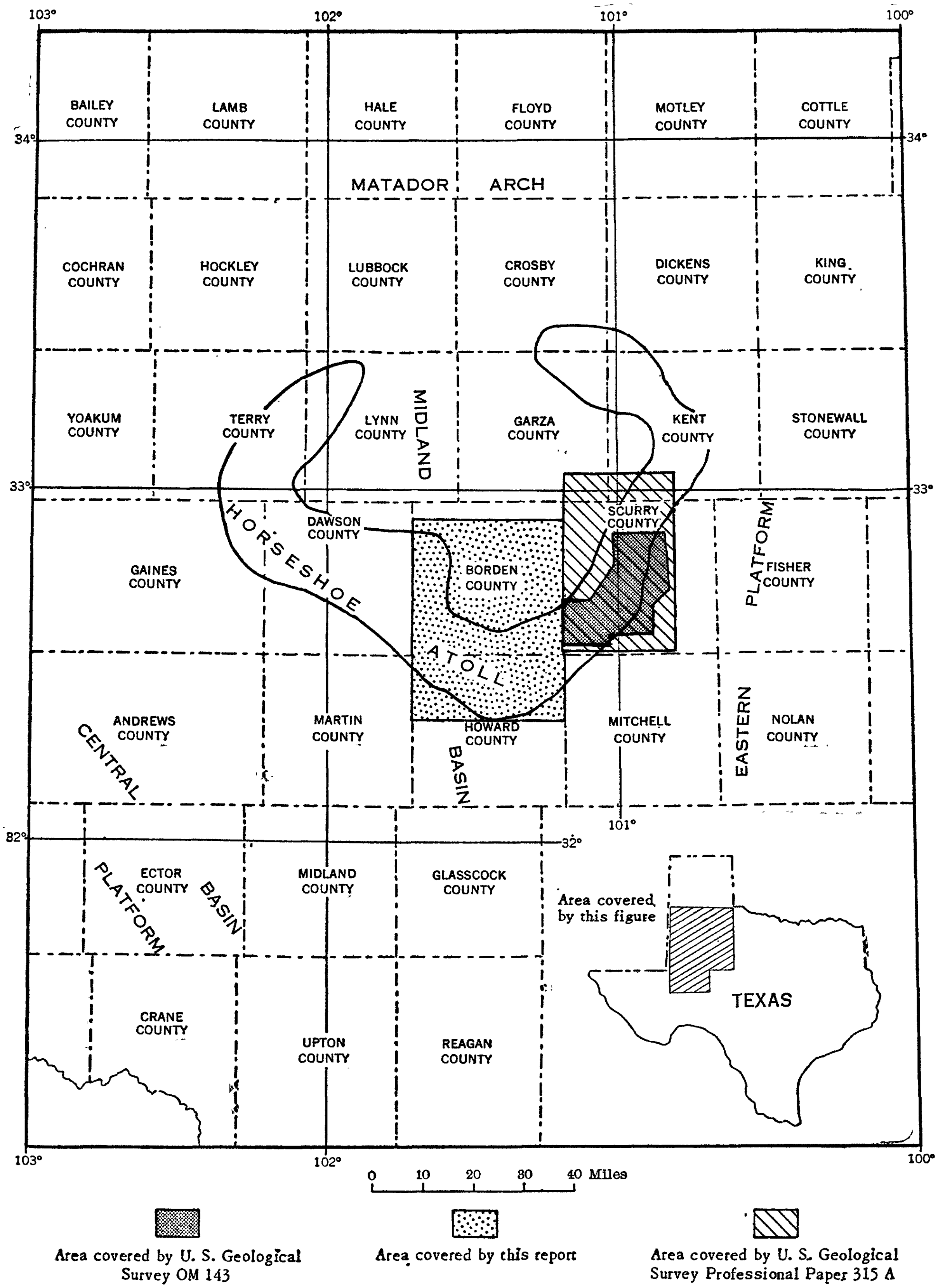

FIGURE 6.—Index map of part of west Texas showing the area of this report and the location of main geologic features.

Seaboard Oil Co. of Delaware (Seaboard's and Pan-American Producing Co's. No. 24 T. J. Good well, Good field); Amerada Oil Co. (Amerada's No. 6 Weathers well, Von Roeder field); Skelly Oil Co. (Skelly's No. 5 Gunn well, East Vealmoor field); and L. H. Armer (Armer's No. 2 McAdams well, Vealmoor field). Also Seaboard Oil Co. permitted the Geological Survey to sample cores from the T. J. Good lease in the Good field, wells 1, 12, 23, 24, 27, and 28; from the North Vealmoor field, the No. 1 Porter Hanks well; and from the Vealmoor field, No. 1 H. W. Zant well. Richard 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. Data from other wells outside the area were also made available by the Paleontological Laboratory; this information revealed many details of the history of the "atoll". The Bureau of Economic Geology of The University of Texas, John T. Lonsdale, Director, has provided funds in support of this work.

Age determinations of many of the reef rocks are based on identifications of fusulinids from cores by Keith A. Yenne and Donald A. Myers, of the Geological Survey.

STRATIGRAPHY

REGIONAL STRATIGRAPHIC RELATIONS

The subsurface Midland basin, the northern part of which is largely occupied by the Horseshoe atoll and its central lagoonal area, is bounded on the north by the Matador Arch and on the west by the central basin platform (fig. 6). The area east of the northern Midland basin is generally known by the term "eastern platform", and although no structural platform actually exists comparable to the central basin platform, nevertheless the term "eastern platform" will be used for that area in this report. The eastern platform area has a relatively thick section of Pennsylvanian rocks, including considerable amounts of limestone, shale, and sandstone; the Midland basin, except for the Horseshoe atoll, has a much thinner section of Pennsylvanian rocks, consisting mainly of dark-colored, unfossiliferous shale and siltstone (Adams and others, 1951). The thickness of Pennsylvanian rocks, mostly fossiliferous limestones, is much greater in the atoll than elsewhere in the basin.

The Permian system in the Midland basin includes shale, siltstone, dolomite, and limestone and is thicker than on the adjacent platforms. The lower part of this sequence of rocks, mostly dark-colored shale, is equivalent in age to some of the limestone in the upper part of the atoll.

During the subsidence of the Midland basin, limestone accumulated in the area of the atoll; as much as 1,500 feet are present in Scurry County in the eastern part of the area covered by this report, and about 3,000 feet in Dawson County on the west side of the area. A maximum of about 2,000 feet of limestone is present in the East Vealmoor oil field, about in the center of the area described (pl. 10).

STRATIGRAPHY OF THE REEF COMPLEX

The limestone accumulations of the Horseshoe atoll range in age from early Strawn (Pennsylvanian) through early Wolfcamp (Permian). Ages of the different parts of the complex have been determined by the study of the fusulinids, but inasmuch as fossils from older parts of the limestone mass have been reworked and incorporated into younger parts of the reef, the age relations are complex and difficult to work out in detail.

