THE REEF LIMESTONES OF THE NORTH SNYDER OIL FIELD, SCURRY COUNTY, TEXAS

by

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A. The Reef Limestones of the North Snyder Oil Field, Scurry County, Texas.

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The North Snyder oil field in West Texas produces from the Canyon Reef Formation of middle Pennsylvanian age. A study of cores from wells drilled in the field was undertaken to gain knowledge of the lithology of the rocks and to determine the structure of the reef.

The report presents a method for the detailed study of the reef by an integrated utilization of data available to oil companies. Extensive use was made of thin sections and polished sections of the samples. The information was then correlated with core analysis data. Since a limited amount of material was examined, many of the conclusions reached are subject to further verification.

The limestones have a fossil content of 46-48% by volume. Foraminiferal and echinodermal debris are the major constituents and make up 38-40% of the rocks. Brachiopods, bryozoans, corals, and algae(?) are present in small numbers. The reef consists of a series of small biohermal accummulations interbedded and interfingered with highly fossiliferous, stratified(?) limestones.

The limestones are various shades of gray or brown, and are very pure. There is no evidence of dolomitization. Clay silt, chert, quartz, and glauconite are the only impurities and all are rare. Oolites are present in 22% of the samples but only one sample can be properly called "oolitic". Recrystallization has been very active and 88% of the

samples show evidence of recrystallization.

Small stylolites are common in the rocks and seem to be closely related to the fracture systems. More than 50% of the samples are fractured; fracture patterns are normally complex.

Oil is present in most of the samples, and the reef limestones that have high porosities are all saturated with oil. Correlation of horizons by means of electric logs, Micrologs, or gama ray logs is unsatisfactory. It is believed that major facies changes occur in such short distances that correlation of horizons is impossible with the normal well-spacing in the field.

The internal structure of the reef was determined by assuming that the extent, continuity, and significance of the fossil horizons could be approximated.

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INTRODUCTION

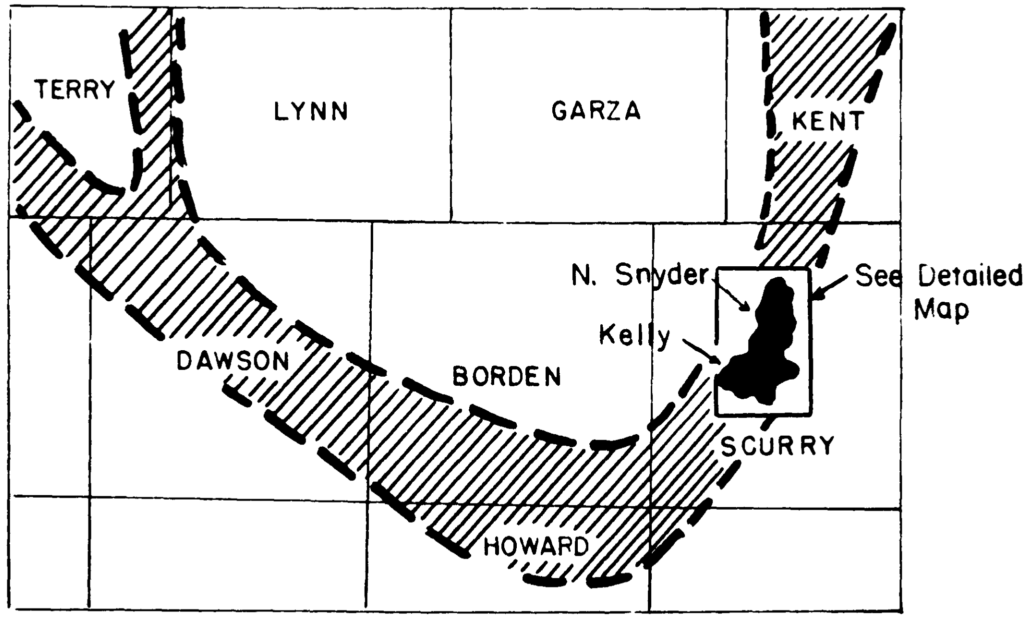
1. General Statement

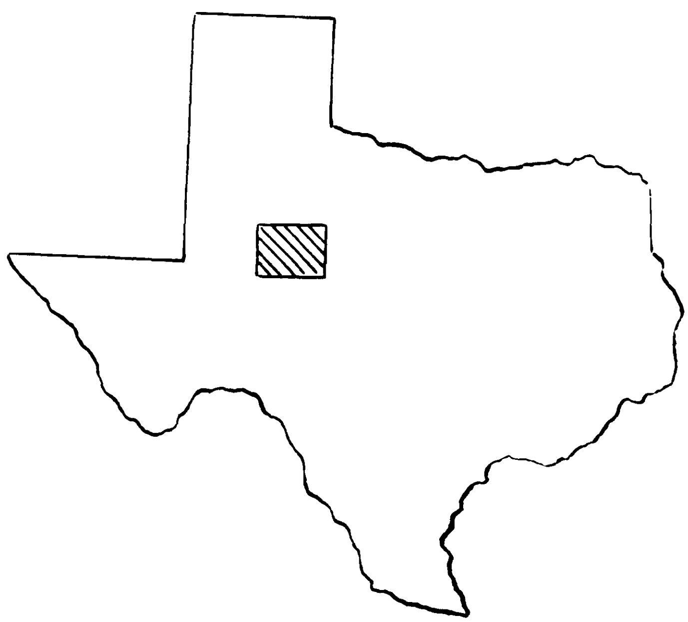
The North Snyder oil field is located some seven miles NNW of the town of Snyder in Scurry County, Texas. It lies on the eastern edge of the Permian Basin. (see plates 1 and 2.)

The discovery well was drilled in November, 1948. At the end of 1949 there were 168 producing wells in the field. The producing horizons are in the Canyon Reef Formation, a highly fossiliferous series of limestones containing many biohermal accummulations. The average thickness of the productive part of the formation is 475 feet; depths to the top of the formation vary from 6100-7000 feet. The oil-water contact lies between -4450 and -4500 feet subsea but some oil is produced from zones below this general water level.[1] The proved acreage is in excess of 6720 acres. Development is on a 40 acre spacing and most wells are drilled at the centers of quarter-quarter sections.

Cumulative production to the end of 1949 was 2,818,375 barrels of oil. The potential production per well varies from 69-2708 BOPD. Core analysis data and Microlog determinations indicate that the percentage of net pay varies considerably between wells but averages 50-70% of the reef section above -4500 feet subsea. Results of the core analysis of 3434 cores from 14 wells[2] show an average porosity of 8.36% with a range in porosity from 3.70-14.40%. Permeabilities are generally low; normal values are 0-100 md. with an average permeability of 10-15 md. Most wells have low productivity indexes.

PROSPECTIVE REEF TREND IN WEST TEXAS





LOCATION MAP FOR ABOVE AREA

Plate 1.

Data released by various companies show the following reservoir characteristics:[2]

Reservoir temperature........................$125^{\circ}F$

Saturation pressure..........................1733 psig

Gas-oil ratio, atmos. flash..................967

Gravity of the oil...........................42.1° API

Original reservoir pressure..................3122 psig

The reserves have been estimated at 4,018,000,000 barrels of oil under reservoir conditions. With a shrinkage factor of 0.625 and an assumed recovery of 30%, the oil expected to be recovered is 750,000,000 barrels.

2. Purpose of the Thesis

The thesis was undertaken to gain a more comprehensive knowledge of the characteristics of the reef limestones of the North Snyder oil field. Chief emphasis was placed on the lithology, faunal content, and sedimentational features of the limestones.

During the investigation every effort was made to secure information that would be of value to oil companies. Since limestones are one of the most prolific sources of oil, information on their characteristics is of importance.

The study shows how such information can be secured, the types of information which are available, and how this information can be put to use. Since a limited amount of material was available for study, this investigation should be considered as a general approach to the study of limestones and not as a final report on any phase of such investigations.

3. Methods of Study

Extensive use was made of microscopic examination of the samples; both thin sections and polished sections were used. In spite of the fertile fields for study in sedimentary petrography, microscopic studies of limestones are relatively rare; this very useful method of study is usually overlooked by most geologists. This investigation indicates that a thin section study of limestones is essential if a better understanding of limestones is to be attained.

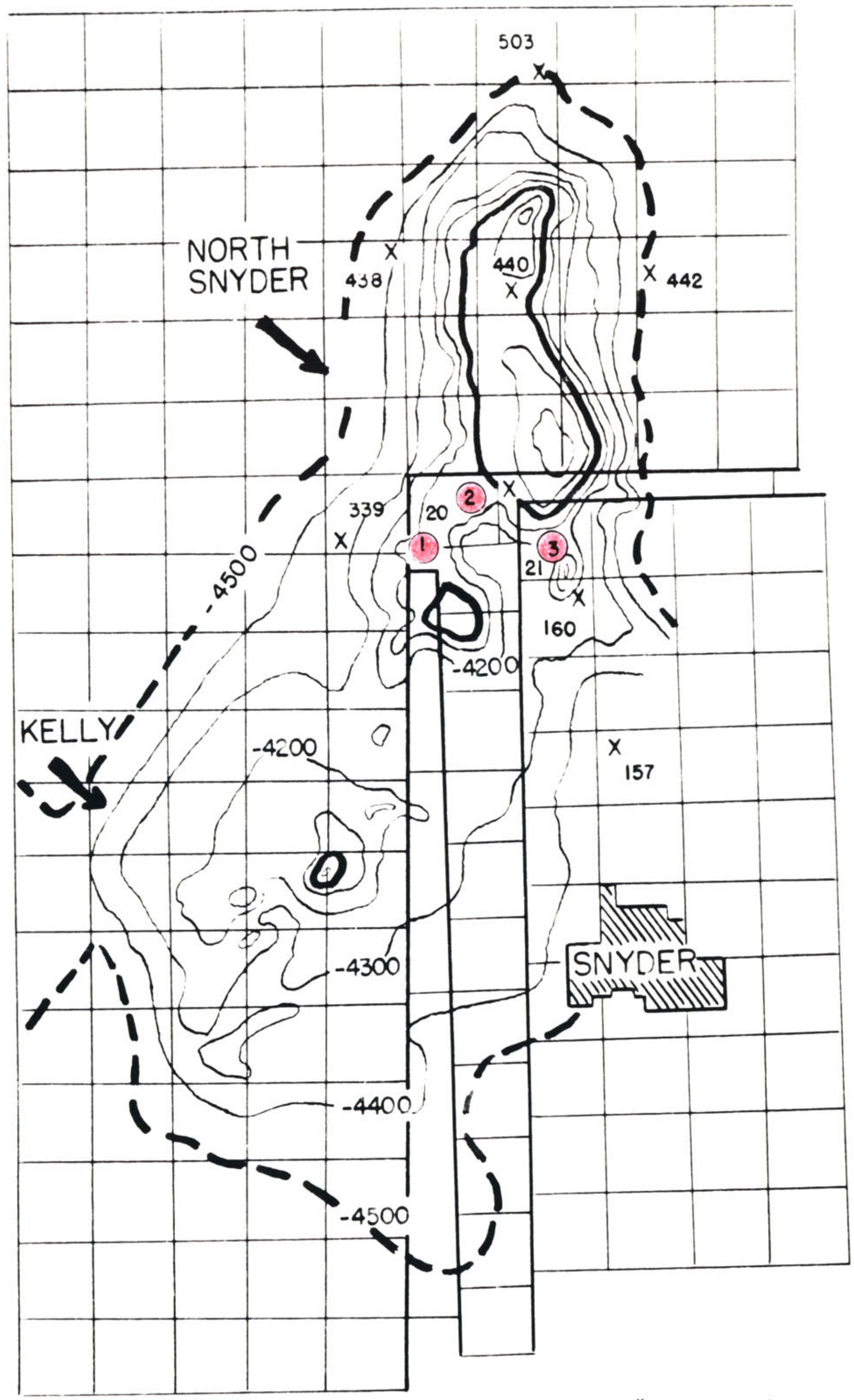
Each sample was subjected to several examinations. First, each sample was examined using a hand lens. Next, one or more polished sections were made and examined under a binocular microscope using low magnifications (10X). Third, thin sections were made and examined under two types of microscopes. A binocular microscope at magnifications of 36X was used for the initial examination. A petrographic microscope was then used to determine any information not revealed by the binocular microscope. The use of binocular microscopes to examine thin sections is not often stressed; this investigation suggests that such an examination is extremely useful and should be made a part of standard procedure. Finally, a 5-10 gram sample of each specimen was treated with cold dilute HCl and the residues collected. These residues were then examined under a binocular microscope.

4. Materials Available for Study

A. Core Samples

Small specimens from 63 cores are the principal source of information and their examination is the basis of this investigation. The samples were supplied by the Barnsdall Oil Company

CONFIGURATION OF TOP OF
CANYON REEF FIELDS
SCURRY COUNTY, TEXAS



CONTOUR INTERVAL = 100 FT.   SCALE: 1" to 12000'

Plate 2.

(since amalgamated with the Sunray Oil Corporation) and came from three wells in the North Snyder field. Well locations are shown on plate 2. (1) is the P.J. Collins #1 well, (2) is the A.L. Wren #2 well, and (3) is the M.J. Womack #2 well. Twenty two samples were available from P.J. Collins #1, 22 from A.L. Wren #2, and 19 from M.J. Womack #2.

(1) The following information on the three wells was obtained from the records of the Barnsdall Oil Company:

(a) Well: P.J. Collins #1

Location: 467 ft. from N&EL Tr 17, Sec 20, Blk 7, J.P. Smith Survey

Elevation: 2482 ft. DF

Maximum Depth: 6899 ft.

Maximum Temperature: 128°F

Producing Interval: 6762-6899 ft.

(b) Well: A.L. Wren #2

Location: 467 ft. from S&EL Tr 9, Sec 20, Blk 1, J.P. Smith Survey

Maximum Depth: 6893 ft.

Elevation: 2481 ft. DF

Producing Interval: 6730-6893 ft.

(c) Well: M.J. Womack #2

Location: 467 ft. from N&WL Tr 6, Sec 21, Blk 1, J.P. Smith Survey

Elevation: 2445 ft. KB

Maximum Depth: 6887 ft.

Producing Interval: 6837-6887 ft.

LIST OF SAMPLES AVAILABLE FOR STUDY

P.J. Collins #1

Core Number	Depth(ft.)
2	6550
3	6551
4	6552
14	6562
27	6575
51	6599
69	6623
91	6646
107	6665
154	6712
164	6722
165	6723
180	6738
216	6774
227	6786
230	6789
235	6694
265	6827
289	6851
290	6852
303	6865
337	6899

A.L. Wren #2

Core Number	Depth(ft.)
49	6630
50	6631
64	6651
70	6660
88	6687
92	6693
98	6702
101	6707
102	6708
103	6710
118	6748
124	6792
126	6795
127	6797
141	6818
149	6830
150	6831
152	6834
153	6836
178	6877
179	6878
188	6893

M.J. Womack #2

Core Number	Depth (ft.)
15	6680
22	6687
24	6689
34	6699
37	6702
38	6703
39	6704
53	6718
57	6722
58	6723
72	6737
79	6744
92	6757
98	6763
109	6774
164	6835
183	6858
190	6865
203	6883

B. Other Information

Electric logs were available for the following wells:

1. Barnsdall Oil Company	Collins #1	Sec 20
2. Barnsdall Oil Company	Wren #2	Sec 20
3. Barnsdall Oil Company	Womack #2	Sec 21
4. Castleman & ONeil	Huckabee #1	Sec 160
5. Magnolia Petroleum Co.	Collins #1-A	Sec 19

Sample logs were supplied for the following wells:

1. Standard Oil of Texas	Brown et al	Sec 440
2. Progress Pet. of Texas	Carden #1	Sec 503
3. Humble O&R Company	Davis #1	Sec 339
4. Olson Drilling Co.	Green #1	Sec 157
5. Sunray Oil Corp.	Brown #1	Sec 20
6. Humble O&R Company	Perriman #1	Sec 438
7. Collins et al	Park #1	Sec 442

These wells may be located on plate 2. They are marked by an "X". The nearby numbers are section numbers. In the report the wells are referred to only by the section numbers; the tract and block numbers are omitted since they are not necessary for an understanding of the report.

Core analysis data were available for the three wells for which samples were studied. Gamma ray traces were present on several of the electric logs.

5. Photography

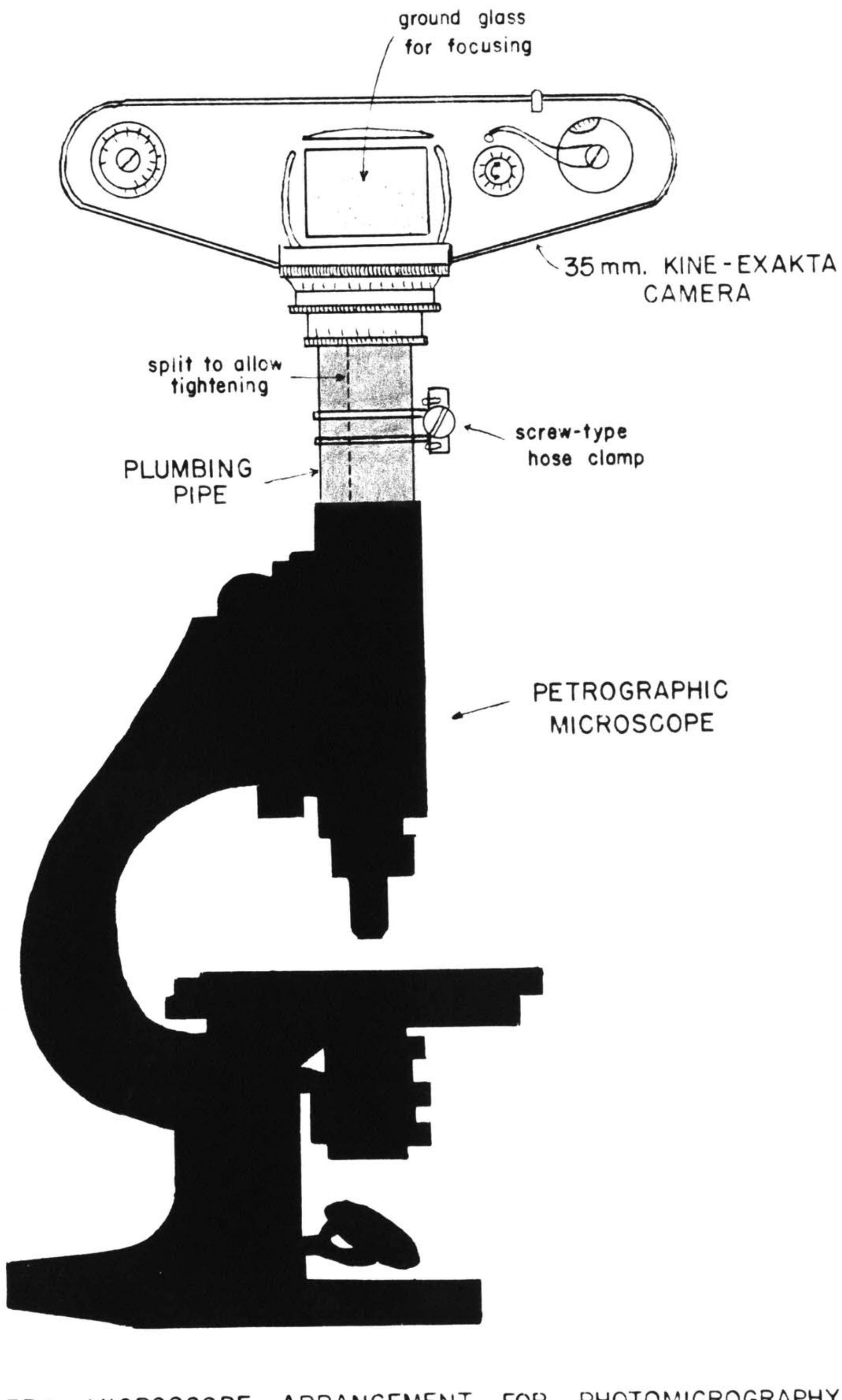
Photographs and photomicrographs were made of every sample. Since it was necessary that the work be inexpensive yet efficient, certain features were desirable including:

1. Use of inexpensive film such as 35 mm.
2. Use of roll film to save time.
3. Ability to work in daylight.
4. Ability to focus images rapidly and accurately.

These problems were solved by the use of a 35 mm. Kine-Exakta single reflex camera. The camera was attached to a petrographic microscope by a simple home-made adapter. A piece of plumbing pipe 2" long was split lengthwise and a hose clamp, similar to those on an automobile radiator hose, was used to tighten the pipe. A section of lead foil was wrapped around the tubing to make it light-tight. Plate 3 shows the arrangement of camera and microscope during taking of the photomicrographs.

Microscope magnifications of 36X and 60X were used during the photomicrography. Since the lens caused a considerable reduction in the size of the image on the film, it was necessary to enlarge the pictures. The final prints are at magnifications of 10-15X.

Several types of printing paper were tested; best results were obtained using Kodabromide F-4 paper.



CAMERA - MICROSCOPE ARRANGEMENT FOR PHOTOMICROGRAPHY

Plate 3.

6. Acknowledgements

The author is indebted to William L. Horner, chief petroleum engineer for the Sunray Oil Corporation, who made available the core samples, electric logs, sample logs, and core analysis data used in this study. Sincere thanks are also extended to Dr. W.L. Whitehead for suggesting and encouraging this study, and to Dr. R.R. Shrock for his helpful criticism of the report.

CHAPTER II

STRUCTURE OF THE REEF

1. Reef or Bioherm?

Early writers described and defined reefs in many ways; the earliest definitions were concerned with the so-called "coral reefs". The confusion which resulted in the meaning of the term reef led Cumings and Shrock[3] to suggest that the word be abandoned and that the terms bioherm and biostrome be substituted. Bioherms are defined as "reef-like, moundlike, lens-like or otherwise circumscribed structures of strictly organic origin, embedded in rocks of different lithology".[3]

The most recent definition of a reef known to the author is that by Wilson[4]. This states that "a reef is a sedimentary rock aggregate, large or small, composed of the remains of colonial organisms that lived near or below the surface of the water, mainly marine, and developed relatively large vertical dimensions as compared with the proportions of adjacent sedimentary rocks".

On the basis of definitions alone, the North Snyder field is either or both. However, the original definitions have been subjected to many qualifications and restrictions.

Cumings and Shrock in their work recognized a central core of unstratified material surrounded and overlain by bedded deposits which rest on or are interfingered with the core. The flank beds commonly show steep dips. In this sense the North Snyder field is not a bioherm.

The structure of the field is discussed at length on pages

10-18, but the following characteristics are pertinent to this discussion:

1. There is no central, unstratified core.
2. Bedded deposits, although rarely observed, are present at all horizons and in all parts of the mass.
3. Bedding, if observed, is horizontal.
4. Individual beds are thin, and have no appreciable lateral extent.
5. There are, so far as is known, no steeply inclined beds on the flanks of the main mass.

In short, the mass does not seem to conform to the type of structure that Cumings and Shrock described in their work.

The proposed internal structure of the mass is shown on plates 8 to 11. These sections show that the mass is a complex series of organic accretions in the form of small biohermal accummulations 10-40 feet high. The accummulations are present at several horizons in widely separated localities. Reef growth took place under the influence of a differential regional warping which shifted the most favorable localities for growth of the various colonial organisms from place to place. Unknown factors, possibly tectonic, were responsible for limiting the favorable localities to a rather narrow arcuate belt.

It seems unlikely that Cumings and Shrock intended that the term bioherm be applied to a complex group of rocks formed under these conditions. Growth at the North Snyder locality was probably discontinuous in as much as the mass is not a single accummulation of colonial organisms in the sense that many bioherms are. However, the definition and qualifications applied to the term biostrome are not fulfilled.

Therefore, it is proposed to call this complex, ridge-shaped accummulation a reef. Some observers might prefer to classify the entire Canyon Reef Formation as a reef complex in which reef-like accummulations of organic debris are common.

2. General Structure in the Vicinity of the Reef

The North Snyder field lies on a north-south structural trend that is considered to be a line of reefs. To the south of the field the trend swings to the southwest. The top surface of the reef is extremely irregular, and differences in elevation of several hundred feet occur in distances of one half mile. The contours on the top of the reef are shown in plate 2.

Ground elevation in the area is 2400-2500 feet, and is fairly constant. There is no surface expression of the reef mass. The top of the reef lies at depths of 6000-7000 feet.

A. Regional Stratigraphy

The stratigraphy from the surface to the reef formation is as follows:

1. Undifferentiated Permian with a thin veneer of Triassic rocks.
2. San Andres Formation - Permian
3. San Angelo Formation - Permian
4. Clearfork and associated formations - Permian
5. Cisco Formation - Upper Pennsylvanian
6. Canyon Reef Formation - Middle Pennsylvanian

The following descriptions of these formations are all taken from the sample logs of wells drilled in the field.

(1) Undifferentiated Permian

In this group are 1500-1800 feet of red and green shales and siltstones with a few thin beds of white anhydrite, and several beds of tan-gray dolomite.

(2) San Andres Formation

There are 700-870 feet of dolomite with a few thin limestones and several beds of anhydrite. The formation is thickest in the northwestern part of the field at thinnest at the southeastern edge. The dolomites and limestones are light brown in color, and the anhydrite is white or gray-white. Gray or light blue-gray chert is common in the dolomites.

(3) San Angelo Formation

This formation seems to have been deposited on a relatively level surface. The formation is only 120-200 feet thick, but it is present in all parts of the field. The rocks are interbedded dolomites, shales, sandstones, and anhydrite. Tan dolomites and gray shales are most abundant; the white anhydrite is relatively scarce; and the thin sandstones are reddish in color. Milky white or gray chert is reported in the dolomites.

(4) Clearfork Formation

This formation and the associated lower Permian beds are 2610-3000(?) feet thick. Examination of the sample logs indicates that the formation may be divided into four recognizable zones.

(a) The uppermost zone is 200-500 feet thick and consists of gray and brownish dolomites with minor amounts of shale and anhydrite.

(b) The second and thickest zone is 1000-1500 feet of interbedded dolomite, shale and anhydrite. The dolomites are light gray to brown in color; the shales are gray, greenish, and greenish-gray, and have a tendency to be sandy or silty; the anhydrite is white.

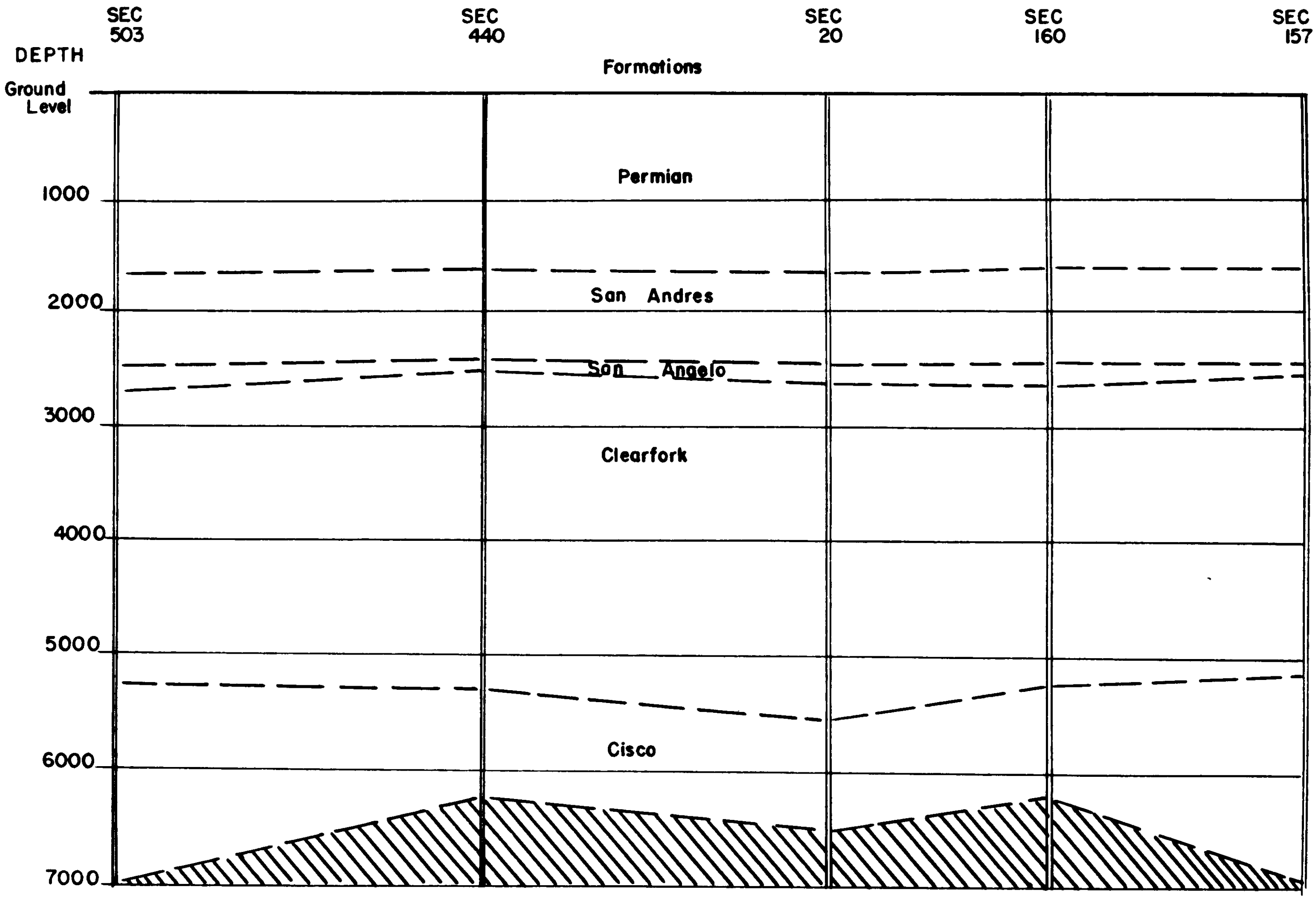
(c) The third zone is 300-600 feet thick and is composed of interbedded dolomites, limestones, and gray or greenish shales. The calcareous rocks are generally brown in color, and contain masses of light gray or light brown chert.

(d) The lowest zone consists of limestone and dolomite, and is 400-700 feet thick. The rocks are brown, gray, light brown, and gray-white in color. Medium to coarsely crystalline textures are generally reported.

(5) Cisco Formation

The formation is 880-1715 feet thick, and is much thicker on the flanks of the reef limestones. It thickens by 500-800 feet both east and west of the reef crest. It seems certain that the Cisco formation was deposited on a surface that had a topographic relief of at least 835 feet. This is an indication that the reef had a considerable relief prior to the deposition of the Cisco formation. Whether this relief was due to (1) reef growth, (2) erosion, or (3) a combination of both, cannot be determined from the information available.

The formation is composed of silty shales and thin sand-



N-S SECTION OF FIELD
SCALE: 1' TO 6000"

Plate 4.

stones. The shales are normally gray in color, and the sandstones are gray-white. More than 90% of the rocks are shale.

(6) Canyon Reef Formation

Since this formation is the subject of the entire study, only a few brief words are needed here. The formation is composed entirely of limestones. Many types of limestones are present but no dolomite was observed. The rocks are light gray, dark gray, white, and various shades of brown. Chert is very rare.

B. Cross-sections of the Area

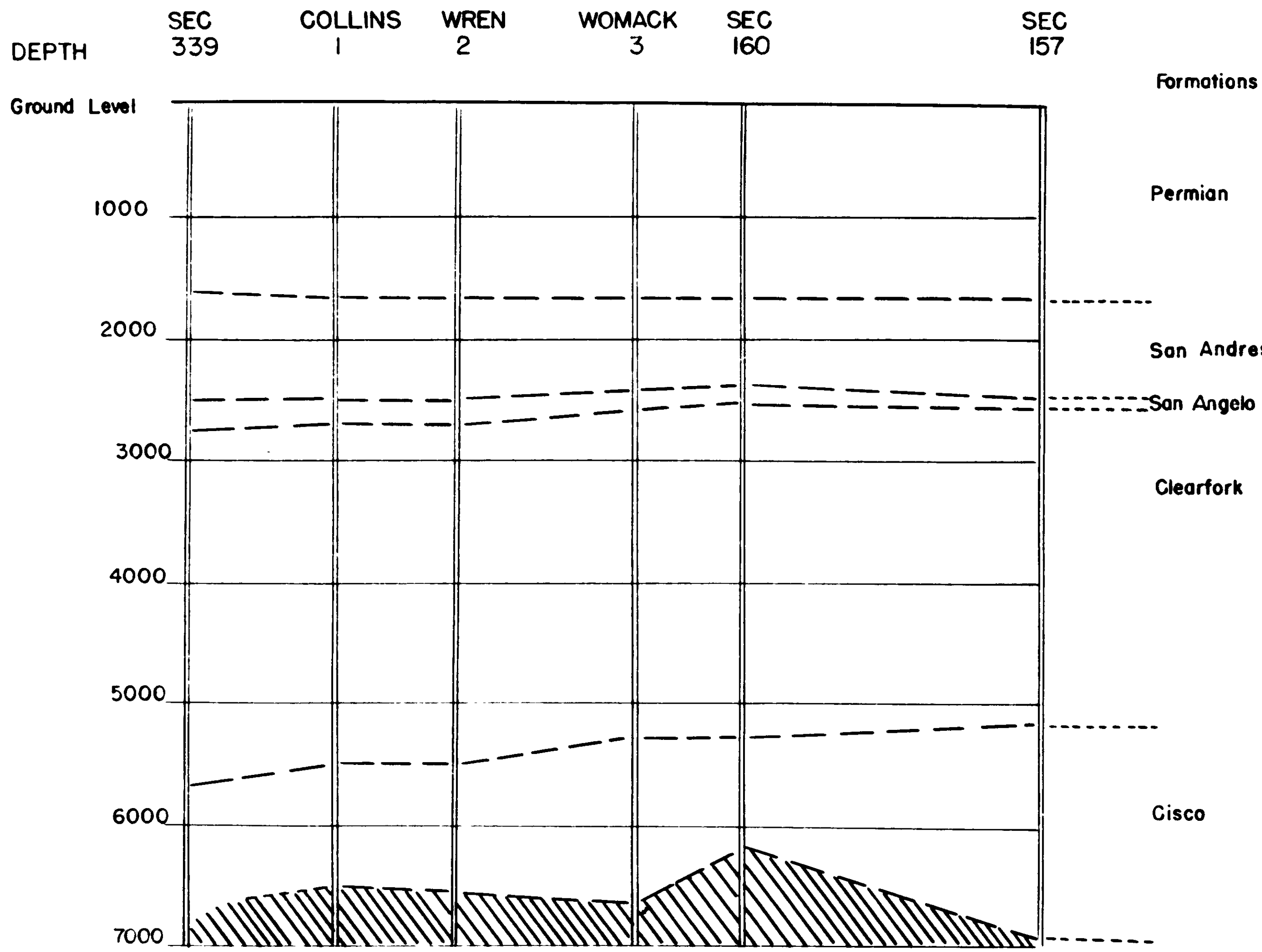
Three cross-sections of the area are shown in plates 4, 5, and 6. The control points for the sections may be located on plate 2.

(1) North-South Section. See plate 4.

This section runs along the crest of the reef and then veers off towards the southeast. The section is much generalized with control at only 5 points; all minor irregularities are omitted. Above the reef, the formation which shows the greatest variations in thickness is the Cisco. By the end of Cisco time, it seems that the depositional surface was relatively level. Minor differential tectonic movements during the lower Permian are suggested by the thickening of the sections in several wells.

(2) East-West Section in Southern Part of Field. See plate 5.

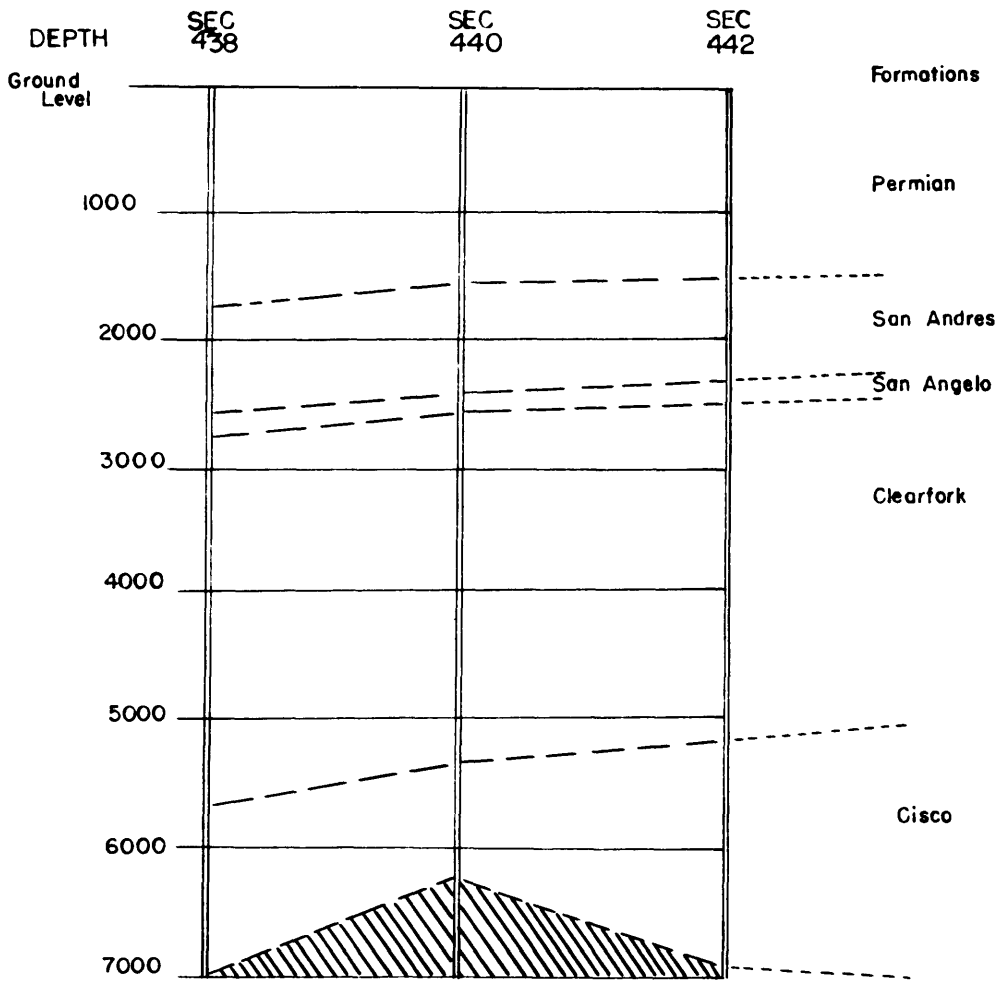
The irregularities of the surface of the reef and variations in the thickness of the Cisco formation are readily apparent in this section. Differential tectonic movements are



E - W SECTION So. PART OF FIELD

SCALE: 1" TO 6000'

Plate 5.



E-W SECTION No. PART OF FIELD

SCALE: 1" TO 6000'

Plate 6.

suggested at several periods; (1) during Cisco time, (2) during Clearfork time, and (3) during San Andres time. Little or no differential movement is indicated in post-San Andres time, although there have been major regional movements.

(3) East-West Section in Northern Part of Field. See plate 6.

The irregularity in the surface of the reef and the variation in thickness of the Cisco formation are again apparent. The section also suggests that there was a regional tilting towards the west or northwest. All formations from the Clearfork to the surface show greater thicknesses in the northwestern part of the field. It seems that the tilting was a slow process that lasted throughout the Permian.

C. Tectonics of the Permian and Pennsylvanian

The reefs of the Canyon Reef Formation were built on a shallow, mildly-oscillating sea-bottom. Following a regional subsidence and perhaps after a period of erosion, the Cisco shales were deposited on a very irregular surface. Minor differential tectonic movements may have occurred at or near the end of Cisco time.

Following the deposition of the Cisco formation, thin-bedded dolomites and anhydrites were deposited in a shallow evaporite basin into which there were periodic influxes of mud and silt. An overall regional subsidence was still in progress.

By the end of Clearfork time there was a nearly level surface, and 100-200 feet of dolomites, shales, sandstones, and anhydrite were deposited in a shallow basin to which clastic sediments were added periodically.

On top of the thin San Angelo formation were deposited 700-870 feet of dolomites. The San Andres formation thickens towards the northwest. A downwarping in the northwestern part of the area is indicated in addition to the regional subsidence.

Over the entire area of dolomite, 1500-1800 feet of red and green shales, chiefly of continental origin, were deposited. Thin anhydrite beds in this sequence show that the area was at or near sea-level much of the time.

The entire area was elevated to its present elevation at some post-Permian period, but a discussion of that event is beyond the scope of this study.

3. Internal Structure of the Reef

The data from the three wells indicate that electric logging is of little value in the correlation of horizons in the reef mass. Consequently, correlations were made of the various fossil horizons.

The distribution of fossil debris was plotted against depth in each of the wells and tentative correlations made. Examination of these data suggested that only minor tectonic movement had occurred within the reef mass. The fossil zones were then plotted against depth with sea level as a datum plane. The correlations are shown in plate 7.

The width of the reef in the vicinity of the three wells is approximately 24,000 feet, and the interval between the

TENTATIVE CORRELATION OF FOSSIL HORIZONS

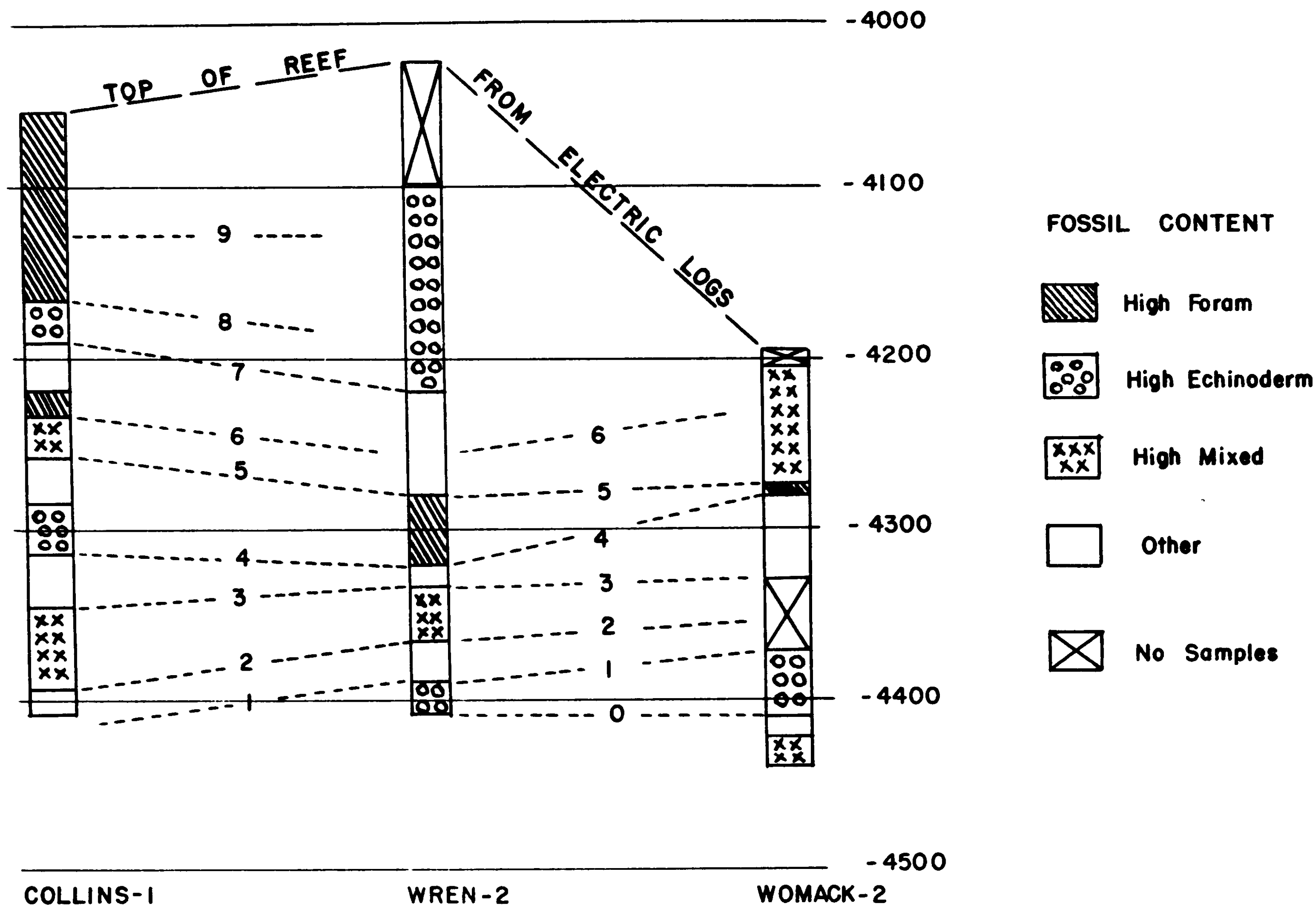


Plate 7.

three wells is about 11,400 feet. The reef mass extends about 7500 feet west of Collins #1 and some 5100 feet east of Womack #2.

The basic assumptions made in the interpretation of the internal structure of the reef are:

1. That fossil correlations are correct.

2. That certain fossil assemblages are typical of a given reef facies.

3. That the top surface of the active part of the reef at the end of any given stage is essentially flat.

4. That thicker sections and fusulinid deposits indicate a greater submergence of that part of the reef.

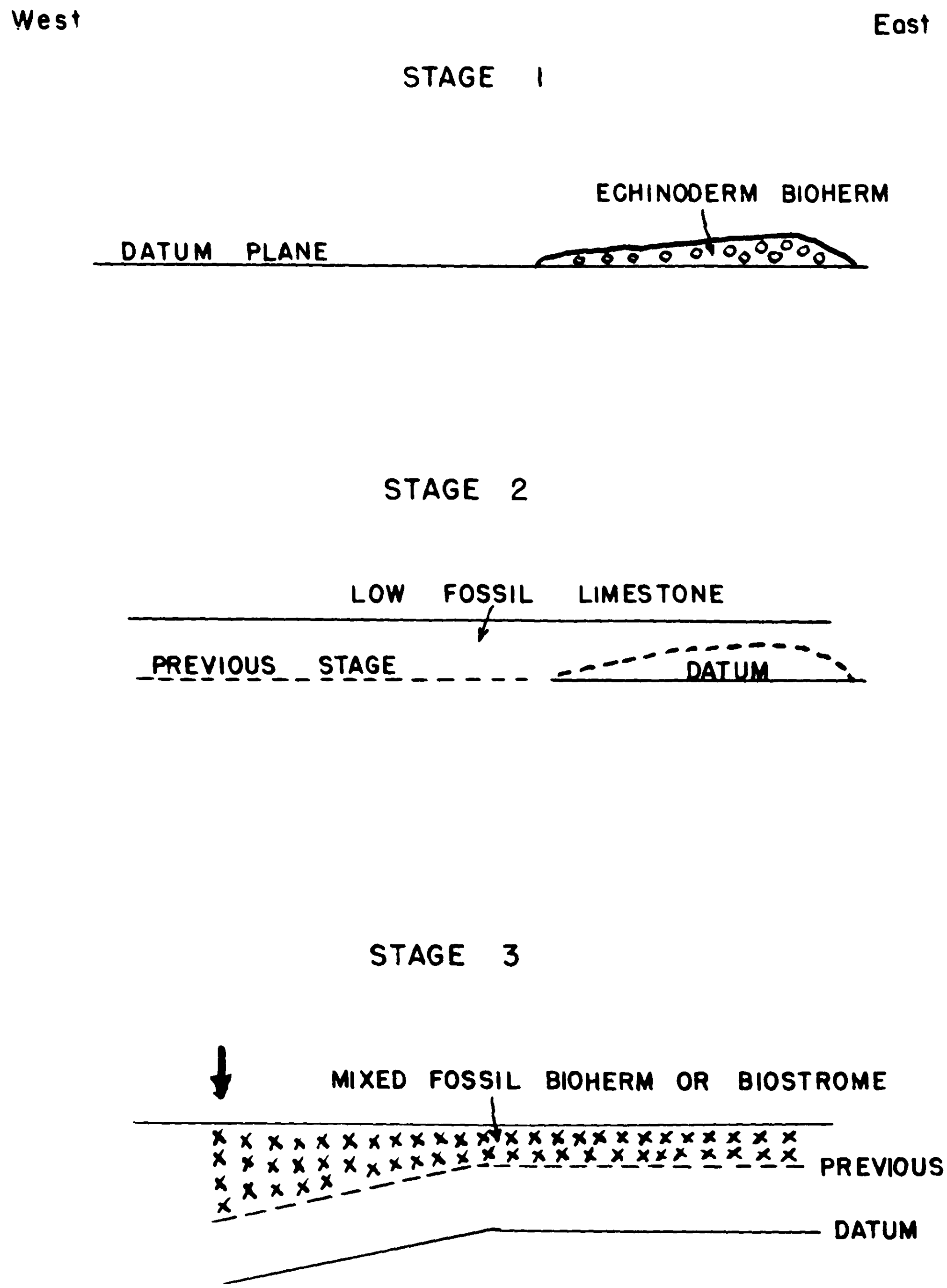
5. That there was no important erosion of the reef until after stage 7 and perhaps none at all.

6. That there was little or no deposition at the site of Womack #2 after stage 6.

If the assumptions are valid, it is possible to determine the pattern of reef growth. Although growth was more or less continuous, minor breaks in deposition probably occurred and the building of the reef is considered in nine distinct stages. This breakdown is wholly arbitrary.

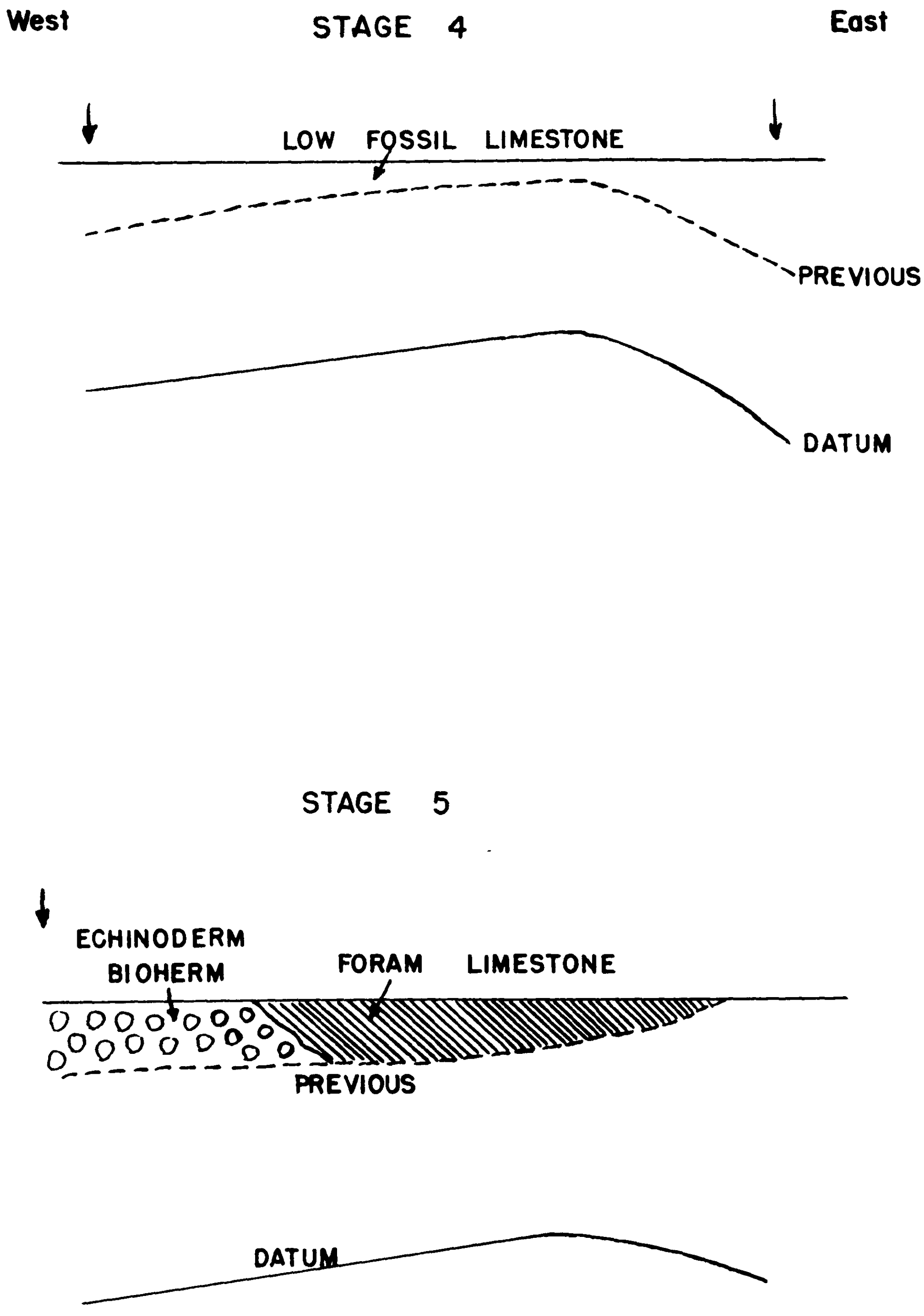
The cross-sections shown in plates 8 to 11 run from Collins #1 at the western edge, through Wren #2, to Womack #2 at the extreme east. It should be remembered that the reef mass maintains a considerable thickness for one and one-half miles west of Collins #1 but decreases very rapidly in thickness east of Womack #2. The datum plane in each drawing is the approximate position of the basement rock at the end of each stage.

During stage 1 there was no reef deposit at Collins #1,



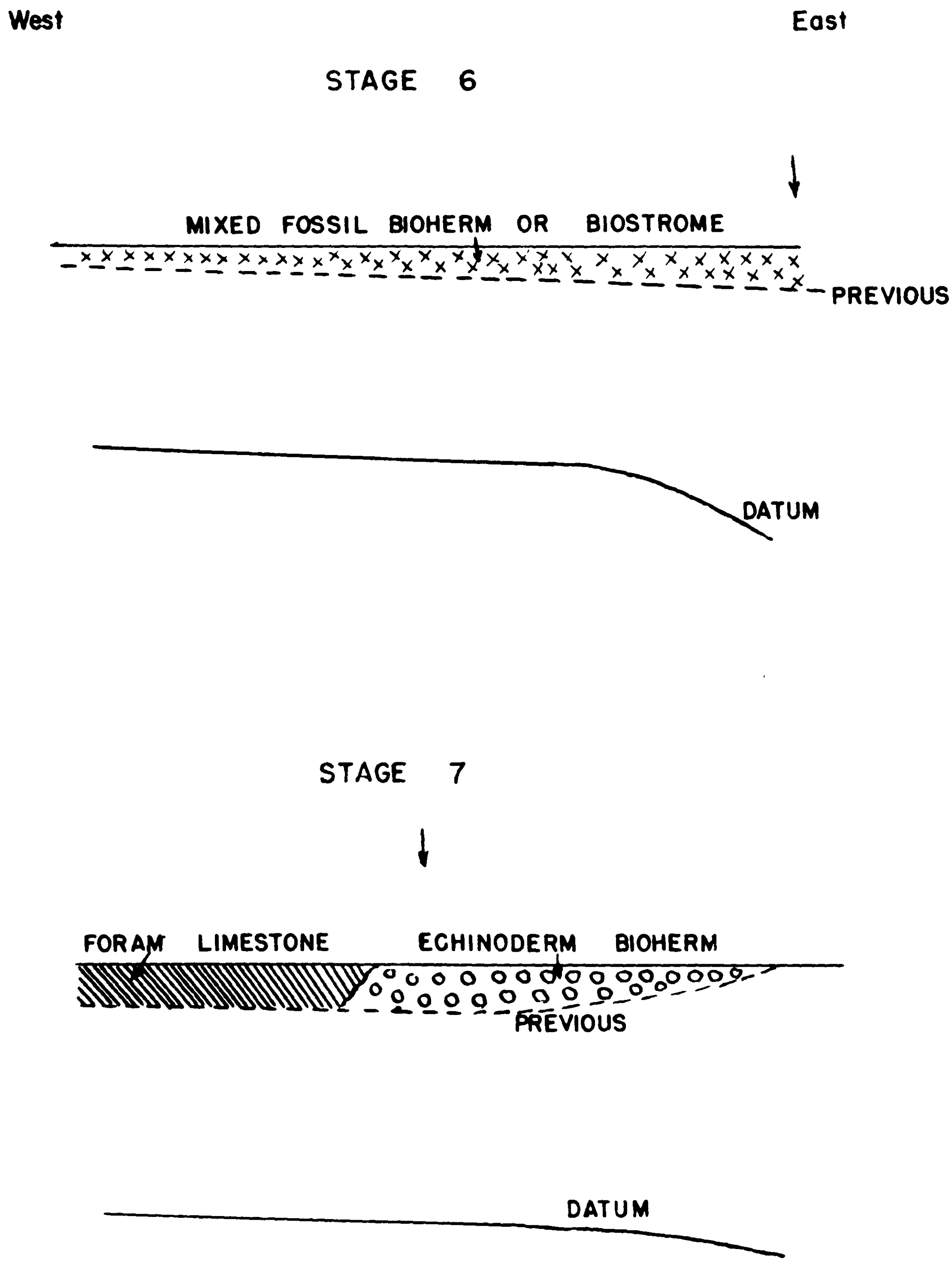
STAGES OF REEF DEVELOPMENT

Plate 8.