The general distribution of rocks of Canyon, Cisco, and Wolfcamp ages in the Horseshoe atoll is shown in the cross sections on plate 12. In many parts of the reef, older rocks are at topographically higher positions than younger rocks. For example, just west of the East Vealmoor field, about 90 feet of limestone of Wolfcamp age was penetrated in the well (marked "V7" in pl. 10) far down on the flank of the reef and more than 300 feet below the top of the rocks of early Cisco age in the center of the reef.

Except for relatively thin discontinuous beds of shale, the rocks in the reef complex show little or no stratification. Where these beds of shale are present, they seem to separate rocks containing significantly different faunas and thus to mark the contacts between rocks of Wolfcamp and Cisco, Canyon and Cisco, and early and late Cisco ages. Zones of different porosities, which have been observed in the reef, may indicate obscure stratification. The significance of these zones is discussed on page 26.

RELATION OF REEF LIMESTONE TO SURROUNDING SHALE

Intertonguing of limestone and shale at the top of the Scurry County part of the atoll has led some authors to consider that the atoll there is contemporaneous with the black shale enclosing the reef (Rothrock and others, 1953). Intertonguing of limestone and shale has not been observed in the southern part of the atoll and is found elsewhere only near the top of the reef. Almost all black shale is of Wolfcamp age. Brinkerhoff Drilling Co.'s No. 1 Jones well (in the extreme western part of Howard County) penetrated about 200 feet of limestone of Wolfcamp age overlying a limestone containing mixed lower Canyon and upper Strawn fusulinids. A similar relation has been found in Phillips Petroleum Co.'s No. 1 Dennis well in northern Borden County, where black shale adjacent to the reef overlies limestone of Wolfcamp age. Therefore, the black shale can be no older than Wolfcamp.

CHARACTERISTICS OF THE REEF ROCK

LITHOLOGIC COMPONENTS

The reef rock in the southern part of the Horseshoe atoll consists mainly of fossiliferous clastic limestone but includes small amounts of dolomitic limestone, chert, and thin beds of black shale. Black bituminous clay is concentrated along stylolites, which are abundant in the reef. Some limestone breccia lies in a black clay matrix. Lithologic constituents of parts of the reef complex are shown in figures 7 and 8.

The reef limestone consists of calcilutite (limestone composed mainly of clay- and silt-sized particles), calcarenite (limestone composed mainly of sand-sized particles), and calcirudite (limestone composed mainly of fragments larger than sand size). The characteristics of these constituents in the Scurry Reef have been described by Bergenback and Terriere (1953); the reef limestones in the southern part of the atoll are generally similar. Typical specimens of calcilutite, calcarenite, and calcirudite are shown in plate 11.

Although the relative amounts of these limestones are different in different cores in general, the proportions of calcilutite, calcarenite, and calcirudite in the reef limestone seem to be roughly 2:2:1.

Calcilutite is generally understood to be a clastic rock, and no doubt many of the reef limestones of this type are clastic. However, this description does not apply to all, and possibly not even to the greater part, of these rocks, although the actual amount of limestone of detrital origin is uncertain. In the absence of a better term for this rock the writer uses calcilutite in a textural sense without regard to origin.

Usual petrographic techniques fail to show definite evidence of the nature and origin of much of the material in the calcilutite. J. Harlan Johnson examined some of the cores and expressed the opinion that some of the calcilutite was probably precipitated by algae, possibly by primitive blue-green algae, which left few structures. How much of the calcilutite was precipitated in this way remains uncertain. Some portion of the calcilutite should be ascribed to the reworking of coarser sediment by bottom-dwelling scavengers.

The calcarenite is composed of grains that seem to be mostly fragments of organisms. Ordinarily the sorting is so poor that it is difficult to determine the precise size classification of the rock. The sorting seems to improve, however, with the degree of rounding of the grains.

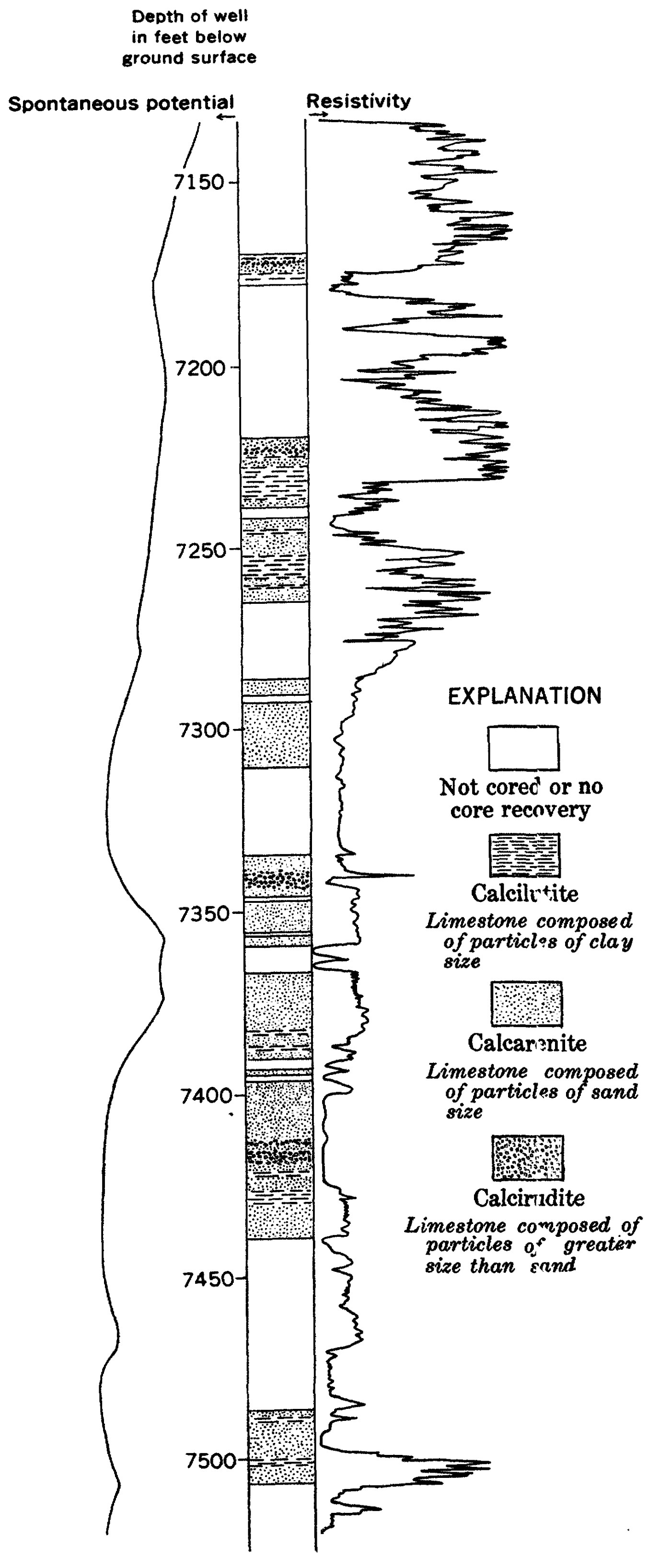

FIGURE 7.—Microlog and lithologic log of Skelly Oil Co.'s No. 5 Gunn well.