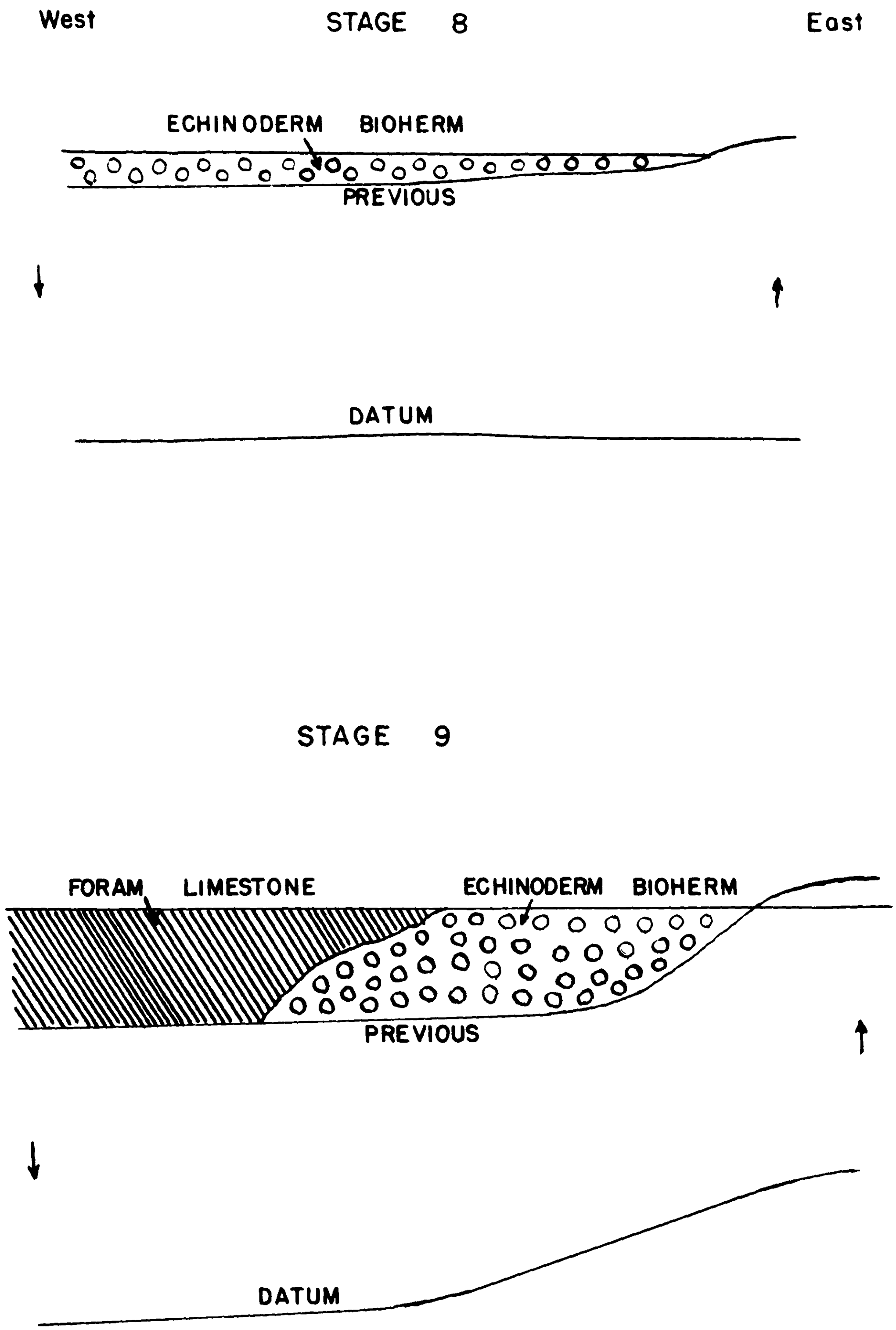
STAGES OF REEF DEVELOPMENT

Plate 9.



STAGES OF REEF DEVELOPMENT

Plate 10.



STAGES OF REEF DEVELOPMENT

Plate 11.

a small growth at Wren #2, and Womack #2 was the locus of reef building. The deposits consist largely of echinodermal debris and fenestellate bryozoans. Towards the end of this phase, brachiopod coquinas were present at the sites of Wren #2 and Womack #2.

During stage 2 a limestone with a very low fossil content was deposited over the entire area. The deposits thicken towards the west and thin slightly towards the east. The marked decrease in the fossil content of the rocks suggests that the depth of the water covering the reef may have increased.

Stage 3 is characterized by a highly fossiliferous limestone which is very widespread. The deposits may be a biostrome or they may indicate a great lateral expansion of reef growth. These deposits are also thicker towards the west, and there may have been downwarping in the vicinity of Collins #1. Samples for this stage were not available for the Womack #2 well. Echinodermal debris and foraminifera are abundant at Collins #1 and Wren #2. Bryozoa are also common in the samples. It is likely that a general shallowing of the water and a spread of favorable ecological conditions were responsible for the large increase in fauna.

Stage 4 is represented by a limestone with a low fossil content. The sparsely fossiliferous limestone is present in all three wells. The deposits are thicker both east and west of Wren #2. There may have been a period of differential warping during a regional submergence. The presence of bryozoans and algae (?) in samples from the Womack #2 well suggests that it was still the locus of reef-building.

During stages 1-4, the main reef growth seems to have been centered in the vicinity of the Womack #2 well. Deeper waters were present in the vicinity of Collins #1.

During stage 5 the locus of reef-building seems to have shifted to Collins #1 where echinoderms and bryozoa were abundant. A thick deposit of foraminiferal limestone is present at Wren #2 and the same deposits, although much thinner, are found at Womack #2. It seems likely that the deposits at Wren #2 and Womack #2 are indicative of lagoonal conditions at those sites.

During stage 6 there was a widespread shallowing of the area, and a reestablishment of ecological conditions favorable for a great lateral spread of reef growth. Fusulinids, echinoderms, bryozoa, brachiopods, and algae are all abundant.

Stage 7 shows a shift in the locus of reef-building to Wren #2. Deeper water fusulinid limestones are characteristic of Collins #1. After the close of stage 7, deposition at Womack #2 seems to have ceased. Although a period of non-deposition seems most likely, it is possible that the deposits were removed by erosion.

Stage 8 is represented by a highly fossiliferous limestone which may be a biostrome. It is possible that the uppermost part of the deposits at Womack #2 belong to this phase. Bryozoa and echinoderms are the dominant fossils in all three wells.

During stage 9 there were (1) no deposits at Womack #2, (2) brachiopods, bryozoa, and corals at Wren #2, and (3) foraminiferal limestones at Collins #1.

During stages 6-9 it seems likely that Wren #2 was the locus of reef-building. The deposits at Collins #1 are typical of lagoons or deep water. There was little or no deposition at Womack #2.

A consideration of all stages seems to suggest that the reef mass is a compound complex which was both a barrier reef and a bank reef. During stages 3 and 6, and possibly 2 and 4, it was a bank reef. During the other stages the mass shows more of the characteristics of a barrier reef.

The principal reef-building organisms seem to have been (1) echinoderms, (2) bryozoa, and (3) algae. Corals were never important in the building of the reef and appeared only during the final stage. The role played by the algae is difficult to evaluate, but is likely of greater importance than this study would indicate.

CHAPTER III

POROSITY OF THE LIMESTONES

1. Introduction

Porosity is one of the mass properties of a rock. It is defined as the percentage of a rock occupied by voids. Commonly these voids are filled with liquids.

Discussions of porosity in the literature deal chiefly with sandstones and shales; limestone porosity is seldom treated at length. The most comprehensive discussions of limestone porosity known to the author are by Hohlt[5]; Imbt[6]; Craze[7]; and Littlefield, Gray, and Godbold[8]. The discussion by Hohlt is a complete but generalized treatment of the problem. The article by Littlefield, Gray, and Godbold is an excellent discussion of the problem from the viewpoint of petroleum geology.

Although the various authors have classified limestone porosity in several ways, the classifications were not deemed suitable for use in this study. The porosity of limestones is complex, and it is not normally feasible to distinguish between primary and secondary porosity. The classifications used in this discussion are based on texture and structure.

The types of porosity to be discussed are (1) vuggy porosity, (2) intergranular porosity, (3) fracture porosity, and (4) solution channels and cavities. Each of these types is easy to recognize even in small samples. Fracture porosity and solution porosity are not discussed at length since they are difficult to evaluate in terms of other characteristics of the rocks. (See Chapter IX).

2. Porosity of the Canyon Reef Formation

Data released by the Scurry County Engineering Committee[2] based on core analyses of 3434 cores from 14 wells show an average porosity for the field of 8.36% with individual porosities ranging from 3.70-14.40%.

The average porosity of the 63 cores available for study is 9.86% with a range from 0.8-22.7%. For the 22 cores of Collins #1 the average porosity is 9.0%, for the 22 cores of Wren #2 12.6%, and for the 19 cores of Womack #2 7.6%.

Using the core analysis data supplied by the Barnsdall Oil Company for the three wells, the following results are obtained:

	Average porosity
1. For 337 cores of Collins #1	3.6%
2. For 189 cores of Wren #2	12.8%
3. For 207 cores of Womack #2	3.8%
4. For 733 cores of all wells	5.73%

Porosity profiles for the wells are shown in plates 48, 49, and 50. The profiles for the producing intervals appear on plates 12, 13, and 14.

A. Porosity of P.J. Collins #1

The average porosity for the entire cored interval of 337 feet is 3.6%. The average porosity of those zones which show some permeability is 14.0%; seventy samples are included in this group with individual porosities ranging from 2.9-22.8%. The average porosity of the 267 feet of reef section that have a reported permeability of 0.0 md. is 3.0% with a range from 0.8-14.0%.

B. Porosity of A.L. Wren #2

The average porosity of the entire cored interval of 189 feet is 12.8%. The average porosity for the 126 samples which show some permeability is 11.3% with individual porosities ranging from 0.9-24.0%. Sixty three samples have a reported permeability of 0.0 md.; their average porosity is 4.1% with a range from 1.1-17.9%.

C. Porosity of M.J. Womack #2

The average porosity for the cored interval of 207 feet is 3.8%. However, examination of the samples shows that there is a considerable solution porosity developed in the well which is not revealed in the core analysis data.

The average porosity of the 72 samples which show some permeability is 11.8%. There are 135 samples with a reported permeability of 0.0 md.; their average porosity is 1.9% with a range from 0.3-7.9%.

D. Summary of the Porosity in the Wells

(1) Porosity of Samples with No Permeability

Porosity Range-%	No. of Samples
0.1-1.0	38
1.1-2.0	172
2.1-3.0	99
3.1-4.0	49
4.1-5.0	35
5.1-6.0	37
6.1-7.0	12
7.1-8.0	5
8.1-9.0	6
9.1-10.0	7
10.1-11.0	3
11.1-12.0	3
12.1-13.0	5
More than 13.1	1

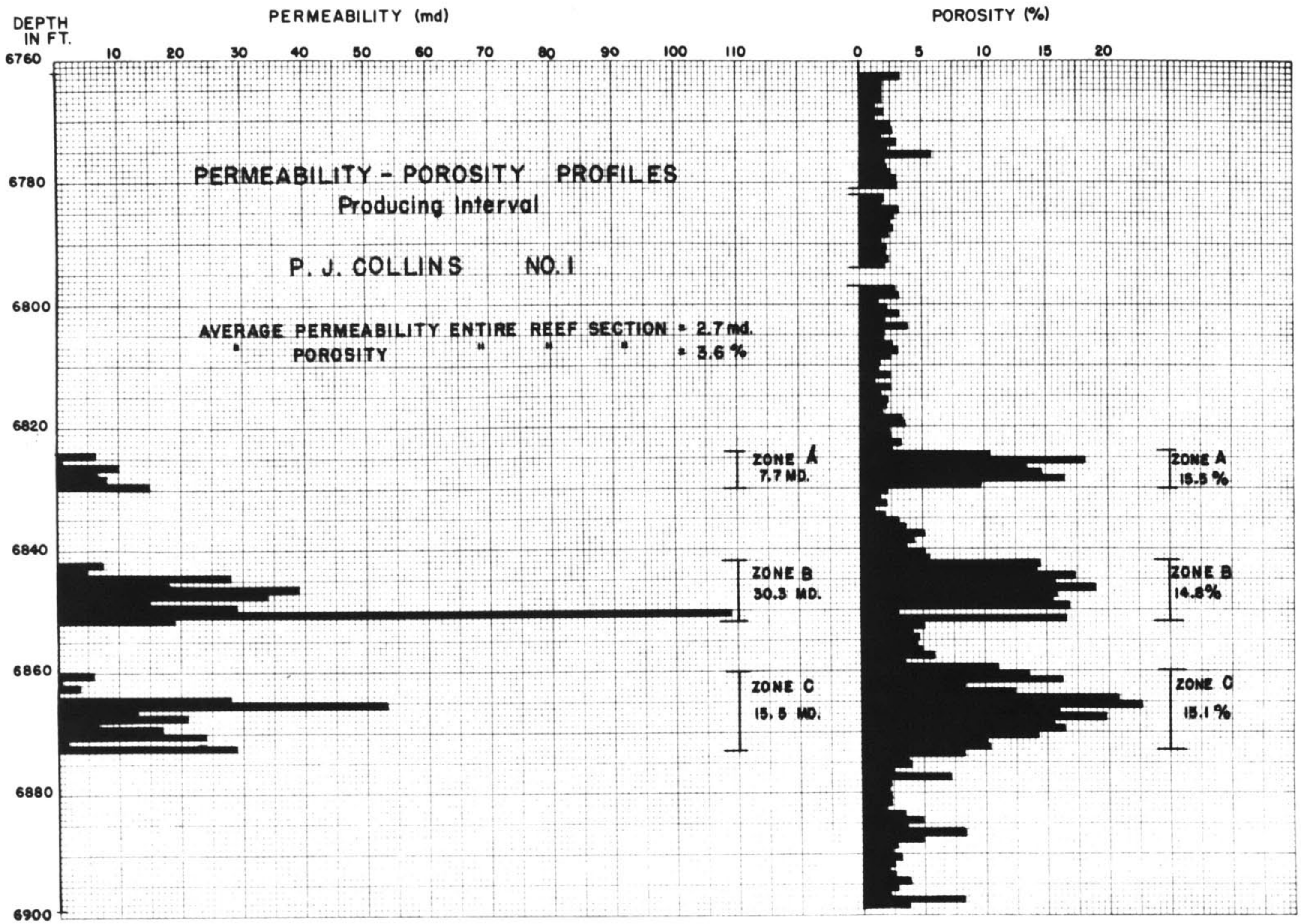

DEPTH IN FT.
PERMEABILITY (md)
POROSITY (%)
6760
6780
6800
6820
6840
6860
6880
6900
10 20 30 40 50 60 70 80 90 100 110
0 5 10 15 20
PERMEABILITY - POROSITY PROFILES
Producing Interval
P. J. COLLINS NO. 1
AVERAGE PERMEABILITY ENTIRE REEF SECTION = 2.7 md.
" POROSITY " " " = 3.6 %
ZONE A
7.7 MD.
ZONE B
30.3 MD.
ZONE C
15.5 MD.
ZONE A
15.5 %
ZONE B
14.8%
ZONE C
15.1 %

Plate 12.

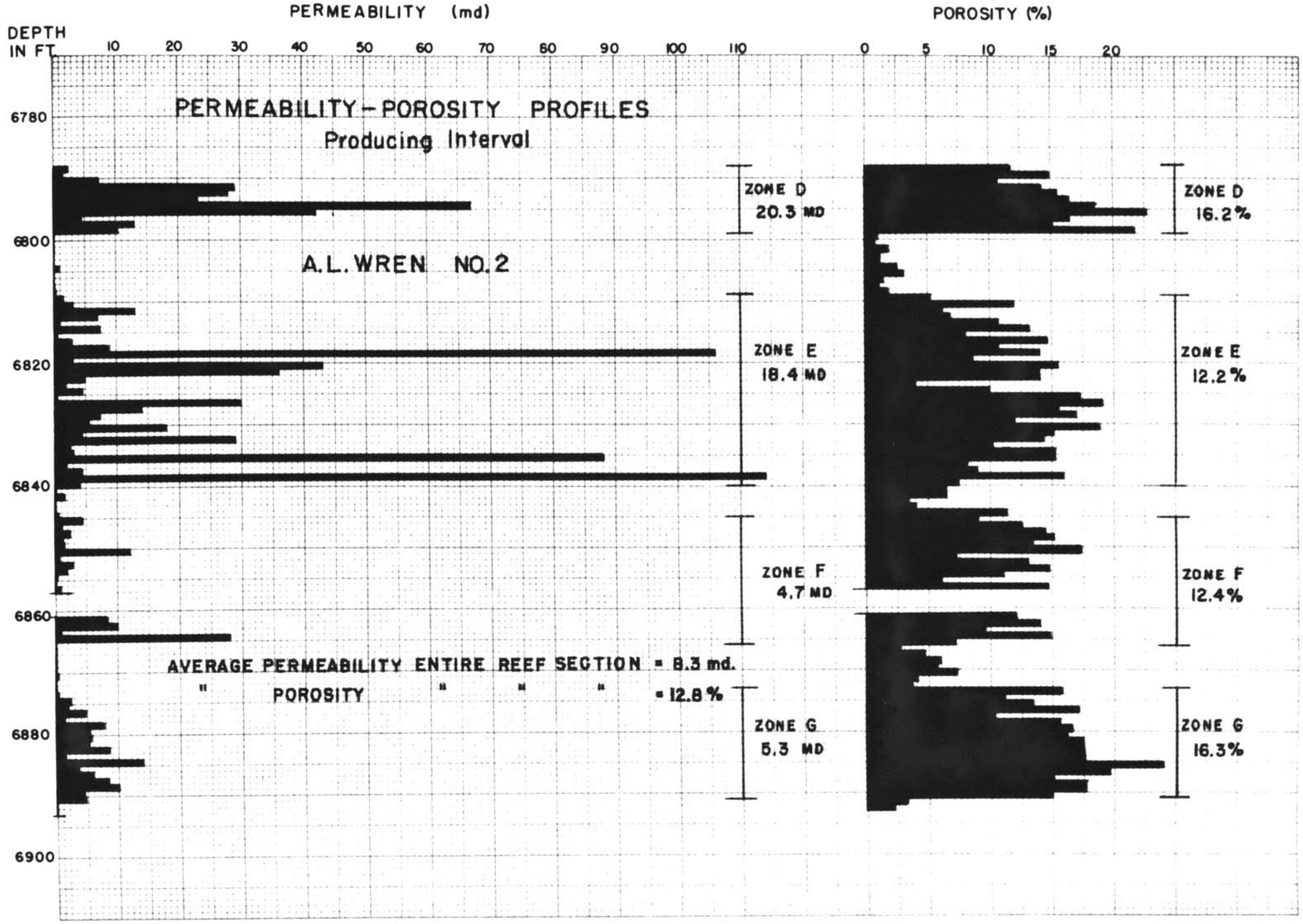

PERMEABILITY (md)
POROSITY (%)
DEPTH IN FT
PERMEABILITY-POROSITY PROFILES
Producing Interval
A.L. WREN NO. 2
ZONE D 20.3 MD
ZONE E 18.4 MD
ZONE F 4.7 MD
ZONE G 5.3 MD
ZONE D 16.2%
ZONE E 12.2%
ZONE F 12.4%
ZONE G 16.3%
AVERAGE PERMEABILITY ENTIRE REEF SECTION = 8.3 md.
" POROSITY " " " = 12.8%
6780
6800
6820
6840
6860
6880
6900

Plate 13.

(2) Porosity of Samples with Some Permeability

Porosity Range-%	No. of Samples
0.7-1.0	7
1.1-2.0	17
2.1-3.0	19
3.1-4.0	9
4.1-5.0	7
5.1-6.0	12
6.1-7.0	8
7.1-8.0	5
8.1-9.0	11
9.1-10.0	12
10.1-11.0	11
11.1-12.0	22
12.1-13.0	16
13.1-14.0	33
14.1-15.0	16
15.1-16.0	20
16.1-17.0	18
17.1-18.0	9
18.1-19.0	7
19.1-20.0	3
More than 20.1	6

The tabulations show that 6% of the samples have a porosity less than 1%, 32% less than 2%, 48% less than 3%, 56% less than 4%, 62% less than 5%, 77% less than 10%, 93% less than 15%, and only 0.9% of all samples have a porosity higher than 20%.

3. Influence of Type of Fossil Content on Porosity

The porosity of the reef limestones is influenced by the fossil content of the rocks. To show the relationships the approximate percentages of the various types of fossil debris in each sample were estimated. The fossil content was then correlated with the porosities reported in the core analysis data. The results appear in the following subsections.

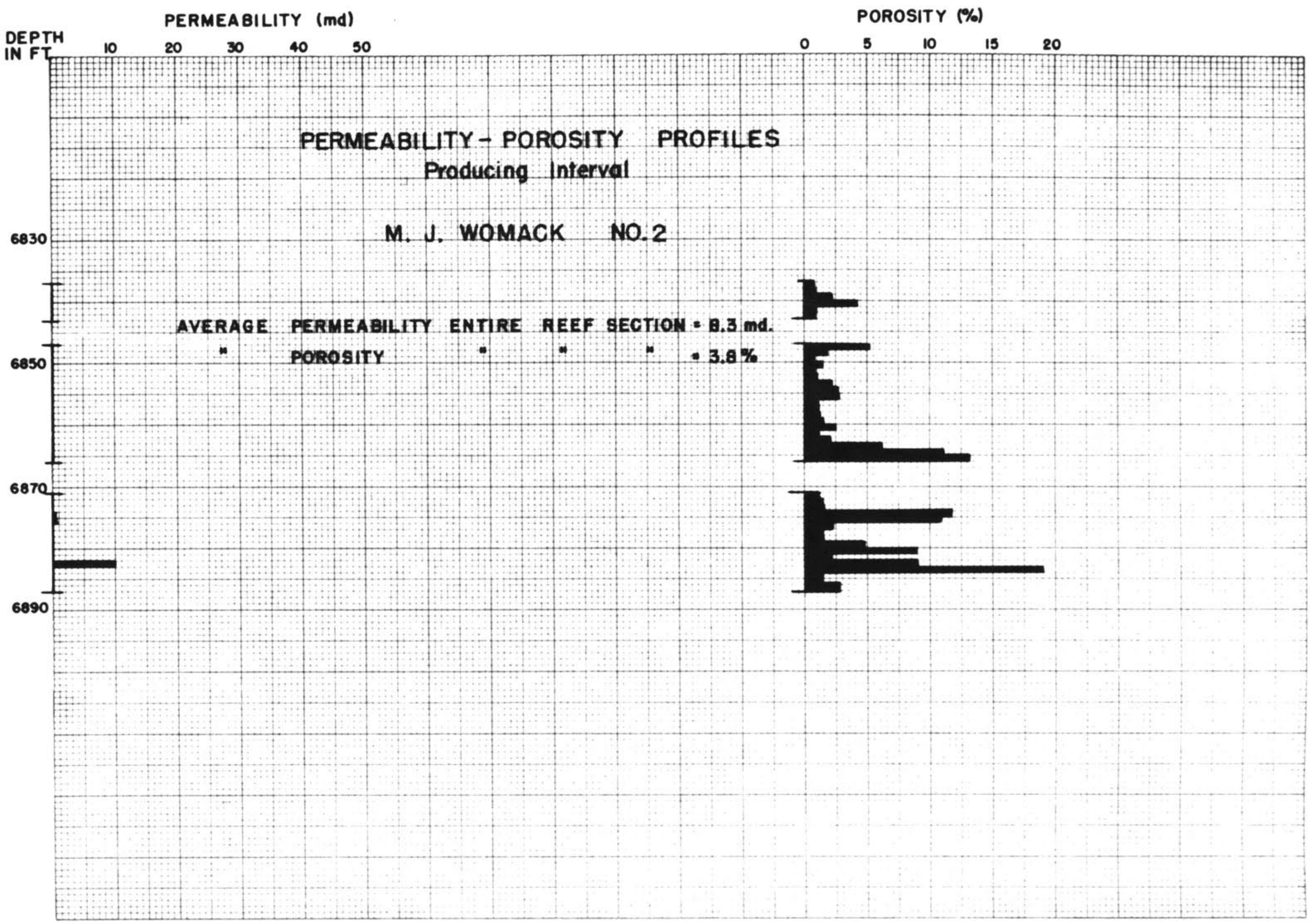

PERMEABILITY (md)
POROSITY (%)
DEPTH IN FT.
10 20 30 40 50
0 5 10 15 20
PERMEABILITY - POROSITY PROFILES
Producing Interval
M. J. WOMACK NO. 2
AVERAGE PERMEABILITY ENTIRE REEF SECTION = 8.3 md.
" POROSITY " " " = 3.8 %
6830
6850
6870
6890

Plate 14.

A. The Relationships of Porosity and Foraminiferal Content

Foraminifera are present in 54 (86%) of the cores examined. More than 85% of the foraminifera are fusulinids; the remainder are pelagic types which were not identified.

Table III-1 Number of Samples in Each Porosity Range vs. Foraminiferal Content of Rocks in %

Porosity Range in %	Range of Foraminifera in %							
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
0-5	8	3	2	1	0	1	1	0
5-10	2	0	2	0	1	0	1	0
10-15	7	3	1	5	0	0	2	0
15-20	1	1	3	3	1	1	0	2
20-25	0	0	0	1	1	0	0	0
TOTALS	18	7	8	10	3	2	4	2

If the foraminiferal content is less than 10% of the rock, the porosity tends to be lower then average. Porosity seems to be highest if the foraminiferal content is between 30-50%; in the 13 samples of this group, 11 have porosities greater than 10%.

B. The Relationships of Porosity and Echinodermal Content

Fragmental material from echinoderms is present in 43 (74%) of the cores examined. Table III-2 shows the relationships between porosity and echinodermal content. The higher porosities are in those samples that have an echinodermal content less than 40%. However, a relatively large number of samples that contain less than 40% echinodermal debris also show porosities less than 5%.

Table III-2 Number of Samples in Each Porosity Range vs. Echinodermal Content of Rock in %

Porosity Range in %	Range of Echinoderm Debris in %						
	0-10	10-20	20-30	30-40	40-50	50-60	60-70
0-5	3	3	1	2	1	1	2
5-10	0	1	2	0	0	0	0
10-15	4	3	5	2	2	1	0
15-20	4	1	3	1	0	0	0
20-25	1	0	0	0	0	0	0
TOTALS	12	8	11	5	3	2	2

C. The Relationships of Porosity and Total Fossil Content

Sixty one (97%) of the cores examined contain fossil debris. More than 90% of this debris has come from echinoderms or foraminifera.

Table III-3 Number of Samples in Each Porosity Range vs. Total Fossil Content of Rock in %

Porosity Range in %	Total Fossil Content in %							
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
0-5	2	3	3	1	0	2	3	5
5-10	0	1	0	0	0	1	2	2
10-15	1	3	3	4	1	3	4	3
15-20	0	0	0	1	4	2	1	4
20-25	0	0	0	0	1	0	1	0
TOTALS	3	7	6	6	6	8	11	14

The higher porosities (over 15%) are associated with high fossil contents; nevertheless, 15 of the 33 samples that contain over 50% fossil debris have porosities less than 10% and 10 have porosities less than 5%.

In the 10 samples which are composed largely of foraminifera, the average porosity is 12.5%. The 12 samples that are composed largely of echinodermal debris have an average porosity of 8.9%. The 16 samples which are highly fossiliferous mixtures of foraminifera and echinoderms have an average porosity of 10.5%. Eleven of the samples contain noticeable amounts of bryozoa in addition to their other fossil debris; the average porosity of these samples is 5.6%. Finally, the 6 cores which have a low fossil content have an average porosity of 3.6%.

D. Summary

In conclusion, the following points may be emphasized:

1. The highly fossiliferous reef limestones have a higher average porosity than those with a low fossil content.

2. There are no direct relationships between porosity and either the fossil types or the amount of fossil debris.

3. Higher porosities seem to be associated with:
   a. Foraminiferal limestones containing more than 30% foraminifera.
   b. Echinodermal limestones containing less than 40% echinoderms.
   c. Limestones with a fossil content greater than 50%.
   d. Highly fossiliferous limestones which are mixtures of foraminifera and echinoderms.

4. Vuggy Porosity in the Reef Limestones

Many limestones have a porosity described as "vuggy". The term is seldom defined, and the origin of this porosity is usually overlooked. Webster's New International Dictionary defines a <u>vug</u> as

" a small unfilled cavity in a rock, usually lined with a crystalline layer". As applied to limestones the term normally indicates pore space of a size larger than intergranular pore space and smaller than the openings called caverns. In this report vugs are considered to be those openings of either primary or secondary origin which are clearly larger than intergranular pore space and not due solely to fracturing or jointing.

Plates 15 and 16 show the size and distribution of vugs in four of the samples. Other examples of vugginess are illustrated in the photographs accompanying this section.

A. Size of the Vugs

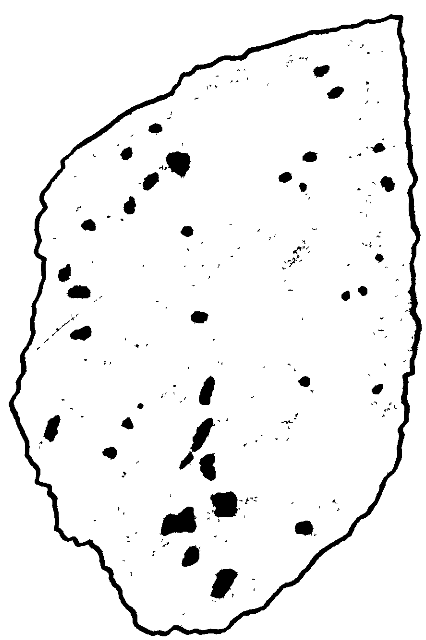
Twenty seven (43%) of the cores examined have a porosity characterized as vuggy. The size of the vugs varies from 0.3 mm. to 75.0 mm. , but the average size in most specimens is less than 1.5 mm. The distribution of average sizes appears in the following tabulation.

Average size of vugs in mm.	No. of samples
0.3-0.5	5
0.6-1.0	11
1.1-1.5	8
1.5-2.0	1
More than 10	2

B. The Relationships of Vugs and Fossil Content

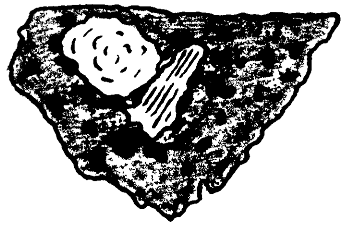
Vugs are common in all types of reef limestones. The highly fossiliferous limestones are more likely to be vuggy than those which have a low fossil content. The distribution of vugs in

WREN NO. 2 CORE 103 3X
PORES 0.4-6.0 mm.
PERMEABILITY 1.6 md. POROSITY 13.9%

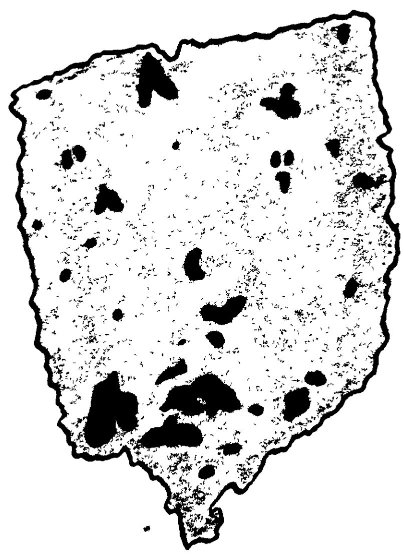


WREN NO. 2 CORE 118 3X
PORES 0.1- 2.0 mm.
PERMEABILITY 0 POROSITY 1.9%

Plate 15.



COLLINS NO. I CORE 3 2X
PORES 0.3 - 1.2 mm.
PERMEABILITY 155 md. POROSITY 17.4%



COLLINS NO. I CORE 289 3X
PORES 0.3 - 3.2 mm.
PERMEABILITY 109 md. POROSITY 2.9%

Plate 16.

the various types of limestones is shown in the following tabulation.

Type of Fossil Content	No. of Samples
Dominantly foraminiferal	7
Dominantly echinodermal	2
Mixed foraminiferal and echinodermal	10
Mixed Other Groups of Fossils	5
Low Fossil Content	3

C. The Relationships of Vugs and Total Fossil Content

No direct relationships were observed between the percentage of fossil debris in the rocks and the vugginess. The distribution of data is as follows:

% Fossil Debris	No. of Samples
0-10	0
10-20	6
20-30	4
30-40	1
40-50	5
50-60	2
60-70	7
70-80	2

D. The Relationships of Vugs and Porosity

In comparing porosity and vugginess, two samples are omitted (Womack #2 cores 164 and 183). The vugs in these samples are so large that it is doubtful that the core analysis data are representative. The average porosity of the other 25 samples is 12.3%, a value much higher than the average for all the cores.

The distribution of the porosities of the 25 samples is shown in the following table.

Table III-4 Porosity vs. Size of the Vugs

Vugs in mm.	Porosity Range in %						Totals
	0-2	2-5	5-10	10-15	15-20	20-23	
0.3-0.5	0	0	2	3	0	0	5
0.6-1.0	0	1	1	4	4	0	10
1.1-1.5	0	0	1	4	1	1	7
1.6-2.0	0	0	0	1	0	0	1
Over 10	0	0	1	1	0	0	2
TOTALS	0	1	5	13	5	1	25

The data indicate that vugs are more common in rocks that have high porosities, and most common in those whose porosities are 10-15%.

In the two samples omitted from the tabulation, the reported porosities are 1.7% and 1.2% although there are vugs with diameters of 5.0 and 75.0 mm. respectively in those samples. Seemingly the cores cut for analysis were taken from the denser portions of the rocks.

E. The Relationships of Vugs and Permeability

Only 25 samples are used in this tabulation since the two samples with the large vugs have reported permeabilities of 0.0 md., and it is felt that the data are not representative. The average permeability of the 25 samples is 23.3 md. Table III-5 shows the actual relationships found during examination of the samples.

Table III-5 Permeability vs. Size of Vugs

Vugs in mm.	Permeability Range in md.						
	0-2	2-5	5-10	11-20	21-50	51-100	101-200
0.3-0.5	4	0	0	1	0	0	0
0.6-1.0	0	2	2	3	2	0	1
1.1-1.5	0	1	1	1	1	2	1
1.6-2.0	0	0	0	1	0	0	0
Over 10	1	0	1	0	0	0	0
TOTALS	5	3	4	6	3	2	2

There is no close correlation indicated in the data. Vugginess does not guarantee good permeability although it is commonly associated with higher permeabilities. The nature of the vugginess seems to be important. Primary vugs are more likely to be associated with low permeabilities and secondary vugs with the higher permeabilities.

F. The Relationships of Vugs and Fractures

Of the 27 vuggy samples, 12 are noticeably fractured. Relationships between vugginess and fractures is shown below:

Table III-6 Fractures vs. Vugginess

Vugs in mm.	Type of Fracturing				Totals
	Vertical	Oblique	Multiple	Horizontal	
0.3-0.5	1	1	1	0	3
0.6-1.0	2	1	1	1	5
1.1-1.5	0	1	1	0	2
Over 10	0	0	2	0	2

The data show that fractures are present in nearly one half of the rocks with vugs whereas vugs are present in less than one third of the fractured samples (12 of 39). All types of fractures are present in the vuggy limestones.

G. Origin of the Vugs

The vugs are of two general types and may be classified as:

1. Primary Vugs - those formed during deposition and consolidation.

   a. Voids between individual particles of the detrital limestones including those voids between individual crystals of the matrix.

   b. Voids within the skeletal material of invertebrates.

2. Secondary Vugs - those formed after consolidation.

   a. Voids along fracture planes.

   b. Voids caused solely by solution.
      1. Along a definite zone.
      2. In interiors of shells, oolites, or fossil fragments.

The primary vugs range from 0.3-75 mm. in diameter. The shape of these vugs tends to have some sort of regularity with the reason for the limitations in size normally apparent; e.g. the interior of a shell or test, or the incomplete filling of an original cavity. The material surrounding the vugs is normally identical with the remainder of the rock. The vug may be lined with calcite crystals if recrystallization has been operative. The diameter of most primary vugs is less than 2 mm.

Vugs that are clearly recognizable as secondary tend to be rather large (more than 4 mm.). All secondary vugs in the samples examined were formed by solution. The shape of the secondary vugs is irregular. Commonly the vugs are elongated and lie along a zone, especially if the vugs are associated with fractures. If the vugs are isolated and widely disseminated throughout the mass of the sample, the openings tend to be rounded.

Differential solution is important in the formation of secondary vugs. The interiors of oolites, foraminiferal tests, shell fragments, and other fossil fragments may be selectively affected. If the vugs are large, they tend to be lined with calcite crystals. These crystals are commonly rather coarse.

Several examples of vuggy porosity are shown in the accompanying photographs on the next two pages; vugs outlined in red.

H. Summary

Vuggy porosity may be primary or secondary. Primary vugs are due to incomplete cementation or to the incomplete filling of an original cavity or opening. Secondary vugs are formed by solution, normally in some selective fashion. The results of the investigation may be summarized as follows:

1. Vugs vary greatly in size. Primary vugs are generally small; secondary vugs may be of any size.

2. Vugs are most common in the more coarsely crystalline varieties of reef limestones.

3. The fossil content of the rocks has only a slight influence on the vugginess of the samples.

4. Fossils whose natural structures include openings or cavities may be responsible for much of the vugginess of a given sample.

5. There is no direct relationship between vugginess and permeability.

6. Vugs are more common in rocks with high porosities.

7. Fractures aid in the development of secondary vugs. There is no observable relationship between fractures and primary vugs.

Figure 1 Collins #1
Core 290 10X

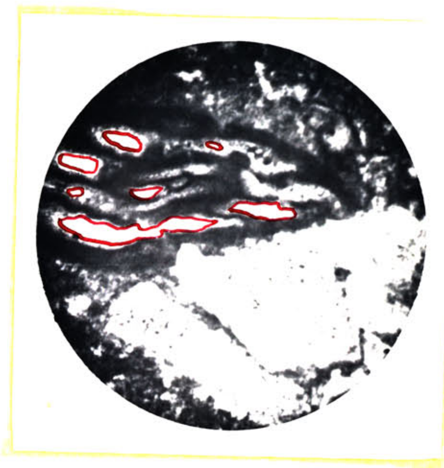


Figure 2 Wren #2
Core 102 10X

Irregular, variable primary pore space in the chambers of fusulinids due to incomplete filling.

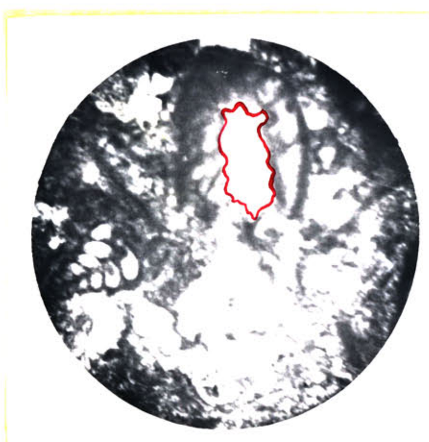


Figure 3 Wren #2
Core 141 10X

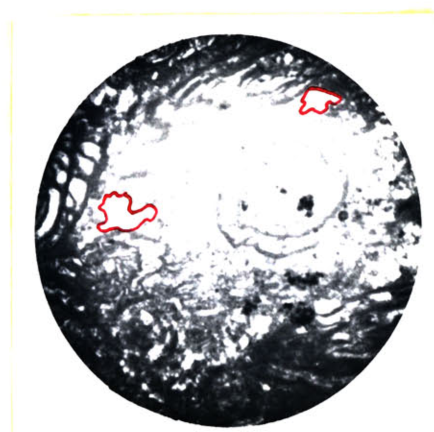


Figure 4 Collins #1
Core 154 10X

Irregular, vuggy porosity, probably primary, in the matrix of fossiliferous limestones.

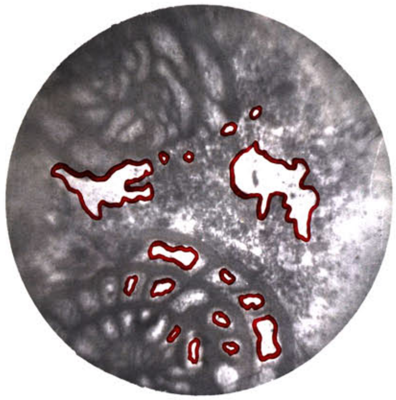


Figure 5 Womack #2
Core 37 15X

Irregular vuggy porosity, probably primary, in the matrix. Some pore space in chambers of fusulinid as well.

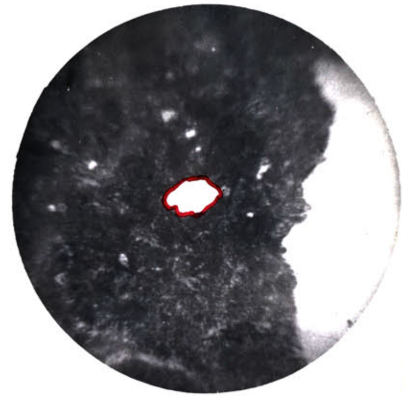


Figure 6 Womack #2
Core 22 15X

Primary vug in a finely crystalline limestone.

Figure 7 Womack #2
Core 109 15X

Irregular secondary vug developed by selective solution of nucleus of an oolite.

Figure 8 Collins #1
Core 290 1/2X

Polished section showing vuggy porosity.

5. Intergranular Porosity in the Limestones

Intergranular porosity is that which exists in closely packed, fragmental limestones and in limestones that are well-cemented. As used in this report, the term includes that porosity which many authors describe as intercrystalline.

In the cores examined, intergranular porosity is confined chiefly to the small spaces between the individual crystals of calcite forming the matrix.

Since this type of porosity is difficult to recognize in thin section and cannot be estimated satisfactorily in hand specimens, 22 samples which appear to be free of vugs were selected for a study of intergranular porosity.

A. Range of Porosity in the Samples

The average porosity of the 22 samples is 6.5%. The individual porosities show the following distribution.

Range of Porosity in %	No. of Samples
0.8-2.0	6
2.1-3.0	4
3.1-5.0	5
5.1-10.0	0
More than 10.0	7

The data indicate that most of the samples with intergranular porosity have porosities of 5% or less. However, there is a large group of samples with porosities of more than

10%. In this latter group are (1) oolitic samples, (2) fractured samples, and (3) errors in the selection of samples to illustrate intergranular porosity.

B. Range of Permeability in the Samples

The average permeability of the samples is 1.05 md. The distribution of individual porosities is as follows:

Range of Permeability in md.	No. of Samples
0	14
0.1-1.0	1
1.1-2.0	3
2.1-3.0	0
3.1-4.0	1
4.1-5.0	1
5.1-5.3	2

The tabulation indicates that the permeabilities of these samples are very low. The highest permeability reported is 5.3 md.; more than half of the samples have a reported permeability of 0.0 md.

With permeabilities so low, it is unlikely that appreciable amounts of oil are being produced from the limestones which have only intergranular porosity.

C. The Relationships of Porosity and Crystallinity of the Matrix

The more coarsely crystalline cores have more perfectly developed calcite crystals and it might be expected that such cores would exhibit typical intergranular porosity. The actual relationships are shown in the following table.

Table III-7 Porosity vs. Crystallinity

Matrix	Porosity Range in %				
	0.8-2.0	2.1-3.0	3.1-5.0	5.1-10	Over 10
Cryptocrystalline	1	0	0	0	0
Finely crystalline	4	2	1	0	4
Medium crystalline	0	3	3	0	2
Coarsely crystalline	0	1	1	0	0
TOTALS	5	6	5	0	6

The finely crystalline and medium crystalline samples show a great range of porosities. The cryptocrystalline and the coarsely crystalline samples tend to show lower porosities.

D. Summary

Intergranular porosity depends on the packing of the fossil fragments and the degree of cementation; cementation seems to be the more important factor. The results of this investigation show:

1. Intergranular porosity is normally less than 5%.

2. Oolitic samples and poorly cemented samples may have porosities greater than 10%.

3. Low permeabilities are almost always associated with intergranular porosity.

6. Verification of Estimates of Porosity

The porosity of each sample was estimated both in thin section and on the polished surface of the cores. These estimates were then compared with the laboratory measurements of porosity obtained by core analysis. The results obtained by such a comparison should vary from observer to observer, but the trends would likely be similar.

There is no reason to assume that such estimates would be accurate or consistent. Accuracy should improve with experience. The author has no previous experience in this line, and the results shown should be comparable to those for any beginner. On the following pages are shown the results of the comparison.

Table III-8 Core Analysis Data vs. Estimated Porosity

Sample		Core Analysis porosity %	Porosity estimated from thin section %	Porosity from polished section %
Wren	-49	12.1	3-5	5-10
	-50	13.3	5-10	5-10
	-64	17.4	15	10-15
	-70	13.0	5-10	4-8
	-88	14.3	10-15	12-15
	-92	1.6	under 2	2-3
	-98	12.6	10	8
	-101	13.3	10	10-12
	-102	16.7	15	10
	-103	13.9	15-18	10-15
	-118	1.9	10	10
	-124	10.7	5-20	5
	-126	16.5	5-10	10

Table III-8 continued-

Samples		Core Analysis Porosity %	Porosity estimated from thin section %	Porosity from polished section %
Wren	-127	22.7	5-8	5-10
	-141	10.6	12-15	15
	-149	12.0	10	5-8
	-150	18.8	8-10	12-15
	-152	10.3	5	5
	-153	15.2	5-10	3
	-178	17.2	5-10	5-10
	-179	10.3	2-4	3
	-188	3.1	2	3-5
Collins	-2	6.0	under 2	5
	-3	17.4	10-15	15-20
	-4	13.2	10-15	5-20
	-14	3.9	under 2	3
	-27	16.5	under 2	1
	-51	4.6	under 2	2
	-69	1.7	under 2	2
	-91	3.4	2	1-2
	-107	4.0	2	1-2
	-154	15.5	1-2	2
	-164	11.7	15	8-15
	-165	15.4	10-12	5-10
	-180	18.1	8-10	3-5
	-216	2.8	2	2-4
	-227	2.7	2-4	2

Table III-8 continued-

Sample	Core Analysis porosity %	Porosity estimated from thin section %	Porosity from polished section - %
Collins -230	2.3	2-4	2
-235	2.0	5	1-3
-265	13.3	5-15	5-10
-289	2.9	10-20	15-20
-290	16.5	5-20	8-15
-303	20.7	10-15	5-7
-337	3.7	2-4	1-2
Womack -15	2.9	1-2	1-2
-22	13.3	15	10-15
-24	16.9	10	5-8
-34	7.9	5	5-10
-37	10.5	10-15	5-30
-39	8.9	5	10-12
-53	1.2	2	1-3
-57	5.3	5	7-8
-58	13.1	5-8	10
-72	1.3	1-2	2
-79	10.8	5-10	8-10
-92	0.8	2	2-4
-98	10.7	10-15	5-20
-109	6.6	10-15	8-15
-164	1.7	5-8	10-15
-183	1.2	1-3	1-3
-203	9.0	1-2	3-5

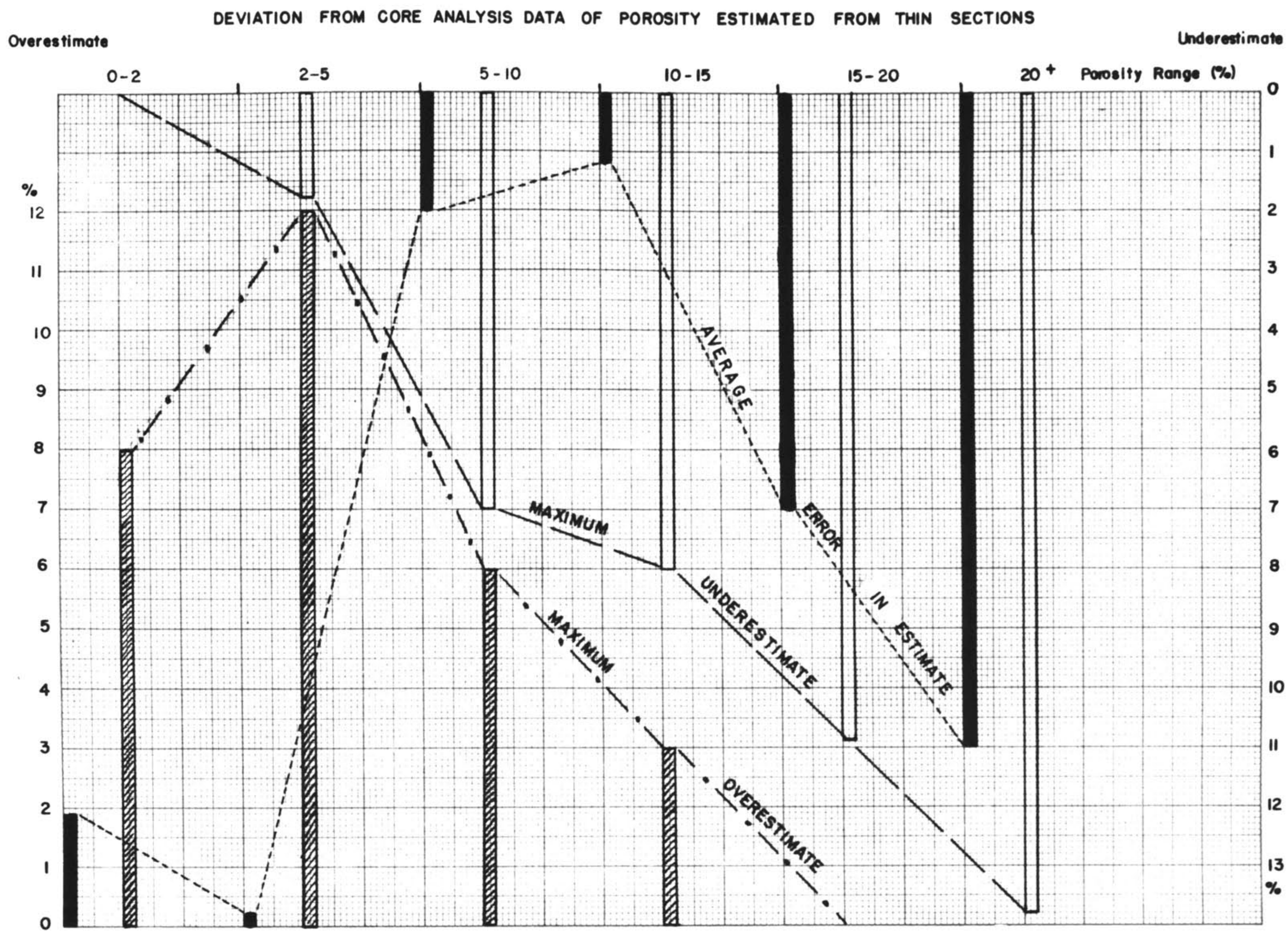

DEVIATION FROM CORE ANALYSIS DATA OF POROSITY ESTIMATED FROM THIN SECTIONS
Overestimate
Underestimate
0-2
2-5
5-10
10-15
15-20
20+
Porosity Range (%)
%
12
11
10
9
8
7
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
12
13
%
AVERAGE
ERROR
IN
ESTIMATE
MAXIMUM
UNDERESTIMATE
MAXIMUM
OVERESTIMATE

Plate 17.

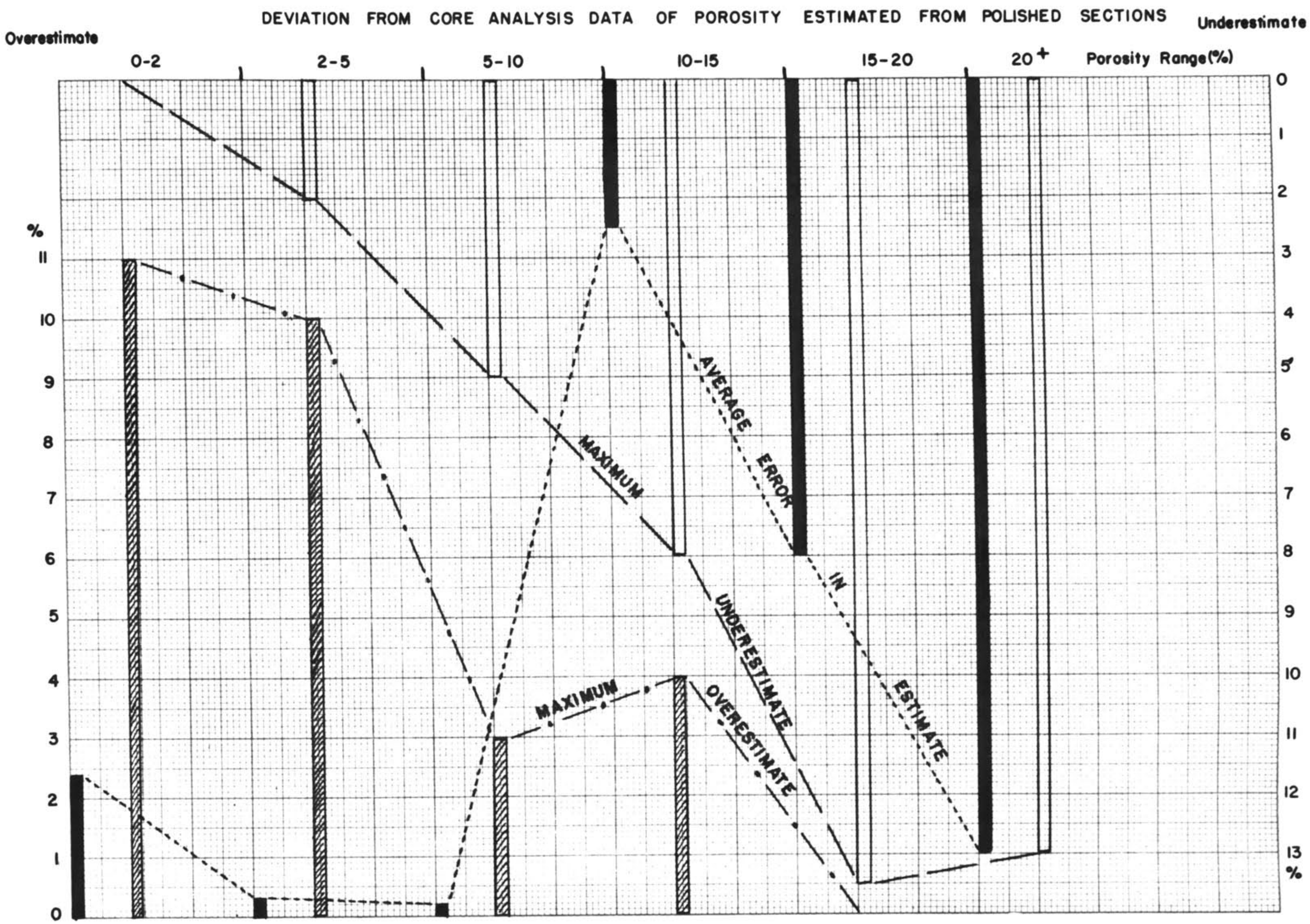

DEVIATION FROM CORE ANALYSIS DATA OF POROSITY ESTIMATED FROM POLISHED SECTIONS
Overestimate
Underestimate
0-2
2-5
5-10
10-15
15-20
20+
Porosity Range(%)
%
0
1
2
3
4
5
6
7
8
9
10
11
12
13
%
MAXIMUM UNDERESTIMATE
AVERAGE ERROR IN ESTIMATE
MAXIMUM OVERESTIMATE

Plate 18.

The results of the comparison are summarized and shown graphically on plates 17, 18, and 19. Plate 17 shows the accuracy attained in estimating porosity from thin sections; plate 18 shows the results obtained in estimating porosity from polished sections.

Three sets of data appear on each graph. The columns in solid black represent the average error in estimating the porosity for a given range. e.g. On plate 17, the average error of the estimate in samples which have porosities reported as 5-10% is 1.2%. Since the column runs from the top of the chart towards the bottom, the error is an underestimate. The average error plotted on the chart is obtained in the following manner. All the samples with reported porosities of 5-10% are separated from the rest; the estimated porosities for the same group of samples are then taken. The average porosity for each group of samples is then computed. Finally, the two averages are compared and the deviation noted. This deviation is the value which appears on the graph.

The columns shown in clear white are the maximum underestimates. e.g. On plate 17, for the samples with reported porosities of 5-10%, one or more samples were underestimated by 7%.

The columns that are cross-hatched represent the maximum overestimates. In order that the deviations be easier to follow, each set of deviations is joined by a distinctive, continuous line.

Plates 17 and 18 show that there is a marked tendency to overestimate porosity if it is very low and to grossly underestimate porosity if it is higher than 15%.

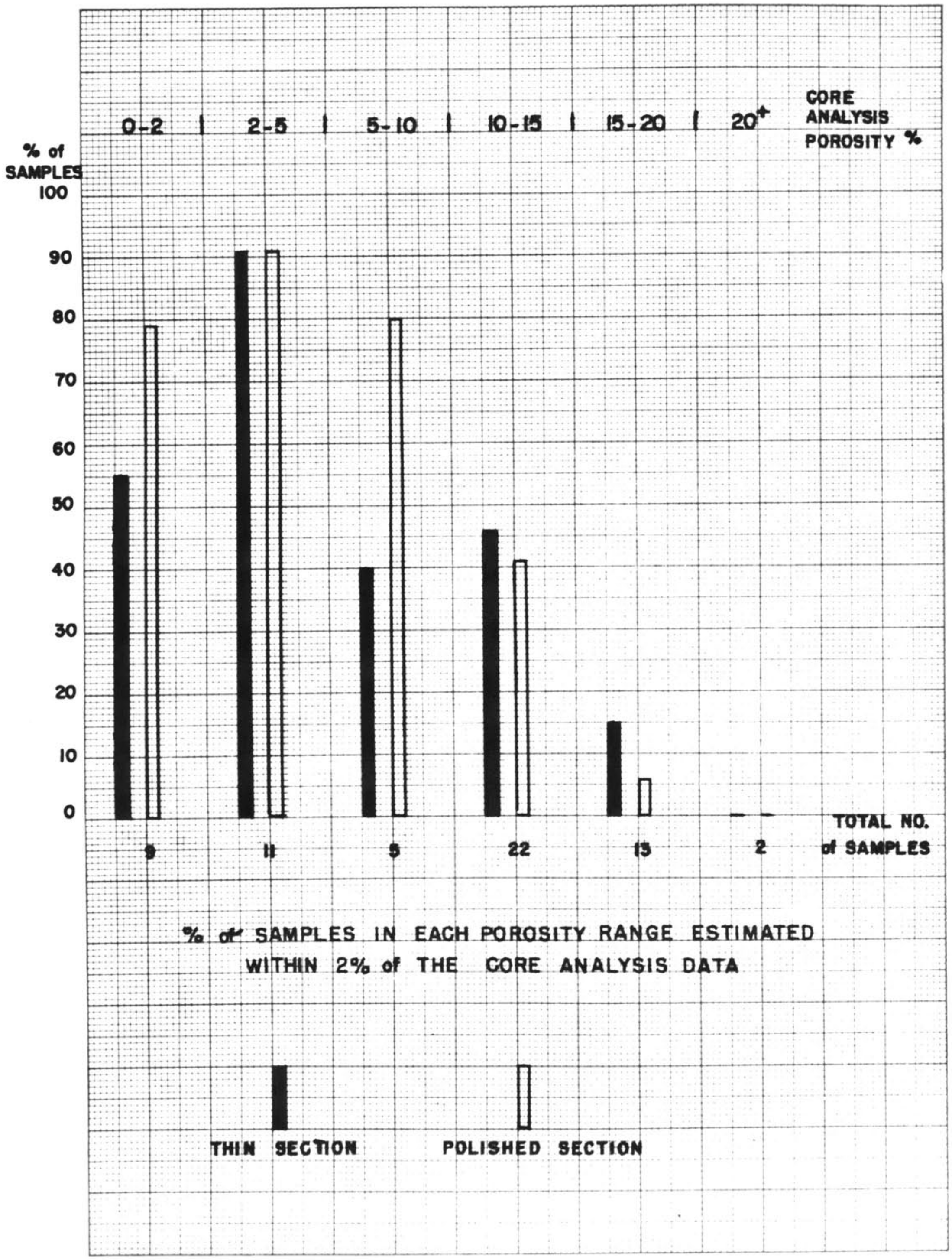

0-2
2-5
5-10
10-15
15-20
20+
CORE ANALYSIS POROSITY %
% of SAMPLES
100
90
80
70
60
50
40
30
20
10
0
9
11
5
22
13
2
TOTAL NO. of SAMPLES
% of SAMPLES IN EACH POROSITY RANGE ESTIMATED WITHIN 2% of THE CORE ANALYSIS DATA
THIN SECTION
POLISHED SECTION

Plate 19.

Plate 19 shows the efficiency attained in the estimation. On this graph are shown the percentages of the samples whose actual porosity was estimated within 2%. e.g. Of the 11 samples which have a reported porosity of 2-5%, 91% of the samples were estimated within 2% of their reported porosity.

The results of the investigation show that:

1. Estimates of porosity made from polished sections are generally more reliable than those made from thin sections.

2. Porosities higher than 15% were not estimated within reasonable limits.

3. There is a marked tendency to underestimate if porosities are more than 15% and to overestimate if porosities are less than 5%.

4. If high porosities exist, they are more likely to be underestimated in polished sections than in thin sections.

CHAPTER IV

PERMEABILITY OF THE LIMESTONES

1. Introduction

Permeability is a mass property of a rock and, as usually expressed, is a measure of the ability of a rock to allow passage of fluids through its mass without impairing the rock structure in any way. A rock is "permeable" if appreciable quantities of fluid may pass through it in a given time and "impermeable" if the rate of passage is negligible. The unit in which permeability is normally expressed is the "millidarcy"; values are computed from a mathematical equation.

In order that a rock be permeable, there must be a connecting set of openings along which liquids and gases can move. Movement in a limestone is confined to fracture planes, solution channels, and interconnecting pore space.

Many limestones show variations in permeability in different directions. If a rock is fractured, the permeability parallel to the direction of fracture may be 10-1000 times as great as that perpendicular to the fracture planes. Other factors, such as bedding, may also be important in influencing the direction of maximum permeability. Few limestones are so homogeneous that their permeability is equal in all directions.

2. Permeability of the Canyon Reef Formation

The average permeability of the 63 cores is 13.0 millidarcies (md.); the range in values is from 0-155 md. For the 22 cores from

Collins #1 the average permeability is 19.2 md., for the 22 cores of Wren #2 11.7 md., and for the 19 cores of Womack #2 7.3 md.

By using the core analysis data supplied by the Barnsdall Oil Company (Sunray) for the entire cored intervals of the three wells, the following results are obtained.

	Average permeability (md.)
1. For the 337 cores of Collins #1	2.7
2. For the 189 cores of Wren #2	8.3
3. For the 207 cores of Womack #2	8.3

The average permeability for the 733 cores of the three wells is 5.7 md. The permeability profiles for the producing intervals of the wells are shown in plates 12, 13, and 14, and the profiles for the entire well sections are shown in plates 48, 49, and 50.

A. Permeability of Collins #1

The permeabilities associated with the 337 cores of the well have the following distribution.

Range of Permeability in md.	No. of Samples
0	267
0.1-1.0	8
1.1-2.0	15
2.1-3.0	5
3.1-4.0	4
4.1-6.0	3
6.1-10	5
11-20	2
21-50	3
Over 100	1

B. Permeability in Wren #2

The permeabilities reported in the core analysis data of 189 feet of cores from the well are distributed as follows:

Range of Permeability in md.	No. of samples
0	63
0.1-1.0	66
1.1-2.0	23
2.1-3.0	14
3.1-4.0	4
4.1-6.0	11
6.1-10	5
11-20	3
21-50	8
51-100	1
Over 100	1

C. Permeability in Womack #2

The distribution of permeability for the 207 cores of the Womack #2 well is shown in the following tabulation.

Range of Permeability in md.	No. of samples
0	171
0.1-1.0	6
1.1-2.0	3
2.1-3.0	1
3.1-4.0	1
4.1-6.0	0
6.1-10	3
11-20	8
21-50	8
51-100	2
Over 100	2

D. Summary of Permeability for All Three Wells

The data given in the above tabulations is compiled in the tabulation on the following page.

Range of Permeability in md.	No. of Samples
0	501
0.1-1.0	80
1.1-2.0	41
2.1-3.0	20
3.1-4.0	9
4.1-6.0	14
6.1-10	13
11-20	13
21-50	19
51-100	6
Over 100	4

The tabulation indicates that 68% of the samples have no permeability, 79% have permeabilities of less than 1 md., 85% less than 2 md., 91% less than 6 md., and that only 0.6% have permeabilities greater than 100 md.

Examination of the cores suggests that permeabilities are generally higher than the tabulations indicate. It seems likely that samples taken for permeability determinations were cut in such a manner that the effects of fractures and solution cavities are largely eliminated. Several well-fractured samples have reported permeabilities of 0.0 md. A part of the difficulty arises because small samples are run in the determinations. The use of larger samples and the selection of more representative samples should result in more accurate values.

Since the measurement of fracture and solution permeability is so difficult, great care should be used in analyzing and interpreting core analysis data. The problem is of extreme importance in reef limestones which are often fractured and/or cavernous. Further brief discussions of permeability appear in Chapters III, V, IX, XII, and XIII.

3. Permeable Zones in the Wells

The zones referred to in this section are taken from the Microlog trace and are more or less theoretical. They are correlated with the core analysis data in plates 48, 49, and 50.

A. M.J. Womack #2

The zones indicated as permeable on the Microlog trace are as follows:

1. 6647-60	6. 6792-96	10. 6855-57
2. 6679-6704	7. 6797-99	11. 6859-68
3. 6716-20	8. 6800-02	12. 6872-74
4. 6738-40	9. 6828-30	13. 6877-83
5. 6766-68		

Two hundred forty feet of the reef section were cored and 13 permeable zones are indicated on the Microlog. The thinnest zone is only 2 feet thick and the thickest is 25 feet. Seventy four feet of the section are indicated as permeable; this represents 30.6% of the cored interval.

B. A.L. Wren #2

Two hundred eighty eight feet of the reef were cored and the Microlog indicates permeability in 24 zones. The thinnest zone is 1 foot thick and the thickest is 29 feet. The Microlog trace indicates that 184 feet of the section are permeable; this represents 64.0% of the entire cored interval.

The permeable zones indicated on the Microlog are shown in the following tabulation.

1. 6510-14	9. 6613-14	17. 6694-6805
2. 6516-19	10. 6620-22	18. 6815-17
3. 6551-53	11. 6624-26	19. 6819-21
4. 6567-79	12. 6633-41	20. 6822-44
5. 6581-83	13. 6648-77	21. 6849-54
6. 6598-6600	14. 6679-6701	22. 6856-67
7. 6606-08	15. 6706-22	23. 6868-69
8. 6609-11	16. 6766-69	24. 6875-94

C. P.J. Collins #1

The permeable intervals indicated on the Microlog trace are as follows:

1. 6539-63	5. 6700-03	8. 6824-29
2. 6576-85	6. 6706-08	9. 6841-50
3. 6635-38	7. 6736-40	10. 6858-74
4. 6680-86		

Three hundred sixty feet of the reef were cored and 10 permeable zones are indicated on the Microlog. The thinnest permeable zone is 3 feet thick and the thickest is 16 feet. Eighty one feet of the total section are permeable; this corresponds to 22.5% of the total cored interval.

D. Correlation of Core Analysis Data and Microlog Intervals

The tabulations on the following pages show the core analysis data reported for the intervals which are indicated as permeable on the Microlog trace. Omitted from the discussion are those zones for which no core analysis data are available. In some cases no cores were analyzed, and in others no material was recovered during the coring. The zones used in these lists all gave strong indications on the Microlog trace; so far as the log is concerned, the zones seem to have equally good permeabilities.

(1) A.L. Wren #2

The following tabulations show the correlations between core analysis data and the permeable zones indicated by the Microlog.

Microlog Zone	Core Analysis Permeability (md.)			
	Highest	Lowest	Average	Median
6516-19	5.5	0	2.7	2.8
6567-79	43	0.1	5.1	0.6
6606-08	0	0	0	0
6620-22	0.1	0	-	0
6624-26	1.6	1.2	1.3	1.2
6633-41	203	0	25	0
6648-77	33	0	2.5	1.3
6679-6701	21	0	3.5	0.4
6706-22	3.3	0	1.1	0.8
6794-6805	67	0	19	13
6815-44	114	0.1	19	5.0
6849-54	12	0.4	3.2	2.2
6875-94	14	1.3	5.7	5.2

(2) P.J. Collins #1

Microlog Zone	Core Analysis Permeability (md.)			
	Highest	Lowest	Average	Median
6576-85	1.1	0	0.2	0
6635-38	0	0	0	0
6680-86	2.0	0	1.0	1.0
6706-18	15	0	3.0	2.0
6736-40	2.9	0	2.0	1.5
6824-29	15	0.5	7.6	7.0
6841-50	109	4.9	30.3	28
6858-74	53	0	14.5	15

(3) M.J. Womack #2

Microlog Zone	Core Analysis Permeability (md.)			
	Highest	Lowest	Average	Median
6679-6704	1040	0	63	18
6716-20	3.7	0	0.8	0
6738-40	11	0	5.5	0
6766-68	1.3	0	0.4	0.2
6792-96	0	0	0	0
6797-99	0	0	0	0
6800-02	0	0	0	0
6828-30	0	0	0	0
6855-57	0	0	0	0
6859-68	1.8	0	0.3	0
6872-74	0.7	0	0.3	0.3
6877-83	10	0	1.6	0

(4) Summary of the Three Wells

The tabulations reveal a discrepancy that needs to be explained. It is obvious that the Microlog and core analysis data are not in satisfactory agreement. If the core analysis data are reliable, the Microlog indicates permeable zones where no permeability exists and in zones where reported permeabilities are only 0-1.0 md. Oil production is unlikely from zones with permeabilities of this order of magnitude.

If the Microlog data are correct, the core analysis data are open to question. Examination of the specimens suggests that, in many cases, the core analysis data are definitely misleading. Where solution channels of considerable extent are present in an otherwise dense limestone, the samples taken for core analysis were commonly taken in such a way that the true nature of the porosity and permeability is not indicated.

It is possible, therefore, that Microlog indications are correct. If such is the case, some of the permeable zones indicated on the Microlog but not by core analysis data probably have (1) large vugs, (2) solution channels, or (3) fractures.

It seems that the interpretation of the producing capabilities of the limestones is more complex than might be assumed. This study indicates that (1) Microlog readings are too sensitive or erroneous, or (2) core analysis data are untrustworthy in many cases. The entire problem needs a further, more comprehensive examination.

4. Influence of Type Of Fossil Content on Permeability

Little has been written on the relationships between fossil content and permeability. In the reef limestones examined the following data were obtained.

A. Foraminiferal Content of the Limestones

Fifty four (86%) of the samples contain foraminifera. The amount of foraminiferal debris ranges from 5-80% of the total rock mass. The relationships between this content and the core analysis permeability are shown in the following table.

Table IV-1 Number of Samples in Each Permeability Range vs. the Foraminiferal Content of the Rocks in %

Permeability Range in md.	Range of Foraminifera in %							
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
0	6	3	2	0	0	0	2	0
0.1-2.0	6	0	0	0	0	0	0	2
2.1-5.0	0	1	3	1	1	1	0	0
5.1-10	3	2	2	2	0	0	2	0
11-20	1	1	1	1	1	0	0	0
21-50	2	0	0	2	1	1	0	0
51-100	0	0	0	2	0	0	0	0
100-200	0	0	0	2	0	0	0	0
TOTALS	18	7	8	10	3	2	4	2

The higher permeabilities are in those rocks which have a foraminiferal content between 30-50%. The limestones with a foraminiferal content of less than 20% and those with a content of more than 60% normally show low permeabilities (less than 10 md.)

B. Echinodermal Content of the Limestones

Forty three of the samples contain echinoderm debris. The amount of echinodermal debris present in the samples ranges from 5-70%. The table shows the relationships between the percentage of echinoderm debris and the reported permeabilities.

Table IV-2 Number of Samples in Each Permeability Range vs. the Echinodermal Content of the Rocks in %

Permeability Range in md.	Range of Echinoderm Debris in %						
	0-10	10-20	20-30	30-40	40-50	50-60	60-70
0	3	3	2	1	1	1	2
0.1-2.0	1	1	2	1	0	0	0
2.1-5.0	1	1	3	0	0	0	0
5.1-10	2	1	2	1	1	1	0
11-20	3	1	1	0	0	0	0
21-50	2	1	1	0	1	0	0
51-100	0	0	0	1	0	0	0
101-200	0	0	0	1	0	0	0
TOTALS	12	8	11	5	3	2	2

The higher permeabilities are associated with samples containing 5-45% echinodermal debris. Nevertheless, low permeabilities can be expected with samples which contain any amount of echinodermal debris.

C. Total Fossil Content of the Limestones

There are several other types of fossils which appear in the cores. However, the other types of fossils are not abundant and tabulations of those groups are not included. The effect of these minor constituents on permeability is discussed in Chapter V.

Fossil debris of some type appears in sixty one (97%) of the samples examined. The relationships between the total fossil content and reported permeability is shown in following table.

Table IV-3 Number of Samples in Each Permeability Range vs. Total Fossil Content of the Rocks in %

Permeability Range in md.	Total Fossil Content in %							
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
0	2	3	3	1	0	2	2	6
0.1-2.0	0	4	2	1	0	0	1	1
2.1-5.0	0	0	0	1	1	3	1	3
5.1-10	0	0	0	0	2	1	1	4
11-20	1	0	0	1	1	1	2	0
21-50	0	0	1	1	1	1	2	0
51-100	0	0	0	1	0	0	1	0
101-200	0	0	0	0	1	0	1	0
TOTALS	3	7	6	6	6	8	11	14

The very low permeabilities are found in the samples containing all amounts of fossil debris. The higher permeabilities are normally found in those rocks which contain 25-65% of fossil debris. The highly fossiliferous limestones and those with a low fossil content usually have low permeabilities.

CHAPTER V

FOSSILS IN THE LIMESTONES

1. General Discussion

An effort was made to identify all the fossil material in the limestones. One or more polished sections were made on each sample, thin sections were cut to show internal characteristics of the fossils, and hand specimens were examined carefully. In spite of these precautions, complete identification was rarely possible. The features which prevented identification or made it extremely difficult are:

1. The samples are small. This decreases the chance of finding a complete fossil, and samples only a small part of the stratum. Unfortunately, the formation does not outcrop anywhere in nearby areas and cannot be examined in detail.
2. Most of the debris is fragmental, and few complete or nearly complete fossils, with the exception of fusulinids, are present.
3. Recrystallization and corrosion have destroyed most of the surface ornamentation and internal structure of larger fossils.

The distribution of fossil debris in each well is shown on plates 20, 21, and 22. The fossil content of each well is correlated with the Microlog resistivity in Chapter XII.

It was possible to identify a few genera of fossils. Those which were identified include: (1) TRITICITES, a fusulinid, (2) FENESTELLA, a bryozoan, (3) PRISMOPORA, another bryozoan, and (4) LOPHOPHYLLIDUM, a cup coral. Two genera of brachiopods belonging

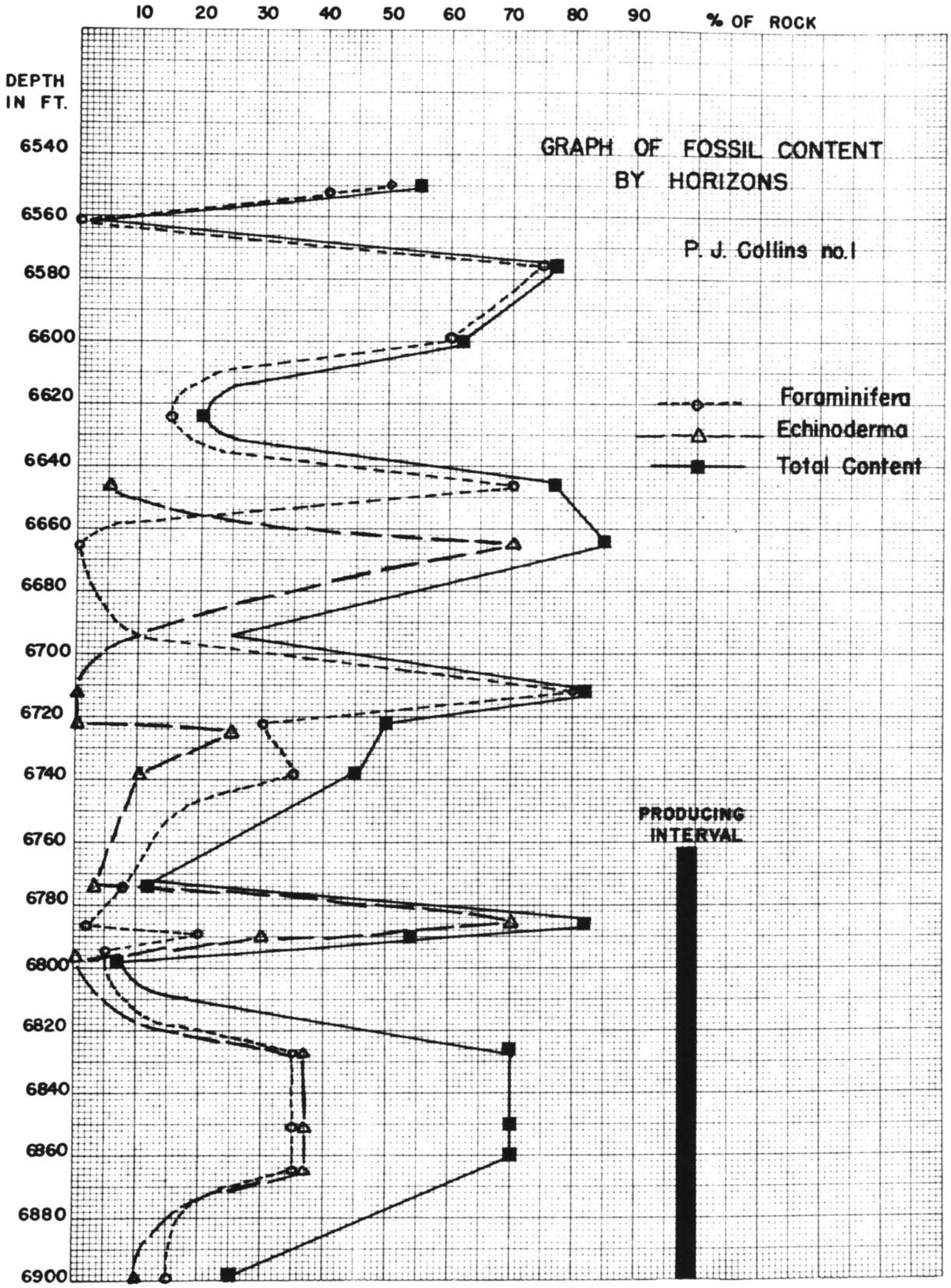

10 20 30 40 50 60 70 80 90
% OF ROCK
DEPTH IN FT.
6540
6560
6580
6600
6620
6640
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
6900
GRAPH OF FOSSIL CONTENT BY HORIZONS
P. J. Collins no.1
Foraminifera
Echinoderma
Total Content
PRODUCING INTERVAL

Plate 20.

to the Productid type were present but were not identified. In spite of the difficulties in identifying genera, it is relatively easy to establish the general family or class to which the fossils belong. Several sections of this study are devoted to limestones which are composed largely of one or more types of fossil debris; these sections may be referred to for additional detail.

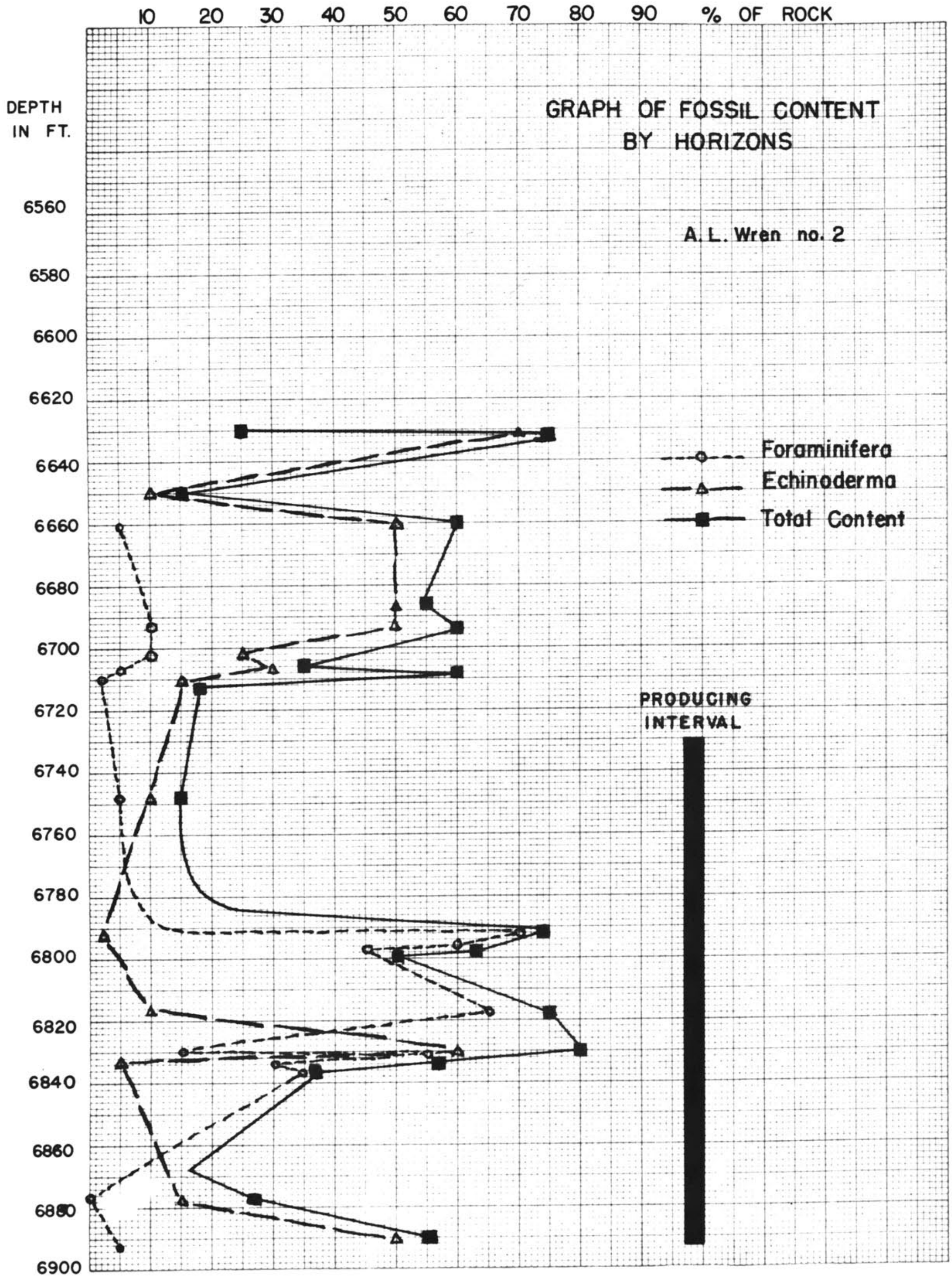
The types of fossil debris found in the limestones are:

1. Foraminifera, chiefly fusulinids.
2. Echinodermal debris in which crinoid remains are prominent.
3. Bryozoa, chiefly fenestellate forms.
4. Cup corals and coralline debris.
5. Algal (?) material.

The frequency with which these forms are encountered is shown in the following tabulation.

Type of Fossil Debris	Average percentage of the reef rocks composed of the fossil type
Foraminifera	22%
Echinoderms	17%
Brachiopods	3.4%
Bryozoa	2.4%
Corals and algal(?) material	1-3%

The tabulation shows that the reef limestones are approximately 46-48% recognizable fossil debris; the remainder of the rocks is pore space and crystalline calcite. These figures are based on the 63 cores examined and not on the entire reef section.



10 20 30 40 50 60 70 80 90 % OF ROCK
DEPTH IN FT.
GRAPH OF FOSSIL CONTENT BY HORIZONS
A. L. Wren no. 2
6560
6580
6600
6620
6640
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
6900
Foraminifera
Echinoderma
Total Content
PRODUCING INTERVAL

Plate 21.

Forty three percent of the fossils are foraminifera, 34% are echinoderms, 7% are brachiopods, 5% are bryozoa, and 3-4% are corals and algal(?) material.

A. The Limestones with Foraminifera

Fifty five samples (87%) contain foraminifera. Included in this group are 21 samples from Collins #1, 18 samples from Wren #2, and 16 samples from Womack #2. Foraminifera are present in 95% of the samples from Collins #1, 82% of Wren #2 and 84% of Womack #2. Figures refer only to the 63 cores examined.

The average foraminiferal content of all 63 cores is 22%. For the 55 cores that contain foraminifera the average is 26%. In samples that contain foraminifera, the average percentage in Collins #1 is 28%, in Wren #2 27%, and in Womack #2 23%.

The distribution of foraminifera in Collins #1 is as follows:

Percentage of the rock composed of foraminifera	No. of samples
0	1
1-10	5
11-20	3
21-30	3
31-40	5
41-50	3
51-60	0
61-70	2

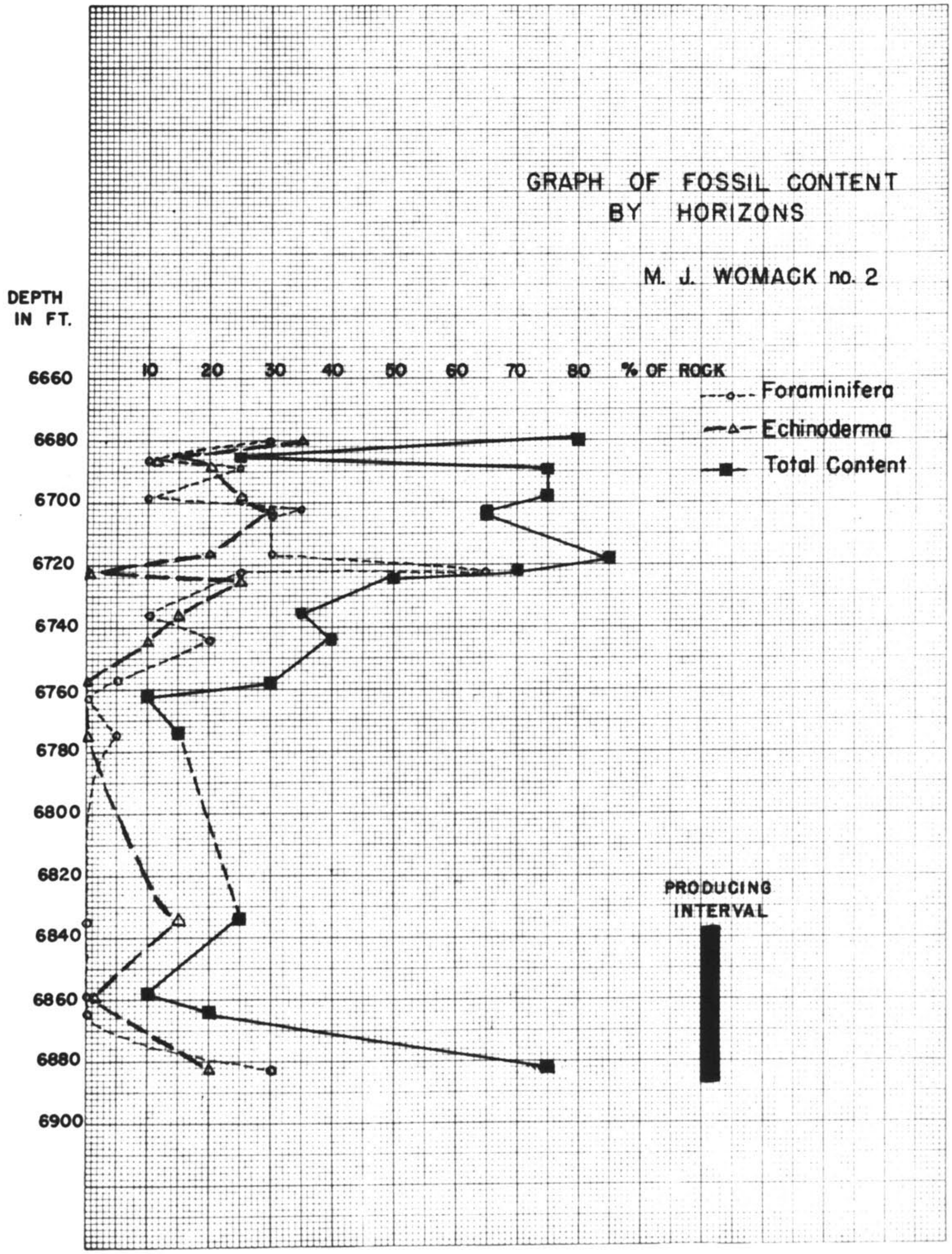

GRAPH OF FOSSIL CONTENT
BY HORIZONS
M. J. WOMACK no. 2
DEPTH
IN FT.
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
6900
10
20
30
40
50
60
70
80
% OF ROCK
Foraminifera
Echinoderma
Total Content
PRODUCING
INTERVAL

Plate 22.

The distribution of foraminifera in Wren #2 is:

Percentage of rock composed of foraminifera	No. of samples
0	4
1-10	8
11-20	2
21-30	1
31-40	2
41-50	2
51-60	2
61-70	1

The distribution of foraminifera in Womack #2 is:

Percentage of rock composed of foraminifera	No. of samples
0	3
1-10	6
11-20	1
21-30	5
31-40	3
41-50	0
51-60	1

Rocks with a high foraminiferal content seem to be more common in the Collins #1 and Wren #2 wells. The foraminiferal content of the reef limestones is quite variable; the range is 0-70%. The foraminifera are normally well-preserved and can be identified readily. The distribution for all three wells is summarized in the following tabulation.

Percentage of rock composed of foraminifera	No. of samples
0	8
1-10	19
11-20	6
21-30	9
31-40	10
41-50	5
51-60	3
61-70	3

A more complete discussion of the foraminiferal limestones appears in part 3 of this chapter.

B. The Limestones with Echinodermal Debris

Forty four (70%) of the samples contain echinodermal debris. Included in this group are 13 samples from Collins #1, 18 samples from Wren #2, and 13 samples from Womack #2. Echinodermal debris is present in 59% of the samples from Collins #1, 82% of the samples from Wren #2, and 68% of the samples from Womack #2.

The average percentage of echinodermal debris in all 63 cores is 17%. For the cores which contain echinoderms the average is 25%. The average percentage in the echinoderm-bearing samples of Collins #1 is 28%, of Wren #2 24%, and of Womack #2 21%.

Although echinoderms are not so abundant in the limestones as foraminifera, they are common. The distribution of echinodermal debris in the various wells is shown in the following tabulations. The distribution of echinodermal debris in the samples of Collins #1 is:

Percentage of rock composed of echinodermal debris	No. of samples
0	9
1-10	5
11-20	1
21-30	2
31-40	2
41-50	1
51-60	1
61-70	1

The distribution in Wren #2 is:

Percentage of rock composed of echinodermal debris	No. of samples
0	4
1-10	7
11-20	3
21-30	4
31-40	0
41-50	3
51-60	1

The distribution in Womack #2 is:

Percentage of rock composed of echinodermal debris	No. of samples
0	6
1-10	2
11-20	6
21-30	4
31-40	1

The distribution of echinodermal debris in all 63 cores is:

Percentage of rock composed of echinodermal debris	No. of samples
0	19
1-10	14
11-20	10
21-30	10
31-40	3
41-50	4
51-60	2
61-70	1

Echinodermal debris is most frequently encountered in the samples of Wren #2, and is least common in the samples from Collins #1. If present, the debris is most abundant in the samples from Collins #1 and Wren #2.

A more complete discussion of the echinodermal limestones appears in part 4 of this chapter.

C. The Limestones with Brachiopods

Fifteen (24%) of the samples contain brachiopod shell material. Included in this group are 6 samples from Collins #1, 6 samples from Wren #2, and 3 samples from Womack #2. Brachiopods are present in 27% of the samples from Collins #1, 27% of the samples of Wren #2, and 16% of the samples from Womack #2.

The average percentage of brachiopod debris in all 63 cores is 3.4%. For the 15 samples which contain brachiopods the average percentage is 14.5%. The average percentage in the brachiopod-bearing samples of Collins #1 is 8%, of Wren #2 14%, and of Womack #2 23%.

The distribution of brachiopod debris in Collins #1 is:

Percentage of rock composed of brachiopod debris	No. of samples
0	16
5	4
10	1
15	1

The distribution of debris in Wren #2 is:

Percentage of rock composed of brachiopod debris	No. of samples
0	16
5	1
10	1
15	2
20	2

The distribution in Womack #2 is:

Percentage of rock composed of brachiopod debris	No. of samples
0	16
5	1
10	0
15	1
50	1

The distribution for all 63 cores is:

Percentage of rock composed of brachiopod debris	No. of samples
0	48
5	6
10	2
15	4
20	2
50	1

The tabulations show that brachiopods are not abundant in the reef limestones. They are most frequently encountered in the samples from Collins #1 and Wren #2. If they are present, they are most abundant in the samples of Wren #2 and Womack #2.

Although complete shells are often present, the surface ornamentation is never preserved and positive identification cannot be made. Many of the brachiopods are clearly of Productid types; several genera are represented.

D. The Limestones with Bryozoa

Eighteen samples (29%) contain bryozoan material. Included in this group are 7 samples from Collins #1, 3 from Wren #2, and 8 from Womack #2. Bryozoa are present in 32% of the samples from Collins #1, 16% from Wren #2, and 42% from Womack #2.

The average bryozoan content for the limestones as a whole is 2.4%. For the limestones which contain bryozoa the average content is 7.5%. The average percentage in the bryozoa-bearing samples is 7% for the samples from Collins #1, 7% for the samples from Wren #2, and 8% for the samples from Womack #2.

The distribution of bryozoan debris in Collins #1 is:

Percentage of rock composed of bryozoa	No. of samples
0	15
5	4
10	3

The distribution of debris in Wren #2 is:

Percentage of rock composed of bryozoa	No. of samples
0	19
5	2
10	1

The distribution of debris in Womack #2 is:

Percentage of rock composed of bryozoa	No. of samples
0	11
5	5
10	2
20	1

The distribution of debris in the three wells is:

Percentage of rock composed of bryozoa	No. of samples
0	45
5	11
10	6
20	1

The tabulations show that bryozoa are not common in the limestones but are nearly as common as brachiopods. However, bryozoa are widely distributed and relatively scarce while brachiopods are sparsely distributed but abundant in samples in which they occur. Bryozoa are most frequently encountered in the samples from Womack #2 and Collins #1. The bryozoa are never found alone; they are always associated with other fossils.

2. Estimation of the Fossil Content of the Rocks

The fossil content of each sample was estimated in both the polished section and in the thin section. The estimates show the percentage of the rock composed of fossil debris. In the following tables the values obtained for two of the wells are shown.

Table V-1 Fossil Content of Collins #1

Core	Polished section estimate in %	Thin section estimate in %
2	30	50-55
3	5-10	10-15
4	50	35-40
14	0	0
27	55	70-80

Table V-1 continued-

Core	Polished section estimate in %	Thin section estimate in %
51	35	50-60
69	10-15	30-40
91	35	60-70
107	75	80
154	65	80
164	35	30
165	40	45-55
180	40	45
216	5-10	12-15
227	65	80
230	65	80
235	5	5-8
265	40	70
289	70	70
290	60	65-70
303	55	60-70
337	20	25

Table V-2 Fossil Content of Wren #2

Core	Polished section estimate in %	Thin section estimate in %
49	30	25
50	40	75
64	5	15
70	15	60

Table V-2 continued-

Core	Polished section estimate in %	Thin section estimate in %
88	10	55
92	20	60
98	15	45
101	25	35
102	10	60
103	15	15
118	10-15	15
124	75	70
126	65	60-65
127	55	50
141	65	65
149	20	80
150	45	55
152	25	35
153	25	35
178	0	0
179	5	20
188	15	55

The tables clearly show that a higher fossil content is estimated if thin sections are used. If the fossil content is very high, very low, or composed of large fragments the two estimates agree closely. The thin section estimates are higher chiefly because many of the smaller fossil fragments are visible only when magnified.

It is likely that estimates made from polished sections would be higher than those made from rough hand specimens.

The results of this examination raise an interesting question. It is, what is the fossil content of a limestone that is classified as highly fossiliferous, or sparsely fossiliferous? It seems to be common practice to call a limestone highly fossiliferous only if the rock contains abundant fossil fragments large enough to be seen with the unaided eye. If this practice had been followed in this study, many samples would have been described as only slightly fossiliferous when, in fact, their fossil content is very high. It seems likely that the fossil content of many limestones is grossly underestimated in many lithologic descriptions.

3. The Foraminiferal Limestones

Foraminifera are present in a large number of the samples but are usually associated with other fossils. A brief tabulation of the foraminiferal content of the cores shows the following:

		% of the samples
Total number of cores examined	63	100
Cores containing foraminifera	55	87
Cores containing more than 30% foraminifera	21	33
Cores containing more than 50% foraminifera	10	16

Several cores are composed largely of foraminiferal tests. This section is concerned with the 10 samples which contain more than 50% foraminifera and have little or no other fossil debris.

The percentage of the rock composed of foraminiferal debris ranges from 50-80% in these samples. These unusual limestones represent a significant and distinctive facies.

Percentage of rock composed of foraminiferal debris	No. of samples
50-60	2
60-70	4
70-80	4

The samples used for this discussion include:

Well	Core numbers
Collins #1	2, 27, 51, 91, 154
Womack #2	57
Wren #2	124, 126, 141, 150

A. Porosity

The average porosity of the 10 samples is 12.5% (127% of the average of all 63 cores). The distribution of the porosities is shown in the following tabulation.

Porosity Range in %	No. of Samples
0-5	2
5-10	2
10-15	2
More than 15%	4

The total range in porosity is 3.4-18.8%. The high porosities of these limestones seems to be due to the incomplete filling of the chambers of the foraminiferal tests.

B. Permeability

The average permeability of the samples is 10.8 md. (83% of the average for all 63 cores). The range of permeability is 0-23 md. with a distribution as follows:

Range in Permeability in md.	No. of Samples
0	2
0.1-2.0	1
2.1-5.0	3
5.1-10	2
11-20	1
More than 20	1

There is a tendency for these limestones to have rather low permeabilities. In spite of their high porosities these rocks are not likely to be of great importance in the production of oil unless their low permeabilities can be improved or overcome.

C. General Characteristics of Foraminifera [9]

Foraminifera are almost exclusively marine animals. They reproduce by an alternation of generations. Individuals of different species tend to be repellent to each other which often leads to a great purity in the species at any given locality. Most foraminifera are benthonic in the adult stage. The most important single factor that controls their distribution and abundance is temperature; warm or tropical temperatures seem to be preferred by the larger, benthonic forms. Depth of water, except as it affects temperature, is relatively unimportant in influencing their distribution.

The larger, living foraminifera of the tropical regions, especially those existing at depths of less than 30 fathoms, are commonly associated with algae. The majority of present-day foraminifera are adapted to normal salinities and do not prosper in waters of high or low salinities.

Glaessner[9] states that foraminifera are not necessarily indicative of a given facies, but may indicate a given set of ecological conditions for a limited time.

At the present time, the sands of many tropical beaches are composed largely of foraminiferal tests, and the shallow waters along tropical shorelines commonly have shoals made of foraminiferal tests.

D. The Fusulinidae

During the Carboniferous foraminifera became abundant, and many thick Paleozoic limestones are composed largely of their debris. The Fusulinidae[10] are believed to have evolved from ENDOTHYRA, a foraminifer that appeared in the late Devonian or early Mississippian. The Fusulinidae include some of the largest and most complex of the foraminifera. The family appeared at the beginning of the Pennsylvanian, evolved very rapidly, and became extinct at the close of the Paleozoic. More than 650 species are presently known.

The Fusulinidae are marine and benthonic; their life zone probably included the middle and lower parts of the zone of light penetration.

E. The Foraminifera of the Canyon Reef Limestones

Three types of foraminifera were observed in the cores examined. They are:

1. A fusulinid type identified as TRITICITES.

2. An unidentified, triserial, calcareous foraminifer.

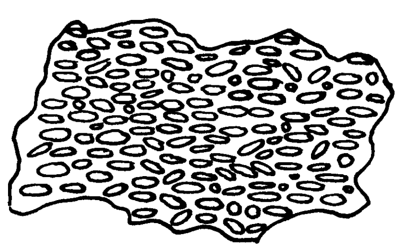
3. An unidentified, small, single chambered foraminifer.

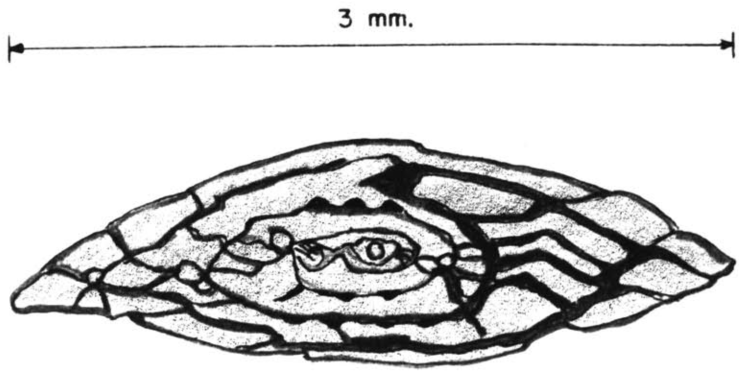
Fusulinids are present in most of the samples examined. Although the species identified is TRITICITES, some of the fusulinids may belong to a TRITICITES-SCHWAGERINA transitional type.

The calcareous, triserial foraminifer that appears in several samples could not be identified. The length of the largest specimen observed is 3.8 mm. and the maximum width, near the aperture, is 2.0 mm. The test is very thin and probably belongs to a pelagic foraminifer. These triserial foraminifers are never abundant in any sample, and are confined to the middle part of the formation.

Several samples contain a great abundance of a small, one-chambered, rounded, test of a pelagic foraminifer. If present, most of the rock is composed of the tests. Rocks containing these foraminifera commonly have an oolitic texture.

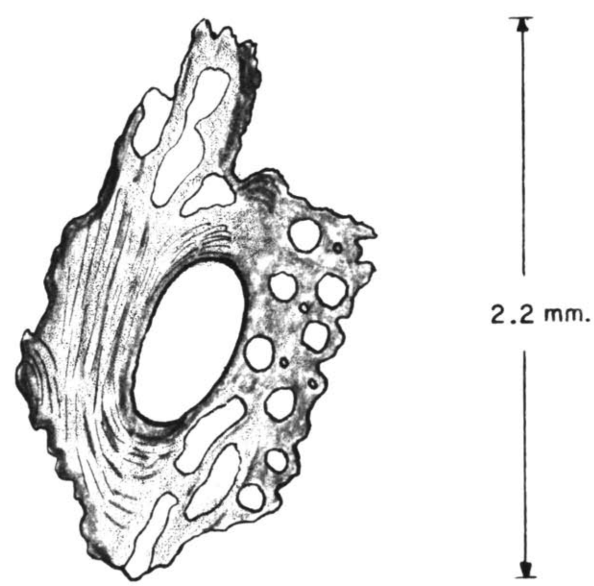
The fusulinid limestones occasionally show a crude bedding which is due to the parallel orientation of the long axes of the foraminiferal tests. This type of bedding is shown diagramatically in the following sketch:





A. L. WREN NO. 2
CORE 126

FORAM - LONGITUDINAL VIEW



P. J. COLLINS NO. 1
CORE 227

BRYOZOAN FRAGMENT

Plate 23.

The amazing numbers of fusulinids present in these limestones is indicated by the following calculation which was made on a one-inch cube of core 124 of Wren #2. In that sample there are more than 100 (possibly as many as 350) foraminiferal tests. Using the value of 100, this is the equivalent of 170,000 tests to the cubic foot or more than 7×10^9 to the acre-foot. These highly fossiliferous zones are commonly several feet thick. Although it was impossible to trace these horizons from well to well, similar zones are present in all three wells.

The single-chambered pelagic foraminifera that are abundant in several zones are even more numerous in a given sample, but the zones do not seem to be so common as those with fusulinids.

F. Size of the Fusulinids in the Limestones

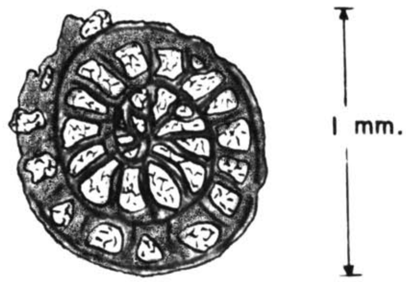
If foraminifera were prominent in the thin sections, the size of the largest foraminifer in each thin section was measured. Since all tests were not cut through the central portion, slight errors in the dimensions are likely. It is believed that none of the values is too small by more than 20%, and that most values are correct to within 10%.

Table V-3 Dimensions of the Fusulinids

Samples		Width (mm.)	Length (mm.)	Ratio of Length/Width
Womack	-37	2.3	4.0	1.74
	-38	2.4	?	
	-39	1.4	?	
	-53	2.1	?	

Table V-3 continued-

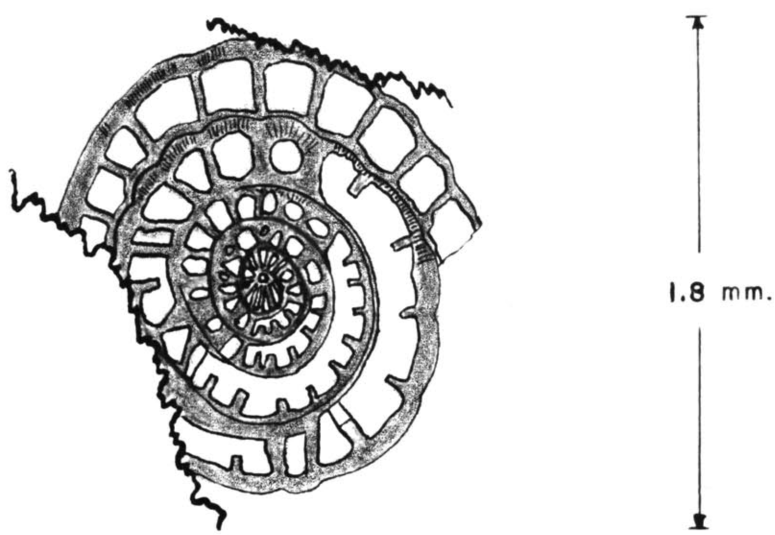
Sample		Width (mm.)	Length (mm.)	Ratio of Length/Width
Collins	-51	2.2	4.3	1.95
	-154	1.5	4.1	2.72
	-164	2.3	4.4	1.93
	-165	1.8	?	
	-180	1.6	4.0	2.50
	-265	3.7	?	
	-289	2.2	?	
	-290	2.8	?	
	-303	1.4	?	
	-337	2.1	?	
Wren	-70	2.1	3.6	1.72
	-88	3.2	?	
	-92	2.1	?	
	-98	1.4	?	
	-102	2.6	?	
	-124	1.5	4.1	2.72
	-126	2.5	4.0	1.60
	-127	2.5	4.0	1.60
	-141	2.0	4.2	2.10
	-149	1.3	3.9	3.00
	-150	1.2	2.9	2.42
	-152	2.9	?	
	-153	1.8	?	



P. J. COLLINS NO. I

CORE 265

FORAM — TRANSVERSE VIEW



P. J. COLLINS NO. I

CORE 164

CORRODED FORAM WITH STYLOLITES

Plate 24.

The distribution in the widths of the fusulinids is shown in the following tabulation.

Width in mm.	No. of samples
1-2	10
2-3	15
More than 3	2

The distribution of the lengths of the fusulinids is:

Length in mm.	No. of samples
Less than 3	1
3-4	2
4.0-4.5	9

A summary of the ratios of length to width shows the following:

Ratio	No. of samples
Less than 1.5	1
1.5-2.0	6
2.1-2.5	2
2.6-3.0	3

G. Significance of the Foraminiferal Limestones

The limestones that are composed chiefly of foraminiferal tests constitute an unsolved problem. It is clear that they are a distinctive facies and imply a given set of ecological conditions. It is also obvious that these limestones formed on a part of the reef where other reef organisms were not abundant, or that they were formed at some distance from the reef proper.

Examination of the cores suggests that these deposits may be classified as foraminiferal sands, and that the interstital calcite which acts as a cement was deposited at the same time as the tests. Although they are abundant, the foraminiferal tests are seldom touching one another. The matrix is finely crystalline to medium crystalline calcite; there is no evidence that the matrix has undergone recrystallization. Nevertheless, recrystallization may have been active and the calcite may have been deposited originally as a lime mud.

The size of the fossil debris in these limestones is not noticeably different from that in the other types of reef limestones, and it is likely that the foraminiferal limestones accummulated at sites where other debris was not available.

Three possibilities should be considered in a discussion of the origin of these foraminiferal limestones.

(a) They are beach accummulations or shoal water deposits.

(b) They are deposits formed in a quiet lagoon.

(c) They were deposited in deeper water during a submergence of the area and are not associated with reef-building.

The principal evidence against the first hypothesis is the complete lack of other types of fossil debris. Although it is possible that such debris is present and was not discovered, the great uniformity of the samples seems to eliminate this possibility.

If the limestones were deposited during a temporary submergence of the reef mass, in water too deep for other types of life to flourish, the horizons should have a considerable lateral extent. Unfortunately, the lack of data on the complete structure of the reef does not permit one to even approximate the extent of these limestones. The strongest objection against the hypothesis is the

The following photomicrographs show the appearance in thin section of the foraminiferal limestones.

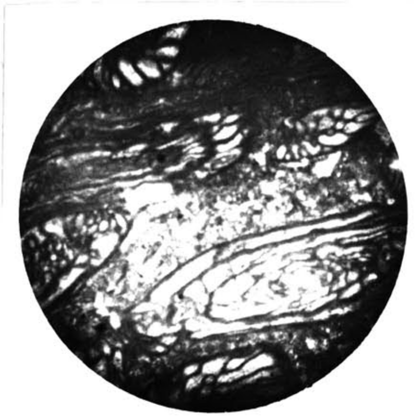


Figure 9 Collins #1
Core 154 10X

Figure 10 Wren #2
Core 127 10X

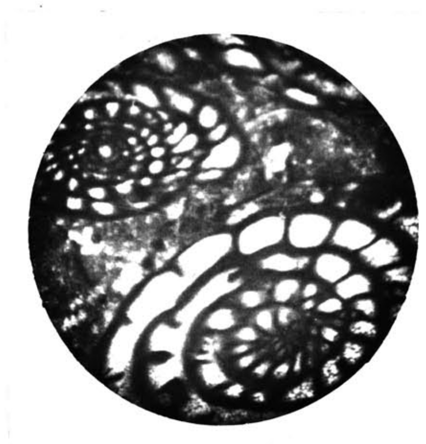


Figure 11 Wren #2
Core 126 10X

fantastic numbers of foraminifera that would be required to cover tens of thousands of square miles of ocean bottom. The size and abundance of the fusulinids indicates that ecological conditions were very favorable. It seems unlikely that such favorable conditions, especially from the standpoint of food supply, could exist over vast areas. It is also unlikely that conditions favorable for the rapid precipitation of calcite would persist over large areas, and the evidence suggests that the calcite cement or matrix was deposited penecontemporaneously with the foraminiferal tests.

The foraminiferal limestones are closely interfingered with the reef mass; they occur at two definite horizons, the first near the middle of the stratigraphic column and the second at the top of the reef mass.

After a consideration of the evidence, it is felt that these fusulinid concentrations can best be explained by the hypothesis that they are lagoonal deposits. Deposition likely took place away from the area of active reef-building, in quiet waters subject to gentle tidal action, at depths of more than 150 feet and less than 300 feet. Since the region was slightly unstable, the position of the lagoon changed slightly from time to time. Conditions in the lagoons were very favorable for the fusulinids. Salinities were probably near normal and the waters warm at all times of the year.

Possibilities that the foraminiferal limestones are either (1) beach or shoal accummulations, or (2) deep water deposits formed during a period of general submergence, cannot be discarded and must be kept in mind pending further investigations.

4. The Echinodermal Limestones

Several samples are composed chiefly of the remains of echinoderms. This section is devoted to a discussion of those limestones which contain more than 30% echinodermal debris and in which other fossils are scarce.

Nine samples belong in this group. They are:

Collins #1	Cores 107, 227, 230, 265
Wren #2	Cores 88, 92, 98, 101, 188

The distribution of echinodermal debris in the 9 samples is shown in the following tabulation.

Percentage of rock composed of echinodermal debris	No. of samples
30-40	3
41-50	4
51-60	1
61-70	1

A. Porosity

The average porosity of the samples is 7.5% (76% of the average for all 63 cores). The distribution of porosity is as follows:

Range of porosity in %	No. of samples
0-5	5
5-10	0
10-15	4

The range in porosity of individual samples is 1.6-14.3%.

The low porosities shown by many of these samples is due chiefly to the fact that they have a higher argillaceous and silt content than the other types of reef limestones.

B. Permeability

The average permeability of the samples is 2.9 md. (22% of the average for all 63 cores). The range in permeability is 0-10 md. The distribution of permeability is shown in the following tabulation.

Range of Permeability in md.	No. of Samples
0	5
0.1-2.0	2
2.1-5.0	0
5.1-10	2

These limestones usually have low permeabilities. The argillaceous content of the rocks may be the cause of these low permeabilities.

C. General Character of the Fragments

The surface detail of most of the fragments is unrecognizable. The fragments are normally less than 2 mm. in diameter and tend to be angular. Approximately 20% of the echinodermal debris are crinoid stems; stems up to one half inch in diameter are present in several of the samples. The remainder of the debris seems to be fragmental material from the plates of unidentifiable echinoderms. The fragments are often badly corroded, and, in two samples, Collins #1 cores 289 and 290, were being replaced by silica.

The following photomicrographs show the appearance in thin section of the echinodermal limestones.

Figure 12 Collins #1
Core 107 10X

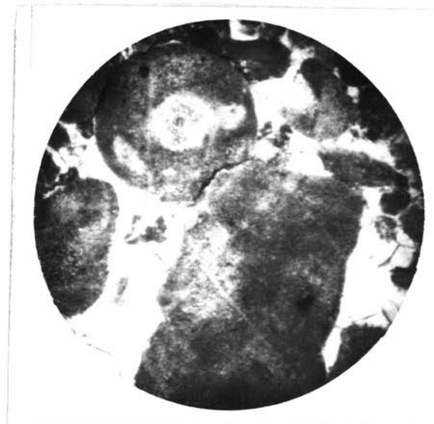


Figure 13 Collins #1
Core 107 10X

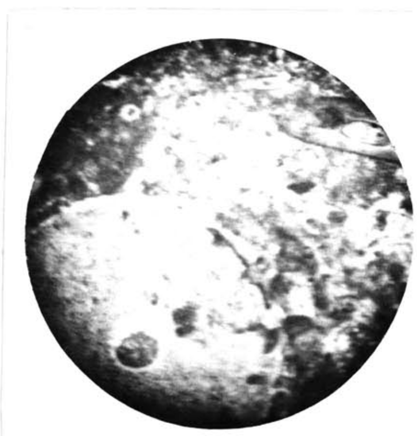


Figure 14 Wren #2
Core 102 10X

Figure 15 Wren #2
Core 102 10X

No species or genus that had contributed to the debris was identified. Identification of the general nature of the debris is not difficult, however, since echinoderms build their hard parts of single crystals of calcite. The debris may be quickly identified by the use of a petrographic microscope.

D. Significance of the Echinodermal Limestones

These rocks are clearly fragmental accummulations and as such reveal little about the habits of the animals that contributed the debris. Examination and correlation of the various horizons in which they occur suggests strongly that these rocks represent biohermal accummulations.

The argillaceous samples probably represent phases that were deposited at times when the waters were too muddy for the other organisms but sufficiently clear for crinoids and possibly for other echinoderms. The non-argillaceous echinodermal limestones are accummulations which might occur at any place that echinoderm debris was abundant. The size of the fragments suggests that many of them would not have been transported any great distance. However, echinoderms of many types are common in reef environments and their presence is in no way unusual.

The presence of limestones composed almost entirely of echinodermal debris is proof that, at certain periods and perhaps under special environmental conditions, echinoderms were a dominant form of life on the reef. Several types of echinoderms were probably abundant although the debris could all have come from crinoids.