A. CALCILUTITE.

B. CALCARENITE.

C. CALCIRUDITE.

D. BIOCLASTIC CALCIRUDITE.

CORES FROM THE SOUTHERN PART OF THE HORSESHOE ATOLL, ILLUSTRATING ROCK TYPES

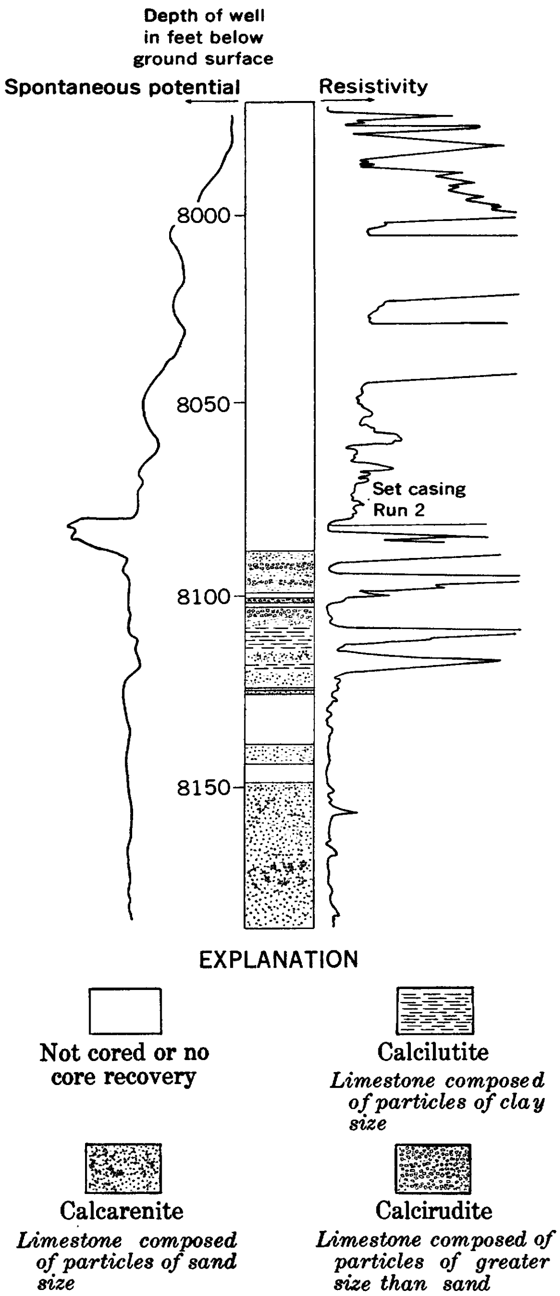

FIGURE 8.—Microlog and lithologic log of Pan-American Producing Co.'s and Seaboard Oil Co. of Delaware's No. 24 Good well.

Two types of calcirudite are present in the reef. The first is breccia made up of broken unsorted limestone fragments in a matrix of calcilutite, or in some places of black clay. A few cores of calcirudite show structures that probably indicate submarine slumping. The second type is bioclastic breccia composed of fragments of crinoid columnals, fusulinids, brachiopods, bryozoans, and other organisms. The writer defines a bioclastic rock as a rock composed mainly of fossils or readily recognizable fossil fragments. Thus, a calcilutite or a fine-grained calcarenite may be bioclastic, but unless it is composed of such very small organisms as Foraminifera, it may not be readily recognized as such.

Both kinds of breccia are commonly cemented by calcilutite, but in some places they have a matrix of black clay. Both types of calcirudite with black-clay matrix are present at the top of the reef. Calcirudites with a black-clay matrix are always stratigraphically either at positions occupied elsewhere by thin beds of shale, or at the top of the reef. Mostly, calcirudite and calcarenite have matrices of calcilutite. Nonbioclastic calcirudite commonly has stylolitic contacts between the larger fragments. These stylolites do not everywhere extend into the matrix.

Sorting in the clastic limestones is almost everywhere very poor to nonexistent, although thin zones in a few cores are well sorted. Coquinas consisting essentially of fusulinids and calcite cement have been found, and the fusulinids are large enough to justify classification of these rocks as calcirudites. This is the only rock type, coarser than fine-grained calcarenite, that shows uniformity in size distribution of constituent particles.

DISTRIBUTION OF LITHOLOGIC COMPONENTS

If Horseshoe atoll had grown normally without interruptions, ordinary facies and stratigraphic relations would be expected. On the seaward side of the reef mainly calcirudite and calcarenite would be formed. The reef core would be made up of organic limestone with many organisms in or near their position of growth. In the reef core considerable calcarenite might be present but little nonbioclastic calcirudite would be expected. The backreef (lagoonal) facies would consist largely of calcarenite and perhaps of a small amount of calcirudite, grading laterally into calcilutite.

Forereef, backreef, and reef-core facies, as these terms are commonly understood (Cumings and Shrock, 1928; King, 1948; Lowenstam, 1948; and Adams and Frenzel, 1950), apparently do not exist in any part of the Horseshoe atoll. Calcirudite is common in what would normally be considered the core of the reef, and calcarenite and calcilutite are abundant throughout the entire reef complex. No organism was observed in its position of life with the possible exception of the rather indefinite algal structures.

In the southern part of the Horseshoe atoll, nonbioclastic calcirudites commonly overlie the thin beds of shale and are confined to such positions. The bioclastic calcirudites are a common constituent of the entire reef, as is indicated by cores. Calcarenites and calcilutites have equally widespread distribution. No stratigraphic significance has been found in the distribution of calcarenites and calcilutites, but the nonbioclastic calcirudites are generally associated with the thin beds of black shale.

Attempts to correlate cores of adjacent wells by lithologic means have been unsuccessful. Occasionally in this study, certain zones of calcarenite or calcilutite seemed to be laterally equivalent, but such equivalence was suspect because of the general lack of correlation.

CHEMICAL COMPOSITION

Chemical analyses of representative cores show that the limestone is almost pure calcium carbonate. The average insoluble residue amounts to slightly more than 1 percent of the total rock, by weight. Analyses of limestone cores from two wells whose columnar sections and micrologs are illustrated in figures 7 and 8 were made by the U. S. Geological Survey (tables 1 and 2).

TABLE 1.—*Insoluble residue of a core from Seaboard Oil Co. of Delaware and Pan-American Producing Co.'s No. 24 Good well in the Good field*

Sample depth (feet below surface)	Insoluble residue (percent)	Sample depth (feet below surface)	Insoluble residue (percent)
8088.3	0.39	8148.0	0.87
8093.5	.91	8153.0	.55
8094.5	.76	8160.3	.51
8096.7	1.34	8167.1	.41
8101.1	.25	8174.0	.43
8102.4	.55	8178.2	.49
8106.0	.49	8181.6	.57
8108.0	1.27	8186.0	.64
8112.0	.36		
8113.1	.37	Average of 20 analyses	0.60
8119.5	.35		
8142.0	.57		

TABLE 2.—*Insoluble residue of a core from Skelly Oil Co.'s No. 5 Gunn well in the East Vealmoor field*

Sample depth (feet below surface)	Insoluble residue (percent)	Sample depth (feet below surface)	Insoluble residue (percent)
7170.3	0.38	7364.0	2.90
7173.7	.31	7367.7	2.50
7220.0	.34	7373.4	1.90
7225.0	.80	7380.7	1.40
7230.0	.74	7386.7	.81
7242.0	.38	7395.8	.53
7247.0	2.40	7402.0	1.00
7253.2	.20	7407.3	.66
7257.0	3.00	7417.8	.28
7261.0	.45	7423.5	.24
7287.3	1.50	7431.0	.29
7292.0	2.20	7439.0	.58
7300.8	7.30	7468.0	.29
7305.4	5.70	7491.0	3.00
7309.0	1.60	7494.6	.52
7334.0	.56		
7338.0	.69	Average of 34 analyses	1.70
7344.4	7.00		
7351.8	5.60		

POROSITY AND PERMEABILITY

The reef, as originally deposited, was probably a very porous mass because of the intergranular pore spaces in the clastic limestones. These pore spaces, however, were subsequently filled by calcium carbonate cement. Later, the entire mass was leached and secondary pores were developed. These pores are interconnected and penetrate both the initially deposited organic debris and the cement. They range in diameter from submicroscopic to as much as 2 inches. This secondary porosity was then reduced by partial filling of pores (especially the larger cavities) with drusy calcite, and, locally, with authigenic quartz. Reports from commercial laboratories indicate that the present pore space is about 6 percent of the reef rock.

Permeability is low except for open fractures; it ordinarily ranges from 0 to 85 millidarcys (measured horizontally to air). The average vertical permeabilities are considerably lower than horizontal ones. This seems to indicate stratification of the porosity.

Cross sections *A–A′*, *B–B′*, *C–C′*, and *D–D′* (plate 12) show interpreted correlations from well to well of porosity data taken from micrologs. The porosity of the porous limestone shown on the cross sections may be 4.5 percent or greater, but that in the less porous limestone may be less than 5 percent. This overlap of porosities is inherent in microlog interpretation. The microlog measures not porosity but the resistivity of the zone invaded by the drilling mud. This is a function of the concentration and penetration of the mud into the sides of the bore hole, the resistivity of the mud, and the resistivity of the host rock.

Stafford (1955) compared nearly 5,000 analyses of cores from the eastern part of the Horseshoe atoll made by commercial laboratories with microlog porosity ("permeability") classes. He found that in 90 percent of the comparisons the microlog shows good porosity where more than 4.5 percent effective porosity exists. He also found that in about 90 percent of the observations the microlog shows very poor porosity where porosity is 5 percent or less. The statistical overlap is 0.5 percent.

Comparison of micrologs with lithologic logs shows that there is little correlation between lithologic character and porosity. However, comparison of the cross section with fusulinid determinations shows a relation between the porosity and faunal zones. The top of each faunal zone almost invariably shows good porosity whereas the base of each zone shows poor porosity and is associated with thin discontinuous beds of shale.

Because the porosity seems to be stratified, the microlog can be an effective aid in preparing cross sections. The cross sections themselves seem to present a reasonable picture of reef growth and a definite relation between the porosity and faunal boundaries. There is, however, wide latitude for interpretation where paleontological control is meager and traceable units such as thin beds of shale are absent.

Porosity resulting from fractures has been observed in several cores. Some fractures were filled or partly filled with calcite. The open fractures markedly influence the permeability measurements of these cores. Whether a system of jointing has been established so that one set of fractures was filled with calcite while another set was not, or whether all fractures were locally filled, is at present undetermined. Further evidence is discussed in the section on Oil accumulation (p. 33).

FAUNA AND FLORA

Crinoids make up the largest part of the fauna in the southern part of the Horseshoe atoll. Bryozoans and brachiopods are next in abundance. Corals are rare—only two were found in the cores examined from this area. Small Foraminifera also are present. Calcitornellid Foraminifera are common, as well as the textularian genus *Climacammina*. Other genera are inconspicuous. None of the more common members of this fauna are capable of erecting a reef framework that would be wave resistant.

Elliott and Kim (1952) identified algae of the families Porostromata and Codiaceae in the core of a well in Terry County on the western side of the atoll. Algae were by far the most abundant of all the organisms recognized by them in this core. The calcilutites as well as some of the calcarenites in the southern part of the atoll commonly contain many structures that apparently are organic but of uncertain taxonomic position. Some of these may well be members of the Cyanophyta (blue-green algae). A few structures resembling *Girvanella* have also been noted. For the most part, however, the structures referable to algae have no diagnostic features, so that they cannot definitely be placed in their proper biologic position. It is difficult to identify the types of algae here involved. Every core examined, however, contained large amounts of material that could be interpreted as algae.

It is worth noting that the algae that are reef framebuilders today (primarily *Lithothamnion*) are the Rhodophyta (red algae), whereas the other algae (primarily *Halimeda*) are found in abundance only in the quiet backreef waters. In the Paleozoic, the only family that has been referred to the Rhodophyta are the Solenoporaceae. No organisms referrable to this family have been found or reported from the Horseshoe atoll.

In addition to the marine biota, Donald A. Myers has identified remains of fossil plants resembling *Calamites* in cores from three wells in the reef in Scurry County. In each well these fossils were in shale just above the base of the limestone of Cisco age.

REEF HISTORY

FACTORS AFFECTING THE CONCEPTS OF REEF DEVELOPMENT

From the foregoing discussion it is obvious that the Horseshoe atoll is considerably different from reefs forming at the present time, and from many fossil reefs described in the literature. The question may well be raised as to whether this structure is a true reef as, for example, defined by Lowenstam (1950, p. 443), who wrote:

> a reef, in terms of ecologic principles, is the product of the actively building and sediment-binding biotic constituents, which because of their potential wave resistance have the ability to erect rigid wave-resistant topographic structures.

It has been shown that the shale surrounding and overlying the atoll is of Wolfcamp age and therefore could not interfinger with the parts of the reef which are of Strawn, Canyon, and Cisco age. Comparison of limestone thicknesses above the base of the atoll in the area of the East Vealmoor field with thicknesses in the distant forereef area reveals that at the site of the East Vealmoor oil field the atoll stood as much as 1,800 feet above the surrounding bottom during Cisco time. Thick masses of calcirudite, composed of fragments of prelithified limestone, suggest that this structure was within the zone of strong wave action and was wave resistant.

Few of the organisms in the biota, however, seem to have been reef framework builders or sediment binders. The holdfasts of crinoids, where great colonies were present, could, to some extent, have bound together the detrital sediments; it is doubtful, however, that crinoids could have lived in a strong surf.