5. The Highly Fossiliferous Limestones Which Are Mixtures of Foraminiferal and Echinodermal Debris

Sixteen of the samples are highly fossiliferous and are mixtures of echinodermal and foraminiferal debris. The echinodermal content of these rocks ranges from 15-50% and the foraminiferal content from 15-40%. The samples that belong in this group are:

Well	Cores
Collins #1	165, 230, 265, 289, 290, 303
Wren #2	149
Womack #2	15, 24, 37, 38, 39, 53, 58, 79, 203

A. Porosity

The average porosity of the 16 samples is 10.5% (107% of the average for all 63 cores). The distribution of porosity is shown in the following tabulation.

Range of Porosity in %	No. of Samples
0-5	4
5-10	2
10-15	6
More than 15	4

The range in porosities of the individual samples is 1.2-20.7%. High porosities seem to be typical of many of these rocks.

B. Permeability

The average permeability of the samples is 24.4 md.

This compares very favorably with an average of 13 md. for all 63 cores. The range in permeabilities of the 16 samples is 0-109 md. with a distribution as follows:

Range of Permeability in md.	No. of Samples
0	3
0.1-2.0	0
2.1-5.0	2
5.1-10	3
11-20	5
More than 20	8

Moderate to high permeabilities are typical in these limestones. Since many also have high porosities, these rocks are probably the best reservoir rocks encountered in the cores available for study.

C. Fossil Content

The foraminifera in these rocks are almost exclusively fusulinids. The echinoderm debris is difficult to identify; crinoid stems and small angular fragments are most common.

The distribution of foraminifera in these samples is given in the following tabulation.

Percentage of rock composed of foraminiferal debris	No. of samples
15-25	5
25-35	10
More than 35	1

The distribution of echinodermal debris in the samples is:

Percentage of rock composed of echinodermal debris	No. of samples
15-25	7
25-35	8
More than 35	1

The tabulations show that the average sample in this group has about as many foraminifera as echinoderm fragments and normally has approximately 30% of each.

D. Significance of These Highly Fossiliferous Limestones

These limestones are another unsolved problem. It is unlikely that they represent a special set of ecological conditions. They seem to be clastic sediments that have accummulated in rather limited areas. Examination of the cores suggests that the ecological conditions were favorable for the growth of foraminifera; the foraminiferal tests are normally complete and show little wear. In contrast the echinodermal debris consists of broken and incomplete fragments that are commonly worn and corroded. It seems likely that the echinodermal debris has been transported into a region where foraminifera were flourishing. The great abundance of the echinodermal debris more or less precludes the possibility that the debris could have been transported very far. Possible depositional areas for these limestones include (1) reef flanks, (2) reef flats, and (3) lagoonal areas.

These rocks show none of the characteristics of reef flank deposits. They might have formed on reef flats, but it is unlikely that the crinoids would flourish in the shallow water normally found on reef flats. Therefore, it seems most reasonable to assume that these deposits were formed in lagoonal areas. Deposition probably took place in the shallow waters adjacent to the main reef mass of that time. Depths of water probably ranged from 30-150 feet.

6. The Limestones with Bryozoa

Bryozoa are not a major constituent of any of the cores examined, but do appear in 18 (29%) of the samples. The amount of bryozoan debris ranges from 5-20% of the individual sample. Several types of bryozoa are present but only two were identified --- FENESTELLA and PRISMOPORA. The lacy forms of bryozoa predominate and fragments of zooaria are common in the samples. The samples with bryozoan debris are:

Well	Cores
Collins #1	3, 51, 69, 91, 107, 227, 230
Wren #2	50, 88, 102
Womack #2	38, 39, 92, 109, 164, 183, 203

A. General Characteristics of the Bryozoa[11]

Bryozoa are colonial organisms that are found in great variety of marine conditions. They are most common in well-aerated, clear water, either shallow or deep. They grow rapidly and are attached to objects on the bottom. The skeleton of the bryozoa consists of an external supporting structure called a zooarium. Zooaria show a great variety in size, shape, and architecture.

The following photomicrograph illustrates the appearance in thin section of the highly fossiliferous limestones that are mixtures of foraminifera and echinodermal debris.

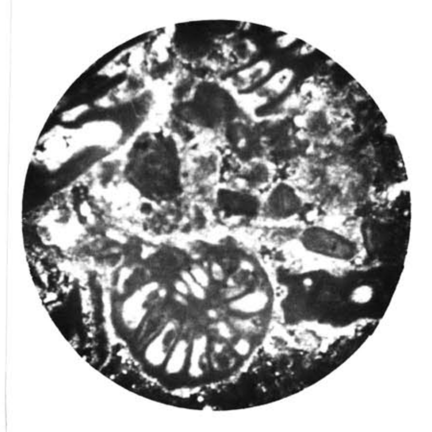


Figure 16 Core 289 Collins #1 10X

The following photomicrographs show the appearance in thin section of the limestones with bryozoa.

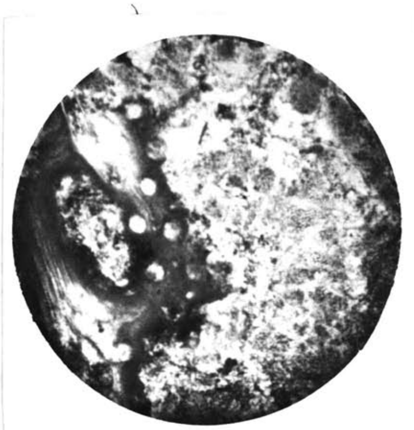


Figure 17 Core 227 Collins #1 10X

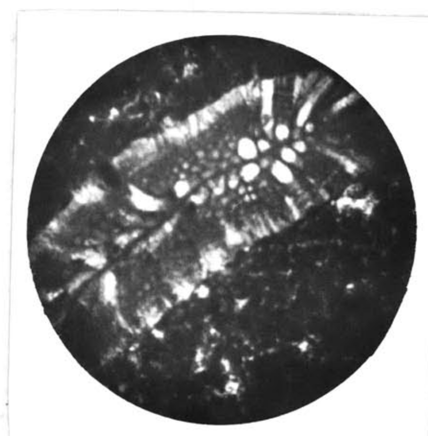


Figure 18 Core 69 Collins #1 10X

These animals have made important contributions to the calcareous deposits of every geologic period since the Cambrian. At the present time bryozoa are among the more important animals of coral reef faunas, and they seem to have had a similar importance on ancient reefs. They were common on the steep peripheral slopes of ancient reefs, but were common on muddy and calcareous bottoms as well. The zooaria are commonly torn loose from the bottoms and transported to nearby localities by wave and tidal action.

B. Bryozoa in the Canyon Reef Formation

The bryozoa in the cores belong to two main groups, the Cryptostomata and the Cyclostomata. Small fragments of the fenestellate Cryptostomata are the most common. Nearly all the fragments are less than 3 mm. in diameter. One sample, Wren #2 core 50, has a fine zooarium of FENESTELLA, the fragment being 2" square.

C. Porosity

The average porosity of the samples is 7.3% (74% of the average for the 63 cores). The distribution of porosity in the 18 samples is shown in the following tabulation.

Range of Porosity in %	No. of Samples
0-5	9
5-10	3
10-15	4
More than 15	2

The range in porosities of the individual samples is

0.8-17.4%. The samples which have foraminifera associated with the bryozoa tend to have the higher porosities and those with echinodermal debris have the lower porosities.

D. Permeability

The average permeability of the samples is 12.3 md. However, the median value is only 1.3 md. and the high average results from the inclusion of one sample that has a permeability of 155 md. The distribution of permeability is as follows.

Range of Permeability in md.	No. of Samples
0	8
0.1-2.0	2
2.1-5.0	2
5.1-10	2
11-20	3
More than 20	1

The tabulation shows that low permeabilities are characteristic of these rocks.

E. Associated Fauna

Since bryozoa are never the dominant form of life in the samples, it is of interest to examine the types of organisms that are commonly associated with the bryozoa. Fourteen (78%) of the 18 samples contain bryozoa and foraminifera although only 3 samples have only these two forms of life. Nine samples contain echinodermal debris, and nine have both echinodermal and foraminiferal debris. Three of the samples contain brachiopod shell fragments, one has a few cup corals, and 2 contain material that is likely of algal origin.

F. Significance of the Limestones with Bryozoa

A study of the samples suggests that conditions favorable for the growth of bryozoa were common at many stages during the building of the reef. Since only small fragments of zooaria are present in the samples, it is likely that wave action and tidal currents were responsible for spreading the bryozoan debris over wide areas.

Examination of the cores suggests that the bryozoa grew in areas where echinoderms were abundant, where brachiopods were occasionally common, and where cup corals could grow. It is very likely that some of the bryozoa grew on the active, growing part of the reef face since bryozoa are found in similar positions on present reefs. The data for the North Snyder field is too limited to permit the assignment of these animals to any definite part of the reef.

G. Summary

Bryozoa are common in the reef limestones of the Canyon Reef Formation. The fossil debris is very fragmental. No evidence was obtained bearing on the habitat of the bryozoa or their role in reef-building.

In general, the limestones containing bryozoa are characterized by lower porosities and lower permeabilities than the other types of limestones investigated.

CHAPTER VI

LITHOLOGY OF THE LIMESTONES

1. General Discussion

Samples from the three wells and sample logs for seven other wells in the field were available for study. The locations of these ten wells are shown on plate 2. The three small circles enclosing numbers 1, 2, and 3 show the locations of the wells for which samples were available. (1) is the P.J. Collins #1 well, (2) is the Wren #2 well, and (3) is the M.J. Womack #2 well. The wells for which sample logs were furnished are indicated by an X. The numbers which appear in the squares are section numbers.

The lithologic descriptions reported by field geologists are shown on plates 25, 26, and 27. Attempts to correlate horizons by means of their lithology alone were unsuccessful. It may be that such descriptions are not satisfactory for this purpose, but there is some evidence which suggests that most horizons have only short lateral extents.

The types of limestones reported by the various geologists are:

1. Tan, vuggy ls
2. Lt gray, brecciated ls
3. Tan, granular ls
4. Lt gray, fragmental ls
5. Tan, soft ls
6. Tan, soft, finely crystalline ls
7. Dark gray-brown ls
8. Dark gray, crinoidal ls
9. Tan, coarsely crystalline ls
10. Brown-gray, coarse ls
11. Lt gray, coarse ls
12. Gray-brown, fine ls

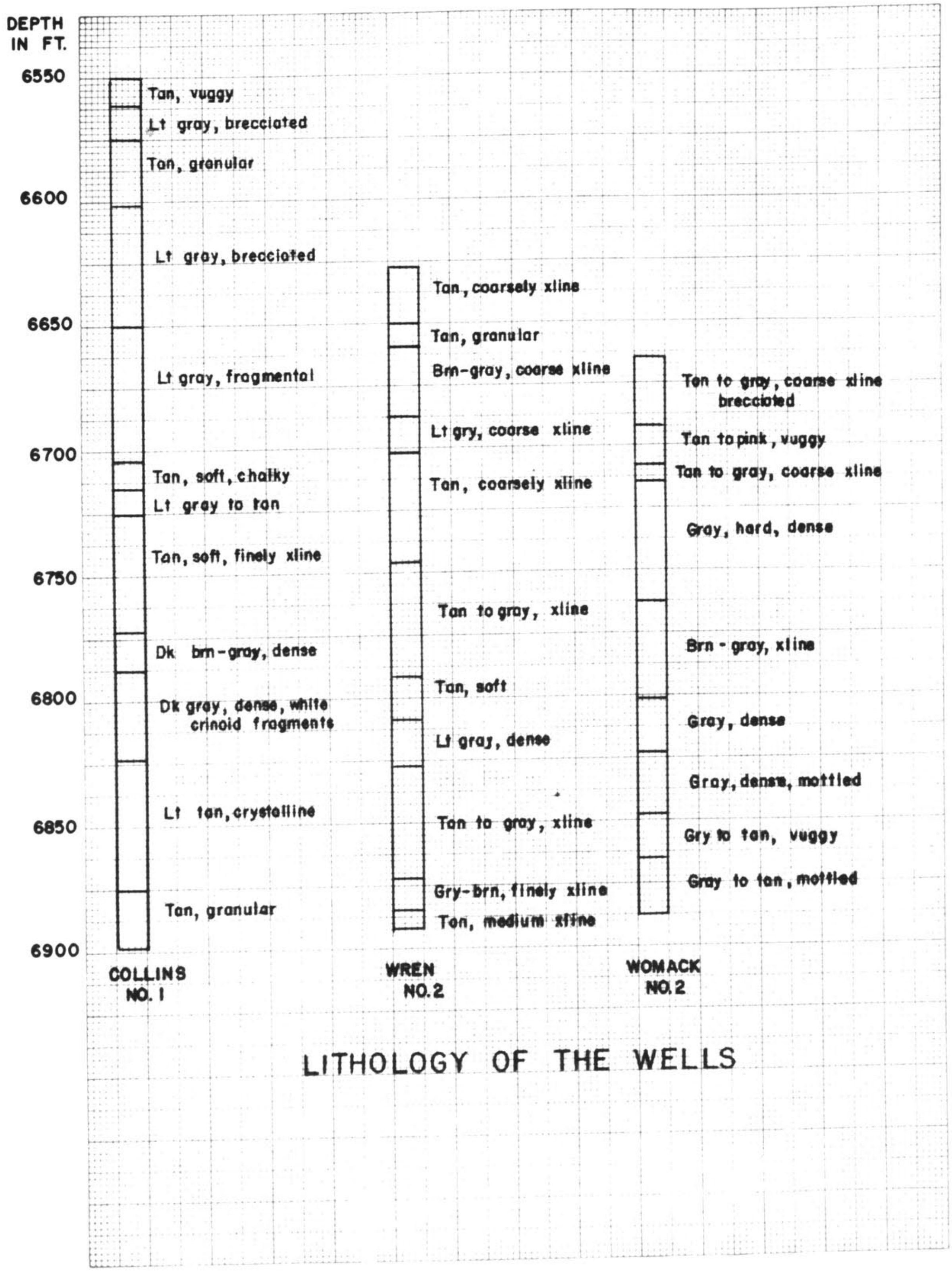

DEPTH
IN FT.
6550
6600
6650
6700
6750
6800
6850
6900
Tan, vuggy
Lt gray, brecciated
Tan, granular
Lt gray, brecciated
Lt gray, fragmental
Tan, soft, chalky
Lt gray to tan
Tan, soft, finely xline
Dk brn-gray, dense
Dk gray, dense, white crinoid fragments
Lt tan, crystalline
Tan, granular
Tan, coarsely xline
Tan, granular
Brn-gray, coarse xline
Lt gry, coarse xline
Tan, coarsely xline
Tan to gray, xline
Tan, soft
Lt gray, dense
Tan to gray, xline
Gry-brn, finely xline
Tan, medium xline
Tan to gray, coarse xline brecciated
Tan to pink, vuggy
Tan to gray, coarse xline
Gray, hard, dense
Brn - gray, xline
Gray, dense
Gray, dense, mottled
Gry to tan, vuggy
Gray to tan, mottled
COLLINS NO. 1
WREN NO. 2
WOMACK NO. 2
LITHOLOGY OF THE WELLS

Plate 25.

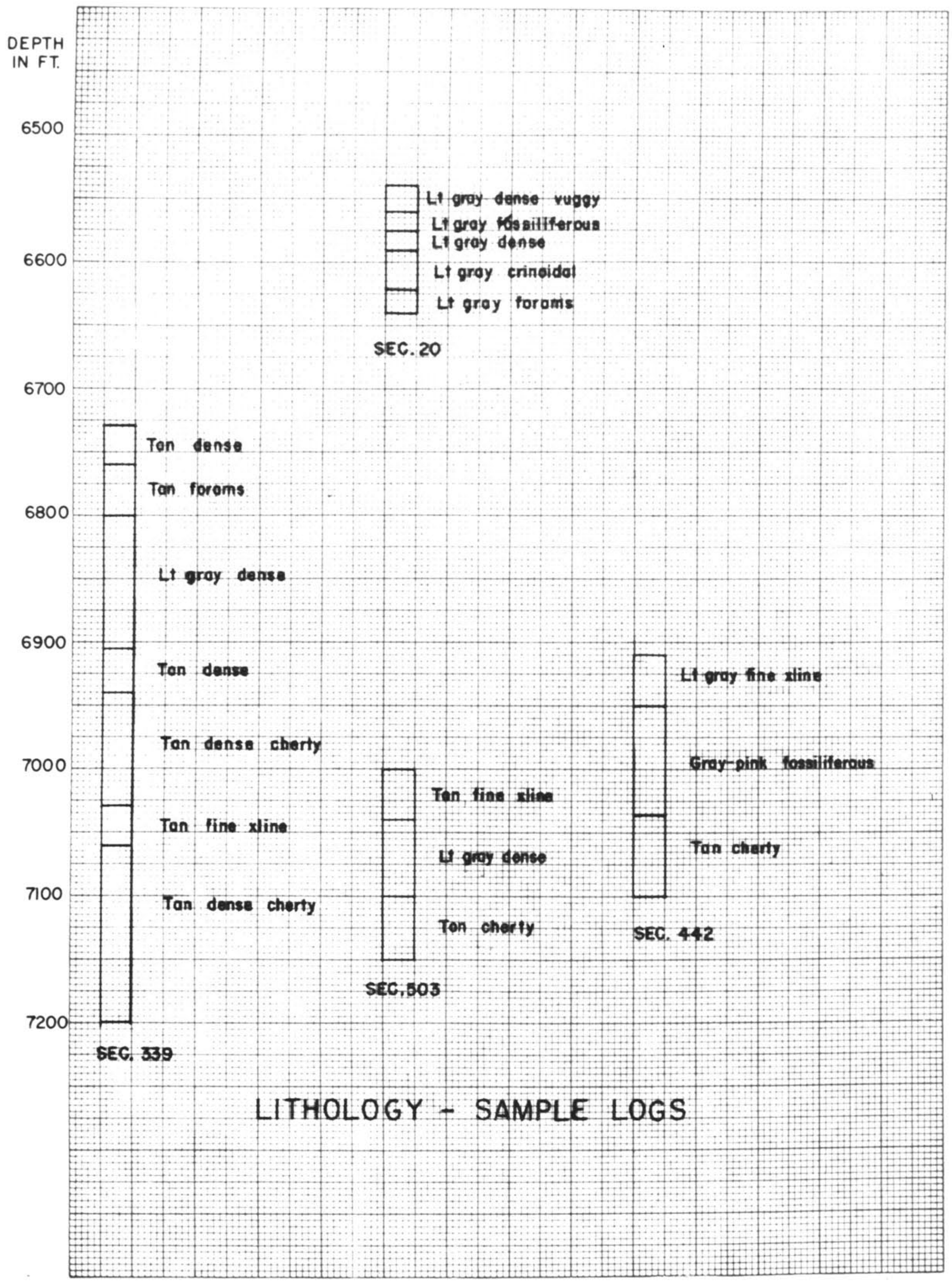

DEPTH IN FT.
6500
6600
6700
6800
6900
7000
7100
7200
Lt gray dense vuggy
Lt gray fossiliferous
Lt gray dense
Lt gray crinoidal
Lt gray forams
SEC. 20
Tan dense
Tan forams
Lt gray dense
Tan dense
Tan dense cherty
Tan fine xline
Tan dense cherty
SEC. 339
Tan fine xline
Lt gray dense
Tan cherty
SEC. 503
Lt gray fine xline
Gray-pink fossiliferous
Tan cherty
SEC. 442
LITHOLOGY - SAMPLE LOGS

Plate 26.

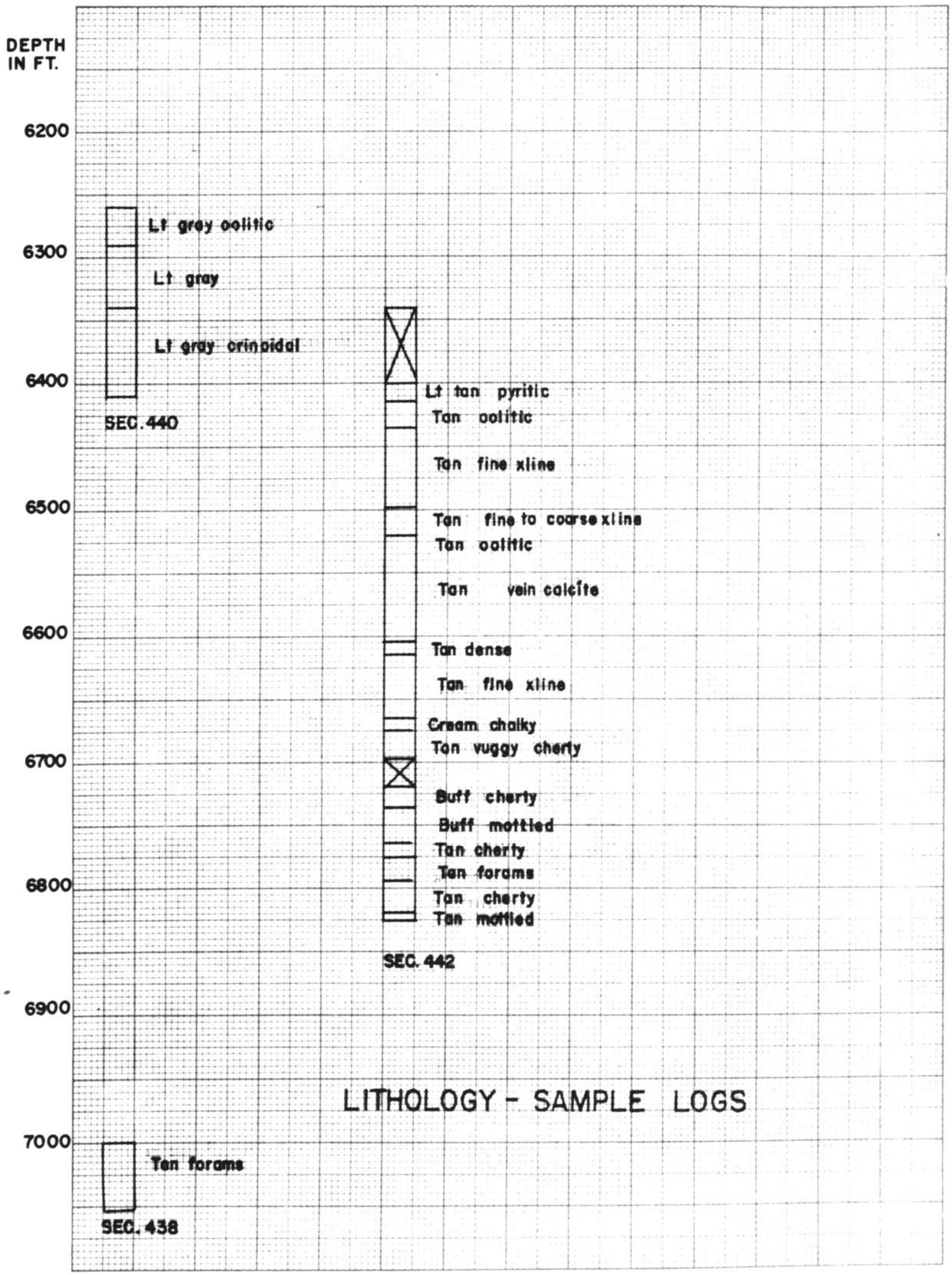

DEPTH
IN FT.
6200
6300
6400
6500
6600
6700
6800
6900
7000
Lt grey oolitic
Lt gray
Lt gray crinoidal
SEC. 440
Lt tan pyritic
Tan oolitic
Tan fine xline
Tan fine to coarse xline
Tan oolitic
Tan vein calcite
Tan dense
Tan fine xline
Cream chalky
Tan vuggy cherty
Buff cherty
Buff mottled
Tan cherty
Tan forams
Tan cherty
Tan mottled
SEC. 442
LITHOLOGY - SAMPLE LOGS
Tan forams
SEC. 438

Plate 27.

13. Lt gray, dense ls
14. Tan, medium crystalline ls
15. Tan to pink, vuggy ls
16. Gray, hard, dense ls
17. Gray-brown, mottled ls
18. Tan, cherty ls
19. Tan, finely crystalline ls
20. Tan, oolitic ls
21. Tan, dense ls
22. Cream, chalky ls
23. Lt gray, oolitic ls

Many of these types are quite similar and the differences are likely due to the fact that the original descriptions were made by several geologists. For this study the list of descriptions has been simplified as follows:

1. Lt gray, fragmental ls
2. Tan, dense to finely crystalline ls
3. Gray-brown, dense to medium crystalline ls
4. Gray, dense, crinoidal ls
5. Tan, medium to coarsely crystalline ls
6. Lt gray, medium to coarsely crystalline ls
7. Lt gray, dense ls
8. Tan to gray, mottled ls
9. Tan, cherty ls
10. Tan, pyritic ls
11. Cream-white, chalky ls
12. Lt gray, medium to finely crystalline ls

The distribution of these samples in each well is shown in the chart on page 88. The chart shows the footage of each of the above classes of limestone reported and the totals of each group.

CHART SHOWING FOOTAGE OF EACH TYPE OF LIMESTONE REPORTED

	Collins #1	Wren #2	Womack #2	Sec. 442	Sec. 503	Sec. 440	Sec. 339	Sec. 440	Sec. 438	Totals
1. Lt gray, fragmental	70									70
2. Tan, dense-fine xline	70	20	20		40		135	270	50	605
3. Gray-brown, dense to medium crystalline	15	35	40							90
4. Gray, dense, crinoidal	35					30				65
5. Tan, medium to coarse	145	45	25							215
6. Lt gray, medium to coarse		50								50
7. Lt gray, dense		20	70	40	60	35	105	35		365
8. Gray-tan, mottled			70							70
9. Tan, cherty				55	50		230	45		380
10. Tan, pyritic								15		15
11. Cream-white, chalky			5					10		15
12. Lt gray, fine to medium	10	90		85		35		170		390
TOTALS	345	260	230	180	150	100	470	545	50	2330

A. Color of the Rocks

Almost all of the rocks are either tan or gray in color. A few are grayish-brown, and occasionally a nearly white sample is encountered. The footage of each reported color is shown in the following tabulation.

Color	Footage	% of Total Footage
Tan or brownish	1215	52.3
Gray	940	40.0
Grayish-brown	160	7.0
Whitish	15	0.7

B. Texture of the Rocks

Texture is difficult to analyze since it is not always well-described in the sample logs. The approximate distribution is as follows:

Texture	Footage	% of Footage
Dense-finely crystalline	1140	48
Fine-medium crystalline	770	34
Medium-coarsely crystalline	280	12
Coarsely fragmental	140	6

C. Fossil Content

Several distinctive fossil groupings can be observed. In the light brown limestones, the fossils in order of abundance are (1) foraminifera, (2) echinoderm debris, and (3) bryozoa. In the light gray limestones the order is (1) echinoderm debris, and (2) foraminifera. In the dark gray rocks only echinoderms are abundant.

Corals and brachiopods are found in the medium to dark gray-brown rocks, although small fragments of brachiopod shells are common in tan limestones. The fenestellate bryozoa are present in both tan and gray limestones. A more complete discussion of the faunal aspect of the rocks appears in Chapter V.

2. Size of the Clastic Fragments

The largest fragments encountered in the rocks are all fossil debris. Several samples contain brachiopod shells which are 1/2" to 2" in their greatest dimension. One sample contains a large fragment of the zooarium of a fenestellate bryozoan. In the other samples, foraminifera tests and crinoid stems are the largest fragments encountered. The foraminiferal tests range up to 5 mm. in length and the crinoid stems up to 1/2" in diameter. Most of the fragmental material in the samples is quite small.

Since the smallest fragments range down to microscopic sizes, it is impossible to estimate their size with any accuracy. To gain some indication of the coarseness of the samples, the largest fragments visible in the thin sections were measured. This data is shown in plate 28. The plate shows that samples from the Womack #2 well are usually coarser than those from other wells, and that the samples from Wren #2 are finer than the others.

The figures on the graph are the reported core analysis data on porosity and permeability. No direct relationships between the size of the fragments and either porosity or permeability can be detected. The degree of cementation seemingly exerts a much greater influence on porosity and permeability than does the coarse-

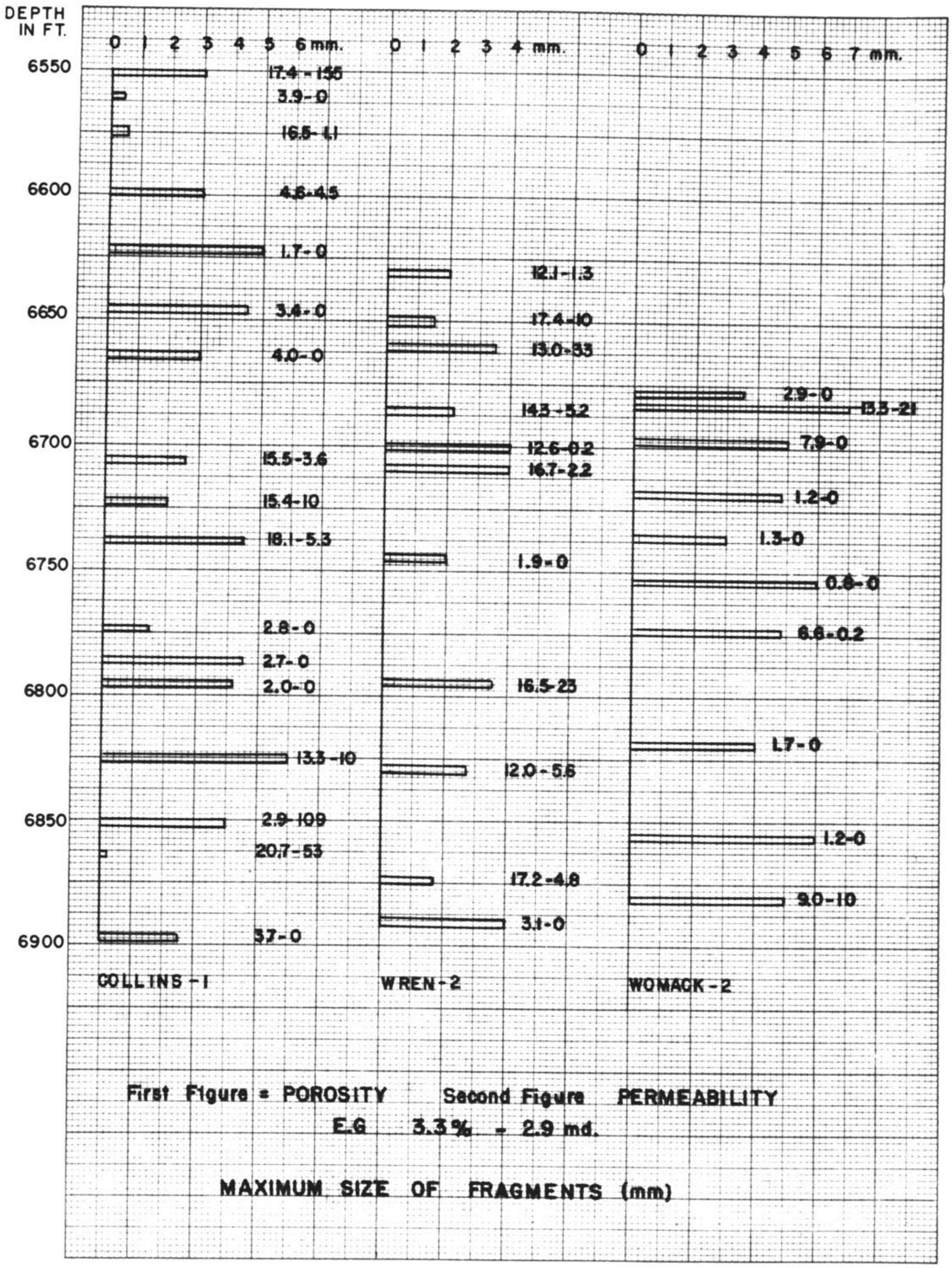

DEPTH IN FT.
6550
6600
6650
6700
6750
6800
6850
6900
0 1 2 3 4 5 6 mm.
0 1 2 3 4 mm.
0 1 2 3 4 5 6 7 mm.
17.4 - 155
3.9 - 0
16.5 - 1.1
4.6 - 45
1.7 - 0
3.4 - 0
4.0 - 0
15.5 - 3.6
15.4 - 10
18.1 - 5.3
2.8 - 0
2.7 - 0
2.0 - 0
13.3 - 10
2.9 - 109
20.7 - 53
3.7 - 0
12.1 - 1.3
17.4 - 10
13.0 - 33
14.3 - 5.2
12.6 - 0.2
16.7 - 2.2
1.9 - 0
16.5 - 23
12.0 - 5.6
17.2 - 4.8
3.1 - 0
2.9 - 0
13.3 - 21
7.9 - 0
1.2 - 0
1.3 - 0
0.8 - 0
6.6 - 0.2
1.7 - 0
1.2 - 0
9.0 - 10
COLLINS - 1
WREN - 2
WOMACK - 2
First Figure = POROSITY Second Figure PERMEABILITY
E.G 3.3% - 2.9 md.
MAXIMUM SIZE OF FRAGMENTS (mm)

Plate 28.

ness of the sample.

The distribution of the sizes of debris shown in plate 28 is as follows:

Range of Fragments in mm.	No. of Samples
Less than 1	3
1-2	6
2-3	8
3-4	8
4-5	9
5-6	3
6-7	1

This tabulation indicates clearly that there are very few samples containing fragments which are all less than 1 mm. in size and very few containing material over 5 mm. in size. The average size of the coarser materials in the samples is 3-4 mm.

3. Stratification

Stratification or "bedding" is one of the most characteristic features of many sedimentary rocks. In limestones the stratification is commonly of two types. First, there is the layering due to mechanical deposition of clastic materials; secondly, there is or may be a layering due to chemical deposition caused by evaporation or chemical reactions.

A. Causes of Stratification in Limestones

The origin of the stratification is clear in many cases and poorly understood in others. The causes listed by Twenhofel[12] include the following:

1. Changes in the Weather
2. Changes in the Climate
3. Changes in Currents not directly due to Weather
4. Changes in Depths of Water
5. Growth of Organisms
6. Settling of Suspended Materials

In reef limestones it is to be expected that (1) and (2) will be of minor importance and that (3), (4), and (5) will be the most important.

B. Features Which Make Stratification Noticeable

Stratification is detectable only because there is some visible evidence of the layering. The features most commonly observed are:

1. Differences in Texture
2. Differences in Hardness and Density
3. Differences in Coloring
4. Differences in Composition
5. Differences in Degree of Cementation
6. Differences in Structural Features
7. Differences in Fossil Attitude or Content
8. Presence of Erosional Surfaces

In reef limestones all of the listed features may be encountered. Normally the layering is so coarse that stratification is more easily observed in field exposures or in large hand samples. In general, the larger the sample the better the chance for observing any layering. Polished sections are usually more satisfactory for observing stratification than rough samples. In a few cases, the bedding is seen most easily on a weathered or eroded surface.

C. The Limestones of the Canyon Reef Formation

Stratification is not prominent in the cores available for study. This is due, in part, to the small size of the samples. Ten (16%) of the cores show some evidence of bedding. This is a rather low percentage in as much as all of the samples are fragmental and can be classified as clastic sediments. Of the 10 samples, only 4 have good bedding; the remainder have only a suggestion of layering. The samples which show stratification are:

Collins #1	Cores 2, 3, 4, 27, 289
Wren #2	Cores 50, 127, 141
Womack #2	Cores 53, 57

The features that led to the detection of bedding are as follows:

1. Color Banding Collins #1 Core 4, Womack #2 core 57
2. Preferred Orientation of Fossil Debris
   a. Long Axes of Foraminiferal Tests Wren #2 Cores 127, 141
   b. Attitude of Brachiopod Shells Collins #1 Cores 2, 3, 27
3. Lamination Womack #2 Core 53
4. Size Gradation Collins #1 Core 4, Womack #2 Cores 53, 57
5. Intercalations of shale lenses Womack #2 Core 53

In all but one case, the bedding is horizontal or at angles of less than 2^{o}. In the exception, there is an irregular contact between a hard, dense limestone and a porous, spongy limestone; the maximum inclination of the irregular surface is 10^{o}. The contact may be an old erosion surface. It seems that the stratification most commonly observed is due to the preferred orientation of fossils and fossil fragments.

4. Oolites in the Samples

Oolites are small spheroidal or ellipsoidal particles ranging in size from 0.25-2.0 mm. in diameter. They may be composed of calcite, aragonite, dolomite, iron oxides, barite, chert, or other materials. This discussion is limited to the calcareous oolites which are original carbonate deposits or replacements.

A. General Characteristics of Oolites

Linck[13] states that all recent oolites that he was able to examine were composed of aragonite and were of inorganic origin. His "fossil" or older oolites were composed of calcite. He proposes that oolites form initially of aragonite and are slowly converted to calcite which is a more stable mineral under normal pressures and temperatures.

Clarke[13] points out that, at temperatures below 60^{o} F, calcite is the original precipitate, and that above that temperature aragonite will form.

Oolites vary considerably in size and shape. However, in a given sample they tend to be rather uniform. In cross-section their structure is (1) radial, (2) concentric, or (3) a combination of both. Examples of these internal structures are shown in the following sketches.

(1) Radial structure (2) Concentric structure (3) Combination

Many oolites form around a nucleus of foreign material. The nuclei may be small rock fragments, mineral grains, shells, or shell fragments. Radial oolites sometimes show, in thin section, a small black cross if the oolite is observed using crossed Nicol prisms. These small crosses are called "psuedo-uniaxial crosses" because they are similar to the crosses observed in the uniaxial minerals under suitable conditions. See figure 19.

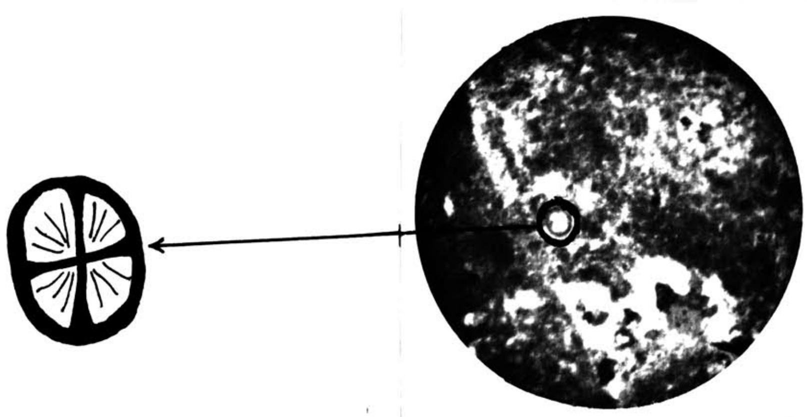


Figure 19 Collins #1
Core 235 10X X Nicols

Psuedo-uniaxial crosses are often indistinct. They usually appear as a Maltese cross slightly darker in color than the remainder of the oolite. See sketch accompanying figure 19.

B. Origin of Oolites

Many hypotheses have been advanced to account for the formation of oolites but no one mode of formation appears to satisfy all cases. It seems likely that most oolites are formed by inorganic agencies. Conditions which favor the formation of oolites are:

1. Constant agitation of water in which calcium carbonate is being precipitated.
2. Heat or warmth.
3. Highly saline waters with high concentrations of calcium and carbonates.

The agitation aids in the release of CO_2 from the bicarbonate and allows $CaCO_3$ to preciptate. Agitation also imparts a rolling action to the particles which allows the carbonate to be deposited more or less uniformly around a center or nucleus.

Oolites are generally considered to be indicators of (1) shallow water with considerable agitation, (2) warm water, and (3) accelerated evaporation.

C. The Oolites of the Canyon Reef Formation

Fourteen (22%) of the cores contain oolites. The oolites are 1-40% of the volume of these samples. None of the samples is of a texture normally designated as oolitic. The samples which contain oolites are:

Collins #1	Cores 235, 265, 303, 337
Wren #2	Cores 50, 92, 98, 124, 153
Womack #2	Cores 57, 58, 109, 164, 190

(1) Size of the Oolites

In 12 of the samples the average size of the oolites is 1.2 mm. or less. In the case of core 164 of Womack #2, a lone oolite 2.2 mm. in diameter is present. Core 109 of Womack #2 has many oolites; their diameters range from 0.60-4.0 mm.

The distribution of oolites by size is as follows:

Average diameter of oolites in mm.	No. of samples
0.30-0.40	5
0.41-0.50	3
0.51-0.99	2
1.0-1.2	2
2.2	1
Up to 4.0	1

With the exception of those in core 109 of Womack #2, the oolites in a given sample are roughly of the same size and shape.

(2) Quantity of Oolites

Oolites are not common in any sample except core 109 of Womack #2; that core contains 35-45% oolites. Generally the oolites are isolated masses in the rocks. Six of the samples contain less than 5% oolites, 6 have 5-10%, and 1 has 10-15%. The size of the oolites seemingly has no relationship with the frequency with which

The following photomicrographs show the appearance in thin section of the oolites.

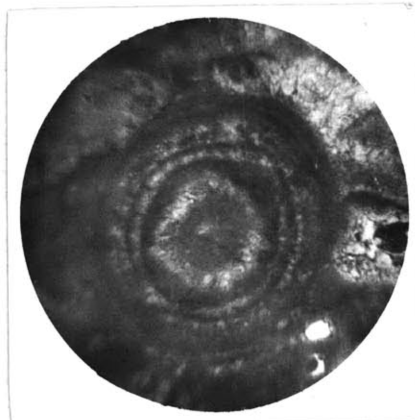


Figure 20 Womack #2
Core 164 15X

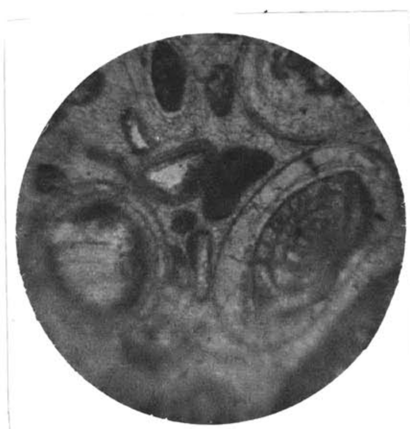


Figure 21 Womack #2
Core 109 15X

Figure 22 Womack #2
Core 109 15X

they are encountered.

(3) Shape of the Oolites

Ten of the samples have oolites which are spheroidal, 3 have oolites which are slightly flattened spheres or ellipsoidal masses, and 1 has both spheroidal and ellipsoidal oolites. The shape of the oolites in a given sample tends to be uniform.

(4) Structure of the Oolites

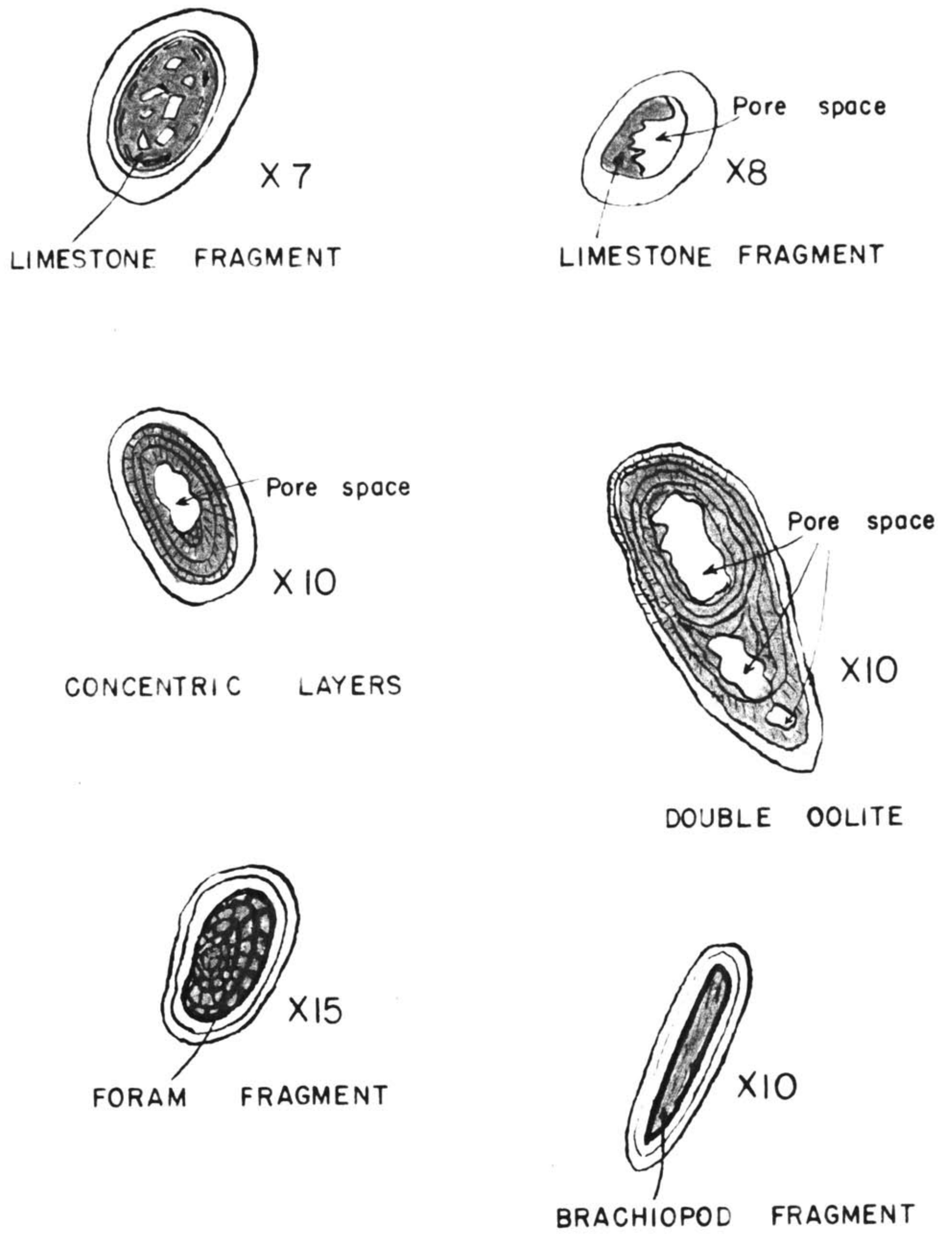
Four samples have oolites that show a pronounced radial structure. These oolites are all small and range from 0.35-0.50 mm. in diameter.

The ten remaining samples have oolites which are basically of the concentric type, some with discernible nuclei and others without. In the two samples with the larger oolites (or pisolites), the oolites of one have no nuclei while the oolites of the other have many types of nuclei. In core 109 of Womack #2, the nuclei are (1) foraminiferal tests, (2) bryozoan fragments, (3) brachiopod fragments, and (4) fragments of limestone. The internal structure of these oolites is shown in plate 29.

(5) Significance of the Oolites

Very limited information can be inferred from a study of these oolites. They are so scarce in most samples that it is possible that they have been washed in from nearby areas of the reef, or even that they may have come from some older oolitic rock. They are not sufficiently numerous to form an oolitic sand such as might be found on a beach or in a tidal channel. It may be that

INTERNAL STRUCTURE OF OOLITES



TAKEN FROM WOMACK No. 2 Core 109

Plate 29.

they were formed in small cavities in the reef where wave action was vigorous; agitated shallow water is common in and near most reef masses. Several of the smaller, solitary oolites are to be found along fracture planes and intimately associated with stylolites.

In contrast with the other cores containing oolites, core 109 of Womack #2 contains nearly enough oolites to be considered oolitic. The sample seems to be a calcareous sand composed of rounded grains and oolites. This sample may represent some type of beach, dune, or bar deposit.

5. Checklist for Study of Limestones and Limestone Cores

After the study had been completed, a form was made up which should answer most of the questions that arise in a study of limestones. Such a form would have aided greatly in assembling the information needed for this study, but could only be made up after a survey of the cores had been made. It is hoped that this form, or a similar form, will aid other workers in compiling information.

The completion of the form requires the use of (1) hand specimens, (2) polished sections and (3) thin sections. It should be valuable even in cases where polished and thin sections are not available however.

In practice the form can be mimeographed on both sides of one sheet of paper for ease in filing. The form appears on the following two pages.

CHECKLIST

LOCATION

State County T&R
Section
Well

DEPTH FORMATION

COLOR (state whether wet or dry or both)

OVERALL TEXTURE		TEXTURE OF MATRIX
a. Cryptocrystalline or dense		
b. Finely crystalline		
c. Medium crystalline		
d. Coarsely crystalline		
e. Brecciated		
f. Conglomeratic		
g. Fossiliferous		
h. Oolitic or spherulitic		
i. Even granular		
j. Porphyroblastic		
k. Coquina		

FOSSIL CONTENT -(total content of rock)

a. Types			
b. Quantity			
c. State of preservation			

d. Remarks
1.
2.

POROSITY

a. Intergranular or intercrystalline -(amount)
b. Vuggy -(size, shape, amount)
c. Fracture or solution -(type, amount)
d. Remarks
1.
2.

FRACTURES

a. Amount
b. Directions of fracture (orientation)
c. Filled or open
d. Evidence of solution
e. Remarks
1.
2.

CLASTIC FRAGMENTS

a. Largest b.Smallest c. Average
d. Type

e. Shapes

COMPOSITION

a.Accessories
1. Amount (%)
2. Size (mm.)
3. Shape

b. Organic materials or hydrocarbons
1. Type
2. Amount
3 Remarks

STRUCTURES

a. Stratification
1. Type
2. Attitude
3. Thickness of beds of laminae
b. Weathered surfaces
c. Mudcracks
d. Ripple marks
e. Concretions
f. Stylolites
g. Oolites or pisolites
h. Flow structure
i. Cone-in-cone
j. Recrystallization
k. Others

SPECIAL REMARKS

1.
2.
3.

CORE ANALYSIS DATA

a. Porosity b. Permeability
c. Residual liquid determinations

CHAPTER VII

RECRYSTALLIZATION IN THE REEF LIMESTONES

1. Introduction

Recrystallization is a process in which there is a change in rock texture, or a rearrangement of the crystals and their boundaries. It is a common process in limestones because they are fairly soluble rocks under natural conditions. The principal change is a redistribution of material; small crystals tend to disappear and larger crystals to grow. In general, recrystallization tends to make the texture of a limestone more coarsely crystalline.

Water and pressure are the most effective agents in causing the recrystallization of limestones. Heat will aid the process but is not so necessary as in many other types of rocks. Good porosity and a complex composition will increase the speed with which recrystallization takes place.

A. Results of Recrystallization

The physical features which are associated with the recrystallization of a limestone may include:

1. Disappearance of smaller crystals and growth of larger ones.
2. Disappearance of strained crystals and growth of unstrained ones.
3. Orientation of the long axes of crystals in the direction of minimum stress.
4. Reduction of pore space.
5. Changes in composition of the limestone.

The presence of metamorphic minerals such as garnets, tremolite, and chlorite is evidence of recrystallization in many limestones. Structural features which may indicate recrystallization are (1) psuedomorphs, (2) secondary growths, (3) large crystals, (4) low porosity, and (5) signs of deformation.

2. Recrystallization in the Canyon Reef Formation

In the 63 cores examined, 55 (88%) show some sign of recrystallization. The recrystallization was estimated with respect to the amount of the rock which has been effected. The following tabulation shows the amount of the sample affected by recrystallization and the terminology used to describe the amount.

Amount of Rock Affected	Terminology
0-2%	None
2-5%	Very slight
5-8%	Slight
8-15%	Moderate
More than 15%	Extensive

A. Amount of Recrystallization in the Samples

Using the terminology defined above, the distribution of recrystallization was found to be as follows:

Recrystallization	No. of Samples
None	8
Very slight	5
Slight	17
Moderate	19
Extensive	14

B. Type of Recrystallization

Recrystallization is found which affects: (1) the matrix of the rock, (2) the fossil fragments, (3) the stylolitic zones, (4) the interiors of foraminiferal tests, (5) pore spaces and cavities, and (6) solution channels and fracture planes. Normally, recrystallization affects more than one of these areas. The frequency with which these types of recrystallization occur in the samples is shown below:

Area Affected	No. of Samples
Matrix	15
Fossil fragments	14
Stylolitic zones	12
Interiors of foraminifera	12
Pore and cavities	28
Fractures and solution channels	13

The tabulation discloses that 24% of the samples show some recrystallization of the matrix. This is indicated by coarsely crystalline matrices, evidence that the grain size of the matrix is being enlarged, and by the penetration of fossil fragments by growing crystals of the matrix.

In 22% of the samples there has been recrystallization of fossil fragments. This can be recognized by the presence of coarsely crystalline calcite and by the lack of normal structures and textures of the fossils. Included in this list are only those fragments which could still be recognized by either their internal or external structure; not included are any fossils that have been totally destroyed or made unrecognizable by recrystallization.

Recrystallization concentrated along stylolitic zones is noted in 19% of the samples. The criteria are ghosts of former stylolites and masses of coarsely crystalline calcite concentrated along the stylolites.

Nineteen percent of the samples contain foraminiferal tests whose interiors are filled with coarsely crystalline calcite. Filling may have occurred either before or after deposition in their present strata; no conclusive evidence on this point was obtained.

Recrystallization indicated by the presence of coarsely crystalline calcite is very common in all the openings in the limestones. Many of the openings, provided there is sufficient porosity and permeability to permit free access of solutions, are filled or partially filled with calcite. The pores and vugs of 45% of the samples have a filling of calcite which is more coarsely crystalline than the matrix of the rock. Twenty percent of the samples have fractures or solution channels partially or completely filled with later calcite.

As has already been noted, recrystallization normally affects more than one part of a limestone. In only 17 (27%) of the samples examined is a single area of the rock being affected. The data for these 17 samples are shown in the following tabulation.

Area Affected	No. of Samples
Along fractures	3
Filling pores	4
Filling foraminiferal tests	4
Along stylolitic zones	6

In all other samples that show recrystallization two or more areas of the rock are affected. Recrystallization seems to be a common process in the limestones, and is likely even more common than this study suggests.

C. The Relationships of Recrystallization and Porosity

Recrystallization which tends to fill pore space or other openings reduces porosity and may destroy it completely. If, on the other hand, there is merely a replacement of existing fossil fragments or structures, the effect on porosity may be negligible. It is seldom possible to determine the porosity prior to recrystallization, and hence the porosity may be reduced without visible evidence.

Table VII-1 shows the relationships between the porosities reported in core analyses and the estimated recrystallization. The table shows that two conflicting processes are in operation. First, porosity is being reduced by the filling of the voids with calcite, and, secondly, recrystallization is most effective in the samples that have or have had a reasonable porosity. It is also apparent that even extensively recrystallized limestones may show relatively high porosities. Twenty three of the samples exhibit moderate to extensive recrystallization but still have porosities higher than 10%.

Table VII-1 Porosity vs. Recrystallization

Recrystallization	Range of Porosity in %					
	0-5	5-10	10-15	15-20	20-25	Totals
None	1	2	4	1	0	8
Very slight	1	0	1	3	0	5
Slight	10	2	1	3	1	17
Moderate	5	2	7	4	1	19
Extensive	3	0	9	2	0	14
TOTALS	20	6	22	13	2	63

In those cases in which the matrices show recrystallization, the average porosity of the samples is 10.3% with a range from 2.3-17.2%. If recrystallization affects the fossil fragments, the samples show an average porosity of 12.8% with a range from 1.2-22.7%. Samples in which recrystallization involves stylolitic zones have an average porosity of 8.2% with a range from 1.3-20.7%. If recrystallization is affecting pore space, the average porosity of the samples is 10.6% with a range from 1.2-22.7%. Finally, if recrystallization is active along fractures and solution channels, the average porosity is 10.7% with a range from 1.2-22.7%.

D. The Relationships of Recrystallization and Permeability

It should be expected that recrystallization would decrease permeability, especially if it causes a filling of the openings in the rock. The following table shows the relationships between the estimated recrystallization and the permeabilities reported in the core analyses.

Table VII-2 Permeability vs. Recrystallization

Recrystallization	Range of Permeability in md.							
	0	0.1-2	2.1-5	5.1-10	11-20	21-50	51-100	1-200
None	3	1	1	0	0	3	0	0
Very slight	1	0	1	1	1	0	0	1
Slight	8	0	4	2	2	0	1	0
Moderate	5	5	1	4	1	2	1	0
Extensive	2	3	2	2	2	1	0	1
TOTALS	19	9	9	9	6	6	2	2

The table shows that 14 samples have moderate to extensive recrystallization, and yet have permeabilities of more than 5 md. Eighteen samples with moderate or extensive recrystallization have permeabilities of less than 5 md.

In those samples in which recrystallization is apparent in the matrix of the rock, the average permeability is 30 md. with a range from 0-155 md. If recrystallization affects the fossil fragments, the average permeability is also 30 md. with a range from 0-109 md. Samples in which recrystallization involves the stylolitic zones have an average permeability of 9 md. with a range from 0-53 md. If recrystallization is active along fractures and solution channels, the average permeability is 9 md. with a range from 0-88 md.

Since recrystallization normally affects more than one part of a rock, the results of Table VII-2 are difficult to interpret. Seemingly, the most detrimental effect of recrystallization is the filling of fractures and solution channels with calcite; recrystallization of fossil fragments and matrices seems to be of less importance.

E. The Relationships of Recrystallization and Color of the Rocks

The following table shows the colors of the rocks affected by recrystallization.

Table VII-3 Color vs. Recrystallization

Color of Rock	Recrystallization					
	None	V. slight	Slight	Moderate	Extensive	Totals
Buff	1	2	5	3	3	16
Buff-brown	1	1	3	5	3	13
Lt gray-brown	0	0	2	0	0	2
Lt gray	2	1	5	4	3	15
Gray-brown	2	1	1	4	2	10
Dk gray-brown	0	0	0	1	0	1
Dark gray	1	0	1	2	1	5
TOTALS	8	5	17	19	14	63

There seems to be no relationship between the color of the rocks and the frequency with which recrystallization is encountered. Recrystallization is normally easier to see in the darker colored rocks, but microscopic examination of the samples indicates that recrystallization is just as common in the light colored limestones.

F. Summary

The followimg points may be emphasized.

1. 88% of all samples examined show some recrystallization.

2. 8% of the samples have only very slight recrystallization, 27% have slight recrystallization, 30% have moderate recrystallization, and 22% show extensive recrystallization.

3. Recrystallization affects all parts of the limestones. It is most commonly observed around pore spaces and vugs. Normally several parts of a given sample are affected.

4. Although recrystallization normally reduces porosity, a considerable porosity may exist even in extensively recrystallized limestones.

5. No definite relationships between recrystallization and permeability were found; a decrease in permeability with increasing recrystallization is to be expected.

6. There is no correlation between the colors of the samples and the amount of recrystallization or the frequency with which it is encountered.

CHAPTER VIII

MICROSTYLOLITES IN THE REEF LIMESTONES

1. Introduction

Stylolites are unique features found in sedimentary rocks and occasionally in metamorphosed sediments. In spite of the volume of literature on these features, the characteristics, descriptions, and interpretations are often contradictory. Part of the difficulty seems to arise from the fact that their mode of formation is not well understood.

There are only two hypotheses for the formation of stylolites that are in serious consideration at the present time. Of the two, most authors seem to be of the opinion that Stockdale's "solution-pressure" hypothesis is the more acceptable.

Briefly Stockdale's[14] theory may be stated as follows: "Stylolitic phemomena result from a differential chemical solution in hardened rock, under pressure, of the two sides of a bedding plane, a lamination plane, or crevice, the dissolved portions of one side fitting into the dissolved out portions of the opposite; the interfitting taking place slowly and gradually as solution takes place."

Schaub[15] proposes a "contraction-pressure" hypothesis. This states that stylolites are formed by the filling of shrinkage cracks formed as a lime mud contracts on drying. During most of the process the lime mud will remain plastic. "The gradual removal of pore water and consequent gradual and continued volume contraction provides the necessary differential stresses for a prolonged transfer of material, which will continue until stress differences become too low to overcome resistance to flow". A clay seam is assumed to be present initially between the two limestones.

2. Microstylolites of Canyon Reef Formation

Stylolites occur throughout the entire thickness of the formation and are abundant in many of the samples. In all, 27 samples containing some 40 stylolitic zones were observed and studied. Nearly half the zones are well-developed and could be studied in detail.

Because the maximum amplitude of the stylolites in the samples is only 9 mm. it was decided to call these features microstylolites. They are, to all appearances, exactly like the larger stylolites reported by other authors. In this study the term amplitude is defined as the maximum distance from the highest point of the crest or cap to the low adjacent point that can be correlated with the individual cone or column. All measurements including those of the thicknesses of residues were made from photomicrographs at 10 magnifications. The lateral extent of the stylolitic seams could not be ascertained since only portions of 6" cores were available.

A. Size and Shape of the Microstylolites

Several measurements are necessary to determine the size of the microstylolites; the heights of the columns, the widths of the columns, the maximum height of columns on a seam, and the

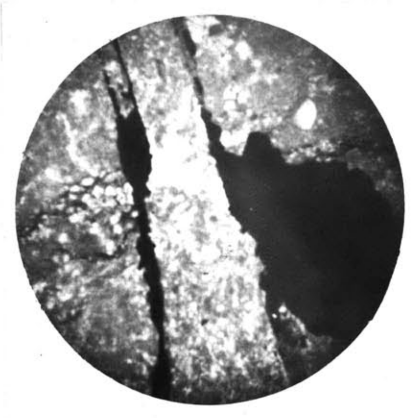


Figure 23.
A.L. Wren #2 Core 178
A large stylolite cut across by a minor stylolitic seam which in the center of the picture is represented by a zone of white calcite. 10X.

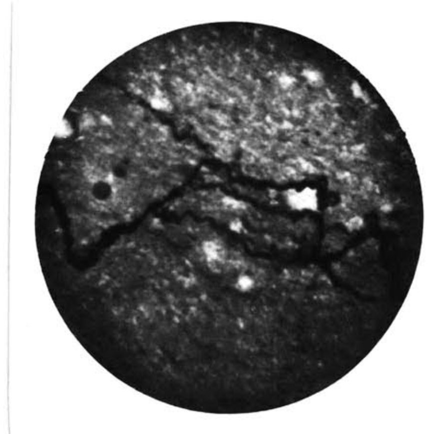


Figure 24.
P.J. Collins #1 Core 216
A complex stylolite showing several ages with younger zones inside a larger column. White spots are calcite. 10X.

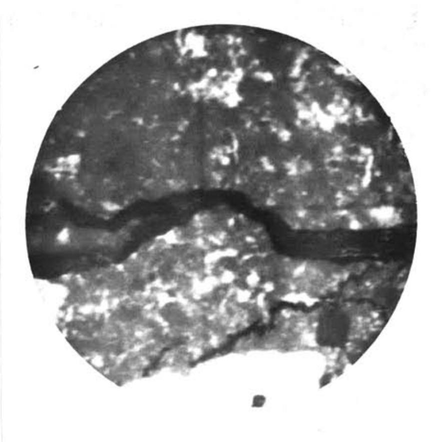


Figure 25.
P.J. Collins #1 Core 69
A brownish, smooth, wavy, bifurcating stylolitic seam. 10X.

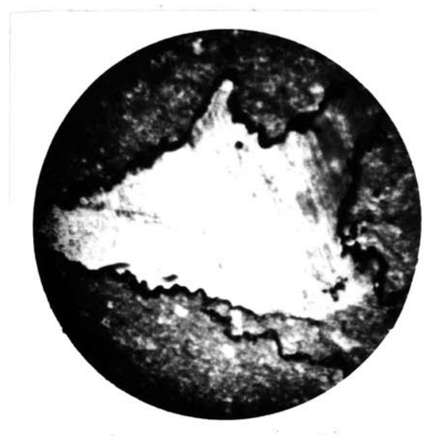


Figure 26.
P.J. Collins #1 Core 216
An echinoderm fragment surrounded on all sides by stylolitic seams. 10X.

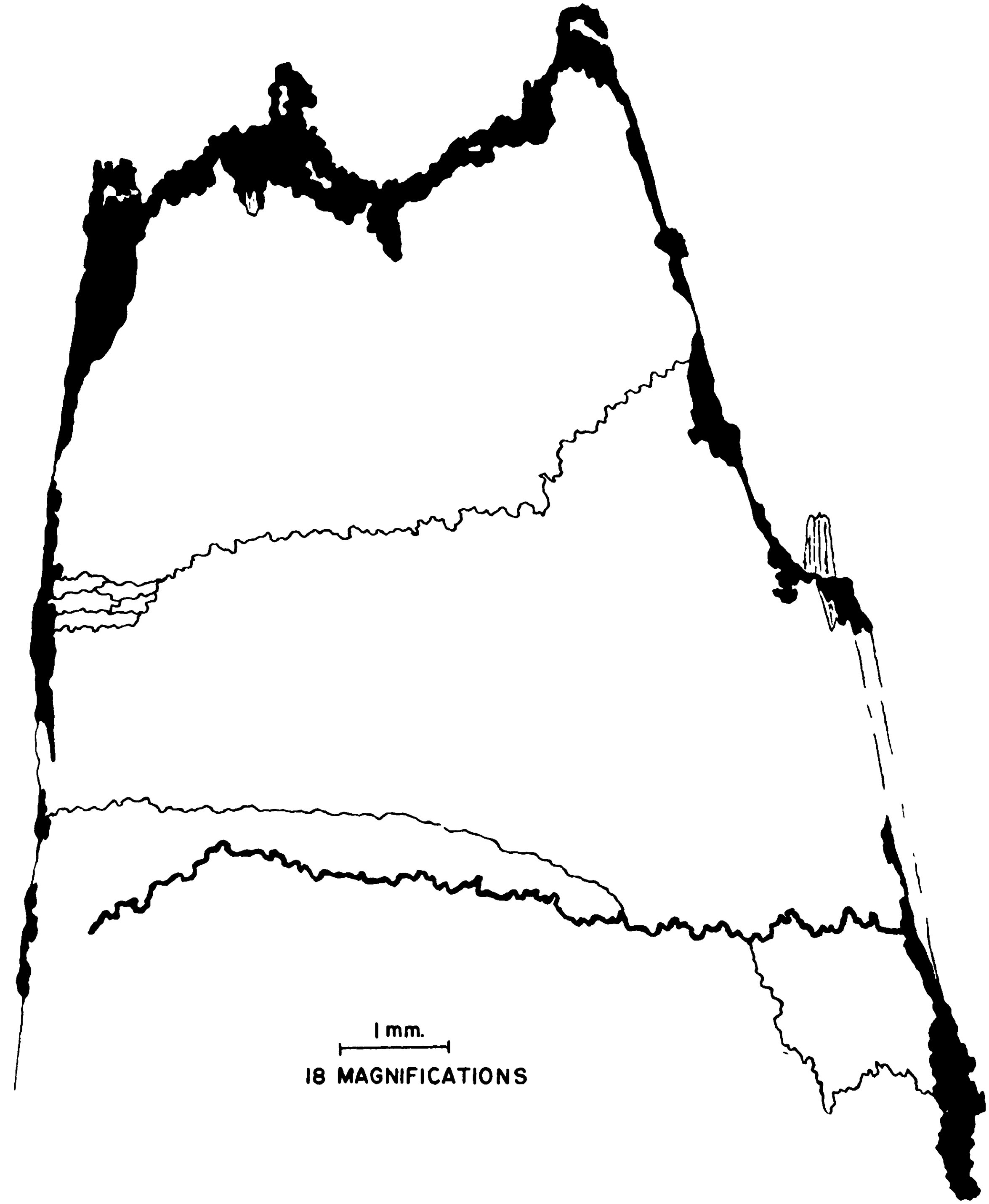
average height of columns on each seam were all measured. Of the 40 seams, only 6 have pronounced columns or cones (over 5 mm. in height). All others are either smooth or wavy. The data for the 6 seams with prominent columns appears in the following table.

Table VIII-1 Size of Stylolitic Columns

Well	Depth (ft)	Max. Height in mm.	Max. Width in mm.	Ave. Height of columns in mm.
Collins	6774	1.4	2.5	---
Collins	6562	1.8	1.5	1.2
Collins	6723	1.5	0.5?	0.6
Wren	6834	3.2	1.2	1.5
Wren	6693	3.2	0.7	2.2
Wren	6877	9.0	7.5	---

The table shows that there is no close relationship between the maximum height of the columns and their widths; in general the columns tend to be higher than they are wide. The height of the tallest columns may be several times the average height of the columns on that seam, but is seldom over three times. Enlargement of the detail on these stylolitic seams is shown on plates 30-41.

Most of the seams are similar in shape. The majority are thin, wavy bands with minor serrations when viewed on a polished surface or in thin section. At least 10 of the seams bifurcate, usually at irregular intervals. Others, on a flat surface, present a braided appearance with the space between the braided lines of black residue filled by clear, medium to coarsely crystalline



ACTUAL TRACE

A.L. WREN NO. 2

CORE 178

Plate 30.

A.L. WREN NO. 2

CORE 178

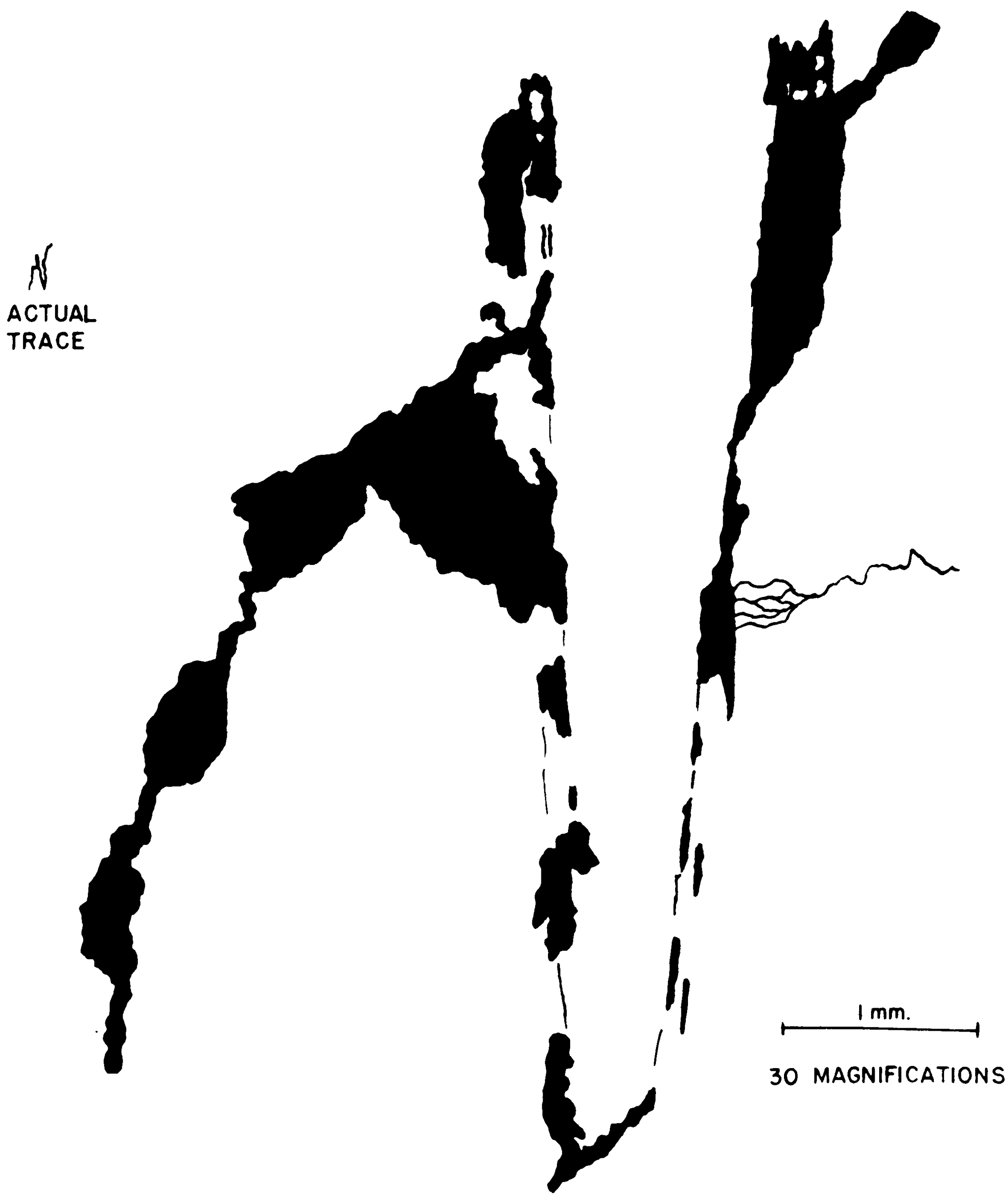
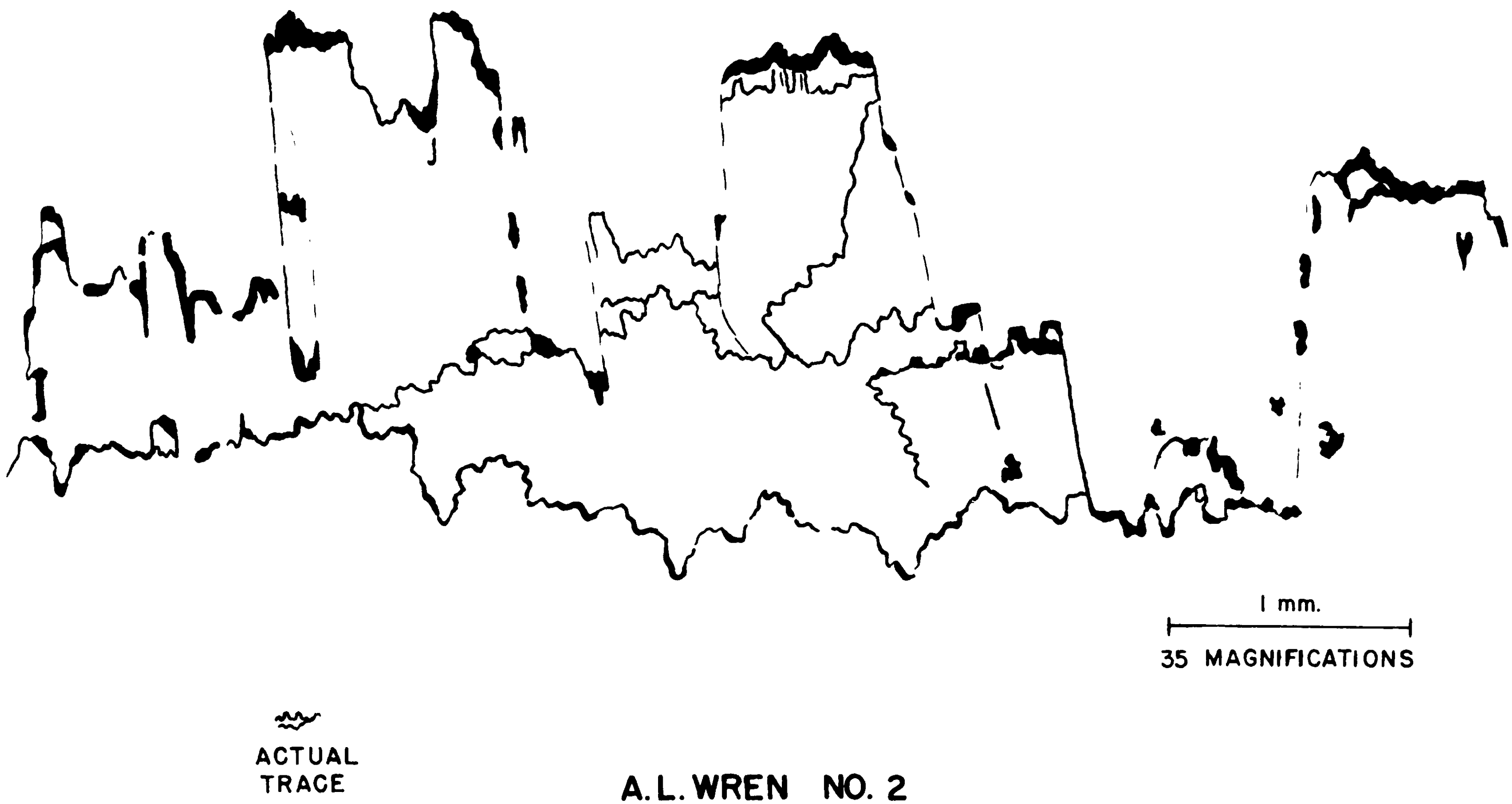


Plate 31.



A.L. WREN NO. 2

CORE 152

Plate 32.

calcite. Collins #1 Core 216 and Wren #2 Cores 152, 178, and 92 all have stylolitic seams that cross. The angle of crossing is normally 90° but occasionally is around 45°.

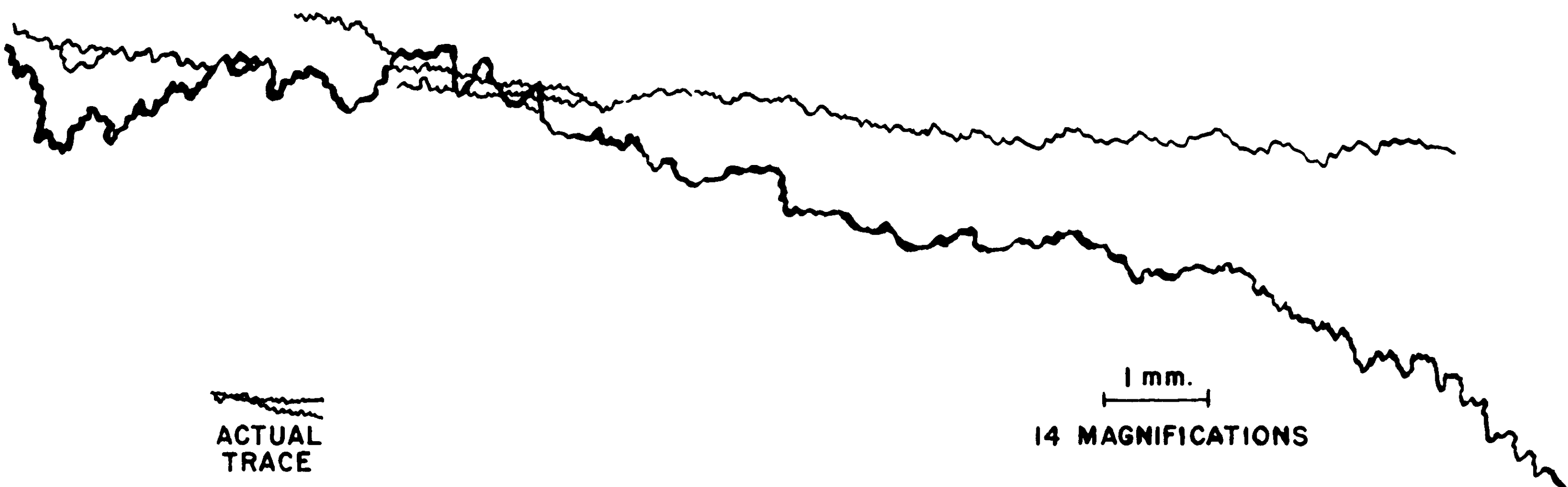
The seams that are strongly serrated usually have flat-topped columns, rectangular to trapezoidal in cross section. A few of the seams have pointed cones on the seams.

B. The Nature and Distribution of the Residues

The material concentrated along the stylolitic seams is an insoluble, black, very fine-grained substance. If striations are present on the sides of the columns, they are still visible on the residue after treatment with acid.

Small 10-gram samples of the limestones in which the stylolitic seams appear were treated with cold dilute HCl, and the residues were examined under a binocular microscope. In many cases a grayish silt or clay was obtained from the acid treatment, and occasionally a small amount of free oil was also present. In several cases neither clay nor oil were obtained, and yet the sample contained well-developed stylolitic seams with appreciable amounts of black residue concentrated along the seams.

In view of the facts that (1) oil does occur in these rocks, and (2) no dark colored residue was obtained from any of the limestones directly, it seems reasonable to suppose that the black color is imparted by the presence of a petroliferous residue. The remainder of the material along the seams is either clay or crystalline calcite. Although it is possible that the residue along some of the seams could consist solely of material that



P. J. COLLINS NO. 1

CORE 216

Plate 33.

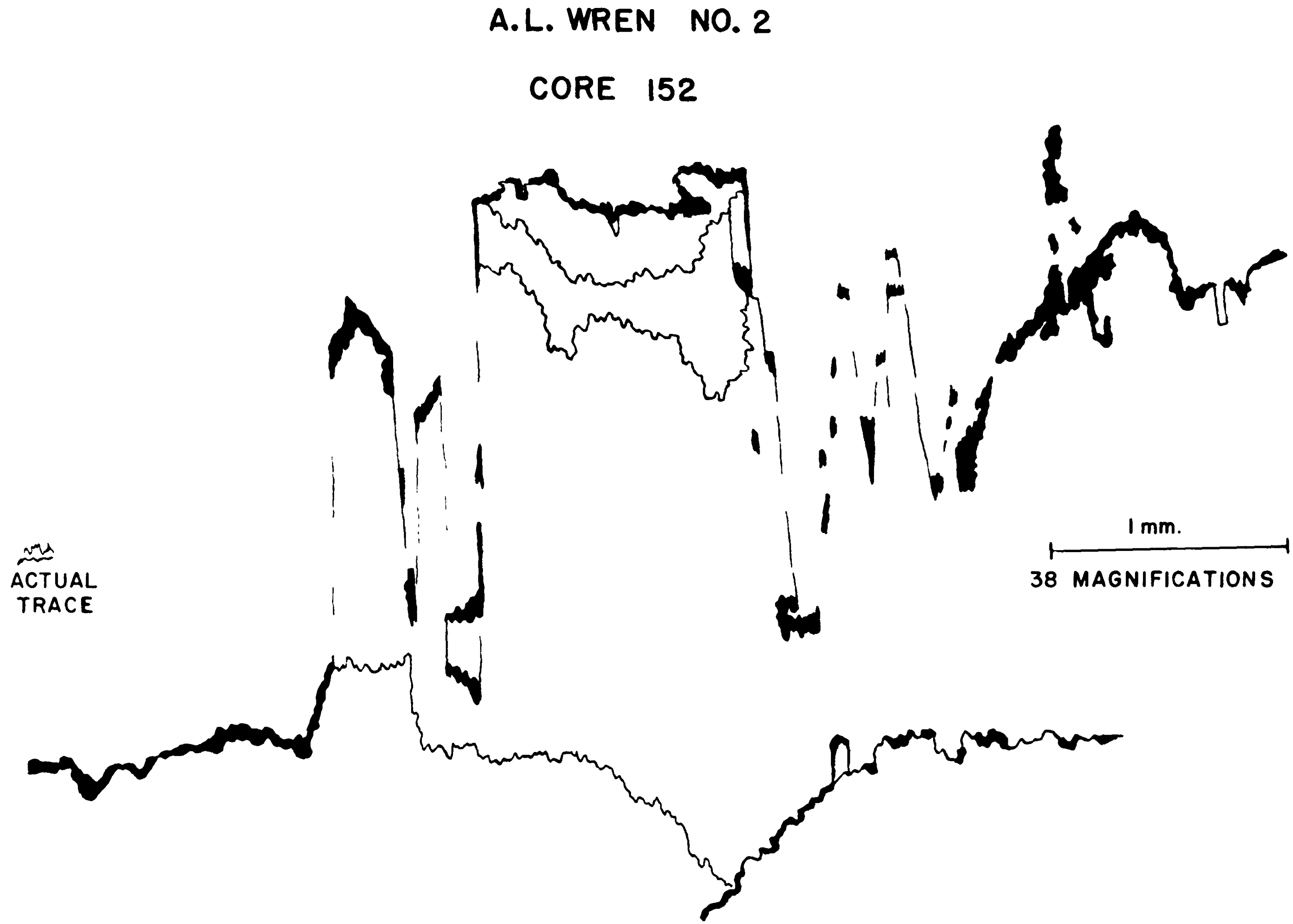


Plate 34.

could result from the solution of the surrounding limestones, it is bvious that this does not explain the presence of stylolites in rocks that contain neither clay nor oil. It is proposed that material moved laterally to fill solution cavities and fractures. The amount of lateral movement is unknown, and possibly only short distances are involved.

Examination of many stylolites shows that the residues are commonly concentrated in areas that are clearly former solution cavities and pore space (see plates 30-33).

The residues obtained by treating the purer parts of the limestones with dilute HCl range from 0-5% of the mass, with values of 1-3% being most common. If the residues resulted from the solution of the surrounding limestones, the approximate amounts of limestone to be dissolved would be 5 mm. for a cap 0.1 mm. thick, 1 mm. for a cap 0.02 mm. thick, and 55 mm. for the thickest capping which is 1.1 mm. thick.

It is difficult to estimate the amount of solution that may have occurred along a stylolitic seam. If stylolites form solely by solution, it is certainly as much as the maximum height of the stylolitic columns. Where stylolitic seams cross, it is often difficult to believe that appreciable solution has occurred, or even that any solution has taken place. In the case of the longest column observed (see plate 31) every indication was that no displacement had occurred. In this case, a small stylolitic seam crosses a major seam, and, at the place where it crosses the main column, the column has a zone of clear, crystalline calcite which is an exact prolongation of the smaller seam; the smaller seam then continues on the other side of the column, but is largely obscured by the major seam.(See also figure 23)

C. The Relationship of Fossils to the Microstylolites

Fossils in contact with a stylolitic seam always show some corrosion (see plates 24, 35, and 36). In some cases only one side of a fossil borders the seam, and in others the seam completely surrounds the fragment (see figure 26).

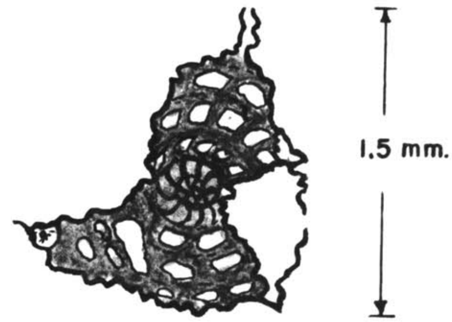
D. Conditions During Formation of the Microstylolites

An interesting feature of the larger columns is that they commonly contain smaller stylolitic seams which usually terminate abruptly at the edges of the larger columns.(See plates 30, 32, 33, 34 and figures 24 and 31). In these cases it seems unlikely that sufficient material could have been removed in solution to form these seams from residual material alone.

Most of the stylolitic seams were oriented perpendicular to the sides of the cores, or parallel to bedding planes. A few are oriented at angles running from 15-45° to the most common orientation. Plate 40 shows a stylolitic seam oriented at 45° to the bedding with a minor extension along one of the bedding planes.

In most cases the axes of the cones and the sides of the columns are perpendicular to the general orientation of the stylolitic seams, although deviations up to 10° from the perpendicular are not rare. (See plates 32 and 36).

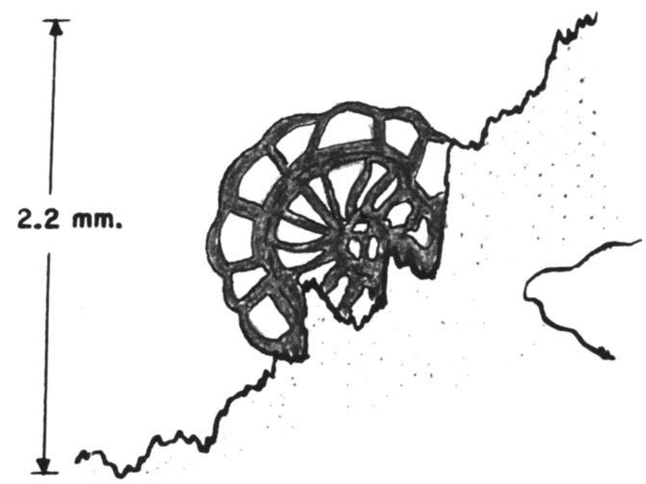
Examination of thin sections proves beyond any doubt that many of the rocks are well-fractured, and that conical or columnar



P. J. COLLINS NO. 1

CORE 165

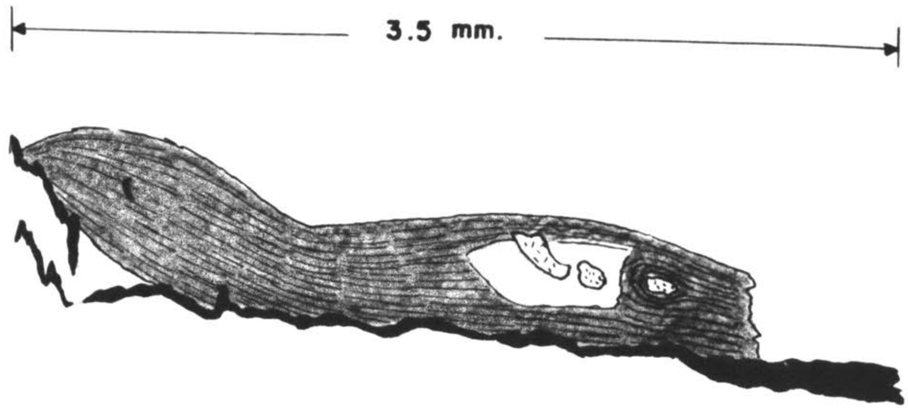
FORAM WITH STYLOLITES DEVELOPED ALONG CORRODED EDGES



A. L. WREN NO. 2

CORE 152

CORRODED FORAM AND ECHINODERM FRAGMENTS ALONG STYLOLITE



P. J. COLLINS NO. I

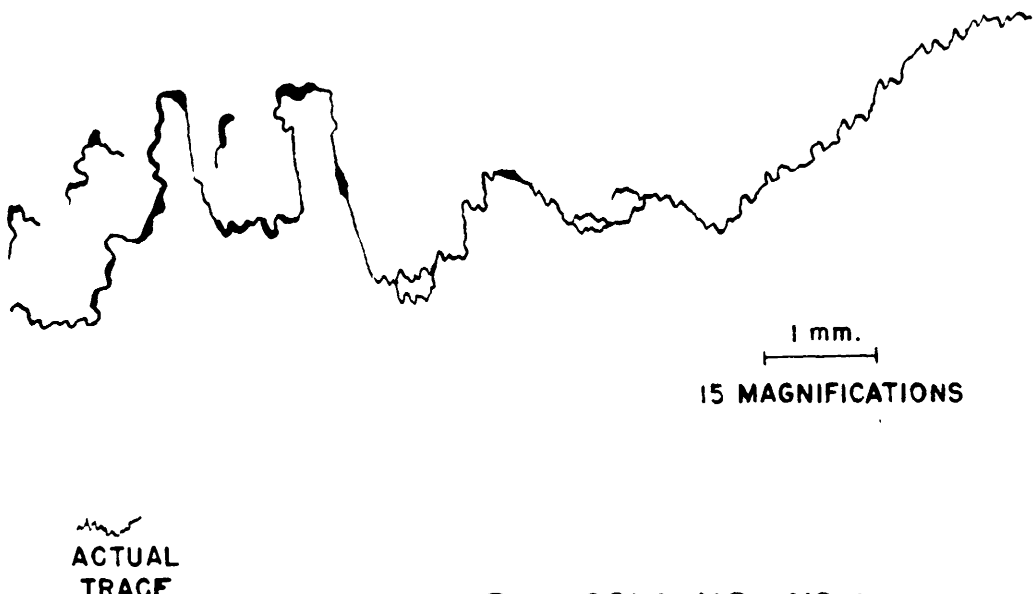
CORE 69

BRYOZOA LYING ALONG A STYLOLITIC ZONE

P. J. COLLINS NO. I CORE 265

FORAM & CRINOID FRAGMENTS IN A COMPLEX STYLOLITIC ZONE

Plate 36.



P.J. COLLINS NO. 1

CORE 14

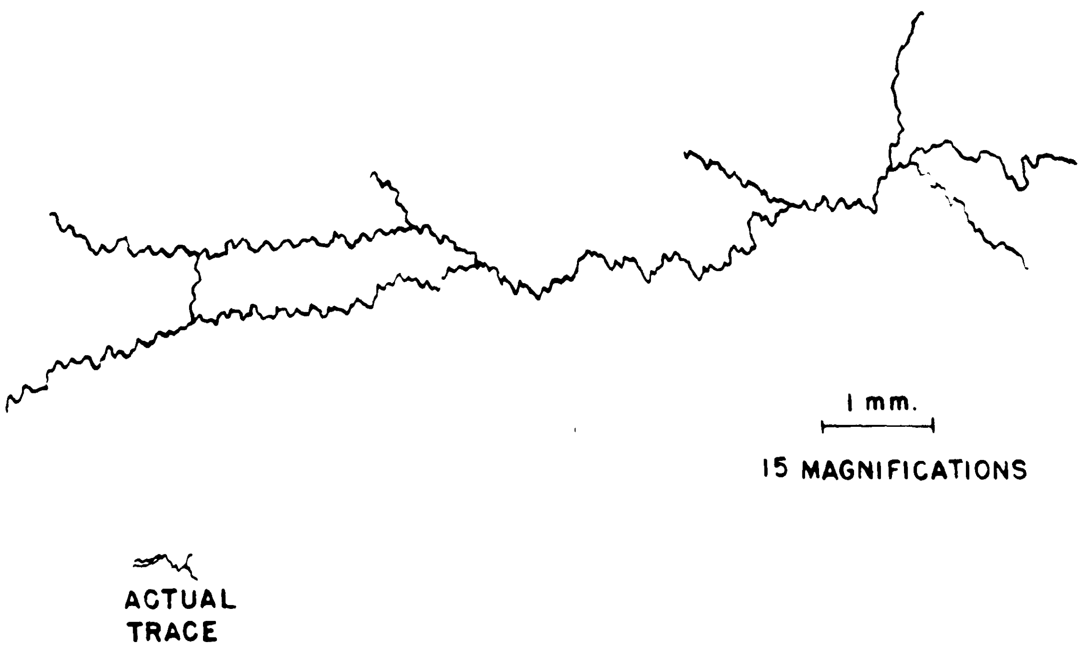


Plate 37.

A.L. WREN NO.2

CORE 92

Plate 38.

pieces have dropped down into solution cavities or have penetrated the limestone opposite the fragment. Generally the two opposing masses fight together rather tightly, but in many cases the openings left after the interfitting were filled with crystalline calcite. The original openings into which these fragments settled are supposed by the author to have formed as a result of normal solution work.

It is to be expected that two limestone masses approaching one another in this way, under pressure, would tend to develop a more or less straight line of contact. As Schaub[15] states, a differential pressure might exist at the start of the process, but the increased solubility at the points of contact should decrease as solution takes place and wider zones come into complete contact. The final result should be a straight or gently waving line of contact. It is of interest to note that 34 of the 40 seams did in fact approximaate a straight line contact.

A study of plates 30-32, 34, 37, 38, and 40 gives the impression that the stylolitic columns are associated with a complex system of fractures. The stylolites shown in plates 31, 33, 34, 37, and 38 are believed to be intimately related to a closely-spaced system of tension fractures. Plate 40 shows a stylolite seam developed along a shear fracture. If this reasoning is correct, there is little doubt that these stylolites formed in hardened rock. Plate 41 shows a stylolite seam that could have formed in hard or soft rock. Since most of the stylolites could have formed only in hardened rock, it seems likely that all did.

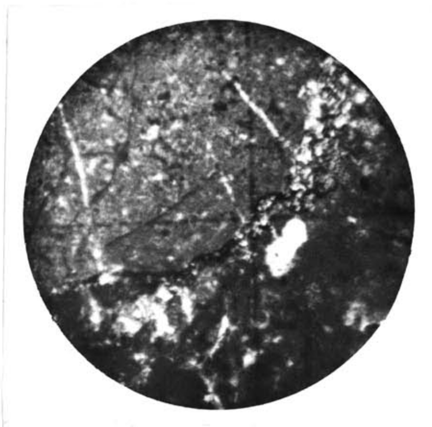


Figure 27.
P.J. Collins #1 Core 14
A thin stylolitic seam at left giving away to a zone of crystalline calcite in upper right. Note evidence of numerous small fractures. 10X.

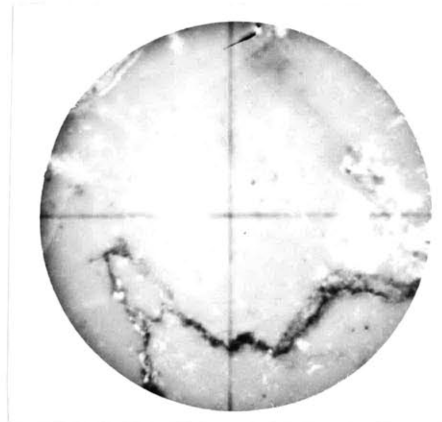


Figure 28.
P.J. Collins #1 Core 14
A stylolitic seam with occasional small masses of calcite along the seam. Rock is an argillaceous limestone. 10X.

Figure 29.
A.L. Wren #2 Core 92
Very complex stylolitic zones with many crossing at 90°. 10X.

Figure 30.
A.L. Wren #2 Core 92
Another view of seam shown in Figure 7. 10X.

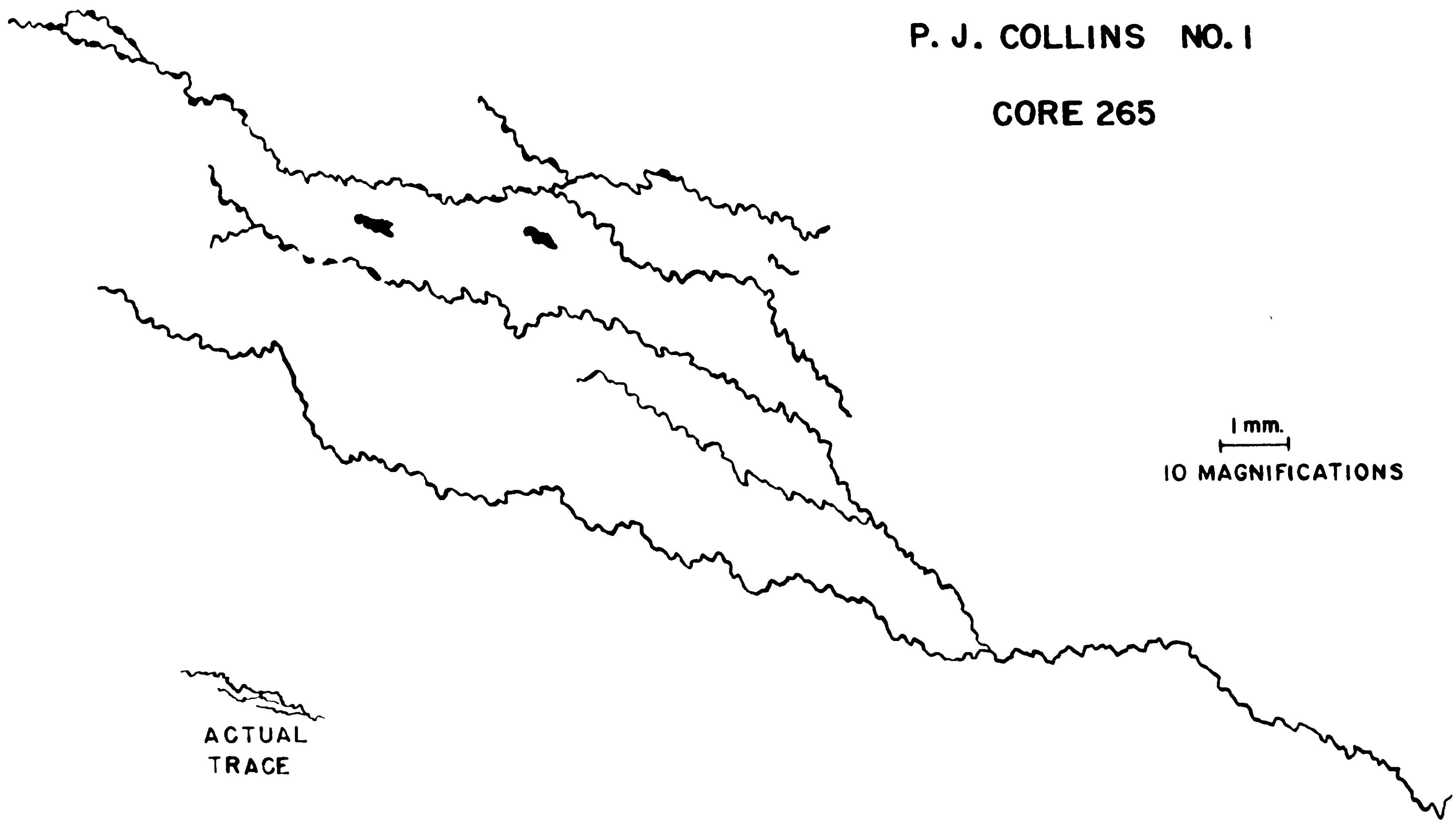
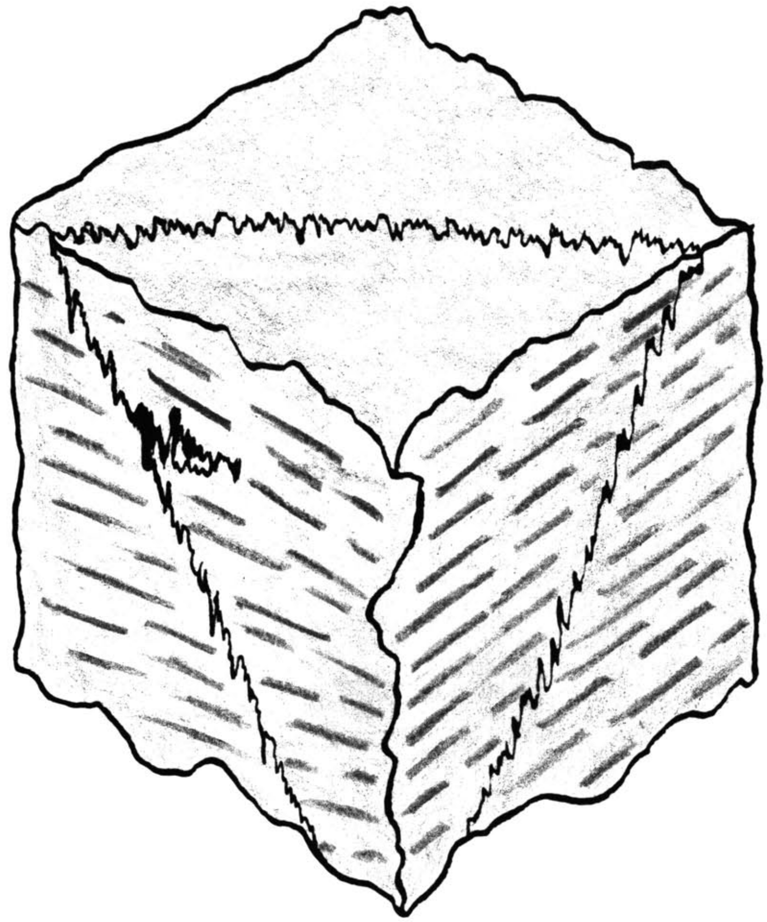


Plate 39.



CORE FRAGMENT SHOWING STYLOLITIC SEAMS DEVELOPED ALONG A FRACTURE PLANE AT 45° TO THE BEDDING. SMALLER SEAM ALONG THE BEDDING. (ON LEFT FRONT FACE FOR SHORT DISTANCE) APPROX. NATURAL SIZE.

P. J. COLLINS NO. I CORE NO. 265

Plate 40.

P. J. COLLINS NO. 1
CORE 69

Plate 41.

The crossing of many stylolites and their frequent bifurcations also suggests that the stylolite seams formed along a complex fracture system. At least part of the material must have been introduced along the seams from a remote area. Whether this material was introduced as a gas, as a liquid, or as a plastic mass is impossible to say. The evidence is clearly against the existence of this material as a solid in the early stages and while it was being transported.

The striations on many of the columns most likely indicate a vertical movement of the column while it was surrounded by a plastic or solid residue that filled the openings around the moving fragment. Although large movements of the columns are possible, a very short movement, perhaps too small to measure, would be sufficient to account for all the striations.

E. The Time of Formation of the Microstylolites

It was not realized at the start of the investigation that several ages of microstylolites would be encountered. That stylolites form at different times and under differing conditions seems to be definitely established by this study. The processes that form stylolites may be continuous or recurrent. Recurring processes seem most likely but definite evidence was not obtained. It may be that several zones can form simultaneously.

Many of the older stylolitic zones are poorly developed; some are represented only by thin wavy zones of clear crystalline calcite. In other cases the stylolite seam starts out as a thin

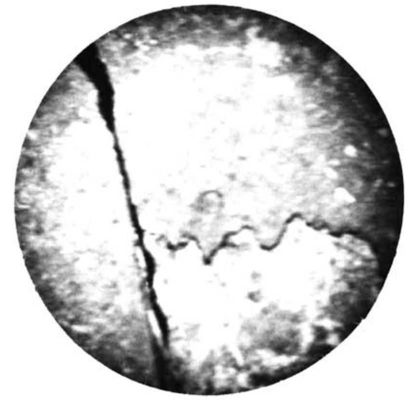


Figure 31.
A.L. Wren #2 Core 178
Two stylolitic zones of slightly different ages meeting at about 80°. 10X.

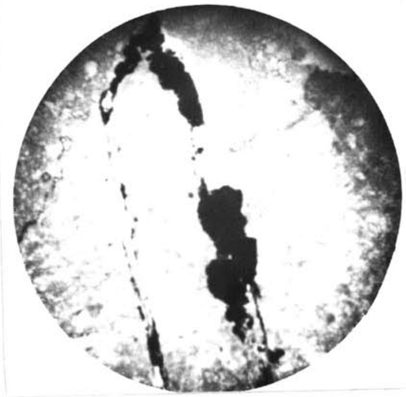


Figure 32.
A.L. Wren #2 Core 178
Top of a long stylolite. Note irregular nature and distribution of black material. 10X.

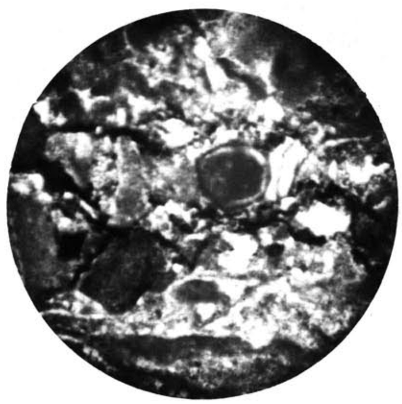


Figure 33.
P.J. Collins #1 Core 265
An irregular, wavy stylolitic seam in a very fragmental limestone. 10X.

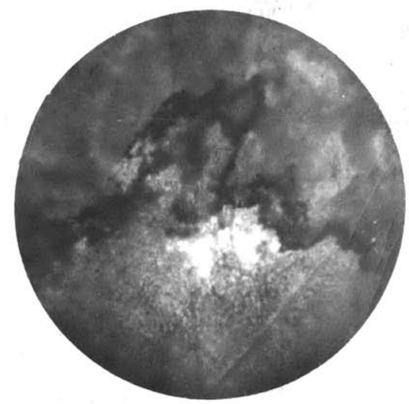


Figure 34.
P.J. Collins #1 Core 165
An old, irregular seam being obliterated. 10X.

wavy black line and passes into a zone of clear crystalline calcite (see figure 27).

Crossing the older zones in many cases are newer and better-developed stylolitic seams. As many as three ages of stylolites can be observed in a single sample. Seemingly there is or may be nearly continuous solution, fracturing, and transfer of material. It is also obvious from the large amount of fracturing and the uniform appearance of the limestones that the capacity for rearrangement and recrystallization is much greater than might be expected. These changes may be completely missed unless a careful thin section study is made.

The most prominent set of stylolites is normally the one that has formed most recently. Stylolite seams being acted upon by circulating ground water are probably subjected to almost continuous change.

The evolution of a given stylolite seam is difficult to describe since so many variations are possible. However, to clarify the authors opinions the following sequence is suggested.

1. Youth – a phase characterized by thin wavy bands with a few and relatively minor serrations; rather clear-cut lines either with or without bifurcations; delicate detail; nearly uniform thickness of bands, usually limited to fractures and lamination planes. See plates 37 and 39.

2. Maturity – a phase characterized by prominent columns with or without striations; bands of great variation in thickness laterally; irregular patches of clear crystalline calcite; rock presents a much fractured appearance; fossils are corroded and may be surrounded by stylolite seams; accummulations of residues on caps and along sides of columns are irregular. See plates 30-32, 34, 37, and 38.

Figure 35.
A.L. Wren #2 Core 152
A sharply serrated stylolitic seam. 10X.

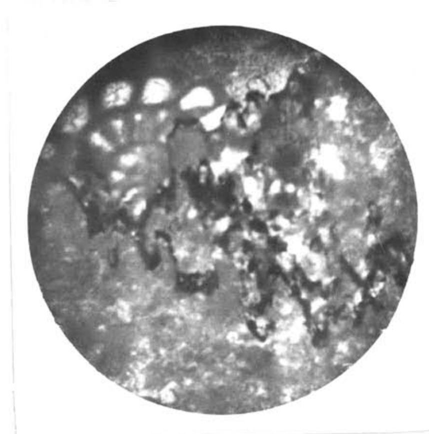


Figure 36.
A.L. Wren #2 Core 152
A corroded fusulinid test bounded by stylolitic seam. Bifurcation of seam. 10X.

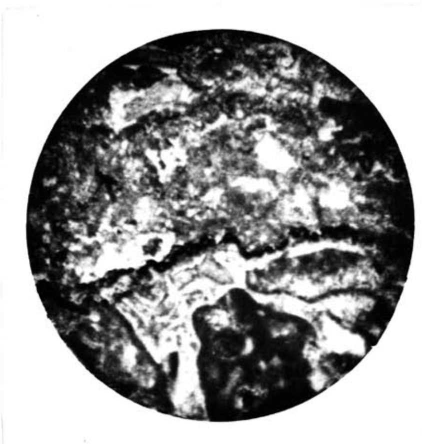


Figure 37.
P.J. Collins #1 Core 265
A thin stylolitic seam with minor serrations. 10X.

Figure 38.
P.J. Collins #1 Core 165
Irregular wavy seam with minor serrations. 10X.

3. Old Age - a phase characterized by smooth wavy lines; thick- of seam laterally may be either uniform or variable; thicknesses tend to be larger than in young zones; zones commonly contain large amounts of clear crystalline calcite in irregular patches; fine detail obscure; zones may be crossed or even obliterated by more recent zones. See plates 32, 33, 34, 36, and 38.

The characteristics shown in the above lists are those visible in thin section or on a polished surface. Not all the characteristics will appear in a given sample. To illustrate the proposed terminology, the following examples are given.

(1) On plate 34 are shown an old age stylolite seam at the base with a young stylolite seam branching off from it. Over this zone is a mature set of stylolites, the columns of which contain youthful stylolites.

(2) On plate 32 is a set of stylolites in late maturity containing three or more sets of youthful stylolites.

The proposed sequence assumes that (1) all steps take place in a consolidated rock, (2) fractures are present or will occur during or after solution, and (3) a transfer of material can take place and material will be introduced to fill openings.

It may be possible to pass from youth to old age without a noticeable mature stage. Such a transformation would occur if no fracturing was present and no fossils were present to complicate the picture.

F. Summary

The remarks made in this discussion apply only to the microstylolites found in the Canyon Reef Formation. It is hoped that the suggestions are applicable elsewhere.

It is believed that a combination of solution and pressure are the most likely causes for the formation of the microstylolites. Special applications of a differential solubility proposed by Stockdale[14] are not believed to be necessary; ordinary solution effects in limestones are considered to be sufficient to explain all the features observed.

Most of the stylolitic seams are gently waving, thin, black bands if viewed in cross section. They are normally parallel to the bedding planes, and the axes of individual cones and columns are perpendicular to the seam or within 10° thereof.

The rocks seem to have been subjected only to a vertical stress caused by simple loading; both tension and shear fractures have been developed. The microstylolites have formed along and are intimately associated with the fractures.

So far as can be ascertained all the microstylolites formed in consolidated rocks. The black material concentrated along the seams is not completely a residue of the surrounding limestones. Petroliferous material and clay have been introduced along the seams into many relatively pure limestones.

The microstylolites have been formed at several times and the process by which they are formed is a continuous or recurrent one in which older zones may disappear and newer ones form.

The nature of the microstylolites is governed by (1)the composition and physical properties of the rocks, (2) nature and amount of introduced material, (3) ground water conditions, (4) the amount and direction of the stresses applied to the rocks.

CHAPTER IX

FRACTURE SYSTEMS IN THE LIMESTONES

1. General Discussion

Fractures are present in 39 (62%) of the 63 cores. The fractures run in several directions, and were probably formed during several periods of fracturing. They are important in the production of oil from the reef, and several zones seem to produce from the fractures alone.

The 39 samples used in the analysis are:

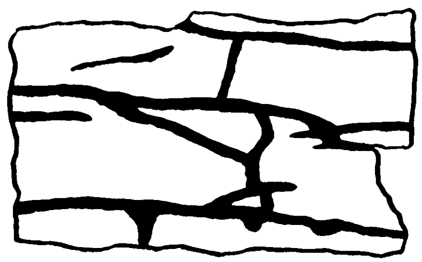
Collins #1	Cores	180, 216, 227, 230, 265, 289, 290, 303, 337.
Wren #2	Cores	49, 50, 64, 70, 88, 92, 98, 101, 102, 103, 118, 127, 141, 149, 152, 153, 178, 179, 188.
Womack #2	Cores	15, 24, 53, 72, 79, 92, 98, 164, 183, 203.

Sketches of the fracture patterns in several of these samples appear in plates 42 to 44.

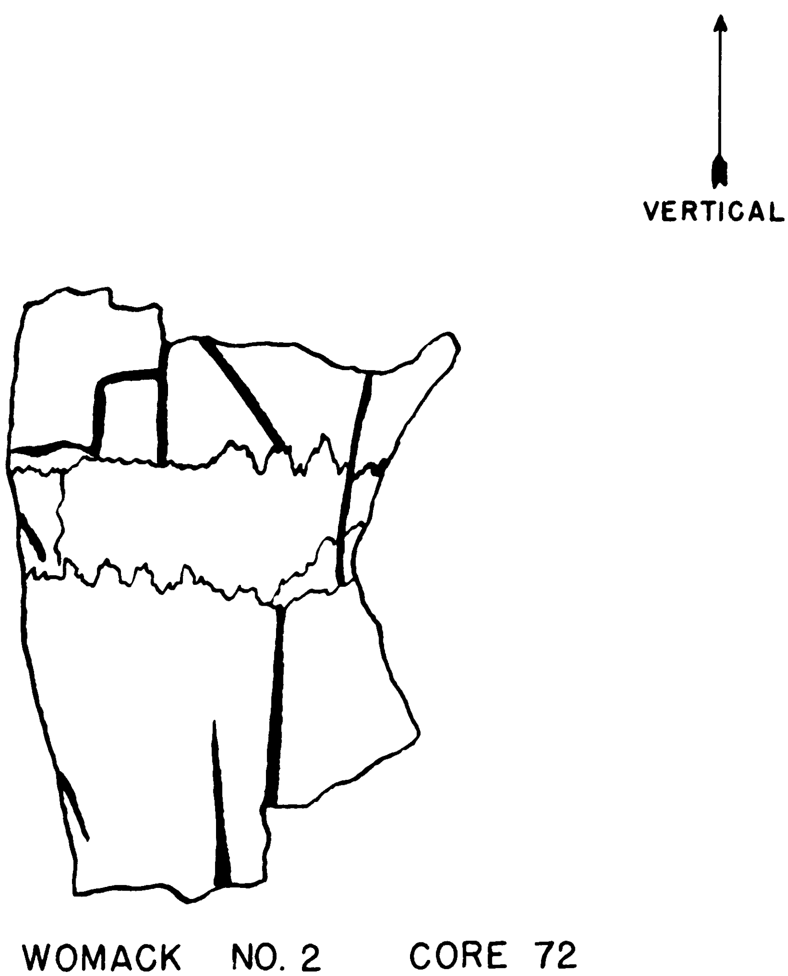
A. Orientation of the Fractures

The borehole is assumed to be vertical, and the orientations given in the following list are with reference to level ground. e.g. a horizontal fracture is one parallel to the normal bedding.

Orientation of Fractures	No. of Samples
Vertical only	14
Oblique (45^o) only	5
Horizontal	3
Multiple	17



M. J. WOMACK NO. 2 CORE 53



M. J. WOMACK NO. 2 CORE 72

FRACTURE PATTERNS

Plate 42.