Most of the fossils, other than Foraminifera, are present as broken fragments. The rare shells of brachiopods or "algal" structures found intact are closely associated with fragmented shells. The implication is that the unbroken shell was only fortuitously transported whole from its place of growth to its place of entombment, while most of the neighboring shells were broken. The angularity of the fragments indicates that these organic remains were not strongly abraded or transported far from their places of growth. The unsorted nature of the deposits and the angularity suggests that the agencies of erosion and transportation were strong but very local. Coarse and fine fragments alike were dropped at the point of deposition almost immediately after being torn from their places of origin.

The fauna of the reef limestone seems to indicate growth in quiet water. Unsorted, angular fragments, however, seem to contradict this evidence. These contradictions may perhaps be explained by the occurrence of occasional storms that attack the atoll. Thus, a relatively fragile biota, flourishing in the normally quiet waters around the atoll, could have been torn from the bottom during storms and cast into the more protected waters beneath wave base or behind the atoll. Some fragments may have been deposited above sea level on the beaches of the carbonate islands.[1]

Thus, the evidence suggests that the Horseshoe atoll was not a reef but a giant shell bank that was not wave resistant enough to meet Lowenstam's definition of a reef.

Identifiable reef core could not be found in the Horseshoe atoll, as pointed out elsewhere in the text. MacNeil (1954a), however, has strongly urged that the lack of a reef core does not prove that none ever existed. Ladd (1950, p. 204), who was of like mind, wrote:

> 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 quantitatively be very unimportant and only in rare elevated reefs is it preserved and satisfactorily exposed.

Ladd and Tracey (1949) wrote:

> Since 1945 Hoffmeister and Ladd have studied both existing and elevated reefs in various parts of Micronesia and now feel that they were too restrictive in their identifications of "reef limestone." They failed to recognize that "reef structure" (imbricating colonies of flat corals in positions of growth such as characterized the marginal zones of existing reefs) forms a very small percentage of the entire reef. It is an important part, to be sure—as important as the sides of a pail that holds water—but it may make up only 5 to 10 percent of the reef mass, and, furthermore, may be the first part to be destroyed when the reef is elevated and eroded. By thus recognizing the quantitative unimportance of reef structure, the occurrence of scattered reef corals that are *not* [sic] in position of growth assumes greater significance. Such occurrences may indeed suggest a talus slope or deposition on a submarine bank, only parts of which projected into the zone of reef growth, but it is perhaps more likely that such scattered corals were deposited on the side reef flat behind the marginal zone or in the shallow waters of a lagoon.
>
> A second factor overlooked by Ladd and Hoffmeister was the significance of texture in sediments. Fine sediments do not accumulate on unprotected banks, and, therefore, the occurrence of thick sections of such materials is evidence of the existence of a protecting rim at the time of accumulation, even though such a rim may no longer exist.

MacNeil (1954a, p. 392) suggests that solution might play an even more important role than mechanical erosion in the destruction of reef cores. If this is true, no evidence of the core would remain, and it would render interpretation of the remaining deposits extremely hazardous.

The organisms which have been found in the Horseshoe atoll certainly do no violence to the concept that they represent a backreef population. Green algae, echinoids, certain kinds of Foraminifera, and Bryozoa have all been found to be members of modern backreef biota. The fragmentation of organisms and poor sorting of the sediments could perhaps be assigned to the work of the scavengers which constantly work the bottom through their digestive tracts. Furthermore, the relatively abundant calcilutite is better explained as a backreef deposit than as a deposit in the main body of an organic bank. The "scattering of corals" not in positions of growth, which suggested to Ladd and Tracey a possibility of backreef deposition, is also present in these sediments.

MacNeil (1954a) considered that large backreef-type deposits were so conclusive of the former existence of a reef core that "The burden of proof would rest with the one seeking to show that no bioherm ever bounded them." The writer is not quite so certain that backreef-type sediments and organisms could not be produced by other ecologic conditions, and he favors the possibility that the Horseshoe atoll was an extremely large shell bank.

AN HYPOTHESIS OF REEF DEVELOPMENT

A reef tends to maintain its top at or near sea level; thus, the upper surface of a reef is an excellent datum. The thin beds of black shale within the reef complex of the Horseshoe atoll seem to overlie erosional unconformities having several hundred feet of relief. The unconformities strongly suggest oscillations of sea level with respect to the top of the reef. Relative shift of sea level may be due either to tectonic uplift of the Midland basin or to eustatic lowering of sea level.

The presence of about 2,000 feet of reef limestone in the southern part of the Horseshoe atoll indicates that a similar amount of subsidence must have taken place during the growth of the reef. If the indicated shifts of sea level were due to tectonic movements, a basin is indicated that is subsiding most of the time but that now and again rises several hundred feet before starting downward again. This explanation poses problems.

Deep drilling in most of the well explored sedimentary basins has shown that most unconformities found at the margins of these basins are represented in the deeper parts of the basin by a complete section of sedimentary rocks. Where an unconformity extends completely across a basin it usually marks an interval of strong folding and faulting. The history of most basins seems to follow a single pattern of downwarping accompanying sedimentation with minor unconformities at the mar-

[1] For an excellent account of the building and shaping of reefs and "coral islands" by winds and currents, see Fairbridge (1950, p. 356–362).

gins. The downwarping may eventually have been followed by strong folding and faulting, but before that the deeper part of the basin seems to have been an area of almost continuous downwarp. These considerations lead one to consider some alternate explanation for the unconformities.

The second explanation—lowering and rising of sea level—seems more reasonable. The mechanism for these postulated fluctuations is not known.

If it is assumed that the unconformities within the reef are related to eustatic shifts of sea level, then several consequences may be postulated. Probably the most important is the lowering of the base level of erosion which should cause more rapid erosion in areas that had formerly undergone only slight erosion. In areas that formerly had been receiving sediments and were near sea level, streams should cut deep channels. The sediments exposed in north-central Texas were apparently deposited in such an area. The limestones interbedded with continental shales and sometimes coals seem to have been deposited in an area that alternated between shallow sea and continental lowland. The more striking channels, now filled with sandstones, conglomerates and shales may be related to the unconformities in the reef. Plate 13 illustrates these correlations and seems to bear out the hypothesis of eustatic changes of sea level.

Wanless (1950) and others (Wanless and Shepard, 1936; Wanless and Patterson, 1951) have considered that the cyclic type of sedimentation so common to rocks of Pennsylvanian and Wolfcamp age was caused by eustatic changes of sea level. The evidence presented here seems to support this view but with possibly fewer changes of sea level than these authors have envisaged.

EFFECTS OF EUSTATIC CHANGES OF SEA LEVEL ON THE HORSESHOE ATOLL

Lowering of sea level in a reef area would produce islands of increasing areal extent and relief above sea level. The area and relief of these islands would be proportional to the original area of the reef, the amount that sea level is lowered, and the relief of the reef relative to the surrounding sea floor. During the time of lowered sea level the islands would be attacked by the waves, and wave-cut benches and other surface features resulting from subaerial erosion would be formed. The agencies of erosion would eventually plane off the islands to the new wave-base level. If sea level rose again before this planation were complete, such fringing reefs as may have been growing during the time of lowered sea level would advance up the flanks of the islands with the rise of the sea and eventually develop into the new main reef.