The tabulation shows that a complex set of fractures is the most common, that vertical fractures are very common, that oblique fractures are somewhat less common, and that horizontal fractures are the least common. It seems likely that the vertical fractures are due to tension and that the oblique fractures are due to shear. The complex fracture systems presumably have a more complicated history.

B. Types of Limestones in which Fractures are Present

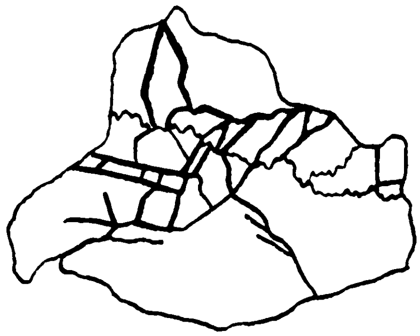
It might be expected that certain types of limestones would be more susceptible to fracturing. The following tabulation shows the results obtained in this study.

Type of Limestone	No. of Samples
Brachiopod limestone	1
Coralline limestone	1
Echinodermal limestone	13
Foraminiferal limestone	5
Mixed echinoderms and foraminifera	12
Low fossil content	5
Algal limestone	2

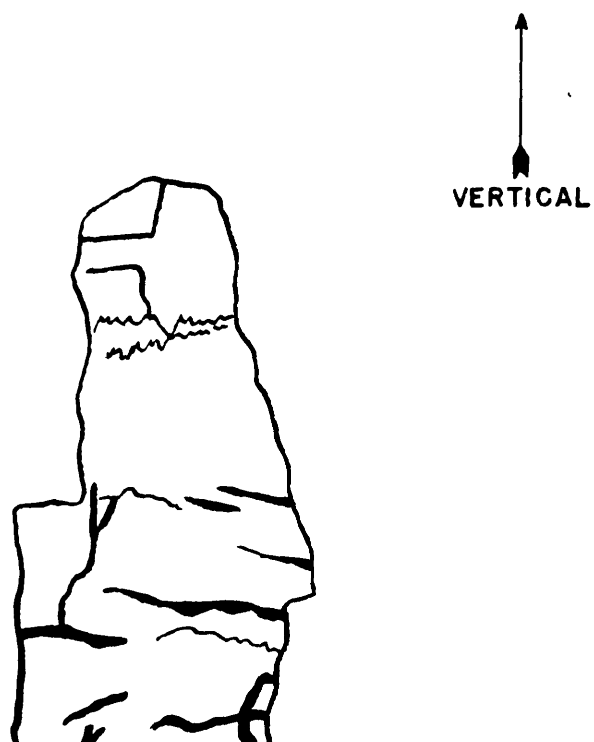
Although there is a wide variation in the values shown in the tabulation, the distribution is roughly the same as the percentage of each type of limestone available for study. Fractures seem to be common in all the types of reef limestones.

C. Types of Fractures Associated with the Various Limestones

The following table shows the distribution of the types



M. J. WOMACK NO. 2   CORE 92



P. J. COLLINS NO. 1   CORE 216

FRACTURE PATTERNS

Plate 43.

of fractures in the various types of limestones.

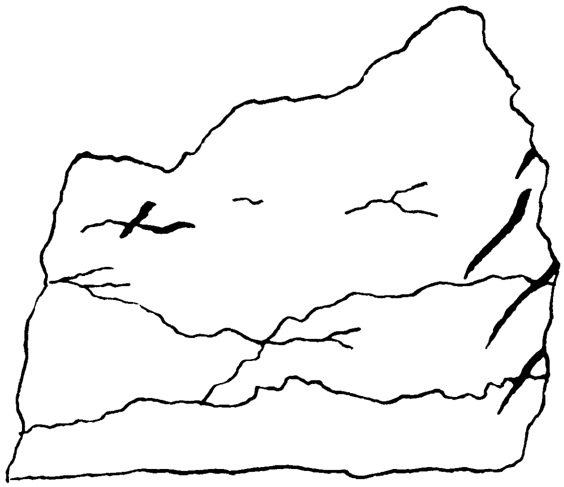
Table IX-1 Types of Fractures vs. Types of Limestones

Type of Limestone	Type of Fractures				
	Vertical	Oblique	Horizontal	Multiple	Totals
Brachiopod	0	0	0	1	1
Coralline	0	0	0	1	1
Echinodermal	6	4	0	3	13
Foraminiferal	2	1	0	2	5
Mixed F&E	6	0	1	5	12
Low Fossil	0	0	1	4	5
Algal	0	0	1	1	2
TOTALS	14	5	3	17	39

D. Cause of the Fractures

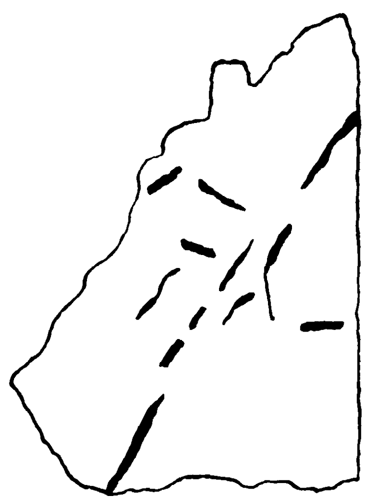
There are two likely causes for the fractures: (1) the load or weight of the overlying sediments, and (2) tectonic movements. Undoubtedly both of these forces have been active. The shear fractures and the large number of tension fractures are probably due to simple loading by the overlying sediments.

There is ample evidence in the stratigraphic section that differential tectonic movements have occurred at several times since the cessation of reef deposition. Since the reef limestones are competent, well-consolidated rocks, it is likely that fracturing occurred when these rocks were subjected to these differential stresses.



M. J. WOMACK NO. 2 CORE 24

VERTICAL



M. J. WOMACK NO. 2 CORE 79

FRACTURE PATTERNS

Plate 44.

2. Influence of the Fractures on Porosity

Fractures that remain open increase the porosity of a rock. Accordingly, it might be expected that the fractured cores would show higher porosities than the unfractured samples.

An examination of the samples shows that the average porosity of the 39 fractured cores is 9.52%, and that the average porosity of all 63 cores is 9.86%. These figures would seem to indicate that there is little difference between the two groups. However, a careful study of the cores shows that the average porosity figure for the fractured samples is misleading. Many of the fractures are filled with calcite, and the samples, in these cases, do not have a true fracture porosity. Moreover, an examination of the reported permeabilities for the fractured samples suggests that the samples selected for core analysis were chosen in such a manner that as many of the fractures as possible were excluded. Therefore, the core analysis data neglect the effects of fractures in many cases.

Table IX-2 shows the distribution of porosity in the fractured samples. Fractures are common in rocks of all porosities.

Table IX-2 Porosity of Fractured Samples

Porosity Range in %	No. of Samples
0.8-2.0	8
2.1-5.0	7
5.1-10.0	1
10.1-15.0	14
15.1-20.0	7
More than 20	2

By analyzing the data with respect to the orientation of the fractures the following results are obtained.

Table IX-3 Types of Fracture in Each Porosity Range

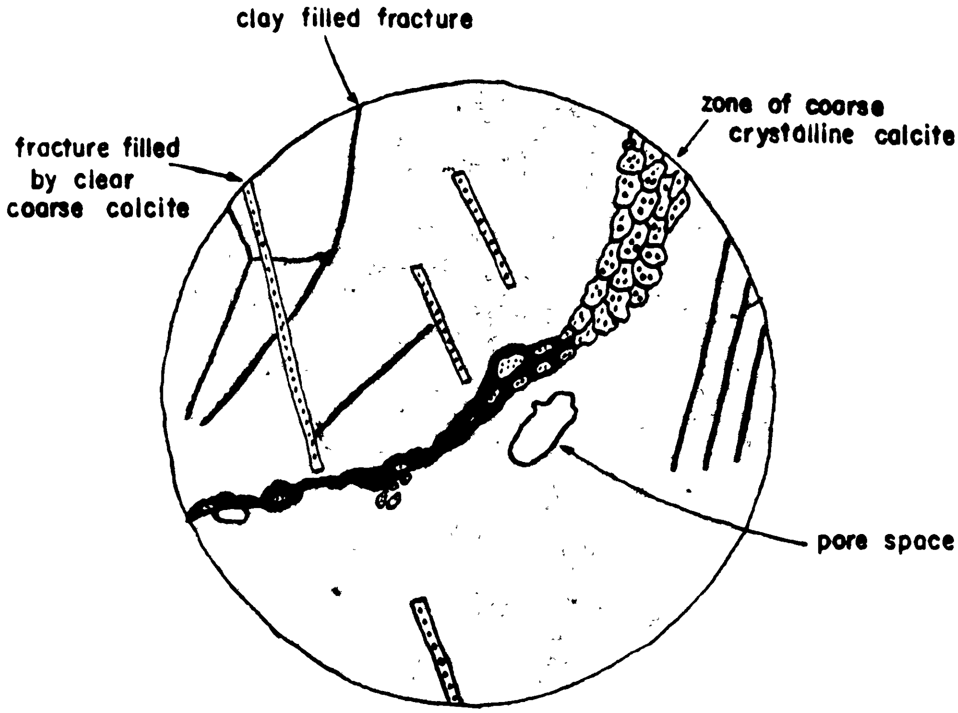
Orientation of Fractures	Porosity Range in %						
	0-2	2-5	5-10	10-15	15-20	Over 20	Totals
Vertical	3	0	0	5	5	1	14
Oblique	0	2	0	3	0	0	5
Multiple	4	4	1	5	2	1	17
Horizontal	1	1	0	1	0	0	3
TOTALS	8	7	1	14	7	2	39

This table indicates that multiple and vertical fractures are about equally common in all porosity ranges. Too few examples of the other types of fractures are available for analysis.

It is interesting to note that shear fractures seldom occur alone in a sample. The type of limestone seems to have no relationship to the frequency with which fractures are encountered.

3. Influence of Fractures on Permeability

Open, connecting fractures increase the permeabilities of all rocks, at least in certain directions. The fracture systems of all cores were compared with the permeabilities reported in the core analysis data in an effort to determine the influence of fractures on permeability. However, examination of the data suggests that many of the samples analyzed were selected in a manner which excluded the effects of the fractures.



P. J. COLLINS NO. 1 CORE 14 15X.

Pore Space

Clear coarsely crystalline Calcite

Fracture filled by light gray Clay

Black Stylolitic Seam

Sequence of Fractures

(1) Thin fractures filled by clay

(2) Fractures filled by calcite

Plate 45.

The average permeability of the 39 fractured cores is 11.3 md. (87% of the average for all 63 cores). The distribution of permeability in the fractured samples is shown in the following tabulation.

Permeability Range in md.	No. of Samples
0	14
0.1-2.0	6
2.1-5.0	4
5.1-10	7
11-20	3
21-50	2
51-100	2
101-200	1

The tabulations shows that permeabilities of all values may be expected in the fractured samples. Since more than 50% of the fractured samples have a reported permeability of less than 2 md., it seems likely that the cores selected for laboratory analysis were often selected in a manner which largely eliminated the effects of the fractures. It would seem that core analysis permeabilities reported for the fractured samples is often of questionable value and may lead to erroneous conclusions as to the suitability of those rocks for oil production.

It is obvious that cores to be used for laboratory analysis must be carefully selected if representative values are to be obtained. A more accurate evaluation can be made if two samples are used for each measurement. One sample should be cut parallel to the direction of fracture and contain at least one fracture; the other should be cut perpendicular to the direction of fracture. The permeability of a horizon can then be evaluated in terms of the orientation and continuity of fracturing. The two permeabilities obtained in this way may differ greatly, and one may be several hundred times as large as the other.

The results of this phase of the investigation must be considered unsatisfactory, and further work on this important problem is needed.

CHAPTER X

INSOLUBLE INORGANIC RESIDUES

Five to ten gram samples of each core were treated with cold, dilute HCl, and the residues were collected on filter paper for examination. Thirty (48%) of the samples contain some insoluble inorganic material. The amount of residue ranges from a trace to an estimated 5%. The 30 samples are divided as follows: 13 from Collins #1, 5 from Wren #2, and 12 from Womack #2. The vertical distribution of residue in each well in shown on plates 48, 49, and 50.

A. Amount of Inorganic Residue

Three samples and their residues were weighed accurately on a chemical balance. The amounts of residue in all other samples were estimated. The percentage of residues found in the samples is shown in the following tabulation.

Amount of Residue (% of rock)	No. of Samples
0	33
0.1-0.9	6
1.0-1.9	6
2.0-2.9	12
3.0-3.9	2
4.0-5.0	4

More than half of the samples contain no inorganic residue and all the samples have less than 5% of residue by weight. The samples are very pure limestones in most cases. Several samples seem to be argillaceous if examined only in hand specimens, but the amounts of residue do not bear out such a classification. The term "argillaceous" applied to a limestone on the basis of inspection in the field seems to be of questionable value in many cases. Fine-grained limy mudrocks commonly appear more or less argillaceous in such samples.

B. Colors of the Residues

The colors of the residues (dry) is as follows:

Color of Residue	No. of Samples
Light gray	7
Gray	7
Dark gray	6
Light brown	1
Gray-brown	4
Dark gray-brown	3
Yellow-white	1
Clear, colorless	1

Gray colored residues are the most common. About 50% of the residues are very dark colored. Most of the residual material is either clay or silt. One sample contains some yellow-white chert, and one contains some clear, colorless, angular quartz.

C. Relationships of Color and Amount of Residue

Table X-1 shows the colors of the residues and the amounts of residues.

Table X-1 Color vs. Amount of Residue

Color of Residue	Amount of Residue (% of rock)				
	0.1-0.9	1.0-1.9	2.0-2.9	3.0-3.9	4.0-5.0
Light gray	2	1	4	0	0
Dark gray	0	0	4	1	1
Gray	1	4	1	1	0
Light brown	0	0	1	0	0
Gray-brown	2	0	0	0	2
Dark gray-brown	0	1	1	0	1
Yellow-white	0	0	1	0	0
Clear	1	0	0	0	0
TOTALS	6	6	12	2	4

The higher percentages of residues seem to be associated with the dark colored residues. There are no clear-cut trends.

D. The Types of Residual Materials

Four types of residues are present: (1) clay, (2) silt, (3) chert, and (4) quartz. Quartz was detected in thin sections of two samples, cores 290 and 303 of Collins #1. Chert was also observed in two thin sections, cores 265 and 290 of Collins #1. Silt is present in 8 samples and clay is found in the residues of 19 samples.

E. Relationships of Color and Types of Residues

The relationships between the color of the residues and the types of residual materials is shown in the following table.

Table X-2 Color vs. Type of Residue

Color of Residue	Type of Residue				
	Clay	Silt	Chert	Quartz	Totals
Light gray	6	1	(1)	(1)	7
Gray	6	1	0	0	7
Dark gray	4	2	0	0	6
Light brown	0	1	0	0	1
Gray-brown	2	2	0	0	4
Dark gray-brown	2	1	0	0	3
Yellow-white	0	0	1	0	1
Clear	0	0	0	1	1
( ) more than one constituent in residue					

Examination of the residues and the thin sections suggest that the chert and quartz have formed in place, and the silt and clay to have been derived from preexisting rock. Since the amounts of clay and silt are small and are evenly disseminated throughout the rock, it seems likely that the source of the clay and silt was rather distant.

F. Relationships of Amount of Residue and Fossil Content of Rocks

Table X-3 shows the relationships between the inorganic residues of the rocks and the faunal content of the samples. An examination of the hand specimens would lead one to the conclusion that the crinoidal limestones have the largest amounts of residues.

Table X-3 Amounts of Residue vs. Faunal Content

Amount of Residue in % of Rock	Faunal Content			
	Hi Foram	Hi Echinoderm	Hi F&E	Low Fossil
0.1-0.9	2	1	2	1
1.0-1.9	0	0	2	3
2.0-2.9	3	1	5	3
3.0-3.9	0	1	0	1
4.0-5.0	0	1	1	2
TOTALS	5	4	10	10

Residues are most common in the limestones with either a low fossil content or with a high echinodermal content. Echinoderms are able to tolerate muddy water that many other forms of life will avoid, and hence are rather common in this group of rocks. The large percentage of sparsely fossiliferous rocks in this group suggests that influxes of mud and silt caused a decrease in the abundance and growth of many reef organisms at certain stages in the development of the reef.

G. Summary

Nearly 50% of the samples contain a small amount of material insoluble in dilute acid. The most common residue is clay, silt is relatively common, and chert and quartz are rare. No dolomite was found in any sample. Gray and brown shades are most common in the residues.

CHAPTER XI

RESIDUAL OIL CONTENT OF THE LIMESTONES

Residual liquid determinations were available for all the samples. This makes it possible to evaluate the oil content of the samples in terms of the other characteristics. The amount of oil in the samples is expressed in terms of the % pore saturation.

It was recognized that the amount of residual oil was dependent on many factors, the chief of which is the porosity of the sample. Caran[16] lists many of these factors and discusses each briefly. Since this study was concerned with the relative amounts of oil in the various samples and not with the absolute amounts, it was felt that those factors could be neglected and correlations made with the lithologic characteristics of the samples.

So that the correlations would be easier to understand a factor C was established which has the following significance:

Factor C equals the % pore saturation of oil x porosity (%)

This factor C was then correlated with the various characteristics of the limestones with the results described in the following pages. Factor C has no absolute significance and cannot be used to estimate the total oil content of the rocks. The upper limits of factor C are fixed both by the largest value of porosity and the greatest saturation of the sample with oil. The factor is useful for showing the relative amounts of oil in the rocks. With suitable modifications, it might be possible to work out a factor that would allow an estimate of the total oil content of the rocks to be made.

A. The Relationships of Factor C and Porosity

Since porosity is one of the multipliers in the determination of Factor C, a reasonably good correlation can be expected. The comparison is, therefore, a test of the uniformity of saturation. The results are shown in the following table.

Table XI-1 Factor C vs. Porosity

Range of Porosity in %	Values of Factor C					
	0	1-100	101-200	201-300	301-400	401-460
0.8-2.0	9	0	0	X	X	X
2.1-5.0	7	3	1	0	0	0
5.1-10.0	1	4	1	0	0	0
10.1-15.0	0	0	9	9	3	1
15.1-20.0	0	0	0	4	5	4
20.1-22.7	0	0	0	0	1	1
TOTALS	17	7	11	13	9	6

In the table X equals an impossible solution. i.e. It is impossible for a sample with a porosity of 2% to have a factor C value of more than 200 because its saturation could not be greater than 100%. To illustrate the manner in which Factor C is computed, a sample with a porosity of 2% and a saturation of 35% pore space has a factor C value of 70. In the above table it would be entered in the block corresponding to a porosity range of 0.8-2.0% and a factor C value of 1-100.

Table XI-1 shows that a good correlation exists between factor C and porosity. Other trends shown in the table are:

1. High porosities are commonly associated with high values of factor C.

2. Limestones with porosities of 5% or less have little or no oil. This indicates that commercial production is unlikely from limestones that have only intergranular or intercrystalline porosity.

3. Limestones with porosities of 5-10% show saturations ranging from 0% to a theoretical maximum of 40% (200/5).

4. Limestones with porosities of 10-15% show saturations ranging from a theoretical minimum of 10% (100/10) to a theoretical maximum of 46% (460/10).

5. Limestones with porosities of 15-20% show saturations ranging from a theoretical minimum of 13% (200/15) to a theoretical maximum of 30% (460/15).

6. Limestones with porosities of 20.1-22.7% show saturations ranging from a theoretical minimum of 15% (300/20) to a theoretical maximum of 23% (460/20).

The increase in minimum values of factor C with increasing porosity shows clearly that oil is present in most samples, and that the amount of saturation is largely a reflection of the porosity of the sample. This suggests a rather uniform saturation for the samples involved. Seemingly, oil is present throughout the reef formation, and the larger amounts of oil are present in the more porous zones. The relationships established in the table do not consider the suitability of these zones for production.

There is a more or less regular decrease in the theoretical maximum saturation. Although this may indicate that the more porous zones are less saturated, it seems more likely that a larger amount of oil escaped from the samples as they were being taken from the well.

B. The Relationships of Factor C and Permeability

If the oil in the rocks has migrated into them, a reasonable correlation can be expected between factor C and permeability. i.e. Rocks with high permeabilities should show higher values of factor C.

Table XI-2 Permeability vs. Factor C

Range of Permeability in md.	Values of factor C					
	0	1-100	101-200	201-300	301-400	401-460
0	17	3	0	0	0	0
0.1-2.0	0	1	0	3	2	2
2.1-5.0	0	1	3	1	3	0
5.1-10	0	1	3	3	0	2
11-20	0	1	3	2	1	0
21-50	0	0	1	2	2	1
51-100	0	0	0	1	1	0
101-200	0	0	1	1	0	0
TOTALS	17	7	11	13	9	6

The table shows that all samples that have no oil also have no reported permeability. In addition, three samples with 0.0 permeability contain small amounts of oil. The data shows that a relatively high oil content may be associated with very low permeabilities. The most permeable samples show only moderate saturations, but oil may have escaped from these cores.

The inferences that can be made from the table are:

1. Much of the oil present in the rocks has been able to migrate at some time, but was not able to get into the more impermeable rocks.

2. The impermeable limestones are not a source of oil unless it has escaped at some former date.

3. At least some of the oil may be original to the rocks in which it is found. Migration of the oil to or from these samples seems unlikely.

C. The Relationships of Factor C and Fossil Content of the Rocks

This subject was investigated to find out the types of rocks in which the oil is concentrated, and to see if any preference is indicated.

(1) The Foraminiferal Limestones

These are the samples that have a high foraminiferal content and contain little or no other fossil debris.

Factor C	No. of Samples
0	1
1-100	2
101-200	3
201-300	0
301-400	2
401-460	2

The tabulation shows that amounts of oil ranging from none to high values are associated with the foraminiferal limestones.

(2) The Echinodermal Limestones

In the rocks in which echinodermal debris is the major constituent, the distribution of values of factor C is:

Factor C	No. of Samples
0	5
1-100	1
101-200	0
201-300	4
301-400	1
401-460	1

In general, less oil is likely to be present in the echinodermal limestones than in the foraminiferal limestones. This is due largely to the fact that echinodermal limestones tend to have lower porosities.

(3) Highly Fossiliferous Limestones with Echinoderms and Foraminifera

Only those limestones which contain both echinoderms and foraminifera in abundance are included in this tabulation.

Factor C	No. of Samples
0	4
1-100	0
101-200	4
201-300	1
301-400	1
401-460	1

Except in rare instances these samples do not seem to contain much oil. However, the porosity and permeability of these rocks is commonly high, and it may be that the oil is able to leak out while the core is being taken.

(4) Limestones containing Bryozoa

Bryozoa are never abundant in any sample but are present in small amounts in about one third of the samples. The distribution of values of factor C for these samples is shown below.

Factor C	No. of Samples
0	6
1-100	6
101-200	1
201-300	3
301-400	2
401-460	0

These limestones seem to have low oil contents, and are not likely to contain appreciable amounts of oil. Low porosities and low permeabilities are typical of these samples.

(5) Limestones containing Brachiopod Debris

Brachiopod debris is not common in most of the samples although it is found in 15 cores. The values of factor C for these samples is shown below.

Factor C	No. of Samples
0	2
1-100	1
101-200	2
201-300	5
301-400	3
401-460	2

The majority of these samples show moderate to good saturations, and seem to contain considerable amounts of oil.

A recapitulation of the effects of fossil content indicates that the highest values of factor C are most consistently met in the foraminiferal limestones, the limestones which are mixtures of foraminifera and echinoderms, and the limestones that contain brachiopod debris. In part, this is due to the higher porosities of these samples. The lowest values of factor C are most consistently met in the echinodermal limestones and those containing bryozoa.

D. The Relationships of Factor C and Color of the Rocks

It would be advantageous to be able to determine the amount oil content of a sample visually. Color of the sample is readily detectable, and could be a useful indication if a satisfactory correlation could be found.

The results of such a correlation are shown in table XI-3. The highest values of factor C are all associated with the light colored rocks, whether light brown or light gray. The limestones with brownish or buff colors have higher oil contents than those with gray colors. The most desirable color seems to be buff, and the poorest color is dark gray.

An examination of plates 25, 26, 27 and the chart on page 88 indicates that, on the basis of color alone, some 92% of the rocks are potential producing horizons. If the rocks with dense matrices are eliminated from the listings, approximately 34% of the rocks can be considered as potential producing horizons.

Table XI-3 Factor C vs. Color of the Rocks

Color of the Samples	Values of Factor C					
	0	1-100	101-200	201-300	301-400	401-460
Buff	2	0	1	2	3	4
Buff-brown	1	2	2	2	3	1
Brownish	0	0	2	1	1	0
Lt brown-gray	6	2	1	4	2	0
Dk brown gray	2	0	0	0	0	0
Light gray	3	3	5	4	0	1
Dark gray	3	0	0	0	0	0
TOTALS	17	7	11	13	9	6

E. Verification of Oil Content Estimated from Insoluble Residues

During the study of the samples, small pieces of core were treated with cold dilute HCl. Although the object was the determination of inorganic insoluble residues, it was found that oil is commonly present in the residues. The amount of this oil was estimated using the following scale: (1) None, (2) trace, (3) slight, (4) moderate, and (5) considerable. The terms are relative and give no indication of the true oil content.

In the 63 samples, 17 have no oil in the residues, 10 have a trace, 16 have slight amounts, 16 have moderate amounts, and 4 have considerable oil. A verification of these estimates with factor C as computed from the core analysis data appears in table XI-4. Except in a very general way, the verification is not satisfactory; the reason for this discrepancy is unknown.

Table XI-4 Factor C vs. Estimated Oil Content

Estimated Oil Content	Values of Factor C					
	0	1-100	101-200	201-300	301-400	401-460
None	10	3	1	2	1	0
Trace	2	2	3	3	0	0
Slight	3	1	1	6	3	2
Moderate	1	1	3	2	5	4
Considerable	1	0	3	0	0	0
TOTALS	17	7	11	13	9	6

If the median values of factor C are used for correlation, the results are somewhat better. The median value of factor C for the samples estimated to contain no oil is 0; the median value of C for samples with an estimated trace is 190; the median value of C for the samples estimated to contain slight amounts is 290; and the median value of C for samples estimated to contain moderate amounts is 360. The values have a very large spread, and little significance can be attached to the median values when dealing with a given sample. The data for the samples estimated to contain considerable oil shows a very poor correlation.

F. Summary

Briefly, the results of this investigation show that:

1. The oil content is largely dependent on the porosity of the samples. Oil is common throughout the reef section, and saturation of the oil-bearing samples is fairly uniform.

2. Estimation of oil content from oil collected in the insoluble residues is not satisfactory except in a generalized way; no reason for this lack of correlation is apparent.

3. The oil content of the samples does not correlate readily with the permeabilities suggesting:
    a. At least some of the oil is original to the rocks in which it occurs.
    b. If migration of oil has occurred, the permeability of some of the samples has changed since the migration.
    c. Considerable migration of oil may have occurred from the more permeable rocks to the less permeable ones.

4. The higher oil contents are associated with the foraminiferal limestones, and the limestones containing brachiopod debris; the lower oil contents are associated with the echinodermal limestones and those containing bryozoa.

5. Light colored rocks have higher oil contents than the dark colored rocks; brownish rocks are likely to contain more oil than gray rocks.

6. The results of this study apply only to <u>residual</u> oil content and do not necessarily have any direct relationship to production possibilities. The investigation shows where the oil is, not whether it can be produced.

CHAPTER XII

ELECTRIC LOGS, MICROLOGS, AND RADIOACTIVITY LOGS

1. Electric Logs of the Reef Limestones

Electric logs are available for all three wells. The spontaneous potential curves and resistivity curves for the reef section of each well are shown on plate 46.

A. Theoretical Interpretation of Electric Logs

Electric logs normally consist of an SP curve and two or more resistivity curves. The SP curve is used chiefly to distinguish between permeable and non-permeable zones; however, a quantitative relationship between permeability and the SP curve does not exist. In some fields an empirical relationship between the two has been established for certain formations.

The characteristics of the SP log, particularly the amplitude of the anomalies, are functions of factors such as the salinity of the formation fluids and the drilling mud, the resistivity of the formation, and bed thickness. The following are typical of most SP logs:

1. The SP anomaly associated with fresh-water bearing formations is usually small.
2. The SP anomaly associated with salt-water bearing formations is generally large and negative with respect to surrounding formation.
3. Changes in SP are normally associated with changes in the physical properties of the formations.
4. High negative values of the SP curve are typical of permeable zones; low values are characteristic of non-permeable zones.

Rock formations are capable of transmitting an electric current because they contain adsorbed water. The higher the salinity of this water, the greater the conductivity and the lower the resistivity. If the rocks are saturated with fluids, the fluids may also transmit currents.

In electric logging, the resistivity between two electrodes is measured. The values obtained by normal logging methods are not the truw resistivities but are apparent resistivities. The "apparent" resistivity of a rock formation varies as a function of (1) bed thickness, (2) electrode spacing, (3) diameter of the bore hole, (4) resistivity of the drilling mud, and (5) the nature of the formation. Two or more resistivity curves, made with different electrode spacings, are generally recorded in order to minimize the effects of some of the variables, and to aid in the interpretation of others. Plate 46 shows only one of the resistivity curves for each well since the others are similar.

The chief uses of electric logs are:

1. For detailed correlation of beds, and for general stratigraphic investigations.
2. To distinguish between permeable and non-permeable beds.
3. To locate exact depths to all horizons.
4. To determine thicknesses of formations and zones.
5. To determine the fluid content of permeable zones.

B. Electric Log for P.J. Collins #1 (see plate 46)

The top of the reef formation is clearly indicated. Since the reef limestones are directly overlain by shales, there is a sharp break in the electric log trace due to the great difference

TRACE OF ELECTRIC LOGS

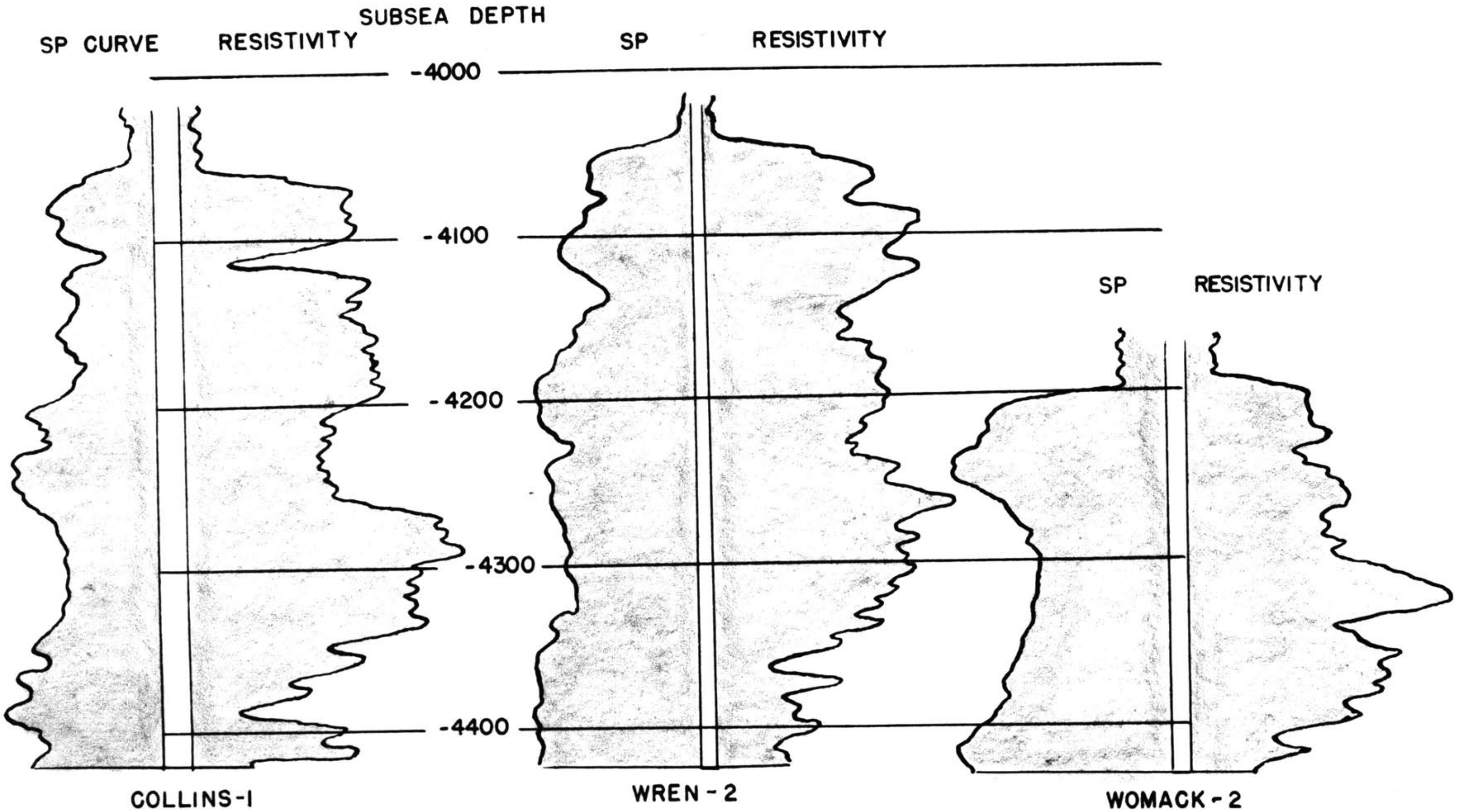


Plate 46.

in resistivities of the rocks involved. The SP curve shows that the entire limestone section is more or less permeable and contains conducting fluids. The SP curve shows a slight drift to the left (negative) as one goes down the hole. This drift may be the result of an increase in the salinity of the formation water with increasing depth. Anomalies on the log are moderately sharp which indicates that there are likely to be major changes in the characteristics of the rocks.

The resistivity curves seem to be most strongly affected by (1) the formation resistivity, and (2) the presence or absence of liquids in the various zones. The thicknesses of the beds are not well-delineated by the 10" AM spacing of the electrodes, and, therefore, it is reasonable to assume that some of the individual beds are less than 5 feet thick.

C. Electric Logs of the Other Wells

Remarks made about the Collins #1 well are applicable to the two other wells and need not be repeated. It should be noted that there is poor correlation between individual horizons in the three wells except for the top surface of the reef.

D. Summary

The SP and resistivity curves of the wells indicate that:

1. The formation is composed entirely of limestones.

2. There may be an increase in the salinity of the formation water with increasing depth.

3. The limestone section generally has good porosity and permeability; the rocks appear to be well saturated with fluids.

4. Many of the beds are less than 5 feet thick.

5. Lateral correlation of the various horizons within the reef is not possible by means of normal electric logs.

6. The top surface of the reef is easily located on all the logs.

2. Micrologs of the Limestones

Micrologs are also available for all three wells. Micrologging is a rather new method of electric logging[17] which measures the electrical characteristics of a very small volume of material near the wall of the borehole. The method provides a very detailed record of the formation, especially the permeable sections. This new system is extremely useful in limestone formations in which the SP curves commonly lack sharp breaks.

The chief virtue of the log is its sensitivity; individual beds of the order of 5-10 feet in thickness are often detectable, and the tops and bottoms of beds may be located with great accuracy. Under some conditions the porosity of the zone can be calculated with fair to good results.

Two resistivity curves are indicated on the normal Microlog. Permeable zones are indicated by a positive separation of the two curves. The curves are very similar and show the same breaks. Plate 47 shows one of the resistivity curves for each of the three wells. The sharp breaks in the resistivity trace make the determination of the tops and bottoms of zones rather simple.

A. P.J. Collins #1

Examination of the Microlog trace allows one to delineate 23 separate zones, some as thin as 4 ft. This compares with the 13

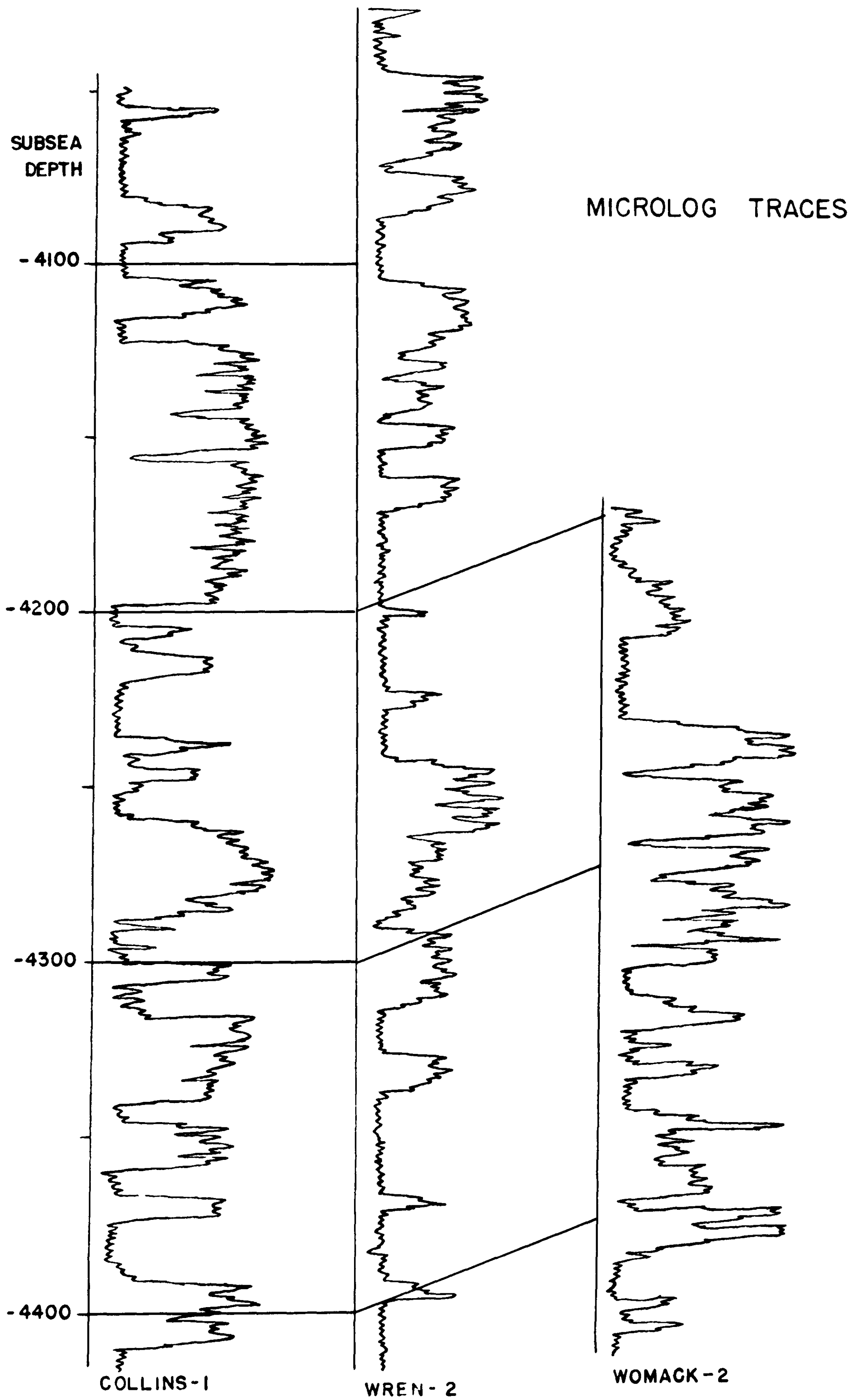

MICROLOG TRACES
SUBSEA DEPTH
-4100
-4200
-4300
-4400
COLLINS-1
WREN-2
WOMACK-2

Plate 47.

zones detected on the normal electric log. Correlations of the Microlog resistivity and the various characteristics of the samples are shown on plate 48.

B. A.L. Wren #2

This well may be divided into 24 zones which compare with 19 zones selected on the normal electric log. Correlation of Microlog resistivity and the characteristics of the limestones appear in plate 49.

C. M.J. Womack #2

The well can be divided into 25 zones on the Microlog, and 11 zones on the normal electric log. A correlation of the Microlog resistivity and the characteristics of the limestones is shown on plate 50.

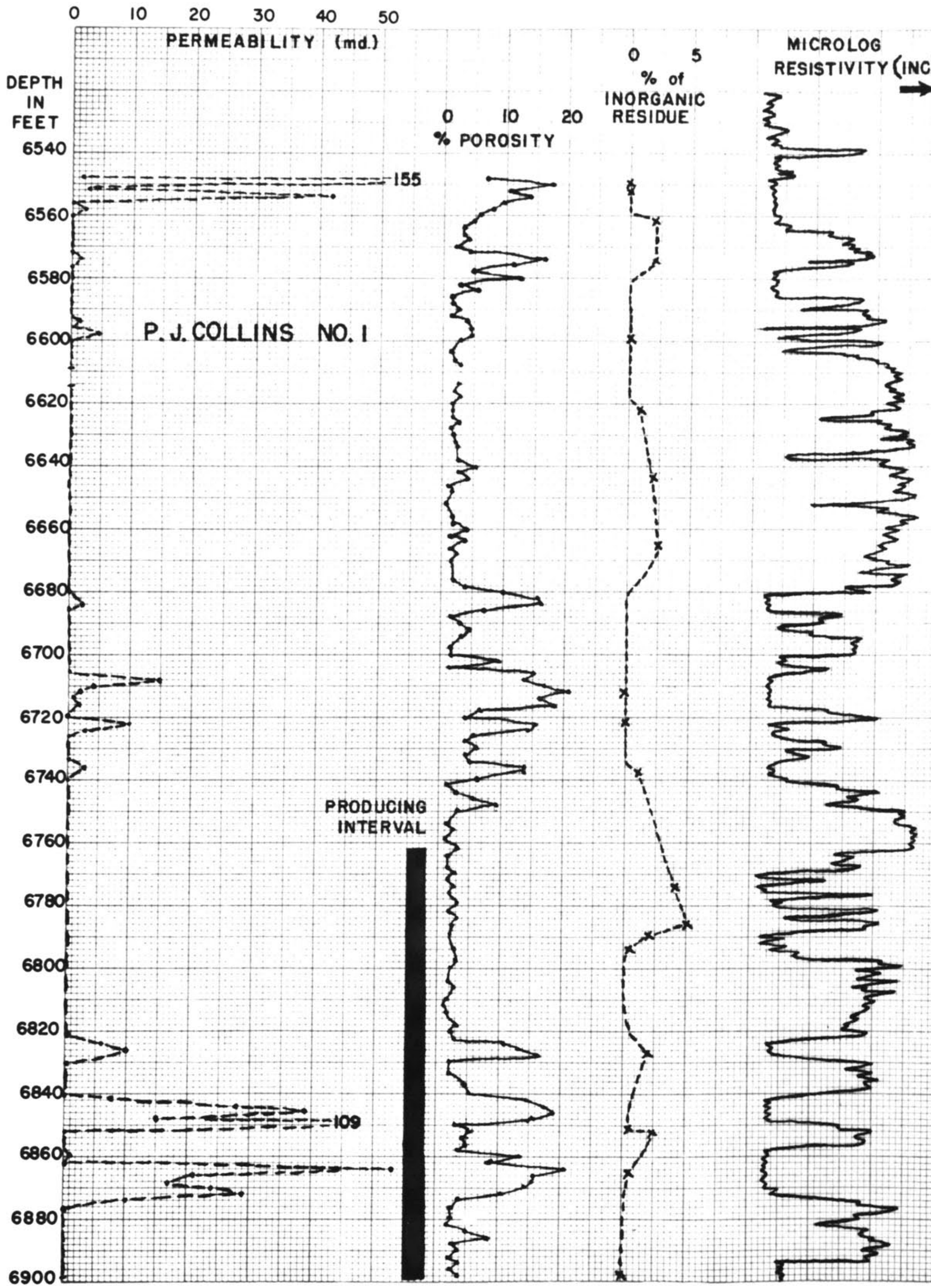
D. Summary

Permeable zones are indicated with great accuracy on the Microlog. This permits a detailed zoning of the formation. Plate 47 indicates clearly that correlation laterally of individual horizons is not possible, even with such a detailed log. It may be inferred from this lack of correlation that there are major facies changes occurring within short distances.

3. Correlations between Microlog Resistivity and Lithologic Characteristics of the Samples

A. Introduction

One of the major problems encountered in any oil field is



PERMEABILITY (md.)
0 10 20 30 40 50
DEPTH IN FEET
6540
6560
6580
6600
6620
6640
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
6900
155
109
P. J. COLLINS NO. 1
PRODUCING INTERVAL
0 10 20
% POROSITY
0 5
% of INORGANIC RESIDUE
MICROLOG RESISTIVITY (INC.)

Plate 48.

the interpretation of the electric logs. In most fields this can be done fairly easily by correlating several electric logs with samples obtained during drilling of the wells, and then by comparing the logs with one another. In general, a simple stratigraphy with distinctive lithologic changes makes interpretation easier.

In limestone fields the problem is complicated because the samples are usually so similar that individual horizons are difficult to identify by means of the normal well cuttings. If the individual beds have a small lateral extent, as they commonly do in reef fields, correlation is even more difficult. In such fields the horizons cannot be traced from well to well by means of the electric logs, and the interpretation of each electric log becomes an individual problem. Since it is not economically feasible to core each well in a field, clues to the nature of the rocks that can be obtained from the logs become of extreme importance.

The breaks on the Microlog are sharp and easy to recognize, and the lithologic characteristics of the limestones have been correlated with the resistivity curves of the Micrologs. (See plates 48, 49, and 50).

Since the chief interest in this section is the existence of any correlations between the lithologic characteristics of the limestones and Microlog resistivity, the fundemental concepts of the significance of the resistivity trace will not be discussed. For further information the reader is referred to the article by Doll[17] which deals with the Microlog and its uses.

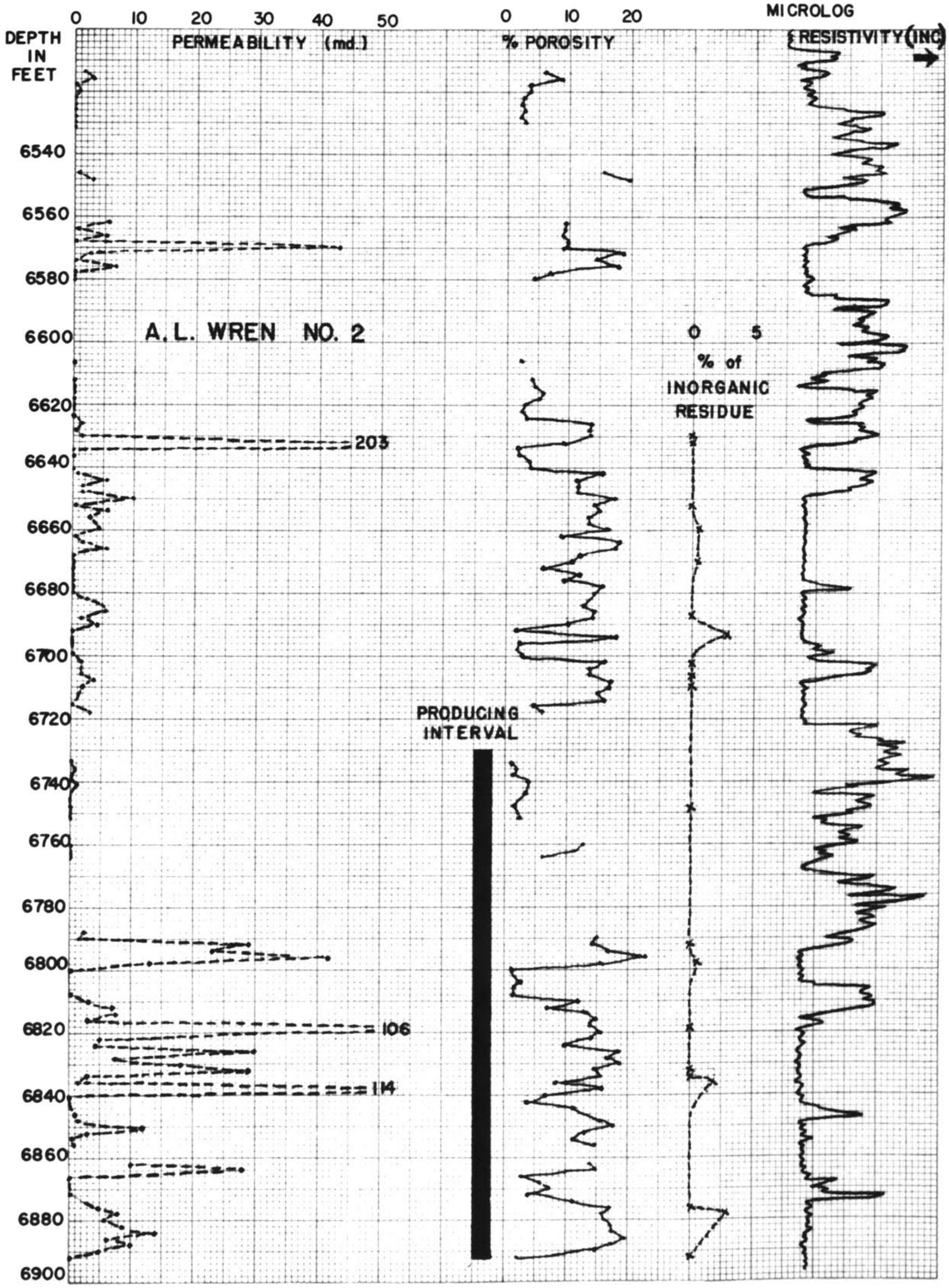

DEPTH IN FEET
0
10
20
30
40
50
PERMEABILITY (md.)
0
10
20
% POROSITY
MICROLOG
RESISTIVITY (INC)
6540
6560
6580
6600
A. L. WREN NO. 2
0
5
% of INORGANIC RESIDUE
6620
203
6640
6660
6680
6700
6720
PRODUCING INTERVAL
6740
6760
6780
6800
6820
106
6840
114
6860
6880
6900

Plate 49.

B. Porosity

Using the core analysis data for the three wells, tabulations can be made which shows the relationship between porosity and resistivity. In the following tabulations only those zones which have clearcut resistivity trends and for which core analysis data are available are analyzed.

1. Collins #1

No. of ft. analyzed	266	
No. of ft. with low resistivity		64
With porosity under 10%		16
With porosity over 10%		48
No. of ft. with high resistivity		202
With porosity under 10%		196
With porosity over 10%		6

2. Wren #2

No. of ft. analyzed	205	
No. of ft. with low resistivity		147
With porosity under 10%		30
With porosity over 10%		117
No. of ft. with high resistivity		58
With porosity under 10%		24
With porosity over 10%		34

3. M.J. Womack #2

No. of ft. analyzed	138	
No. of ft. with low resistivity		60
With porosity under 10%		40
With porosity over 10%		20
No. of ft. with high resistivity		78
With porosity under 10%		74
With porosity over 10%		4

The following tabulation shows the totals for all three wells.

4. Totals for the three wells

No. of ft. analyzed	609
No. of ft. with low resistivity	271
With porosity under 10%	86
With porosity over 10%	185
No. of ft. with high resistivity	338
With porosity under 10%	294
With porosity over 10%	44

The final tabulation shows the relationships in percentage of the footages involved.

5. Tabulation by percentages

Percentage of the Total Footage Analyzed

	Collins	Wren	Womack	Average
A. Low Resistivity	24%	72%	43%	45%
1. Porosity under 10%	25	26	67	32
2. Porosity over 10%	75	74	33	68
B. High Resistivity	76%	28%	57%	55%
1. Porosity under 10%	97	41	95	86.5
2. Porosity over 10%	3	59	5	13.5

Tabulations 4 and 5 show that low resistivity is most apt to be associated with porosities higher than 10%, and that high resistivity is most likely to be associated with porosities of less than 10%. It seems that high resistivity is a more reliable indicator than low resistivity; 68% of the footage with low resistivity have porosities higher than 10%, but 87% of the footage with high resistivity have porosities less than 10%. Unexplained by such simple tabulations is the deviation of Womack #2 from the other wells in the case of low resistivity and the deviation of Wren #2 from the

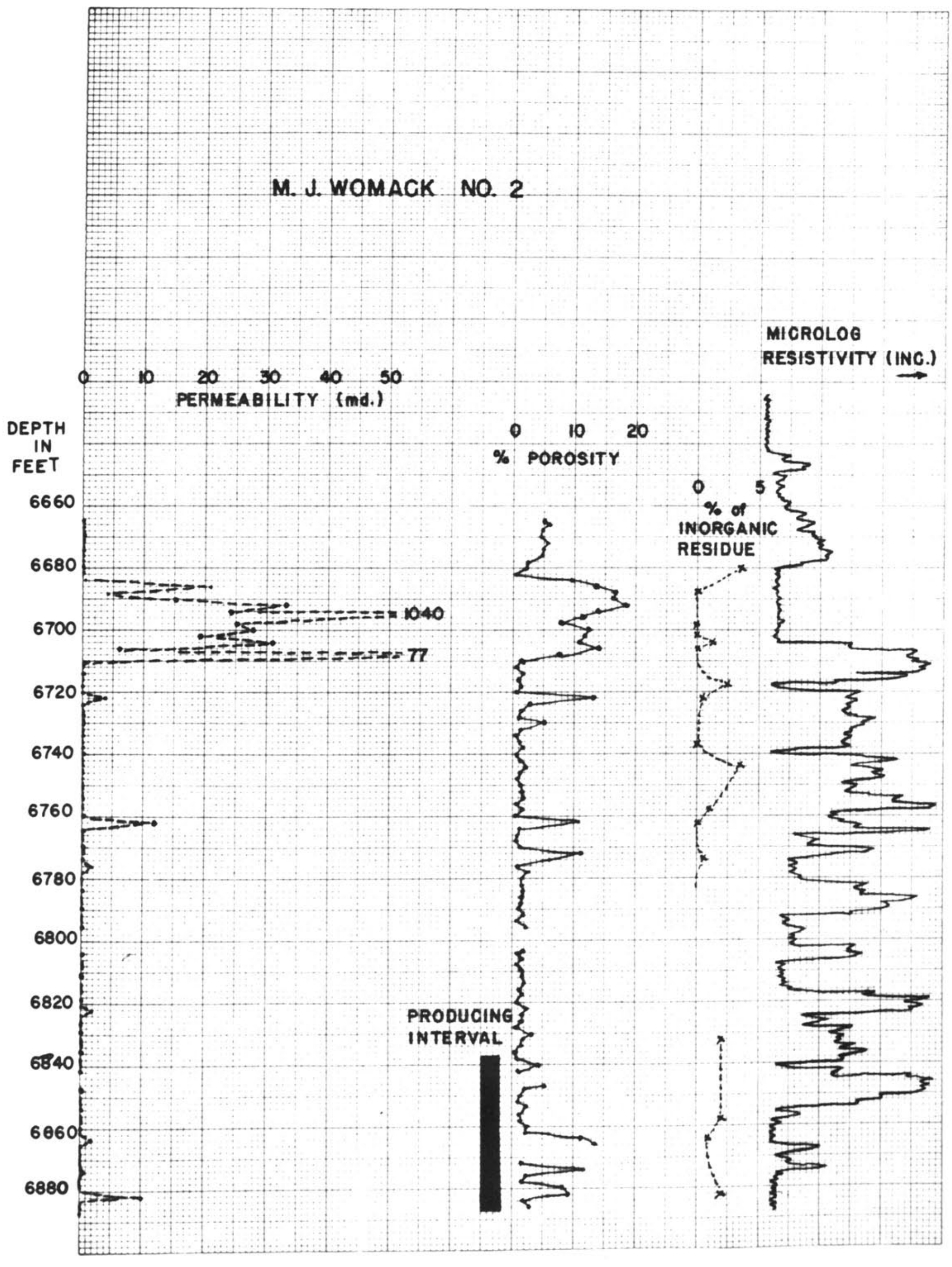

M. J. WOMACK NO. 2
0 10 20 30 40 50
PERMEABILITY (md.)
DEPTH IN FEET
6660
6680
6700
6720
6740
6760
6780
6800
6820
6840
6860
6880
1040
77
0 10 20
% POROSITY
PRODUCING INTERVAL
0 5
% of INORGANIC RESIDUE
MICROLOG RESISTIVITY (INC.)

Plate 50.

other wells in the case of high resistivity.

C. Permeability

Since a basic use of the Micrologs is the determination of permeable zones, a good correlation should be expected. The following analysis was made on the available samples and data.

1. Collins #1

No. of ft. analyzed	266
No. of ft. with low resistivity	64
Permeability less than 2 md.	18
Permeability more than 2 md.	46
No. of ft. with high resistivity	202
Permeability less than 2 md.	196
Permeability more than 2 md.	6

2. Wren #2

No. of ft. analyzed	205
No. of ft. with low resistivity	147
Permeability less than 2 md.	34
Permeability more than 2 md.	113
No. of ft. with high resistivity	58
Permeability less than 2 md.	30
Permeability more than 2 md.	28

3. Womack #2

No. of ft. analyzed	138
No. of ft. with low resistivity	60
Permeability less than 2 md.	26
Permeability more than 2 md.	34
No. of ft. with high resistivity	78
Permeability less than 2 md.	68
Permeability more than 2 md.	10

The following tabulation shows the totals for all three wells.

4. Totals of all three wells

No. of ft. analyzed	609
No. of ft. with low resistivity	271
Permeability less than 2 md.	86
Permeability more than 2 md.	185
No. of ft. with high resistivity	338
Permeability less than 2 md.	294
Permeability more than 2 md.	44

The final tabulations shows the data of tabulation 4 in percentages of the total footage.

5. Tabulation by Percentages

	Percentage of Total Footage Analyzed			
	Collins	Wren	Womack	Average
A. Low Resistivity	24%	72%	43%	45%
1. Permeability less than 2 md.	28	30	47	32
2. Permeability over 2 md.	72	70	53	68
B. High Resistivity	76%	28%	57%	55%
1. Permeability less than 2 md.	97	52	87	86.5
2. Permeability over 2 md.	3	48	13	13.5

The tabulations all show distributions similar to those shown in the analysis of porosity. Low resistivity is most likely to be associated with zones that are permeable, and high resistivity is most likely to be associated with zones having little or no permeability. It should be mentioned that the permeabilities are those reported in the core analysis data, and that doubt has been cast on their accuracy in some instances.

Unexplained by the tabulations is the deviation of Womack #2 from the other two wells in the case of low resistivities, and the deviation of Wren #2 from the other wells in the case of high resistivities.