F. Stearns MacNeil (1954b, p. 402–426) has recently discussed the effects of emergence and subaerial erosion on reefs and limestone banks. In general, MacNeil believes that the emergence of a table reef or limestone bank will result in the solution of the central area to a greater degree than the rim, and that this will produce a rimmed foundation ideally suited for the growth of an atoll if the island again becomes submerged. The Horseshoe atoll was never a table reef, but the rim of the old atoll did become the site of a renewed growth following each emergence. MacNeil considered such a situation and pointed out that such foundations will cause reef growth to follow the topography developed by subaerial erosion. The topography of the southern part of the Horseshoe atoll resembles that described by MacNeil.

During the time of lowering of sea level, the time during which the sea is at the lower level, and also during the rise of sea level, large amounts of clastic material derived from erosion of the reef would be deposited on wave-cut benches and shore platforms, as well as on the flanks of the reef. The resulting complex facies distribution would then be preserved as the younger reef grows over the older detritus with the rise of sea level. The abnormal abundance of detritus would cause the normally steep reef slopes to become much less steep. This detritus would contain a fauna older than the sea in which it was deposited and faunas of two different ages would therefore be mixed. This mixing of faunas has contributed to some confusion about the age of parts of the Horseshoe atoll.

HYPOTHESES OF REEF GROWTH

If the cyclic deposition of the Pennsylvanian and early Permian in the Midcontinent region is a result of periodic fluctuations of sea level, then the growth of the Horseshoe atoll would also have been cyclic, in a manner somewhat similar to the growth of the Pleistocene reefs in response to changes in sea level related to periods of glaciation, as visualized by Daly (1910, 1915, 1934). The complex textural and faunal relations, which have been observed within the limestone mass, represent, in part, facies conditions that may be expected in a reef complex whose development is modified and interrupted by oscillation of sea level.

Two hypotheses may be advanced to relate the growth of the Horseshoe atoll more directly to the postulated changes in sea level in the Midland basin. In the first, normal reef growth is proposed, together with several lowerings of sea level to account for the reworked faunas and superabundance of clastic limestone; it is also proposed that sea level was lowered only after subsidence of the basin was sufficiently rapid to cause the reef to restrict itself to small areas of growth such as the Good, East Vealmoor, and Reinecke hills. These hills were then exposed to erosion for a very short interval and sea level rose again. Marine organic growth over the old "highs" recommenced. This process was repeated several times; the erosion intervals are marked by the thin beds of shale. Thus the reef hills are considered to be essentially a natural-reef configuration due to rapid subsidence, slightly modified by erosion.

Several objections can be raised to this theory.

1. If the sea level were lowered less than the height of the hills above the main body of the reef, then these hills would be truncated or partly so and the wave-cut bench would be well above the surrounding, but topographically lower, main body of the reef. The unconformity of middle Cisco age in the Good field seems to have the proper configuration for a lowering of sea level less than the height of the restricted reef knob. Under this assumption, however, no explanation can be found for the limestone of late Cisco age that lies 90 feet or more down the flanks from the unconformity, below the probable depth at which the Codiacae can flourish when sea level is at the position of the unconformity. (See Cloud, 1952, p. 2134.) Some of this limestone could be attributed to reef detritus, but the distribution of limestone of Cisco age, as shown in plate 10, is too widespread to attribute it all to scree.
2. The rapid subsidence, which caused the restriction of reef growth to the scattered hills on the crest of the Horseshoe atoll, must be stopped at precisely the right time. If sea level were to commence rising again before the subsidence has stopped or slowed, then surely the rate of sea-level rise and rapid subsidence combined would drown the reef, and its top would be placed below the zone of biotic potential.
3. Comparison of reef thicknesses shows that the thinnest part of the reef is in the northeast. In the Salt Creek field (Galbraith and Barker, 1952), in the northeastern part of the atoll in Kent County, the reef has a maximum thickness of about 1,100 feet. In the East Vealmoor field the reef has a maximum thickness of about 2,000 feet. The limestones in these different parts of the atoll were deposited during the same interval of time; and inasmuch as the biota probably had a rather limited depth at which it could flourish, the subsidence of each area was probably about equivalent to the thickness of the reef. The rate of subsidence would, therefore, have been a function of the thickness. If subsidence is required to be so rapid that growth is restricted to small patches in the Salt Creek area, the East Vealmoor field area would surely have drowned, inasmuch as the thicknesses indicate the rate of subsidence in the East Vealmoor area to be twice that in the Salt Creek area.

Because of these objections, the above hypothesis is rejected in favor of an hypothesis which postulates that the internal "highs" are erosional remnants of an older, thicker, and broader structure, rather than configurations of restricted growth resulting from rapid subsidence. These "highs" certainly caused the reef to accommodate its growth to the older topography, but before the existence of these highs the top of the reef was probably rather smooth and continuous.

ECOLOGIC CONTROLS

The direction of the prevailing winds and currents has a strong effect upon reefs and organic banks. If current and wind direction very nearly coincide for the greater part of the year, the strongest growth will be on the windward side. Horseshoe-shaped atolls and carbonate cays develop where winds have a fairly constant direction during the entire year (Kuenen, 1950, p. 441–442; Fairbridge, 1950, p. 361). From this we may assume that the wind and currents in the northern Midland basin had a fairly constant direction coming from slightly west of south.

By analogy with modern carbonate environments the environment of this area was probably warm and tropical. Similarly, at the very start of reef growth in early Strawn time a very shallow epeiric sea probably covered the area. The sea bottom was nearly flat, but it had a regional slope toward the south and west where reefs of pre-Strawn age are known (Imbt and McCollum, 1950, p. 246).

From the shape of the atoll it may be inferred that a fairly constant wind and current came from the south or slightly west of south. Almost no terrigenous clastics were entering this area and we may therefore assume that the water was clear. Normal salinity is suggested by the abundance of varied types of organisms.

This environment prevailed from early (but not earliest) Strawn time, through Canyon, Cisco, and earliest Wolfcamp times, but not without several interruptions. The thin beds of shale shown in the cross sections probably indicate increased turbidity, and mark unconformities that in some places show several hundred feet of relief.

The black shales, which accumulated on the floor of the Midland basin during the time of reef growth, indicate that a nonaerated toxic environment probably was present. Thus, two environments were probably superimposed: stagnant, toxic water on the sea floor; and warm, clear, oxygenated water at the surface. Newell and others (1953, p. 12–14) have pointed out similar relations of several fossil reefs. The Capitan reef of Trans-Pecos Texas, the Mississippian reefs of the Central Province Basin north of England, the Permian reefs of eastern Greenland, and the Upper Triassic reefs of the Italian Tyrol all are associated with stagnant basins. Newell (Newell and others, 1953, p. 14) is of the opinion that the deep stagnant waters may provide "an unusually rich source of upwelling nutrient salts for lime-secreting reef plants."