D. Combinations of Porosity and Permeability

Since there seems to be a close relationship between porosity and permeability in their effects on the Microlog trace, the following tabulations were made to investigate the relationships.

(1) Footage with Low Resistivity 271 ft.

	Footage in each range				Percentage of Total Footage
	Collins	Wren	Womack	Total	
a. Non-permeable low porosity	16	14	30	60	22%
b. Non-permeable high porosity	2	24	0	26	9.6
c. Permeable-low porosity	0	28	6	34	12.5
d. Permeable-high porosity	40	87	26	153	56

(2) Footage with High Resistivity 338 ft.

	Footage in each range				Percentage of Total Footage
	Collins	Wren	Womack	Total	
a. Non-permeable low porosity	196	20	68	284	86%
b. Non-permeable high porosity	0	10	0	10	3.5
c. Permeable-low porosity	2	4	4	10	3.5
d. Permeable-high porosity	4	16	4	24	7

The tabulations show that low resistivity is most common in the samples that are permeable and have high porosity. High resistivity is most common in those samples which have low porosity and very low permeabilities. These results are in accord with the theoretical interpretations.

It should be pointed out that, in those samples which are shown to have low resistivities by the Microlog, 44% of the samples would normally be considered unsatisfactory for the production of oil by virtue of either low porosities or low permeabilities. A zone of low resistivity on the Microlog is not always a good reservoir horizon. However, it should also be remembered that the core analysis data seem to be unreliable in some instances, especially in zones that are fractured.

In the samples with high resistivities only 7% of the footage can be considered as having possible production.

E. Insoluble Residues

Since insoluble residues were obtained for every sample, the effects of clay and silt on the Microlog trace can be evaluated.

	Footage in each range				Percentage of Total Footage
	Collins	Wren	Womack	Total	
A. Low Resistivity	44	107	52	203	44%
1. No residue	22	20	0	42	9
2. Slight residue	12	52	30	94	20
3. Considerable	10	35	22	67	14
B. High Resistivity	184	22	58	264	56%
1. No residue	26	22	0	48	10
2. Slight residue	40	0	32	72	15
3. Considerable	118	0	26	144	31

Some of the intervals used in the tabulations in parts B, C, and D are not represented by actual core samples, and, therefore, only 467 feet of section were used for the tabulation instead of the 609 feet used in the preceding paragraphs.

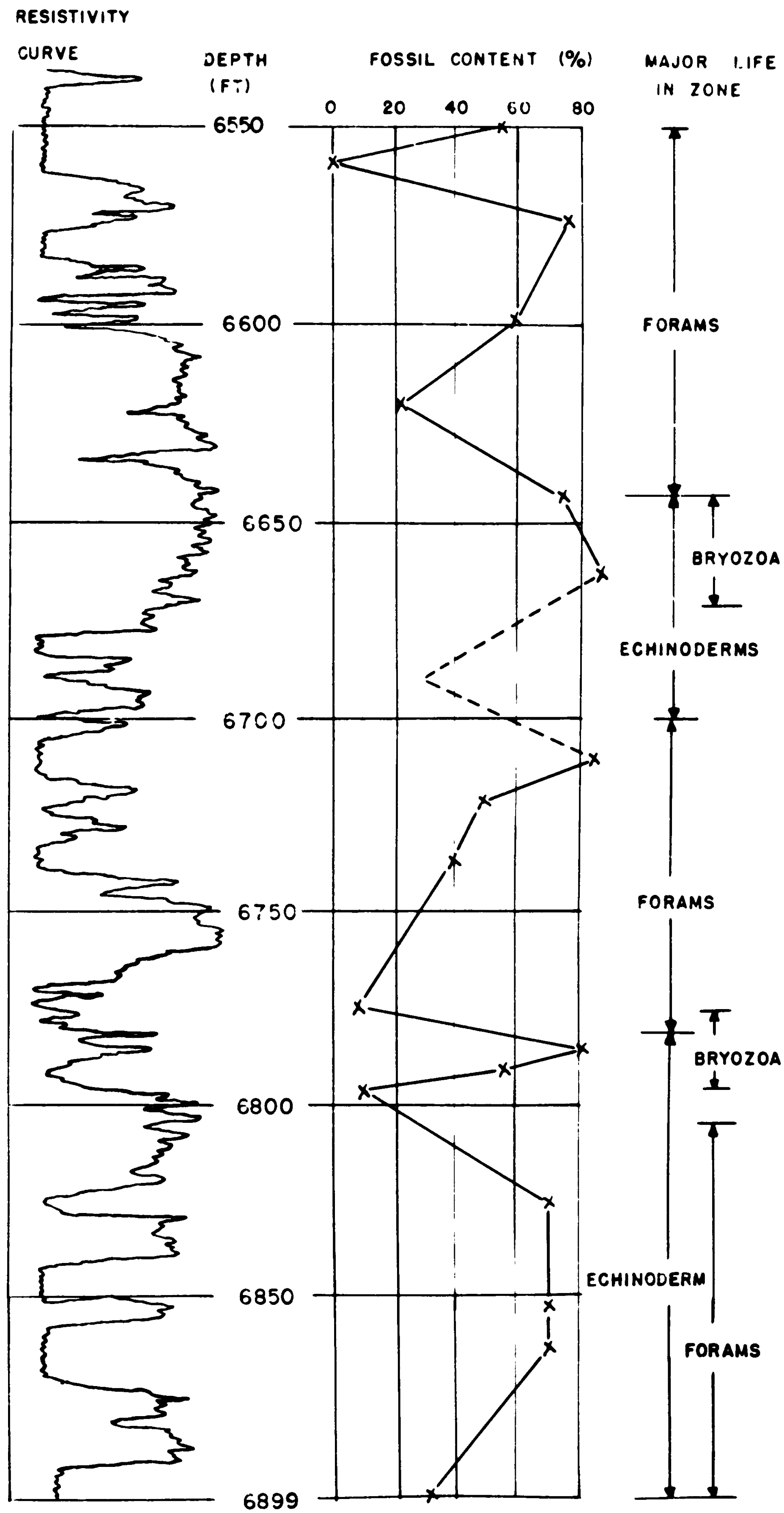
If the samples with no residues are considered, it is found that 42 feet (46.5%) have low resistivity, and that 48 feet (53.5%) have high resistivity. In the samples with slight residues, 94 feet (57%) have low resistivity and 72 feet (43%) have high resistivity. In those samples with moderate or considerable amounts of residue, 67 feet (32%) have low resistivity and 144 feet (68%) have high resistivity. From a study of this information it would seem that small amounts of residual material exerts no noticeable effect on the Microlog resistivity, but that amounts greater than 4-5% are likely to be associated with high resistivities.

F. Fossil Content

The distribution of fossil debris for each zone was plotted against the resistivity trace. The results are shown in plates 51, 52, and 53. From these plates it is possible to make the following analysis.

1. Collins #1

No. of ft. analyzed	202	
No. of ft. with low resistivity		64
Foraminifera dominant		36
Echinoderms dominant		28
No. of ft. with high resistivity		128
Foraminifera dominant		52
Echinoderms dominant		40
Mixed F&E		36



P. J. COLLINS NO. 1

Plate 51.

2. Wren #2

No. of ft. analyzed 130

No. of ft. with low resistivity	86
Foraminifera dominant	50
Echinoderms dominant	16
Brachiopods dominant	6
Mixed F&E	14

No. of ft. with high resistivity	44
Foraminifera dominant	10
Echinoderms dominant	4
Brachiopods dominant	14
Mixed F&E	6
Corals	10

3. Womack #2

No. of ft. analyzed 90

No. of ft. with low resistivity	52
Foraminifera dominant	24
Echinoderms dominant	8
Brachiopods dominant	8
Mixed F&E	14

No. of ft. with high resistivity	38
Foraminifera dominant	0
Echinoderms dominant	24
Mixed F&E	14

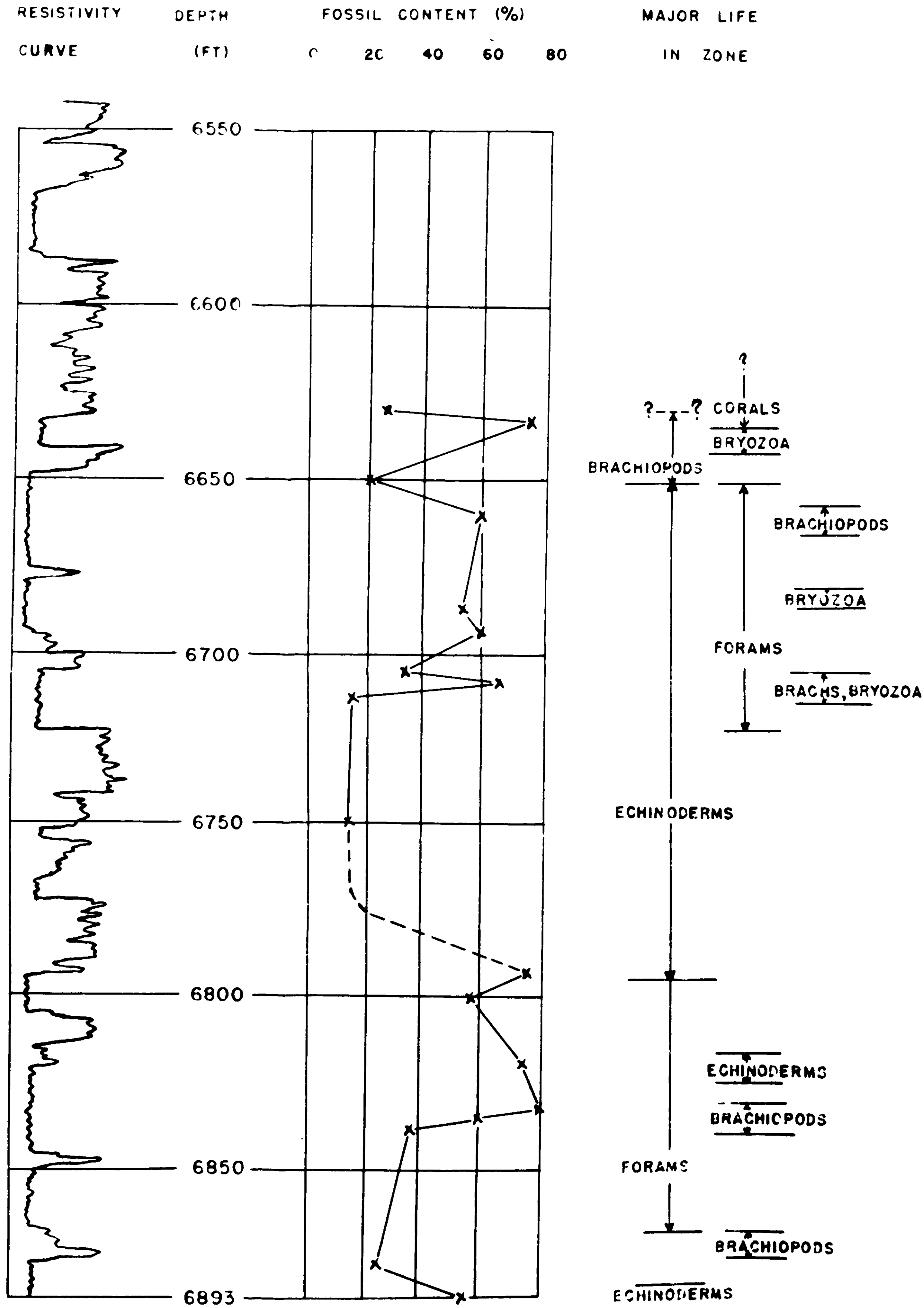
4. Total of all three wells

No. of ft. analyzed 412

No. of ft. with low resistivity	202
Foraminifera dominant	110
Echinoderms dominant	52
Brachiopods dominant	14
Mixed F&E	28

No. of ft. with high resistivity	210
Foraminifera dominant	62
Echinoderms dominant	68
Brachiopods dominant	14
Mixed F&E	56
Corals	10

On the next page is a tabulation of the figures in 4. by percentages.



A. L. WREN NO. 2

Plate 52.

5. Tabulation by Percentages

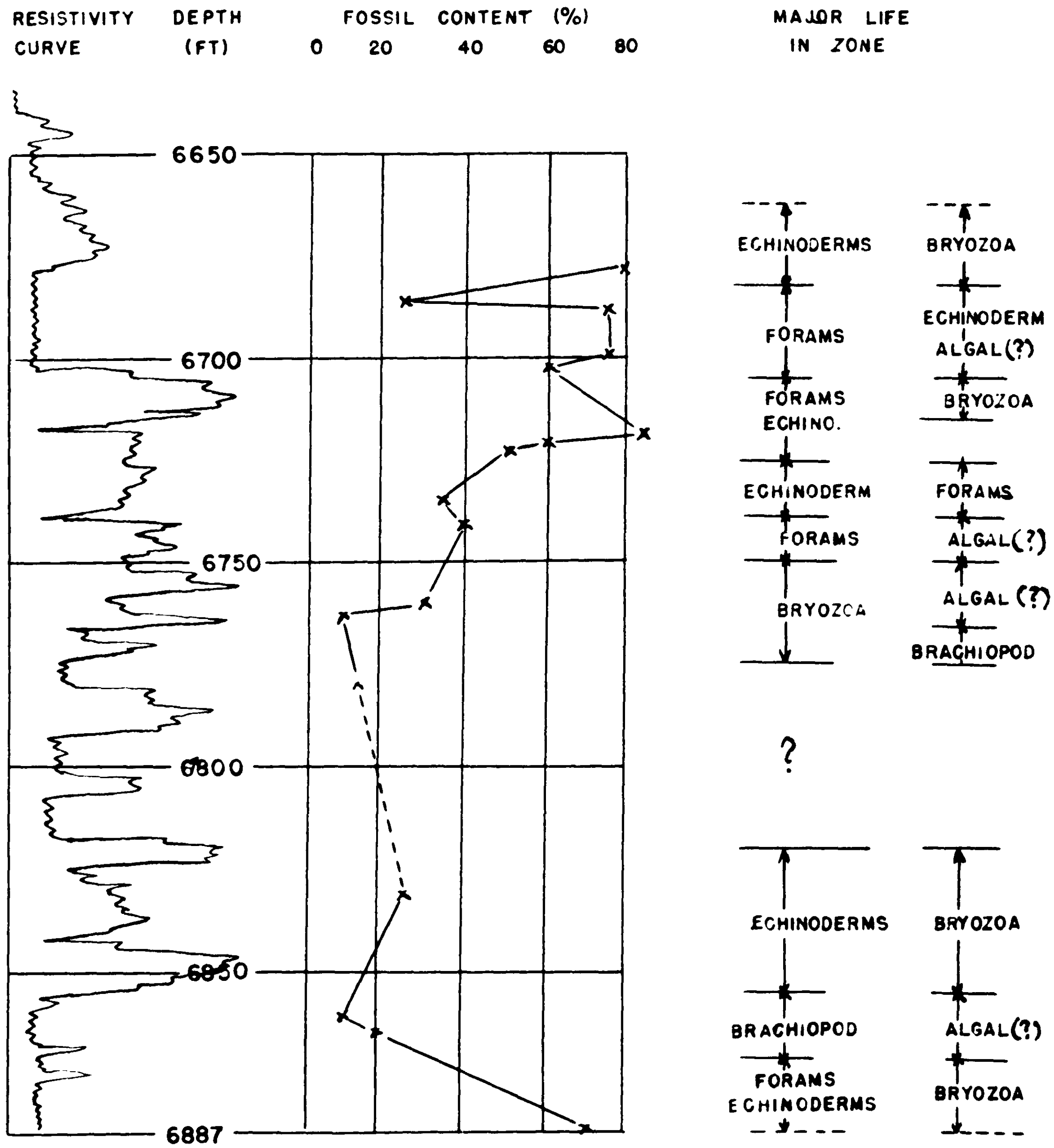
	Percentages of Total Footage			
	Collins	Wren	Womack	Average
A. Low Resistivity	32%	66%	58%	48%
1. Foraminifera	18	38	27	27
2. Echinoderms	14	12	9	13
3. Brachiopods	0	5	9	3
4. Mixed F&E	0	11	13	6
B. High Resistivity	68%	34%	42%	52%
1. Foraminifera	28	8	0	15
2. Echinoderms	22	3	27	16
3. Brachiopods	0	10	0	3
4. Mixed F&E	18	5	15	14
5. Corals	0	8	0	3

The tabulations do not reveal any significant trends. The foraminiferal limestones are more commonly associated with low resistivities, 64% of the footage showing low resistivity. Fifty seven percent of the footage of echinodermal limestones have high resistivities. The limestones with brachiopods are about equally divided, and the limestones with bryozoa tend to have high resistivities.

G. The Amount of Fossil Debris

The relationship between the amount of fossil debris and Microlog resistivity can be tested only on those limestones for which samples are available. Only 51 samples which have clearcut resistivity trends are used in the following tabulation.

There do not seem to be any definite trends indicated by the tabulation. High fossil content seemingly may be associated with either low or high resistivity.



M. J. WOMACK NO. 2

Plate 53.

Percentage of Rock composed of Fossils

Fossil Content	Resistivity	1-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Total	Low	1	5	3	4	1	5	6	6
	High	0	3	3	2	0	3	2	9
Foram. ls.	Low	1	1	0	0	2	0	2	2
	High	0	0	0	0	0	1	2	2
Echino-dermal ls.	Low	0	1	0	0	0	3	0	2
	High	0	1	0	0	0	1	1	2
Mixed F&E	Low	0	0	0	0	1	1	2	3
	High	0	0	0	0	1	1	1	3

H. Fractures

Vertical, oblique, horizontal, and complex fractures were noted during the examination of the samples. It should be expected that fractured zones would have higher permeabilities and better saturations than the non-fractured zones. Therefore, fractured zones should have lower resistivities than the zones without fractures. It is surprising to find that many zones that are well-fractured have high resistivities. The results of the investigations are shown in the following tabulations.

1. Collins #1

	Low Resistivity	High Resistivity
No. of zones examined	8	9
Zones with fractures observed	4	4
1. Vertical fractures	1	1
2. Oblique fractures	1	1
3. Complex fractures	2	2
4. Horizontal fractures	0	0

2. Wren #2

	Low Resistivity	High Resistivity
No. of zones examined	9	8
Zones with fractures observed	5	3
1. Vertical fracture	3	1
2. Complex fractures	2	2

3. Womack #2

	Low Resistivity	High Resistivity
No. of zones examined	5	6
Zones with fractures observed	3	3
1. Vertical fractures	0	1
2. Complex fractures	2	2
3. Horizontal fractures	1	0

4. Totals for all three wells

	Low resistivity	High resistivity
No. of zones examined	22	23
Zones with fractures observed	12	10
1. Vertical fractures	4	3
2. Oblique fractures	1	1
3. Complex fractures	6	6
4. Horizontal fractures	1	0

I. Summary

It was found that porosity and permeability show the best correlation with Microlog resistivity. Although inferences concerning porosity and permeability can be made from the resistivity curves, the inferences are not necessarily conclusive in themselves. It is regretable that no certainity can be attached to conclusions made on the basis of the Microlog alone, but the results of this study clearly indicate that inferences made from Micrologs may be misleading or erroneous.

4. Gamma Ray Logs

Radioactivity logs normally consist of two curves:

(a) a gamma ray curve - reflects natural radioactivity of the rocks; is used to determine lithology.

(b) a neutron curve - reflects artificially induced radioactivity of the rocks; amplitude of the curve is related to porosity and fluid content of the rocks.

No neutron curves were available; four of the available logs have gamma ray traces superimposed on the normal electric logs. Unfortunately, only one well for which samples were on hand has a gamma ray trace. The others come from nearby wells.

A. Theoretical Interpretation of Gamma Ray Logs

A complete discussion of the interpretation of these logs is beyond the scope of this study, but a summary of those points of interest to the study is given below.

1. Sandstones and limestones generally have low radioactivities.
2. Shales generally have high radioactivities.
3. An irregular trace with sharp breaks normally indicates interbedded strata of differing lithology.
4. Prominent changes in trace usually indicate major changes in lithology.
5. Gamma ray measurements are not directly related to oil content.
6. Gamma ray logs are generally satisfactory for the vertical definition of strata and for lateral correlation of strata. This is especially true in regions where there are good shale horizons.

In certain circumstances the characteristics listed above do not apply; it seems likely that they do apply to the wells studied. For a complete interpretation of a well, a neutron curve is essential.

B. Gamma Ray Curves of Canyon Reef Formation

Plate 54 shows three gamma ray traces. The top surface of the reef is easily determined because the reef is directly overlain by black shales of the Cisco formation. This combination of rock strata results in a sudden and sharp increase in natural radioactivity as soon as the reef limestones are encountered.

Individual horizons within the reef limestones cannot be traced from well to well. There are two reasons for this lack of correlation. First, the limestones do not differ from one another sufficiently to permit a differentiation, and second, facies changes occur rapidly in reef limestones. The uniformity of the traces and the low radioactivities are indications of the purity and uniformity of the limestones.

The zone from 6718-6736 feet in the Wren #2 well is interesting because it shows a relatively high radioactivity. Unfortunately, samples from this zone were not available. On a theoretical basis, an increase in radioactivity would be expected with an increase in shale content. At the Collins #1 well, a short distance to the southwest, there is a dark gray argillaceous limestone at the same stratigraphic horizon. The same zone may be present in the Wren #2 well, and be responsible for the sharp break in the gamma ray trace.

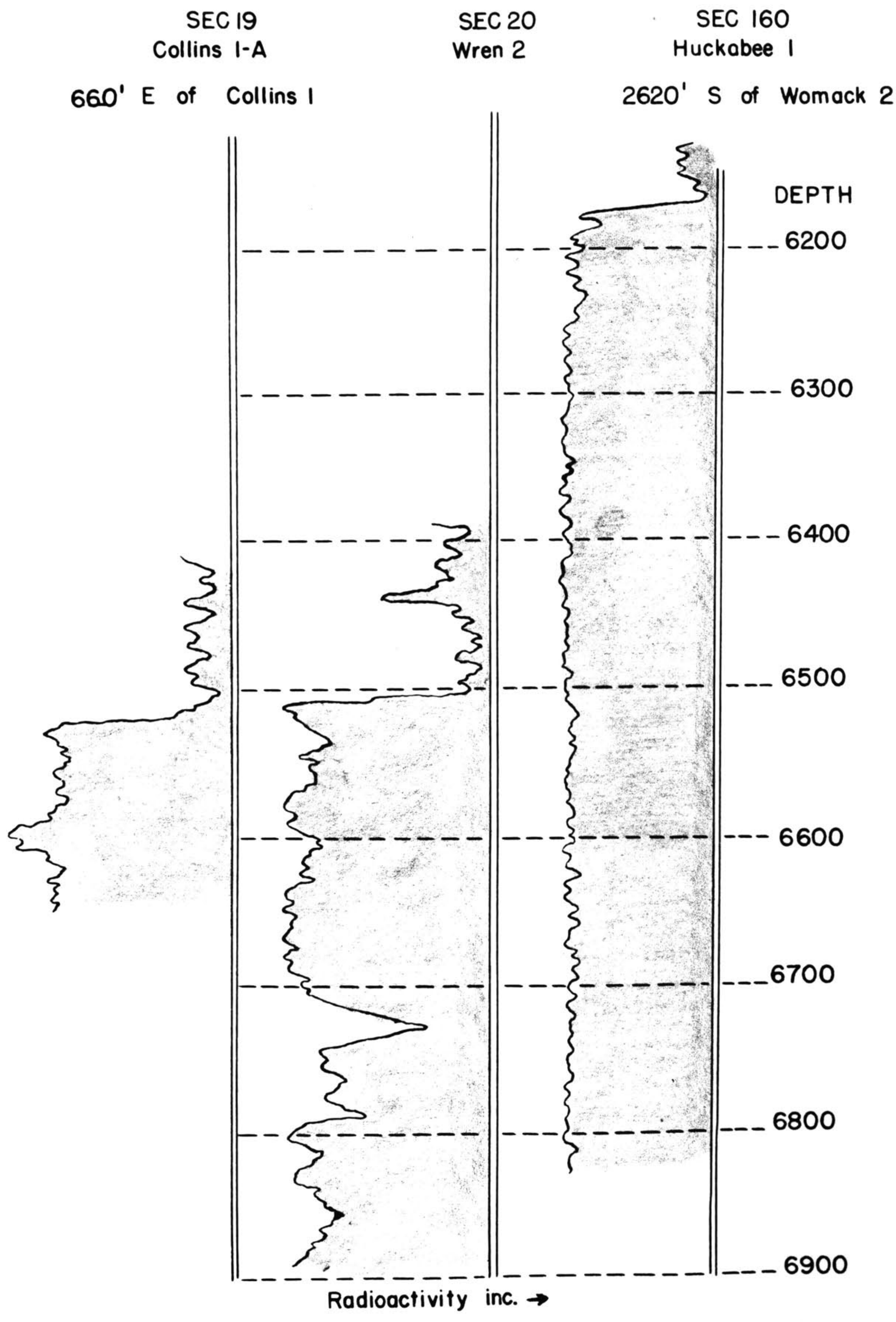

SEC 19
Collins 1-A
660' E of Collins 1
SEC 20
Wren 2
SEC 160
Huckabee 1
2620' S of Womack 2
DEPTH
6200
6300
6400
6500
6600
6700
6800
6900
Radioactivity inc. →
RADIOACTIVITY LOGS

Plate 54.

CHAPTER XIII

PAY ZONES OF THE WELLS

The following discussion is concerned with the pay zones of each of the well studied. Since no drill stem tests were made on the wells, the zones were selected from the core analysis data and by means of theoretical considerations. Evaluation of the data suggests that zones with a porosity of less than 5% and/or a permeability of less than 2 md. are not likely to produce commercial quantities of oil.

1. Pay Zones of Collins #1

The producing interval of the well (from company records) is from 6762-6899 feet. The porosity-permeability profile for this interval is shown on plate 12. The initial production of the well was 888 BOPD through a 3/4" choke. Gravity of the oil is 43.1° API, and the gas-oil ratio is 763 to 1. Plate 12 shows three zones A, B, and C that are likely to be the major producing horizons.

A. Zone A (6824-30)

The average porosity of the zone is 15.5% with a range from 2.4-18.2%. The average permeability of the zone is 7.7 md. with a range from 1-15 md. One core sample was available for the interval.

The sample has a fossil content of 70%. The fossil debris is predominantly echinodermal, but foraminiferal debris is common. Stylolites are well-developed along a plane at an angle of 45° to the bedding. The rock contains many small oolites. Recrystallization has been extensive, and has destroyed several stylolitic zones.

Clear, coarsely crystalline calcite fills part of the former pore space. The limestone is tan in color, and samples treated with acid yield considerable amounts of black oil. The porosity of the sample is 13.3% and the permeability is 10 md.

B. Zone B (6842-52)

The average porosity of the zone is 14.8% with a range from 2.9-18.9%. The average permeability is 30.3 md. with a range from 4.9-109 md. Two samples were available for the interval.

The first is a tan-brown, coarsely crystalline limestone with clear, coarsely crystalline calcite along fractures. The rock has a fossil content of 70%; echinodermal and foraminiferal debris are present in about equal amounts. Recrystallization has been extensive. Numerous vugs are present and the rock has a spongy texture. Moderate amounts of black oil are obtained if the sample is treated with acid. The permeability of the sample is 109 md. The porosity reported on core analysis data is 2.9% although it was estimated at 15%.

The second sample is also tan-brown and coarsely crystalline. Many widely-disseminated small vugs are present, and there are numerous vertical fractures. The fossil content is 70%, and large, well-preserved foraminifera are the most common fossils. Other fossil debris consists of smaller foraminifera and echinoderm fragments. Secondary silica replaces part of the echinoderm fragments. There are old stylolite zones. The residue from treatment of the sample with acid contains small amounts of oil, clay, and silica. The permeability is 19 md. and the porosity is 16.5%

C. Zone C (6860-73)

The average porosity of the zone is 15.1% with a range from 6.0-22.8%. The average permeability is 15.5 md. with a range from 0-53 md. One sample was available for the interval.

The rock is a tan-brown, porous, soft limestone. The fossil content is 65%, and both foraminiferal and echinodermal debris are abundant. There are numerous well-developed stylolitic zones, and several "ghost" stylolite zones that have been destroyed during recrystallization. Many complex fractures are present, and the sample contains a few oolites. Slight amounts of oil are obtained if the sample is treated with acid. The permeability is 53 md. and the porosity is 20.7%.

2. Pay Zones of Wren #2

The producing interval of the well is from 6730-6893 feet. The porosity-permeability profile for this interval is shown on plate 13. Initial production of the well was 492 BOPD through a 24/64" choke. Gravity of the oil is 44° API, and the gas-oil ratio is 1136 to 1. Plate 13 shows four zones D, E, F, and G that are likely to be the major producing horizons.

A. Zone D (6788-99)

The average porosity of the zone is 16.2% with a range from 11.0-22.8%. The average permeability is 20.3 md. with a range from 2-68 md. Three samples were available for the interval.

The first is a tan, soft limestone with a fossil content of 70%. Foraminiferal debris is the chief constituent, and the individual tests are well-preserved. The interiors of the tests are commonly filled with medium to coarsely crystalline calcite. There is an irregular vuggy porosity. Old stylolite zones are largely destroyed by recrystallization. Treatment of the sample with acid yields considerable oil. The permeability is 7.2 md. and the porosity is 10.7%.

The second sample is similar to the first. Excellent stylolites are developed along bedding planes. The permeability is 23 md. and the porosity is 16.5%.

The third sample is a light gray limestone with prominent vertical fractures. The rock has a fossil content of 50%, and is almost entirely foraminiferal debris. Coarsely crystalline calcite can be seen filling the interiors of foraminiferal tests and reducing pore space. Considerable black oil is present in the residue from acid treatment of the sample. The permeability is 42 md. and the porosity is 22.7%.

B. Zone E (6809-40)

The average porosity of the zone is 12.2% with a range from 2.4-19.1%. The average permeability is 18.4 md. with a range from 0.5-114 md. Five samples were available for the interval.

The first is a tan, foraminiferal limestone with many shear fractures. The fossil content is 65%. The rock is extensively recrystallized. The permeability is 8.8 md. and the porosity is 10.6%.

The second sample is a dense, light gray limestone containing both shear and tension fractures. The rock is largely echinodermal debris but foraminifera and brachiopods are present. Recrystallization has been extensive and large amounts of clear, coarsely crystalline calcite are scattered throughout the rock. The permeability is 5.6 md. and the porosity is 12.0%.

The third is a tan limestone with a pinpoint, vuggy porosity. The fossil content is 60% with well-preserved foraminifera most common. The acid residue contains small amounts of oil. The permeability is 18 md. and the porosity is 18.8%.

The fourth is a light gray, medium crystalline limestone with a few vertical fractures. The fossil content is 40%; foraminifera are most abundant but echinoderms are plentiful. There are well-developed stylolites. The permeability is 2.4 md. and porosity is 10.3%.

The fifth sample is similar to the fourth. The permeability of the sample is 88 md. and the porosity is 15.2%.

C. Zone F (6845-64)

The average porosity of the zone is 12.4% with a range from 6.0-17.4%. The average permeability is 4.7 md. with a range from 0.1-28 md. No samples were available.

D. Zone G (6873-91)

The average porosity of the zone is 16.3% with a range from 10.5-22.8%. The average permeability is 5.3 md. with a range from 1.5-14 md. Two samples were available for the interval.

The first is a gray-brown, much-fractured limestone with well-developed stylolites. There is no recognizable fossil debris. Recrystallization has been extensive and many, coarse, twinned calcite crystals are present. There is no oil in the acid residue. The permeability is 4.8 md. and the porosity is 17.2%.

The second sample is a dark gray-brown limestone with numerous vertical fractures. There has been extensive recrystallization. The fossil content is 15%; the major constituent is echinodermal debris. The acid residue contains dark gray silt. The permeability is 1.3 md. and the porosity is 10.4%.

3. Pay Zones of Womack #2

The producing interval of the well is from 6837-6887 feet. The porosity-permeability profile for this interval is shown on plate 14. The initial production of the well was 910 BOPD through a 3/4" choke. Gravity of the oil is 42.8° API, and the gas-oil ratio is 766 to 1. No specific zones are delineated on plate 14. Examination of the core analysis data suggests that they are misleading. It seems likely that the well has a large solution and fracture porosity that is not indicated in the core analysis data.

A. Discussion of the Producing Interval (6837-87)

Discussions of permeability and porosity are omitted since it is felt that they are misleading. Three samples were available for the interval.

The first sample is a dense, gray-brown limestone. Horizontal and vertical fractures are common, but are normally filled with calcite. There are large vugs, over 2" in diameter, lined with calcite crystals. The vugs are oil-stained. Bryozoa and algal(?) material are the fossil debris; fossil content is 35-40%.

The second is a loosely-cemented, brachiopod limestone that was probably once a coquina. The rock is gray-brown, and contains numerous vugs and cavities. Pore space has been reduced by coarsely crystalline calcite. Moderate amounts of oil and slight amounts of clay are present in the acid residue.

The third sample is similar to the second except that the openings are larger, and there is less coarse calcite. Foraminiferal, echinodermal, and bryozoan debris are present. There are prominent stylolites. Treatment of the sample with acid yields moderate amounts of oil and some dark brown clay.

4. Summary

Most of the samples are tan or light gray in color. The average porosity of the producing zones is around 15%. The following tabulation shows the fossil content of the samples.

No. of samples	17
No. with foraminifera	13
No. with echinoderms	11
No. with brachiopods	4
No. with stylolites	8

The type of fossil content does not seem to be a decisive factor. However, the mixed fossil zones and the brachiopod-bearing zones seem to be especially good. This is probably due to higher initial porosities and permeabilities. Most sample are well-fractured.

BIBLIOGRAPHY

1. Keplinger and Wanenmacher. New Reef Fields of Texas. WORLD OIL, Sept. '50: pp. 181-88

2. Barnes and Carlson. Scurry Analysis. O&G Jl. 27 April 1950 pp. 64-65

3. Cumings and Shrock. Niagaran Coral Reefs of Indiana and Adjacent States. GSA: 39: 1928: 579-620

4. Wilson, W.B. Reef Definition. AAPG: 34: 1950: 181

5. Hohlt, R.B. Nature and Origin of Limestone Porosity. Qrtrly of Colo. Sch. Mines, vol. 43 no. 1, 1948

6. Imbt, W.C. Carbonate Porosity and Permeability. Chapter 33, APPLIED SEDIMENTATION by Trask

7. Craze, R.C. Performance of Limestone Reservoirs. AIME TP 2935 Oct. 1950

8. Littlefield, Gray and Godbold. A Reservoir Study of West Edmond Hunton Poorl, Oklahoma. AIME TP 2203, Nov. 1947

9. Glaessner, M.F. PRINCIPLES OF MICROPALEONTOLOGY. Wiley & Sons. 1947. pp. 183-94

10. as (9). pp. 108-116.

11. Twenhofel and Shrock. INVERTEBRATE PALEONTOLOGY. McGraw-Hill. 1935 pp. 220-250

12. Twenhofel, W.H. PRINCIPLES OF SEDIMENTATION. McGraw-Hill. 1939. pp. 498-505

13. USGS Bull. 770. DATA OF GEOCHEMISTRY. pp. 559-60

14. Stockdale, P.B. Stylolites; Their Nature and Origin. Univ. of Indiana Study No. 55, 1922.

15. Schaub, B.M. Origin of Stylolites. JSP: 9: 1939: 47-61

16. Caran, J.G. Residual Oil and Condensate. SUBSURFACE GEOLOGIC METHODS. Colo. Sch. Mines. 1949. pp. 246-248

17. Doll, H.G. The Microlog, a New Electrical Logging Method for Detailed Determination of Permeable Beds. AIME TP 2880 L950.

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North Quincy High School, Quincy, Mass. 1933-36.

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American Geophysical Union, American Geographical Society, American Association for Advancement of Science, American Meteorological Society, American Institute of Mining and Metallurgical Engineers, American Association of Petroleum Geologists.

APPENDIX

Descriptions of the Samples from Each Well

WELL: P.J. COLLINS #1 CORE: #2

WELL ELEVATION: 2498 ft. DEPTH: 6550 ft.

MACROSCOPIC DESCRIPTION:

Buff-brown, moderately fossiliferous limestone composed largely of comminuted shell debris. There is a crude, ireegular bedding and a low, vuggy, pinpoint porosity estimated at 5%. Pore space is confined largely to the matrix; pore space likely has poor interconnection.

MICROSCOPIC DESCRIPTION:

Rock is 50-55% fossil debris; most prominent are proloculi and fragments of foraminifera. Brachiopod shell fragments are noticeable but not abundant. The matrix consists of fine to medium crystalline calcite; minor recrystallization is apparent in both the matrix and fossil debris. Porosity has been decreased by this recrystallization and intergranular porosity is now the most important.

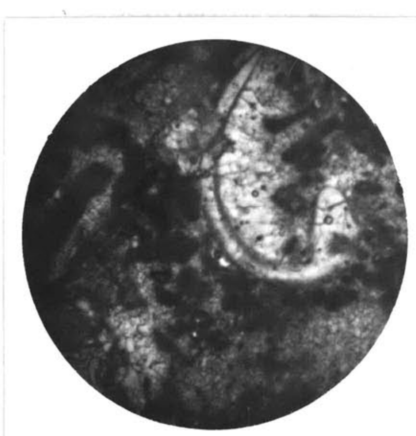
ACID RESIDUE:

2% black petroliferous material; no other.

CORE ANALYSIS DATA:

Permeability is 5.9 md. Porosity is 6%

PHOTOMICROGRAPHS:



10X. Ordinary light.

WELL: P.J. COLLINS #1 **CORE: #3**

WELL ELEVATION: 2498 ft. **DEPTH: 6551 ft.**

MACROSCOPIC DESCRIPTION:

A brownish, granular, porous limestone containing 10-15% large, coarsely crystalline shell fragments. Attitudes of the brachiopod shell fragments suggest bedding as they are occasionally concentrated along parallel zones. Bedding(?) is about parallel to the surface. Porosity variable from 15-25% with good interconnection of pore spaces. Rock shows slight staining by iron oxides.

MICROSCOPIC DESCRIPTION:

Rock is 10-15% fossil debris, most of which is foraminiferal but bryozoa are also present. The matrix consists of medium crystalline calcite, occasionally of rhombohedral habit. Pore spaces are widely disseminated, irregularly rounded openings about 0.1 mm. in diameter. There has been some slight recrystallization, which is most noticeable in the matrix and at the edges of the pore spaces. Petroliferous material(?) is irregularly distributed throughout the sample.

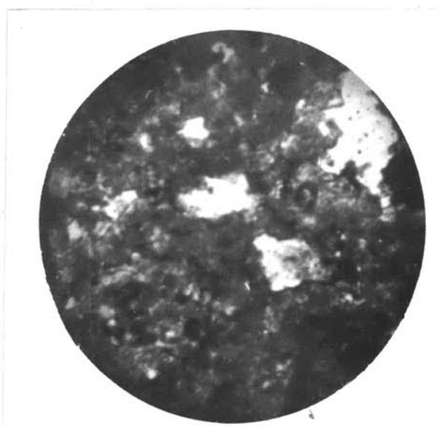
ACID RESIDUE:

1-2% black petroliferous matter; no other.

CORE ANALYSIS DATA:

Permeability is 155 md. Porosity is 17.4%

PHOTOMICROGRAPH



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: #4

WELL ELEVATION: 2498 ft. DEPTH: 6552 ft.

MACROSCOPIC DESCRIPTION:

A brownish, granular, fossiliferous limestone locally stained by iron oxides. There is an irregular, vuggy porosity varying from 5-20% within short distances laterally. Good interconnection of pore spaces occurs laterally along zones. Brachiopods and foraminifera are abundant in the shell debris. There is one poorly developed stylolitic zone along which are corroded fossil fragments; different types of limestone occur each side of the stylolite.

MICROSCOPIC DESCRIPTION:

Rock is rather porous with irregular, branching pore spaces. It is 35-45% fossil debris, most of which is foraminiferal fragments. The matrix consists of fine to medium crystalline calcite. Little to no evidence of recrystallization was seen.

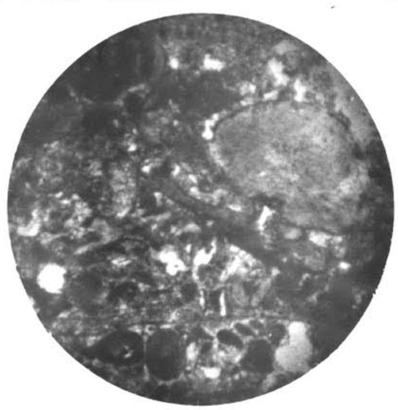
ACID RESIDUE:

Less than 1% of black petroliferous matter; no other.

CORE ANALYSIS DATA:

Permeability is 44 md. Porosity is 13.2%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 | CORE: #14

WELL ELEVATION: 2498 ft. | DEPTH: 6562 ft.

MACROSCOPIC DESCRIPTION:

A light gray, brecciated limestone containing rounded inclusions of a dense, light brown limestone. There are numerous, well-developed stylolitic zones spaced at 1/16-1/2" intervals vertically. Porosity estimated at 3%; pore spaces are irregular, non-connecting openings along the various stylolitic zones.

MICROSCOPIC DESCRIPTION:

Rock appears to be a finely crystalline, slightly argillaceous limestone. The stylolitic zones are marked by accummulations of a black impurity or residue. Porosity appears to be under 2%. There is some slight recrystallization irregularly developed along the stylolites. Maximum amplitude of the stylolites is about 1.5 mm. No fossils of any type were seen in the sample.

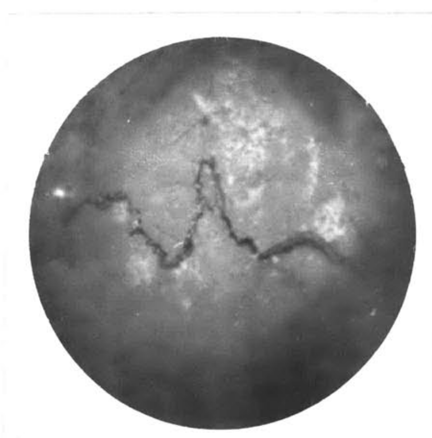
ACID RESIDUE:

2% of fine silty clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 3.9%.

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1

CORE: #27

WELL ELEVATION: 2498 ft.

DEPTH: 6575 ft.

MACROSCOPIC DESCRIPTION:

A very fossiliferous, finely granular, buff limestone with an irregular, spotty, pinpoint porosity estimated at 10%. Rock is stained locally by iron oxides. The bedding is indicated by the parallel arrangement of the long axes of shell fragments. There is a slight tendency towards an oolitic texture.

MICROSCOPIC DESCRIPTION:

Rock contains 70-80% fossil debris, most of which is foraminifera proloculi. The oolitic appearance is due to these proloculi. There is a very low vuggy porosity; the high values shown by the Core Analysis Data are probably caused by a high intergranular porosity. The matrix consists of finely crystalline calcite; little to no evidence of recrystallization present.

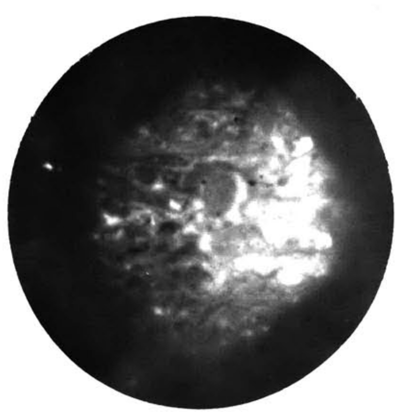
ACID RESIDUE:

1% of black petroliferous matter. 2% of a fine white, glassy material which may be quartz; the grains are too fine for identification.

CORE ANALYSIS DATA:

Permeability is 1.1 md.   Porosity is 16.5%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: #51

WELL ELEVATION: 2498 ft. DEPTH: 6599 ft.

MACROSCOPIC DESCRIPTION:

A light brownish-white, massive, finely granular limestone. There are imprints of small brachiopod shells, 3/8-3/8", and numerous foraminifera. Coarse calcite crystals occur in scattered masses throughout the rock. Porosity estimated at 3-5% with rather poor interconnection of pore spaces.

MICROSCOPIC DESCRIPTION:

Rock is 50-60% fossil debris; foraminifera are the most prominent. A few of the foraminifera tests are well-preserved and can be identified as fusulinids. There is a large fragment (3 mm.) of a lacy bryozoa. The interior of fossil fragments is normally filled by coarsely crystalline calcite. The low porosity is due to the filling of original cavities by this calcite.

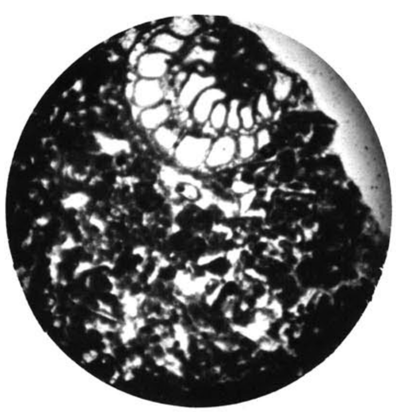
ACID RESIDUE:

Less than 0.1% of a whitish clay; no oil.

CORE ANALYSIS DATA:

Permeability is 4.5 md. Porosity is 4.6%

PHOTOMICROGRAPHS:



10X. Ordinary light.

WELL: P.J. COLLINS #1 **CORE: #69**

WELL ELEVATION: 2498 ft. **DEPTH: 6623 ft.**

MACROSCOPIC DECRIPTION:

A light gray, brecciated limestone with inclusions of a dense, light brown limestone. The sample is only moderately fossiliferous but has many stylolitic zones. Porosity estimated at 2 %.

MICROSCOPIC DESCRIPTION:

A slightly argillaceous limestone containing 30-40% fossil debris, mostly foraminifera. Porosity is very low. Stylolitic zones have a black petroliferous(?) material concentrated along them. There is some recrystallization along the stylolites but not in the main mass of the rock. The stylolites are generally thin wavy bands with very minor serrations; their width varies from 0.05-0.5 mm. Although the bands frequently branch and wander, the separation of the stylolites is of the order of 2 mm. There is a well-preserved bryozoan zooarium in the sample.

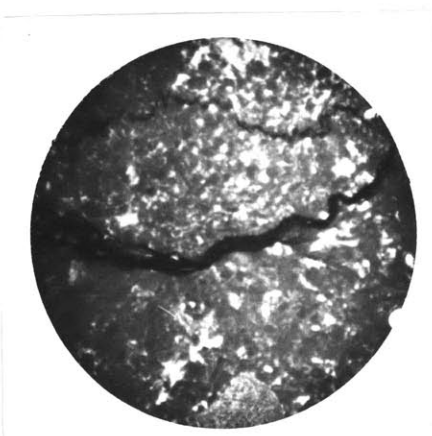
ACID RESIDUE:

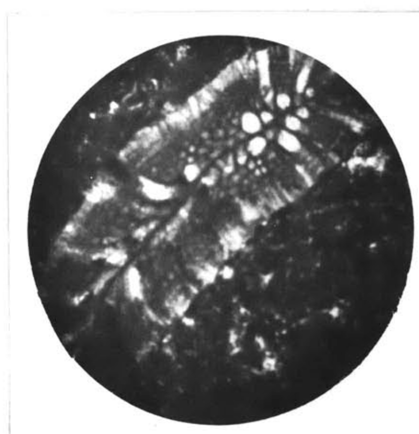
1% of a fine, light gray clay; no oil. It is likely that the material along the stylolites was introduced after consolidation.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 1.7%

PHOTOMICROGRAPHS:





10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 91

WELL ELEVATION: 2498 ft. DEPTH: 6646 ft.

MACROSCOPIC DESCRIPTION:

A light gray, moderately fossiliferous limestone with an irregular fracture. Porosity estimated at 2-3%; pore spaces are concentrated along the fractures and occasional stylolitic zones. A moderate amount of recrystallization is indicated by occasional large crystals of calcite and areas of coarsely crystalline calcite.

MICROSCOPIC DESCRIPTION:

A very fossiliferous limestone which is 60-70% foraminiferal debris. Small amounts of bryozoan and echinoderm debris are present. Many of the foraminiferal tests are well-preserved. Two medium-sized, rounded grains of glauconite are present in the sample.

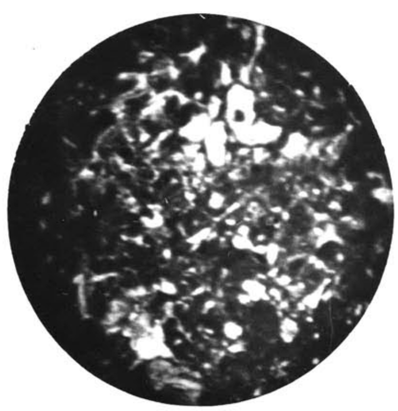
ACID RESIDUE:

2% of fine, light brownish silt; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 3.4%

PHOTOMICROGRAPHS:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 107

WELL ELEVATION: 2498 ft. DEPTH: 6665 ft.

MACROSCOPIC DESCRIPTION:

A light gray, coarsely crystalline, fragmental limestone with occasional stylolitic zones. Porosity estimated at less than 2%. The sample is composed largely of recrystallized fossil debris cemented by a light brownish calcareous matrix.

MICROSCOPIC DESCRIPTION:

Rock has 85% fossil debris, mostly echinoderm fragments but with occasional bryozoa and foraminifera. The angular echinoderm fragments are from 1x2 mm. to 1.5x4 mm. in size; crinoid stems up to 1.8 mm. in diameter are present. The porosity is variable along the stylolitic zones; low to non-existent in the main mass of the rock. This variation may explain the discrepancy between the estimated porosity and the measured; in addition, the slight porosity may be largely intergranular.

FOSSILS IDENTIFIED:

PRISMOPORA

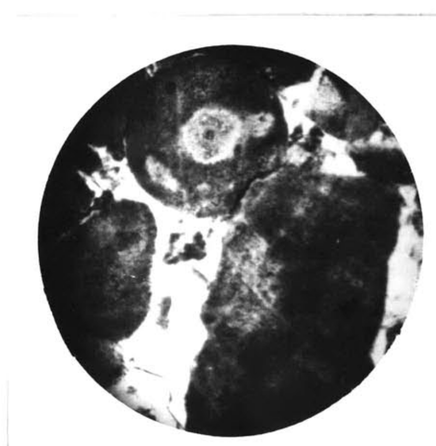
ACID RESIDUE:

2-3% of a light gray clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 4%

PHOTOMICROGRAPHS:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 154

WELL ELEVATION: 2498 ft. DEPTH: 6712 ft.

MACROSCOPIC DESCRIPTION:

A light buff, soft, almost chalky limestone composed largely of foraminifera.

MICROSCOPIC DESCRIPTION:

Rock is about 80% fusulinids, most very well-preserved. The matrix is clear, medium crystalline calcite. Porosity is estimated at 2-3% with most pore space and cavities in the foraminifera filled by clear, crystalline calcite. The porosity is quite variable due to the irregularity of these fillings.

FOSSILS IDENTIFIED:

TRITICITES

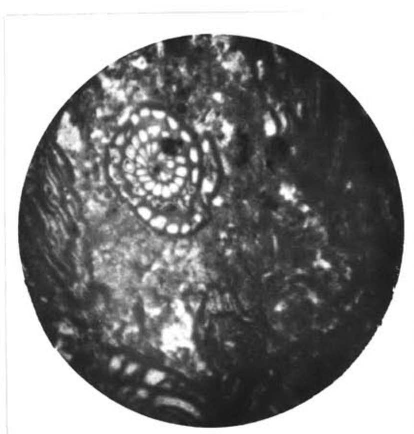
ACID RESIDUE:

Less than 0.5% oil scum; no other.

CORE ANALYSIS DATA:

Permeability is 3.6 md. Porosity is 15.5%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: " 164

WELL ELEVATION: 2498 ft. DEPTH: 6722 ft.

MACROSCOPIC DESCRIPTION:

A light grayish-buff, porous, foraminiferal limestone. Variable porosity estimated at 8-15% with irregular-shaped, poorly-interconnected openings.

MICROSCOPIC DESCRIPTION:

Rock is moderately fossiliferous, being 30% foraminifera. There is one thin stylolitic zone. Extensive patches of clear, coarsely crystalline calcite are found in the matrix and concentrated in the interiors of foraminifera tests. Patches of iron oxides occur around the edges of pores.

FOSSILS IDENTIFIED:

TRITICITES.

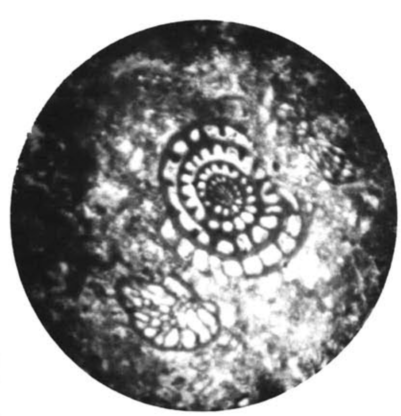
ACID RESIDUE:

Less than 0.1% oil scum; no other.

CORE ANALYSIS DATA:

Permeability is 3.8 md. Porosity is 11.7 %

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 165

WELL ELEVATION: 2498 ft. DEPTH: 6723 ft.

MACROSCOPIC DESCRIPTION:

A finely granular, moderately fossiliferous, buff-gray limestone with many well-developed stylolitic zones. Some light greenish material (probably glauconite) is present at irregular intervals along the stylolitic zones. Recrystallized patches of calcite are dispersed throughout the main mass of the rock.

MICROSCOPIC DESCRIPTION:

Rock is 45-55% fossil debris; most prominent are fragments of echinoderms and foraminifera. Porosity estimated at 10-12%. Recrystallization is confined largely to the areas adjoining the stylolitic zones.

ACID RESIDUE:

Less than 0.1% oil scum; no other.

CORE ANALYSIS DATA:

Permeability is 10 md. Porosity is 15.4%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: P.J. COLLINS #1

CORE: # 180

WELL ELEVATION: 2498 ft.

DEPTH: 6738 ft.

MACROSCOPIC DESCRIPTION:

A buff, soft, finely crystalline, moderately fossiliferous limestone. A pinpoint, vuggy porosity is estimated at 8-10% but may be higher. A poorly-developed set of vertical fractures can be seen; no stylolites are present.

MICROSCOPIC DESCRIPTION:

Rock is 40% fusulinids; a few large fragments of echinoderms are also present. The matrix is finely crystalline and there is little evidence of recrystallization. The irregular, vuggy porosity is quite variable; pores of the order of 1 mm. are common. Interconnection of pore space is difficult to determine but tends to be fair. The largest foraminifera are 4x1.5 mm. in section.

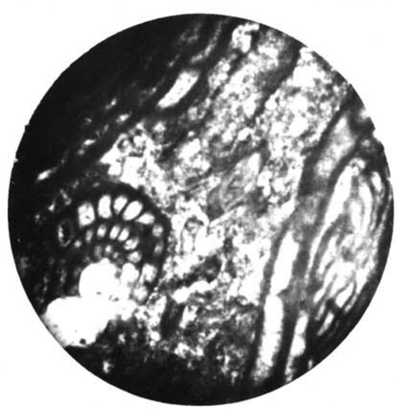
ACID RESIDUE:

About 1% of black oil; 1% of a very fine white angular material, possibly dolomite.

CORE ANALYSIS DATA:

Permeability is 5.3 md.   Porosity is 18.1%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 216

WELL ELEVATION: 2498 ft. DEPTH: 6774 ft.

MACROSCOPIC DESCRIPTION:

A dark brownish-gray, dense, badly fractured limestone. Fracture planes run in three directions, two shear and one tension. Two kinds of brachiopods of the Productid type are present; the larger has a maximum width of 10 mm. There are many complex stylolitic zones developed principally along fracture planes. The porosity and permeability are low to nil except along fractures.

MICROSCOPIC DESCRIPTION:

A finely crystalline, argillaceous limestone containing 5-8% small foraminifera, bryozoa, and an occasional large echinoderm fragment. There are many well-developed, complex stylolitic zones with much interesting detail. Porosity estimated at 2%. A moderate recrystallization is best developed along stylolitic zones and has nearly destroyed an older set of stylolites.

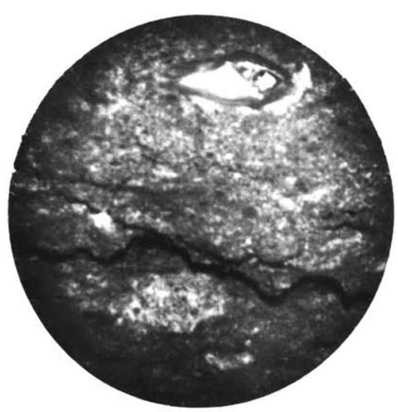
ACID RESIDUE:

3-4% of a gray-brown silt; traces of black oil material.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 2.8%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1

CORE: # 227

WELL ELEVATION: 2498 ft.

DEPTH: 6787 ft.

MACROSCOPIC DESCRIPTION:

A hard, dense, dark gray limestone with abundant white crinoid stems and echinoderm remains; a typical crinoidal limestone. Stylolitic zones are developed parallel to bedding and at 45° to bedding. Porosity and permeability are low to nil except along fractures and stylolites.

MICROSCOPIC DESCRIPTION:

Rock is 80-90% fossil debris ; most prominent are rounded fragments of echinoderms but 10% are bryozoa and 3-5% are foraminifera. The stylolitic zones are poorly developed. The rock as a whole presents a very heterogeneous appearance. Porosity is estimated at 2%.

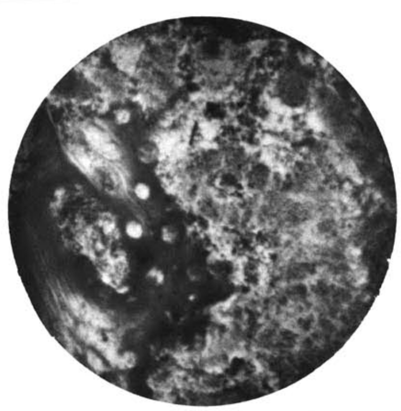
ACID RESIDUE:

3-5% of a gray-brown silty clay; minor amount of quartz; little to no oil.