HISTORY OF THE REEF DURING PENNSYLVANIAN TIME

Rocks of Strawn age have been recognized throughout the area covered by the atoll. The lowest 50 to 200 feet are limestones containing thin shales that can be traced in the subsurface far from the atoll. This part of the section is not considered a part of the reef rock. From this foundation the reef growth began. More than 750 feet of reef rock of Strawn age accumulated above the earlier stratified limestone of Strawn age. Thin beds of shale within the reef of Strawn age probably mark unconformities much as those found at the top of rocks of Strawn age and within rocks of Canyon, Cisco, and Wolfcamp age.

Sea level was lowered in early Canyon time and the atoll was then truncated. Large quantities of limestone, removed from the crest and deposited in both the forereef and lagoonal areas, were spread for tens of miles over the sea floor. The top of the rocks of Strawn age has little relief in the area of the crest of the atoll, but the tremendous quantities of limestone that must have come from this truncation suggest that this period of erosion probably lasted longer and contributed more clastic limestone to the surrounding area than any previous or later erosion interval. A rise of sea level—or possibly subsidence of the basin—then placed the crest of the atoll beneath the effective action of the waves, and the thin beds of shale at the base of the reef of Canyon age were deposited over the truncated reef of Strawn age. The source of the argillaceous material may have been land areas that emerged or extended closer to the Midland basin as a result of the fall of sea level. Some of this material, however, may have been derived from the atoll itself as insoluble residues concentrated on the surface of the atoll. Chemical analysis and lithologic appearance show that the clay concentrations on the stylolites and these thin shales are very similar. This surface was the site of renewed reef growth during Canyon time.

Similar cycles of reef development, growth during high sea level combined with basin subsidence, and later erosion during low sea level, were probably repeated four more times during the Pennsylvanian period, twice during Canyon time, and twice during Cisco time; but with the possible exception of the succeeding Canyon erosion cycle, which occurred in middle or late Canyon time, the atoll was never again so completely truncated as at the beginning of Canyon time, and never again was so much limestone detritus contributed to the environs of the Horseshoe atoll. Plate 12 illustrates the partial planation that took place during middle Cisco time.

HISTORY OF THE REEF DURING WOLFCAMP TIME

Four types of limestone of Wolfcamp age are believed to be present in the southern part of the Horseshoe atoll. They will be discussed in the order of their deposition.

The first type is normal reef limestone that was deposited on the top of the East Vealmoor, Vealmoor, and Good fields, and that is essentially free of clastic material derived from erosion of the old reef.

The second type probably is a fringing deposit containing scree derived from the subaerial topographic "highs" and deposited around the margins of the hills having large amounts of relief. This took place after sea level had been lowered in early Wolfcamp time. This type is represented by limestone of Wolfcamp age found in the dry hole immediately west of the East Vealmoor field. (Marked with a "*W*" on pl. 10.)

The third type is limestone of Wolfcamp age found in a dry hole southwest of the Vealmoor field in extreme western Howard County. (Also marked with a "*W*" on pl. 10.) The base of the Wolfcamp in this well (Brinkerhoff Drilling Co.'s No. 1 Jones well) is at 6,693 feet below sea level, some 1,600 feet lower than the highest part of the Vealmoor field and about 800 to 1,000 feet lower than the lowest Wolfcamp known from the reef-crest area. (See pl. 14.) Newell and others (1953) have described tongues of limestone, apparently derived from the Capitan reef, transported by submarine landslides, and deposited several miles from the reef crest on the floor of the Delaware basin. It is very difficult to identify deposits of this kind in the subsurface, but the extremely low position (with reference to the reef crest) of this type of limestone, which seems to have been brought into a black-shale environment, suggests that it was transported by submarine landsliding from a higher position on the reef. The presence of this limestone indicates that the reef had more than 1,800 feet of relief in early Wolfcamp time, and that nearly all the shale surrounding and overlying the reef is of Wolfcamp age. The second and third types of limestone are probably for the most part contemporaneous.

The fourth type of limestone of Wolfcamp age is represented by tongues extending into the surrounding black shale near the top of the reef (Rothrock and others, 1953). These limestone tongues probably are erosional products derived from a dead reef.

Every hill west of the Hobo field has reef limestone of Wolfcamp age on its crest. All reef hills east and northeast of the Hobo field, as well as those in the Hobo field itself, have reef limestone of Cisco age on their crests, but limestone of Wolfcamp age is present low on the flanks of these hills. (See pl. 10, and Heck, Yenne, and Henbest, 1952.) The limestone of Wolfcamp age low on the flanks of the eastern reef hills may represent either detrital limestone from a topographically higher source, a fringing reef developed during a low stand of the sea, or a combination of both. Examination of cores from this limestone (Wilshire Oil Co.'s No. 8 Lunsford well and Pan-American Producing Co.'s No. 1 Glass) by geologists of the Geological Survey has shown that in large part it is of detrital origin.

From the Hobo field westward, successively thicker and younger deposits of limestone of Wolfcamp age are present on the crest of the Horseshoe atoll. This relation and the presence of what look like foreset beds in the terrigenous Wolfcamp rocks suggest that reef growth was stopped by the encroachment of deltas onto the atoll from the east and north in Wolfcamp time. The southwestern part of the reef continued to grow for a considerable part of Wolfcamp time after the clastic sediments were spread as aprons over the eastern and northern parts of the atoll. The increased turbidity probably even more strongly limited the depths at which the reef could grow in the southern part of the atoll, and restricted growth largely to the highest parts of the old hills developed during the erosion interval during early Wolfcamp time.

During this time vast quantities of calcareous clay and silt were deposited in the northern part of the Midland basin. The mud eventually covered the reef. As the mud filled the basin the fourth type of limestone was deposited as lenses of carbonate detritus in muds of Wolfcamp age, which then surrounded the dead reef.

CEMENTATION AND CYCLICAL REEF GROWTH

In the borings of the Cenozoic reefs of the Pacific Fairbridge (1950) and Ladd and others (1953) have noted that, except for their surfaces, these reefs are generally not well cemented. In those areas which are alternately wetted and dried, cementation is very rapid. Cans and bottles have been incorporated into the so-called "beach rock" by this rapid process of cementation. The length of time involved in the postulated fluctuations of sea level should have been more than adequate to accomplish the same process of cementation by wetting and drying in the Horseshoe atoll. As sea level was lowered, successive parts of the reef that came into the tidal range became cemented. Thus, by the time a particular part of the reef was undergoing subaerial erosion it was already a well-cemented rock because of the previous wetting and drying—and consequent loss of CO_2 and precipitation of $CaCO_3$—inherent in any such lowering of sea level.

The secondary porosity was probably caused by leaching of the exposed reef by meteoric water after the cementation had taken place. The leaching was probably facilitated by the presence of humic acids. It seems likely that the exposed reef would develop a tropical type of vegetation. In this respect "*Calamites*" remains found at the base of the Cisco probably are significant. With the rise of sea level such vegetation that may have developed on the exposed island would have been drowned; fossilized plants may be expected to be found at the unconformity—the position at which these fossils were found in three separate bore holes.

The sequence of growth and cementation in each reef cycle seems to have been as follows:

1. Normal reef growth with subsidence of the basin amounting to several hundred feet.
2. Lowering of sea level—which probably is never completely stationary—and emergence and erosion of the upper part of the reef. As sea level was lowered, the alternate wetting and drying by the tides caused loss of the CO_2 in the water trapped in the pore spaces in the reef, with consequent precipitation of $CaCO_3$, which cemented the reef.
3. Wave attack of the islands formed by the lowering of sea level and formation of wave-cut benches and platforms. Solution by ground water abetted by humic acids caused secondary porosity and other solution features in the islands. Streams on the surface left their imprint in the form of deep gullies. Considerably greater amounts of clay-sized particles entered the basin as a result of the much closer shoreline. At the same time, new sources of material for erosion were made available by the lowering of sea level.
4. Rise of sea level, so that the wave-cut benches and platforms were placed beneath the zone of wave activity and received such clay particles as were still entering the area, plus the insoluble residue concentrate resulting from the solution and weathering of the reef itself. Thin clay deposits covered the older wave-cut benches, which were formerly kept clear by their proximity to the surface and by the action of the waves. Deposition of mud may have been more rapid in the lee of the islands than on the seaward side. Fringing reefs grew upward

with the rise of sea level (principally on the seaward side) and as the top of the old island was covered over, they became the new reef proper.

OIL AND GAS

OIL FIELDS

Seventeen fields producing oil from the reef have been discovered (October 15, 1954) in the area shown on the accompanying map (pl. 10). From west to east, the following larger fields are producing oil from the reef: Good, Oceanic, Vealmoor, North Luther, East Vealmoor, Hobo, Reinecke, Von Roeder, and Scurry. In the area between the Vealmoor and East Vealmoor fields is a Stanolind Oil Co. well named the Central Vealmoor field. The Von Roeder field in the northeast is a composite field of three small structures. The Vincent, Vealmoor-Read, and Sara Mag fields are on the seaward flank of the atoll and entirely within Howard County, while the Pancho-Mag and Pancho-Mag Southwest fields are in the lagoonal area of the atoll. The very large Scurry field extends northeastward from the mapped area. The Luck Pot field, northwest of the Good field, seems to be on the crest of the reef, but more drilling will be necessary before it can be placed in the class with the other reef-crest fields.

DISCOVERIES AND PRODUCTION

The first company to find oil in the Horseshoe atoll in the area mapped in this report was the Seaboard Oil Co. of Delaware. This discovery was made in the Vealmoor field in January 1948. The discovery well was structurally low and is now shut in, because of excessive production of salt water.

The discovery wells for this and other fields in the area of this report are shown in table 3.

TABLE 3.—*Discovery wells in the Vealmoor and other fields in the area of this report*

Discovery date	Field name	Company	Well No. and lease
Jan. 31, 1948	Vealmoor	Seaboard Oil Co. of Delaware	1–B Caldwell.
Mar. 21, 1949	East Vealmoor	Barnsdall Oil Co. (now Sunray Oil Co.)	1 Wilson.
Apr. 14, 1949	Good	Seaboard Oil Co. of Delaware and Pan-American Producing Co.	1 Good.
Dec. 21, 1949	Von Roeder	Amerada Petroleum Corp	1 Von Roeder.
Feb. 21, 1950	Reinecke	George P. Livermore, Inc	1 Reinecke.
Mar. 2, 1950	North Vealmoor	Seaboard Oil Co	1 Porter Hanks.
Aug. 10, 1950	O'Daniel (Canyon age)	Shell Oil Co	1 O'Daniel.
Nov. 11, 1950	Bond (Canyon age)	Stanolind Oil & Gas Co	1 Burton.
Dec. 20, 1950	Vincent	Fred M. Manning, Inc	1 Chester L. Jones.
July 14, 1951	Hobo	Lario Oil & Gas Co	1 T. L. Griffin.
Nov. 21, 1952	North Luther	Pan-American Producing Co	1 Pauline Hamlin.
Apr. 27, 1953	Central Vealmoor	Stanolind Oil & Gas Co	1 Minnie Smith.
Aug. 3, 1953	Oceanic (Pennsylvanian)	Oceanic Oil Co., Green & McSpadden	1 Lou Winans.
Jan. 27, 1954	Pancho-Mag	Russell Maguire	1 Beal.
Mar. 16, 1954	Luck Pot	Falcon-Seaboard Drilling Co. and Green & McSpadden.	1 Clayton and Johnson.
Mar. 26, 1954	Sara-Mag	Russell Maguire	1 Chandler.
June 8, 1954	Vealmoor-Read	Trans-Texas Drilling Co	1 Read Ranch.
Aug. 2, 1954	Pancho-Mag Southwest	Hanley Co	1–A Beal.

All the oil fields shown on plate 10 produce oil which ranges from 43° gravity A. P. I. to 47° gravity A. P. I. The following information on cumulative production from the reef in the southern part of the Horseshoe atoll, to January 1, 1954, was taken from the files of the Oil and Gas Division of the Texas Railroad Commission.

Fields	*Oil produced (bbls)*
Bond (Canyon)	47, 980
Central Vealmoor	3, 708
East Vealmoor	8, 587, 612
Good	7, 210, 054
Hobo	1, 888, 574
North Luther	134, 416
North Vealmoor	43, 981
Oceanic (Pennsylvanian)	92, 788
O'Daniel (Canyon)	21, 749
Reinecke	9, 920, 695
Vealmoor	7, 447, 432
Vincent	60, 413
Von Roeder	3, 956, 056
Total	39, 415, 458

OIL ACCUMULATION

A few wells, such as Seaboard and Pan-American's Nos. 19 and 27 T. J. Good wells, which are structurally high enough to be commercial producers, nevertheless were dry or very short-lived producers. Porosity studies show that the rocks penetrated by these wells either lacked sufficient porosity, or the porous zone was not connected with the main reservoir. Commercial amounts of oil did not accumulate in these disconnected porous zones during the time of oil migration from source rock to reservoir rock, apparently because the permeability of rocks surrounding the porous zones was too low to permit the passage of oil, and fractures in the reef did not allow unrestricted migration of oil to all parts of the reef.

Structural closure for those fields on the crest of the Horseshoe atoll is the result of eroded reef topography, but it involves regional tilting to the southwest at the rate of about 30 feet per mile.

COMPLETION PRACTICES

Some operators drill only 10 or 20 feet into the reef before placing a well into production. They probably consider that vertical migration of the oil will give their wells adequate drainage of the reservoir. Inspection of the porosity zones on the cross sections shows that the vertical movement of oil in these reservoirs is impeded or impossible. Wells drilled into oil reservoirs in the Horseshoe atoll should therefore be carried to depths just short of the oil-water interface to obtain adequate reservoir drainage.

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