CORE ANALYSIS DATA:

Permeability is 0.   Porosity is 2.7%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 230

WELL ELEVATION: 2498 ft. DEPTH: 6789 ft.

MACROSCOPIC DESCRIPTION:

A dark gray, dense, crinoidal limestone with abundant white crinoidal remains set in dark matrix. The rock is badly fractured. Porosity estimated at 2-3%; higher along fractures.

MICROSCOPIC DESCRIPTION:

Rock is 85% fossil debris; 25% foraminifera of a non-fusulinid type, 40-50% echinoderm fragments, and a few bryozoa. The rock shows considerable recrystallization and the interiors of the foraminifera are filled by medium crystalline calcite. Average size of the fragments is 1x2 mm. A few ellipsoidal oolites, 0.8 to 1 mm. in diameter, are irregularly dispersed in matrix.

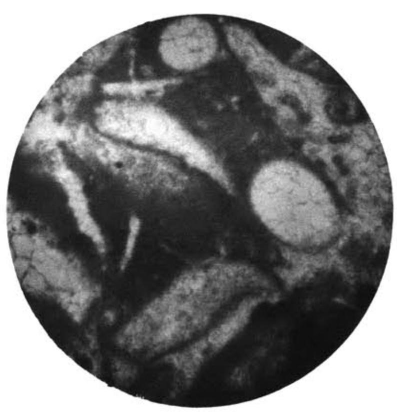
ACID RESIDUE:

1-2% of dark gray, silty clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 2.3%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 235

WELL ELEVATION: 2498 ft. DEPTH: 6794 ft.

MACROSCOPIC DESCRIPTION:

A hard, dense, light gray, mottled limestone. The rock has been greatly fractured at some previous time and is now re-cemented. There is moderate recrystallization in both the matrix and the fracture zones. Porosity estimated at 1-3%.

MICROSCOPIC DESCRIPTION:

A very pure limestone with fossil content only 5-8%. Large, very finely crystalline masses of limestone are imbedded in a medium crystalline matrix. There are a few concentric oolites, 0.3 mm. in diameter, which show a psuedouniaxial cross when observed under crossed Nicols. An interesting calcareous triserial foraminifera was observed but could not be identified. It was 4.2 mm. long and 2.5 mm. wide at maximum width. The pore space of the rock has been considerably reduced by the formation of coarsely crystalline calcite.

ACID RESIDUE:

0.5% of light gray silty clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 2%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 265

WELL ELEVATION: 2498 ft. DEPTH: 6827 ft.

MACROSCOPIC DESCRIPTION:

A light buff, porous, fragmental limestone containing brachiopod shells and echinoderm fragments. There is a stylolitic zone developed on a fracture plane at 45° to the bedding. Patches of clear, coarsely crystalline calcite are dispersed throughout the rock. Pore space consists of widely distributed, small to medium pores; permeability is probably fair to good.

MICROSCOPIC DESCRIPTION:

Rock is 70% fossil debris; there are many echinoderms and moderate amounts of foraminifera (two types). Occasional grain of glauconite(?) along the stylolitic zone. Several small oolites which show psuedouniaxial crosses under crossed Nicols are present. Porosity is variable from 8-15%. There has been moderate recrystallization which has destroyed the stylolites locally.

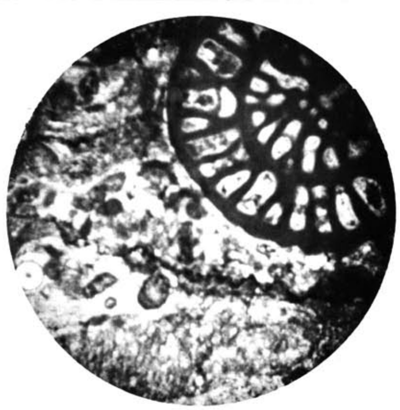
ACID RESIDUE:

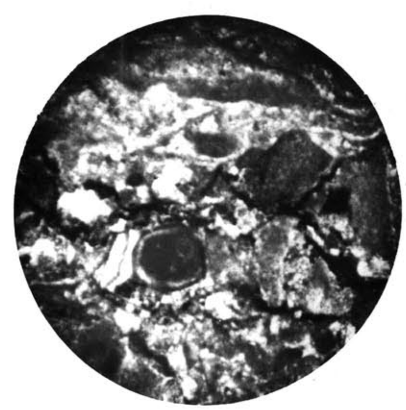
2-4% of black oily matter; 1% of a yellowish-white mineral which occured as fillings of pore spaces; vaselike shapes are common; may be silica.

CORE ANALYSIS DATA:

Permeability is 10 md. Porosity is 13.3%

PHOTOMICROGRAPHS:





10X. Ordinary light.

WELL: P.J. COLLINS #1 **CORE: # 289**

WELL ELEVATION: 2498 ft. **DEPTH: 6851 ft.**

MACROSCOPIC DESCRIPTION:

A buff-brown, coarsely crystalline limestone with coarsely crystalline, clear calcite developed along the fractures. There are two types of limestone present; one is quite dense, has a porosity around 3%, and low permeability while the other is spongy, has a porosity of 10-15% and excellent permeability.

MICROSCOPIC DESCRIPTION:

Rock is 70% fossil debris, about equally divided between foraminifera and echinoderm fragments. The rock is very distinctly fragmental with rounded fragments being the most common. There is a slight tendency for an oolitic texture. Secondary silica is present as a filling of pore space. The rock is considerably recrystallized.

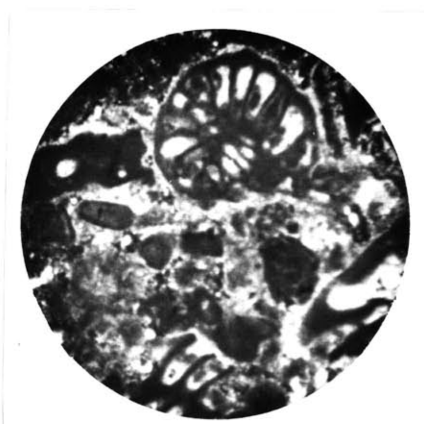
ACID RESIDUE:

2-3% of black oil matter; minor amounts of silica.

CORE ANALYSIS DATA:

Permeability is 109 md. Porosity is 2.9%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 290

WELL ELEVATION: 2498 ft. DEPTH: 6852 ft.

MACROSCOPIC DESCRIPTION:

A buff-brown, porous, medium to coarsely crystalline, fossiliferous limestone. There is good, widely distributed, pinpoint porosity. A set of vertical fractures can be observed. There are two old stylolitic zones which have been slightly destroyed by re-crystallization.

MICROSCOPIC DESCRIPTION:

Rock is 65-70% fossil debris; 35-45% of the rock is foraminifera (two types) and 25% is echinoderm fragments, some of which are partially replaced by silica. The silica seems to be confined entirely to the echinoderm fragments. Porosity is rather high and ranges from 10-20%. Permeability is fair to good.

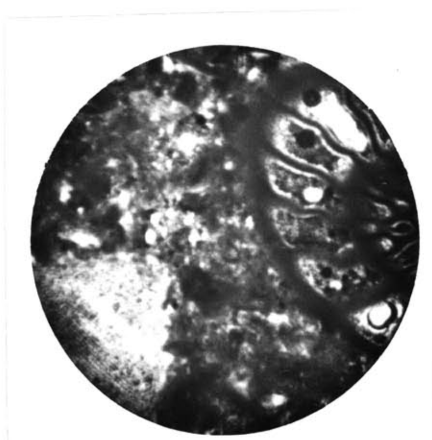
ACID RESIDUE:

Traces of black oil; 2-3% of light clay and silica.

CORE ANALYSIS DATA:

Permeability is 19 md. Porosity is 16.5%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 303

WELL ELEVATION: 2498 ft. DEPTH: 6865 ft.

MACROSCOPIC DESCRIPTION:

A light buff, porous, soft, very fossiliferous limestone. The rock is considerably fractured; the stylolites are well-developed. Foraminifera 2-4 mm. long are abundant.

MICROSCOPIC DESCRIPTION:

Rock is 60-70% fossil debris; many well-developed foraminifera are present. Spines and fragments of echinoderms are also plentiful, some showing partial replacement by silica. Porosity is estimated at 15% with numerous small pores well distributed; permeability is good. A few rounded or ellipsoidal oolites are present. The average size of fragments ranges from 0.1-0.4 mm.

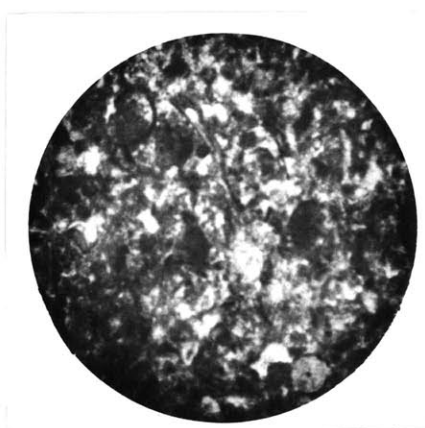
ACID RESIDUE:

Trace of oil; 0.5% of clear glassy quartz fragments.

CORE ANALYSIS DATA:

Permeability is 53 md. Porosity is 20.7%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: P.J. COLLINS #1 CORE: # 337

WELL ELEVATION: 2498 ft. DEPTH: 6899 ft.

MACROSCOPIC DESCRIPTION:

A light buff, even-grained, finely crystalline limestone. There are 3 directions of fractures visible, two shear and one tension. Porosity is very low except 2-4% along fractures. Stylolites are poorly developed.

MICROSCOPIC DESCRIPTION:

Rock is 25% fossil debris; 10% are large echinoderm fragments and the other 15% are large, well-preserved foraminifera. The total fossil content may be considerably higher as most of the smaller fragments are unidentifiable. Occasional oolites are present. Moderate recrystallization has occurred.

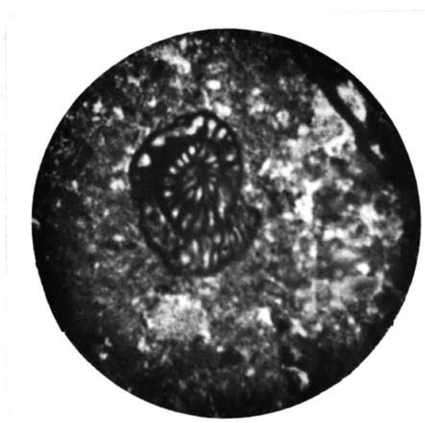
ACID RESIDUE:

Traces of oil; no other.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 3.7%.

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN #2

CORE: # 49

WELL ELEVATION: 2491 ft.

DEPTH: 6630 ft.

MACROSCOPIC DESCRIPTION:

A buff-brown, massive, fragmental limestone with many stylolitic seams. There is some clear, coarsely crystalline calcite along the fractures and stylolitic zone. Previous fractures are generally filled by this later calcite. Porosity variable from 5-10%; may be higher along the fractures. The overall permeability is probably low.

MICROSCOPIC DESCRIPTION:

Rock is 25% fossil debris; fragments of brachiopod shells are prominent. There are many rhombohedrons of calcite, some with twinning, concentrated along the fracture zones. The matrix is dense, very finely crystalline calcite.

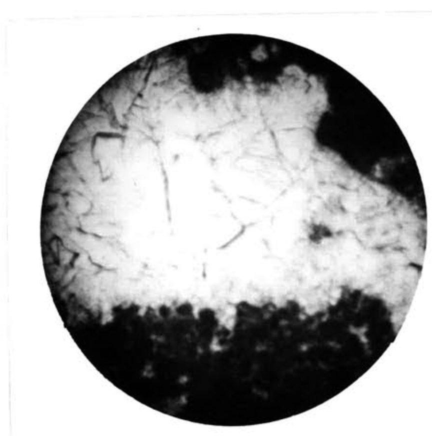
ACID RESIDUE:

Minor amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 1.6 md. Porosity is 12.1%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2

CORE: # 50

WELL ELEVATION: 2491 ft.

DEPTH: 6631 ft.

MACROSCOPIC DESCRIPTION:

A massive, coarsely crystalline, buff limestone showing considerable recrystallization. Fenestellate bryozoa and solitary cup corals are visible, a few small brachiopods (3-5 mm.) are present and there are many shell fragments. A few fractures are partially filled by clear calcite. The ground mass is brownish; the fossil material is recrystallized. Crude bedding (horizontal) is indicated by the attitude of shells. A variable pinpoint porosity is indicated of order of 8-12%; permeability is very low.

MICROSCOPIC DESCRIPTION:

Rock is 70% fossil debris; the fragments are 0.2-0.4 mm. in size, chiefly echinoderms and cup corals. There is an occasional oolite. The matrix is finely crystalline.

FOSSILS IDENTIFIED:

FENESTRELLINA(?), LOPHOPHYLLIDIUM(?).

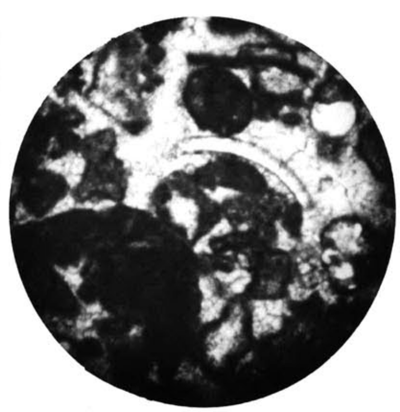
ACID RESIDUE:

Minor amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 1.3 md. Porosity is 13.3%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 | CORE: # 64

WELL ELEVATION: 2491 ft. | DEPTH: 6651 ft.

MACROSCOPIC DESCRIPTION:

An even-textured, medium granular, buff limestone. There are prominent vertical fractures. The fossil content is low but scattered fragments of brachiopods and foraminifera are visible. A variable pinpoint porosity estimated at 10-15%; pores are of the order of 0.5-1 mm; permeability is fair to good.

MICROSCOPIC DESCRIPTION:

Rock is about 15% recognizable fossil debris but much of the fine material is unidentifiable. Echinoderms and a few foraminifera are all that can be seen. The matrix is finely crystalline.

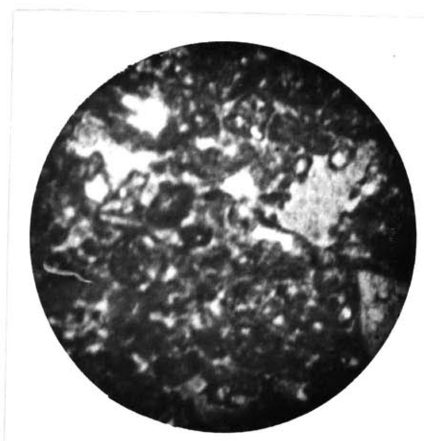
ACID RESIDUE:

2% of black oil; no other.

CORE ANALYSIS DATA:

Permeability is 10 md. Porosity is 17.4%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 70

WELL ELEVATION: 2491 ft. DEPTH: 6660 ft.

MACROSCOPIC DESCRIPTION:

A light brownish-gray, coarsely crystalline limestone with considerable recrystallization. There is a prominent stylolitic zone with strongly striated vertical columns. The rock is very fragmental with a large range in fragment size. Crinoid stems, a few foraminifera and a lone brachiopod shell are visible. The porosity is estimated at 5-10% and is probably higher along the fractures; the permeability is likely good.

MICROSCOPIC DESCRIPTION:

Rock is 60% fossil debris with irregularly packed fragments of crinoids, foraminifera, and brachiopods. The matrix is dense. Many fossil fragments are now coarsely crystalline calcite.

ACID RESIDUE:

Traces of a light gray clay; 1-2% of oily material.

CORE ANALYSIS DATA:

Permeability is 33 md. Porosity is 13.0%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 88

WELL ELEVATION: 2491 ft. DEPTH: 6687 ft.

MACROSCOPIC DESCRIPTION:

A dense, light gray, badly fractured limestone with considerable coarse calcite in the fractures. The most prominent set of fractures is vertical. The rock is coarsely fragmental with foraminifera up to 7 mm. long and crinoid stems up to ½" in diameter. The stylolitic zones are partially destroyed by later solution activity along them; coarse, clear calcite is concentrated along these solution channels. The porosity is variable, as high as 30% in places but averaging 10-15%; large vugs (over 1 mm.) are common. The permeability is fair to good.

MICROSCOPIC DESCRIPTION:

The rock is 55% fossil debris, chiefly coarse fragments of crinoids but with bryozoa and well-preserved foraminifera as well. There has been extensive recrystallization filling fractures and reducing the size of pores.

ACID RESIDUE:

1% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 5.2 md. Porosity is 14.3%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: A.L. WREN # 2

CORE: # 92

WELL ELEVATION: 2491 ft.

DEPTH: 6693 ft.

MACROSCOPIC DESCRIPTION:

A medium to coarsely crystalline, fragmental, buff limestone with a large amount of echinoderm debris. Two excellent stylolitic zones, 3" apart, are developed along the bedding. There are a few minor vertical fractures. Porosity is low and estimated at 1-3%; permeability is low to nil.

MICROSCOPIC DESCRIPTION:

The rock is 60% fossil debris, chiefly echinoderm fragments but with a few well-preserved foraminifera (fusulinids). There are scattered oolites. The stylolitic zones are very complex and have been partially destroyed by recrystallization.

ACID RESIDUE:

3-5% oil; 1-2% of gray clay.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 1.6%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: A.L. WREN # 2

CORE: # 98

WELL ELEVATION: 2491 ft.

DEPTH: 6702 ft.

MACROSCOPIC DESCRIPTION:

A buff-brown, fragmental limestone with vertical fractures. Considerable recrystallization is evident. Scattered foraminifera and crinoid stems are visible. Porosity is estimated at 8-10%; permeability is low.

MICROSCOPIC DESCRIPTION:

The rock is 35% fossil debris; there are abundant echinoderm fragments, some badly corroded. A few foraminifera are present; occasionally an ellipsoidal or flattened oolite can be seen. Moderate amounts of coarse calcite are confined to fossil fragments and edges of pore spaces.

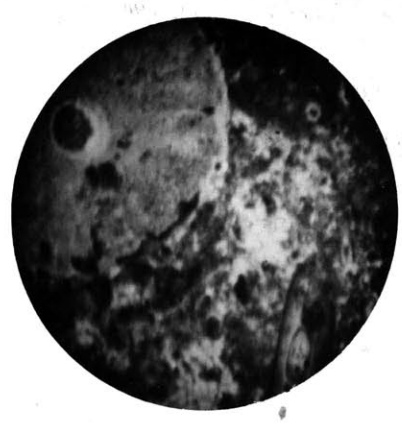
ACID RESIDUE:

1% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 0.2 md. Porosity is 12.6%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 101

WELL ELEVATION: 2491 ft. DEPTH: 6707 ft.

MACROSCOPIC DESCRIPTION:

A light buff, medium to coarsely fragmental limestone containing crinoid stems (up to 3/8" diameter) and imprints of small brachiopods. There are prominent stylolitic zones and poorly developed shear fractures. An irregular, vuggy porosity is estimated at 10-12%; low permeability is likely.

MICROSCOPIC DESCRIPTION:

The rock is 30% fossil debris, practically all echinoderm fragments but with an occasional foraminifera. There has been considerable recrystallization which has destroyed some old stylolitic zones and filled some of the fractures. The matrix is finely crystalline and shows some recrystallization.

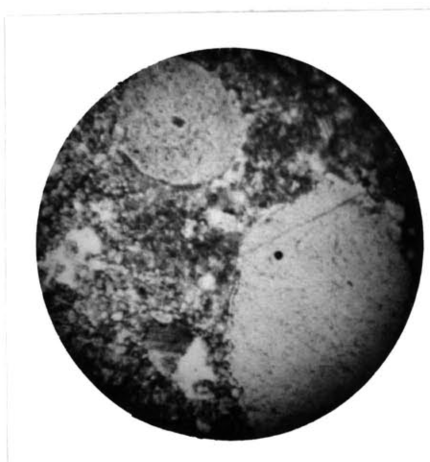
ACID RESIDUE:

0.5% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 1.6 md. Porosity is 13.3%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN #2 **CORE: # 102**

WELL ELEVATION: 2491 ft. **DEPTH: 6708 ft.**

MACROSCOPIC DESCRIPTION:

A buff, medium fragmental limestone containing a fenestellate bryozoa and crinoid fragments (up to $\frac{1}{2}$" diameter). There is an excellent stylolitic zone with striated columns. There are a few vertical fractures.

MICROSCOPIC DESCRIPTION:

The rock is 60% fossil debris, about half foraminifera and half echinoderms. A variable porosity is estimated at 5-15% with large vugs. Extensive recrystallization has occurred. The matrix is generally finely crystalline.

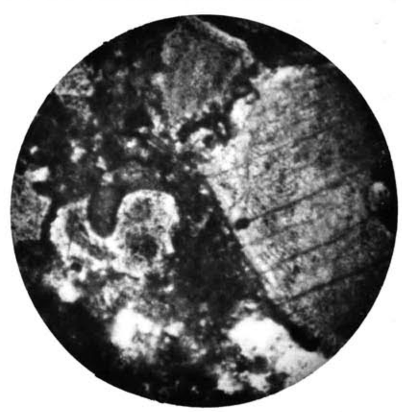
ACID RESIDUE:

2-3% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 2.2 md. Porosity is 16.7%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 103

WELL ELEVATION: 2491 ft. DEPTH: 6710 ft.

MACROSCOPIC DESCRIPTION:

A buff, fragmental limestone containing brachiopod and crinoid fragments. There are numerous vertical fractures and well-developed stylolitic zones lie along shear plane fractures. An irregular vuggy porosity is estimated at 10-15% and as high as 25% locally.

MICROSCOPIC DESCRIPTION:

The rock is 15% fossil debris, chiefly echinoderm fragments but occasionally a poorly-preserved foraminifera. There has been considerable recrystallization. The matrix is finely to medium crystalline.

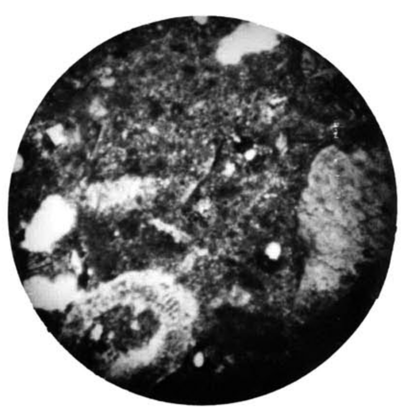
ACID RESIDUE:

2-3% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 1.6 md. Porosity is 13.9%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 118

WELL ELEVATION: 2491 ft. DEPTH: 6748 ft.

MACROSCOPIC DESCRIPTION:

A light grayish-buff, massive, medium crystalline limestone containing foraminifera and crinoid fragments. The matrix is dense; there are a few vertical fractures. The foraminifera are large and well-preserved. Recrystallization is of minor importance. There is an old stylolitic zone which is nearly destroyed. An irregular vuggy porosity is estimated at 10-15%; permeability probably very low.

MICROSCOPIC DESCRIPTION:

The rock is 15% fossil debris, chiefly worn, rounded fragments of echinoderms. There are fragments of a darker, dense limestone as well as the fossil debris set in a porous finely crystalline matrix. Minor coarse recrystallization has occurred along old fractures.

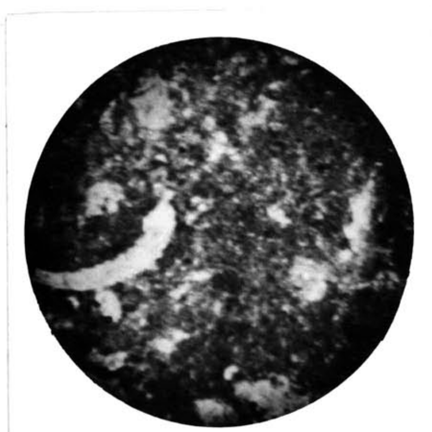
ACID RESIDUE:

0.5-1% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 1.9%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 124

WELL ELEVATION: 2491 ft. DEPTH: 6792 ft.

MACROSCOPIC DESCRIPTION:

A light brown, fossiliferous, foraminiferal limestone. There are no stylolites or fractures visible. Bedding is suggested by the attitude of the long axes of foraminiferal tests. Porosity is high in the interiors of shells but otherwise only 5-8%; the permeability is fair.

MICROSCOPIC DESCRIPTION:

The rock is 75% well-preserved fusulinids. There is considerable, medium to coarsely crystalline calcite filling the interiors of foraminifera; the matrix is finely crystalline. Occasional fragments of echinoderms and ellipsoidal oolites are present. The oolites show a psuedouniaxial cross under crossed Nicols. Both megalospheric and microspheric fusulinids are present; the microspheric forms predominate.

FOSSILS IDENTIFIED:

TRITICITES.

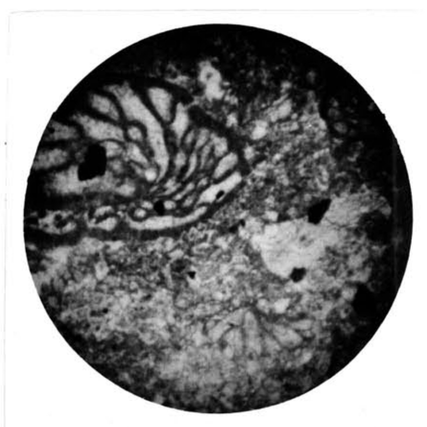
ACID RESIDUE:

3-5% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 7.2 md. Porosity is 10.7%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 | **CORE: # 126**

WELL ELEVATION: 2491 ft. | **DEPTH: 6795 ft.**

MACROSCOPIC DESCRIPTION:

A light brown, massive, fossiliferous, foraminiferal limestone. No fractures were seen; well-developed stylolites are present. There is an irregular vuggy porosity ranging from 5-12% but higher locally; permeability is fair to good.

MICROSCOPIC DESCRIPTION:

The rock is 60-65% fossil debris, almost entirely foraminiferal tests; a few echinoderm spines and crinoid stems are also present. The stylolitic zones are well developed along the bedding and occasionally along a shear fracture. Coarsely crystalline calcite fills the interiors of many foraminiferal tests as well as some of the original pore space. The matrix is dense, very finely crystalline calcite.

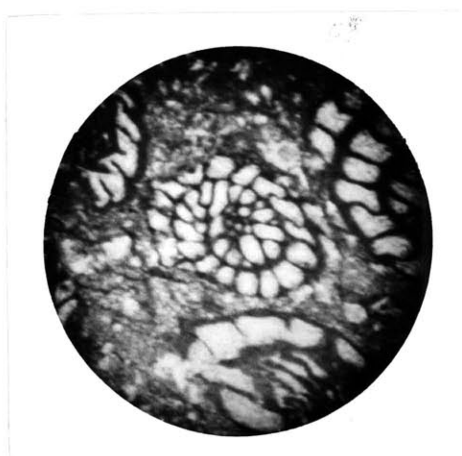
ACID RESIDUE:

1-2% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 23 md. Porosity is 16.5%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 127

WELL ELEVATION: 2491 ft. DEPTH: 6797 ft.

MACROSCOPIC DESCRIPTION:

A light gray, fossiliferous, foraminiferal limestone with minor vertical fracturing; rock is distinctly lighter in color than # 124 or #126. Many of the fractures are filled by a light gray material, probably clay. Porosity estimated at 5-10% but is higher along fractures and in the interiors of shells; permeability is fair.

MICROSCOPIC DESCRIPTION:

The rock is 50% fossil debris, chiefly foraminifera but also with fragments of echinoderms and brachiopods. There is considerable recrystallization of fossil debris; some coarsely crystalline calcite fills pore space and destroys a previous higher porosity. The matrix is finely to medium crystalline.

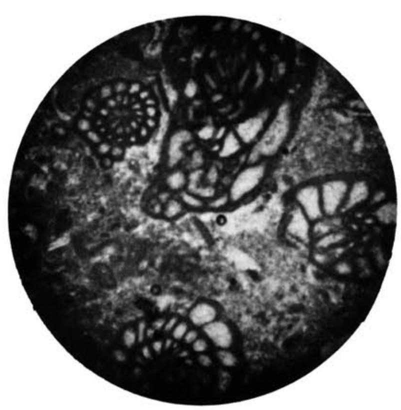
ACID RESIDUE:

1-3% of black oil; trace of gray clay.

CORE ANALYSIS DATA:

Permeability is 42 md. Porosity is 22.7%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2

CORE: # 141

WELL ELEVATION: 2491 ft.

DEPTH: 6818 ft.

MACROSCOPIC DESCRIPTION:

A buff, very fossiliferous, foraminiferal limestone containing some echinoderm fragments. Crude bedding (horizontal) is noted and there are many shear fractures. Irregular vuggy porosity is estimated at 12-15%; permeability is fair to good.

MICROSCOPIC DESCRIPTION:

The rock is 75% fossil debris, 10% of which is from echinoderms. The other 65% is foraminifera, most of which are fusulinids; there is one specimen of a calcareous triserial foraminifera. The rock shows moderate recrystallization. The matrix is finely crystalline.

ACID RESIDUE:

1% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 8.8 md. Porosity is 10.6%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 149

WELL ELEVATION: 2491 ft. DEPTH: 6830 ft.

MACROSCOPIC DESCRIPTION:

A light gray, dense, massive, fractured limestone with prominent vertical and shear fractures. Foraminifera and brachiopods are visible. The porosity is estimated at 10% but is better along fractures; permeability poor to fair.

MICROSCOPIC DESCRIPTION:

A very fragmental rock consisting about 80% of finely ground-up fossil fragments. There are a few well-preserved fusulinids; the bulk of the fossils are echinoderm fragments. There is considerable coarsely crystalline calcite concentrated along the fractures. The matrix is medium to finely crystalline calcite.

ACID RESIDUE:

0.5% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 5.6 md. Porosity is 12.0%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 150

WELL ELEVATION: 2491 ft. DEPTH: 6831 ft.

MACROSCOPIC DESCRIPTION:

A buff-brown, medium crystalline limestone with little evidence of fracturing. Foraminifera are the most prominent fossil. There is an irregular pinpoint porosity estimated at 8-10%; permeability probably fair to good.

MICROSCOPIC DESCRIPTION:

The rock is 50-60% well-preserved foraminifera in a finely crystalline to dense matrix. The porosity is confined largely to the foraminiferal tests; there is probably important intergranular porosity since the estimate is so much less than that measured in the core analysis data.

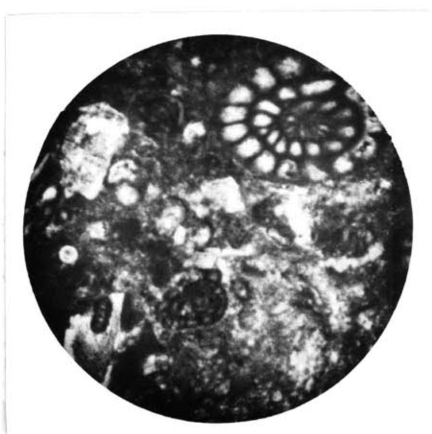
ACID RESIDUE:

1-3% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 18 md. Porosity is 18.8%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 152

WELL ELEVATION: 2491 ft. DEPTH: 6834 ft.

MACROSCOPIC DESCRIPTION:

A light gray, medium crystalline limestone with vertical fractures. There is a well-developed stylolitic zone with vertically striated columns. Many of the rock fractures are filled by calcite. The elements of the rock present a contorted appearance as if the rock had been subjected to flow. There is extensive recrystallization. Porosity is estimated at 3-5%; permeability poor.

MICROSCOPIC DESCRIPTION:

The rock is 40% fossil debris, mostly foraminifera but with some echinoderm fragments. There are several ages of stylolites and the stylolitic zones are generally well-developed.

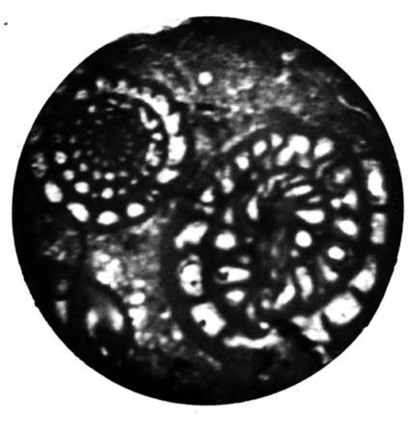
ACID RESIDUE:

Trace of oil; no other.

CORE ANALYSIS DATA:

Permeability is 2.4 md. Porosity is 10.3%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 153

WELL ELEVATION: 2491 ft. DEPTH: 6836 ft.

MACROSCOPIC DESCRIPTION:

A light gray, medium crystalline limestone very similar to # 152. The rock is considerably fractured and there has been extensive recrystallization. An older stylolitic zone has been nearly destroyed. Porosity estimated at 2-4%; permeability poor to fair. Most fractures are filled by coarsely crystalline calcite. The sample is apparently not representative of that analyzed for the core data.

MICROSCOPIC DESCRIPTION:

The rock is about 35% well-preserved foraminifera. There is considerable recrystallization irregularly disseminated and concentrated in and around foraminiferal tests. There are scattered oolites or psuedoolites.

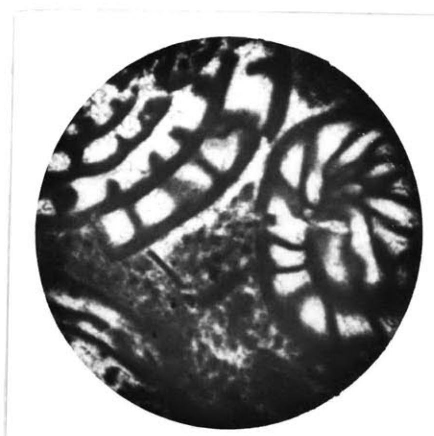
ACID RESIDUE:

No oil; 2% gray silty clay.

CORE ANALYSIS DATA:

Permeability is 88 md. Porosity is 15.2%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 178

WELL ELEVATION: 2491 ft. DEPTH: 6877 ft.

MACROSCOPIC DESCRIPTION:

A gray-brown, much fractured, fine to medium crystalline limestone with a well-developed, striated stylolitic zone parallel to the bedding. There are several directions of fracture visible. Patches of coarsely crystalline calcite can be seen filling fractures. There is an irregular vuggy porosity along solution channels that is hard to estimate but may be 8-10% or higher; permeability is fair.

MICROSCOPIC DESCRIPTION:

No fossil material identified. The stylolites show excellent detail. The distribution of the black matter along the stylolites suggests that much of the material has moved laterally in old solution channels and is not merely a residual accummulation. The large patches of coarsely crystalline calcite frequently show twinned crystals. The matrix is fine to medium crystalline.

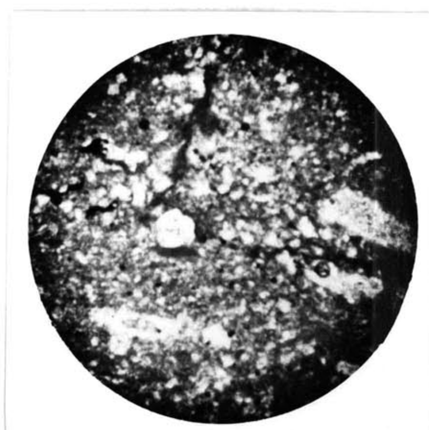
ACID RESIDUE:

No oil; black, coaly material from stylolitic zones.

CORE ANALYSIS DATA:

Permeability is 4.8 md. Porosity is 17.2%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 **CORE: # 179**

WELL ELEVATION: 2491 ft. **DEPTH: 6878 ft.**

MACROSCOPIC DESCRIPTION:

A brownish-gray, medium crystalline limestone with numerous vertical fractures and extensive patches of coarsely crystalline calcite along the fractures. Fractures run in several directions. Visible fossils include foaminifera and brachiopods. Porosity is estimated at 3-5%; permeability poor.

MICROSCOPIC DESCRIPTION:

The rock is 25-30% fossil debris, mostly echinoderm fragments. The stylolitic zone is rather simple and nearly flat. There is some coarsely crystalline calcite along the stylolitic zone as well as the fractures.

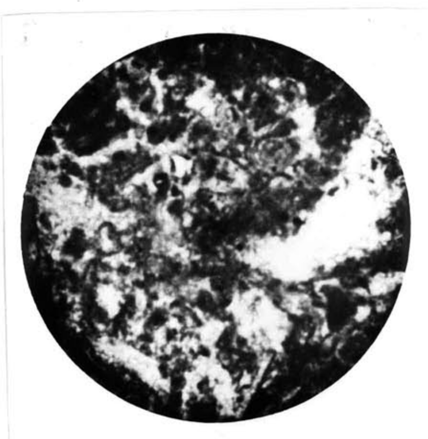
ACID RESIDUE:

2-3% of dark gray, fine silt; no oil.

CORE ANALYSIS DATA:

Permeability is 1.3 md. Porosity is 10.3%

PHOTOMICROGRAPH:



10X. Ordinary light.

WELL: A.L. WREN # 2 CORE: # 188

WELL ELEVATION: 2491 ft. DEPTH: 6892 ft.

MACROSCOPIC DESCRIPTION:

A massive, fractured, brownish-buff, medium crystalline limestone with extensive recrystallization. The most prominent fractures are vertical. There are poorly developed stylolites. Porosity estimated at 2-5% with widely disseminated pinpoint porosity; permeability fair to poor.

MICROSCOPIC DESCRIPTION:

The rock is 55% fossil debris, almost entirely echinoderm fragments with a few foraminifera. The matrix is fine to medium crystalline. The fossil content may be higher as many fragments are too small to identify.

ACID RESIDUE:

1-3% of oil; no other.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 3.1%

PHOTOMICROGRAPH:

10X. Ordinary light.

WELL: M.J. Womack #2 — CORE: # 15

WELL ELEVATION: 2445 ft. — DEPTH: 6680 ft.

MACROSCOPIC DESCRIPTION:

A gray-brown, brecciated limestone with fragments up to 20 mm. in diameter; the fragments are angular to sub-rounded. There are prominent, flat, irregular stylolites surrounding many of the fragments. The large fragments are either light gray or light brown with the brown being more numerous. Porosity was formerly good but is now low; permeability very poor. The porosity estimated at 1-3%. Some clear, coarsely crystalline calcite along old fractures.

MICROSCOPIC DESCRIPTION:

The rock is 75% fossil debris, being 35% foraminifera, 35% echinoderms and 10% bryozoa. The matrix is medium crystalline.

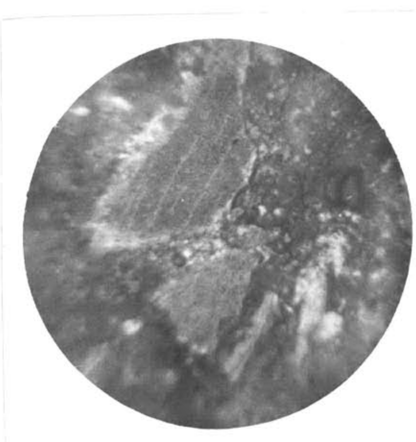
ACID RESIDUE:

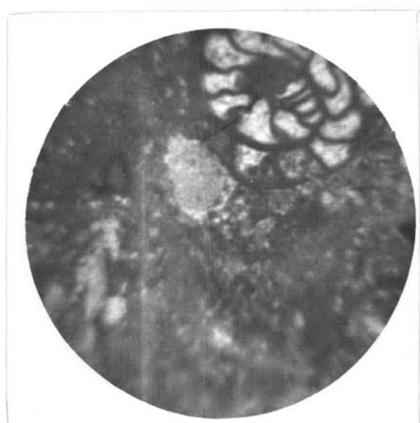
3-5% of dark, gray-brown clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 2.9%

PHOTOMICROGRAPHS:





15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 22

WELL ELEVATION: 2445 ft. DEPTH: 6687 ft.

MACROSCOPIC DESCRIPTION:

A light gray-white, porous, finely crystalline limestone. Rather spongy in texture, the rock is still well-consolidated. There are numerous vugs up to 1.5 mm. in diameter but averaging 1.0 mm. Porosity estimated at 10-15%; there may be poor interconnection of vugs.

MICROSCOPIC DESCRIPTION:

The rock is 25% fossil debris, 10% foaminifera, 10% echinoderms and a few fragments of brachiopod shells. The matrix is finely crystalline calcite. There is some dark petroliferous residue at the edges of pores.

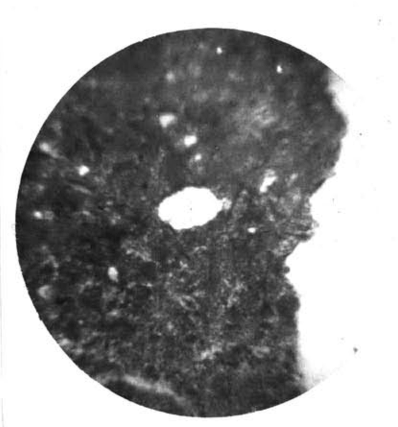
ACID RESIDUE:

Traces of oil; no other.

CORE ANALYSIS DATA:

Permeability is 21 md. Porosity is 13.3%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 24

WELL ELEVATION: 2445 ft. DEPTH: 6689 ft.

MACROSCOPIC DESCRIPTION:

A light, brownish-tan, much fractured, very finely crystalline limestone; many of the fractures are filled by light gray-white calcite. Some of the fractures, especially vertical are open. There are small areas of coarsely crystalline calcite. Except for fractures, porosity is estimated at 5%. There is a suggestion of bedding due to a horizontal streakiness in the coloring.

MICROSCOPIC DESCRIPTION:

The rock is very fragmental; fossil content estimated at 75%. Fusulinids are about 25%, echinoderms 20%, and the remainder is difficult to identify but may be of algal origin.

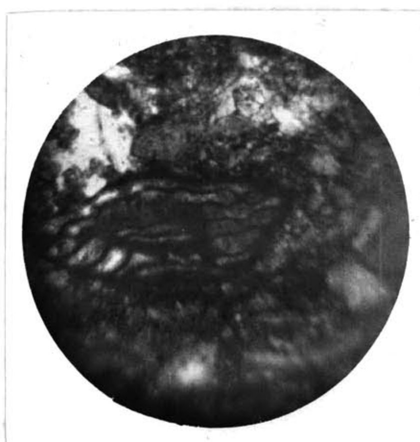
ACID RESIDUE:

Small amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 4,0 md. Porosity is 16.9%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 **CORE: # 34**

WELL ELEVATION: 2445 ft. **DEPTH: 6699 ft.**

MACROSCOPIC DESCRIPTION:

A light gray, smooth, fine-textured limestone. Two prominent, sharply serrated, stylolitic seams present. There are a few well-preserved foraminifera visible. Porosity is irregular and vuggy; it is estimated at 5-8%. Permeability probably poor.

MICROSCOPIC DESCRIPTION:

Rock is about 75% fossil debris. It consists of 10% fusulinids, mostly benthonic but with an occasional triserial pelagic form. About 25% of the rock is echinoderm fragments; the remainder is largely unidentifiable but may be partly of algal origin. The matrix is finely crystalline calcite.

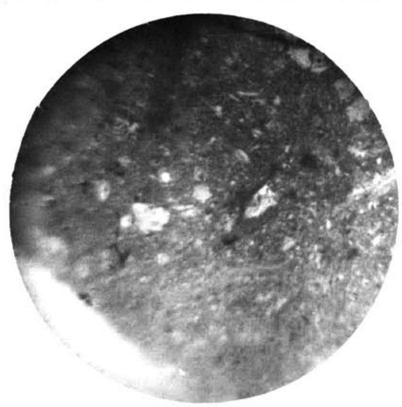
ACID RESIDUE:

Minor amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 7.9%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 **CORE:** # 37

WELL ELEVATION: 2445 ft. **DEPTH:** 6702 ft.

MACROSCOPIC DESCRIPTION:

A light gray, fine-textured limestone with some vuggy porosity. The porosity is variable and ranges from 5% to 30% in the more open areas. Permeability is fair to good. There are a few crinoid stems and several well-preserved foraminifera.

MICROSCOPIC DESCRIPTION:

Rock is 65% fossil debris, 35% foraminifera and 30% echinoderms. The matrix is finely crystalline calcite. Some vuggy porosity.

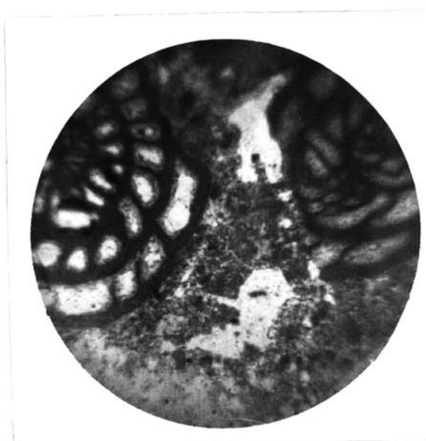
ACID RESIDUE:

None.

CORE ANALYSIS DATA:

Permeability is 44 md. Porosity is 10.5%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 38

WELL ELEVATION: 2445 ft. DEPTH: 6703 ft.

MACROSCOPIC DESCRIPTION:

A light gray-brown, medium crystalline limestone. There is a considerable vuggy porosity estimated at 15%; the vugs are up to 2 mm. in diameter. Permeability fair to good. Irregular scattered masses of petroliferous residue in the vugs.

MICROSCOPIC DESCRIPTION:

The rock is 65% fossil debris, 40% foraminifera, 20% echinoderms and 5% bryozoa. Both pelagic and benthonic foraminifera are present. The matrix is medium crystalline calcite.

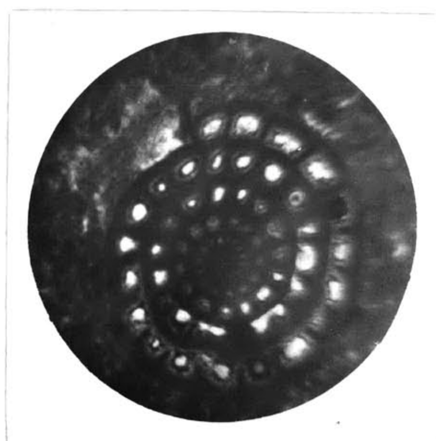
ACID RESIDUE:

1-2% of dark brown clay; trace of oil.

CORE ANALYSIS DATA:

Permeability is 19 md. Porosity is 11.7%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 39

WELL ELEVATION: 2445 ft. DEPTH: 6704 ft.

MACROSCOPIC DESCRIPTION:

A light brown, medium crystalline limestone with irregularly scattered masses of coarsely crystalline calcite. Porosity estimated at 10-12% with vugs up to 1 mm. in diameter. There are prominent horizontal, serrate stylolitic zones. Some petroliferous residue in vugs and along solution channels. Permeability fair.

MICROSCOPIC DESCRIPTION:

The rock is about 65% fossil debris, 30% foraminifera, 30% echinoderms and 5% bryozoa. The matrix is finely crystalline calcite.

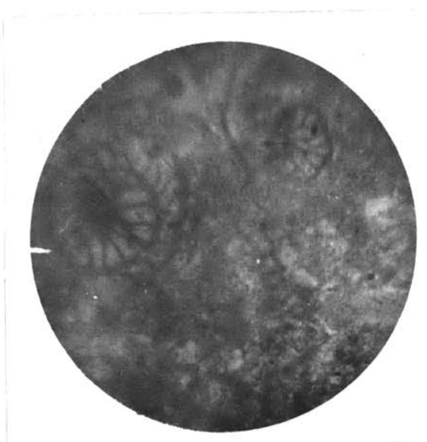
ACID RESIDUE:

Minor amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 12 md. Porosity is 8.9%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 53

WELL ELEVATION: 2445 ft. DEPTH: 6718 ft.

MACROSCOPIC DESCRIPTION:

A dark. gray-brown, dense limestone with irregular, angular, white masses up to 6 mm. in diameter. The rock is thin-laminated and separates into sheets or plates 1-5 mm. thick. The rock is considerably fractured and fractures filled by fine white calcite; both horizontal and vertical fractures are present. Porosity estimated at 1-3% and permeability low to nil.

MICROSCOPIC DESCRIPTION:

The rock is 85% fine debris, some unidentifiable. Well-preserved foraminifera are about 25-30% of the rock and echinoderm debris is about 20%. Clay bands are present; probably indicate bedding.

ACID RESIDUE:

3-5% dark gray clay; no oil.

CORE ANALSYSIS DATA:

Permeability is 0. Porosity is 1.2%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 57

WELL ELEVATION: 2445 ft. DEPTH: 6822 ft.

MACROSCOPIC DESCRIPTION:

A gray-brown, sandy-textured, even granular limestone with a few small vugs. Porosity is estimated at 6-8%; permeability fair.

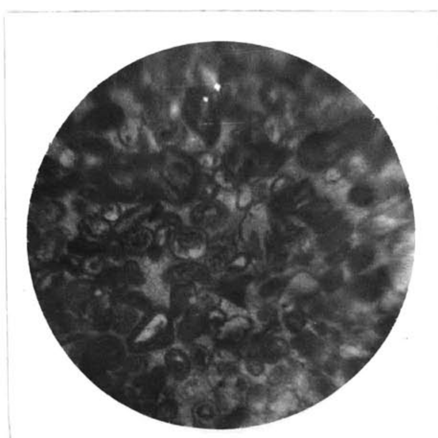
MICROSCOPIC DESCRIPTION:

A foraminiferal limestone with 65% single-chambered, pelagic foraminifera. The rock is also about 10% oolites and has some small unidentified globular masses. The matrix is very finely crystalline. Occasionally small fragments of echinoderms and brachiopods are present.

ACID RESIDUE:

Traces of gray clay; no oil.

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 | CORE: # 58

WELL ELEVATION: 2445 ft. | DEPTH: 6723 ft.

MACROSCOPIC DESCRIPTION:

A gray, sandy limestone with vuggy porosity. Sample is similar to core #57. Overall porosity estimated at 10%; permeability fair.

MICROSCOPIC DESCRIPTION:

The rock is about 40% recognizable fossil debris, 25% echinoderms and 15% fusulinids. There are a few oolites and a large number of small globular masses which may be of organic origin. Matrix is fine to cryptocrystalline calcite.

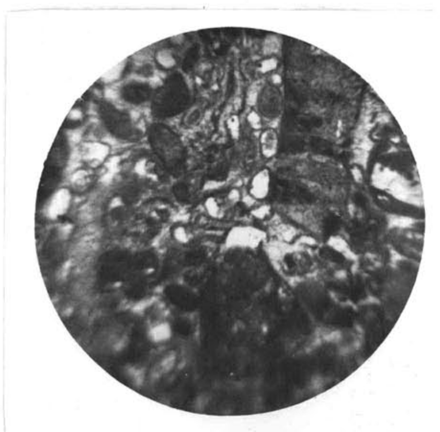
ACID RESIDUE:

1% of gray-brown clay; trace of oil.

CORE ANALYSIS DATA:

Permeability is 3.7 md. Porosity is 13.1%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2

CORE: # 72

WELL ELEVATION: 2445 ft.

DEPTH: 6737 ft.

MACROSCOPIC DESCRIPTION:

A light gray-brown, dense limestone. The rock is much fractured with many of the fractures filled by whitish calcite. The most prominent fractures are vertical. There is one, flat stylolitic zone with minor serrations along it. Porosity is estimated at 1-2% and permeability very low.

MICROSCOPIC DESCRIPTION:

The rock is made up of extremely fine fragments and is similar in appearance to a chalk. Fossil content is around 35% with 10% fusulinids and 20% echinoderms. Little to no recrystallization.

ACID RESIDUE:

None.

CORE ANALYSIS DATA:

Permeability is 0.   Porosity is 1.3%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 79

WELL ELEVATION: 2445 ft. DEPTH: 6774 ft.

MACROSCOPIC DESCRIPTION:

A light gray, crystalline limestone with a more or less sandy texture. The rock is much fractured and there is considerable petroliferous residue along the fractures. Porosity estimated at 8-10%, about half in vugs of 0.5 mm. diameter and the rest intergranular. Permeability fair to good.

MICROSCOPIC DESCRIPTION:

Fossil content about 40%, 10% echinoderms and 25% fusulinids; there are occasional triserial pelagic forams. The rock may contain some coral fragments but there has been too much recrystallization to be certain. Well-developed stylolites are present. There are many rounded masses of calcite similar in size and shape to oolites. Much former pore space is now filled by coarsely crystalline calcite.

ACID RESIDUE:

3-5% of a dark gray clay; trace of oil.

CORE ANALYSIS DATA:

Permeability is 11 md. Porosity is 10.8%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 92

WELL ELEVATION: 2445 ft. DEPTH: 6757 ft.

MACROSCOPIC DESCRIPTION:

A hard, dense, dark gray, considerably fractured limestone. One minor, flat stylolitic zone. Large areas of clear, brownish-white, coarsely crystalline calcite in the sample. Porosity estimated at less than 2% and permeability poor.

MICROSCOPIC DESCRIPTION:

Fossil content is difficult to determine but is probably under 30%. Fossils include 5% bryozoa, about 20% small unidentified rod-like masses and 5% foraminifera. The matrix is largely cryptocrystalline and shows only slight recrystallization. The fossil fragments have been much recrystallized and are largely unidentifiable.

ACID RESIDUE:

1-2% of gray clay; trace of oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 0.8%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2

CORE: # 98

WELL ELEVATION: 2445 ft.

DEPTH: 6763 ft.

MACROSCOPIC DESCRIPTION:

A light gray, medium crystalline limestone with a sandy texture. There are open horizontal fractures. Many small, widely disseminated vugs (less than 1 mm.) are present. Variable porosity which ranges from an estimated 3% in the denser areas to 20% in the more porous areas; permeability from poor to good.

MICROSCOPIC DESCRIPTION:

The rock has a low fossil content estimated at 10% but extensive recrystallization may have destroyed some fossil material. At present the rock contains 5% bryozoa and 5% pelagic foraminifera. There are dark, irregular-shaped masses throughout the rock. Much of the rock consists of medium-sized crystals of calcite.

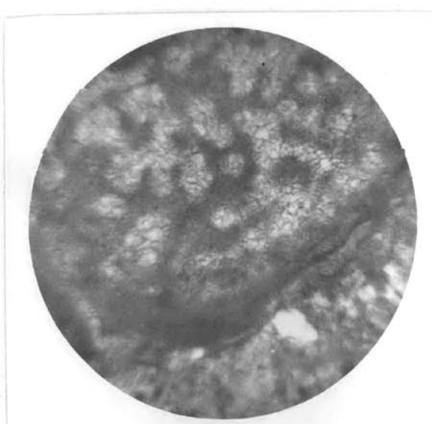
ACID RESIDUE:

Moderate amounts of oil; no other.

CORE ANALYSIS DATA:

Permeability is 12 md.   Porosity is 10.7%

PHOTOMICROGRAPH:



15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 109

WELL ELEVATION: 2445 ft. DEPTH: 6774 ft.

MACROSCOPIC DESCRIPTION:

A brownish-gray, oolitic, vuggy limestone. Porosity is very variable and estimated to range from 2-25% but generally about 10%. Permeability is likely to be poor as the vugs appear to be unconnected.

MICROSCOPIC DESCRIPTION:

The rock is very oolitic. Oolites are formed as concentric layers around (1) small rounded fragments of calcite, and (2) small fossils and fossil fragments. The fossil content is around 20% with bryozoa, foraminifera, and brachiopods being most noticeable. The matrix makes up about 65% of the rock and consists of medium to coarsely crystalline calcite with a few good calcite rhombohedrons present. Porosity is confined largely to fractures and to the nuclei of oolites.

ACID RESIDUE:

1-2% of a light gray clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0.2 md. Porosity is 6.6%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 164

WELL ELEVATION: 2445 ft. DEPTH: 6835 ft.

MACROSCOPIC DESCRIPTION:

A dark gray and light brown, mottled, brecciated limestone being half light brown and half dark gray limestone. There are many large open vugs (over 5 mm. in diameter) along old solution channels. Coarse calcite crystals line many of the openings. The rock has been considerably fractured. Porosity and permeability both estimated fair to good. Fractures run in all directions but the vertical ones are the most prominent.

MICROSCOPIC DESCRIPTION:

The rock is about 25% fossil debris, being 15% echinoderms and 10% bryozoa. There are prominent serrated stylolitic seams. Areas of clear, coarsely crystalline calcite fill older openings. Sample contains one large concentic oolite (2.2 mm. diameter).

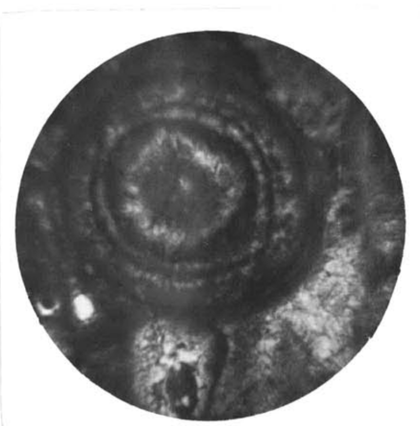
ACID RESIDUE:

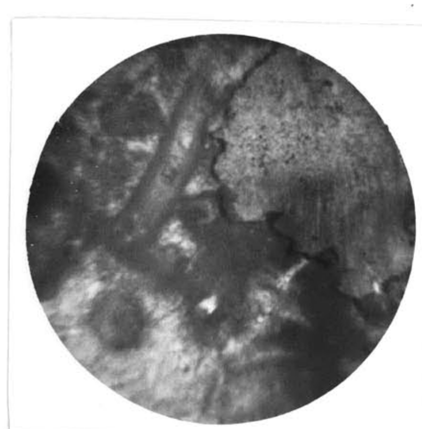
2-3% dark gray clay; no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 1.7%

PHOTOMICROGRAPHS:





15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 183

WELL ELEVATION: 2445 ft. DEPTH: 6858 ft.

MACROSCOPIC DESCRIPTION:

A dense, finely crystalline, gray-brown limestone with horizontal fractures. The fractures are normally filled by white calcite. A great deal of solution work and recrystallization is evident. The rock has large cavities, some of 4" diameter, lined with large calcite crystals (scalenohedrons) up to 5/8" long. The interiors of the large vugs are stained by oil. Overall porosity impossible to gauge; it is only 1-3% in the denser portions.

MICROSCOPIC DESCRIPTION:

Rock contains about 35% irregular, light buff masses with a laminated structure; may be algal in origin. The matrix is very coarsely crystalline calcite with many excellent rhombohedrons showing twinning. Bryozoan fragments make up 5-10% of the rock. Definitely identified fossil fragments are only about 10% of the rock.

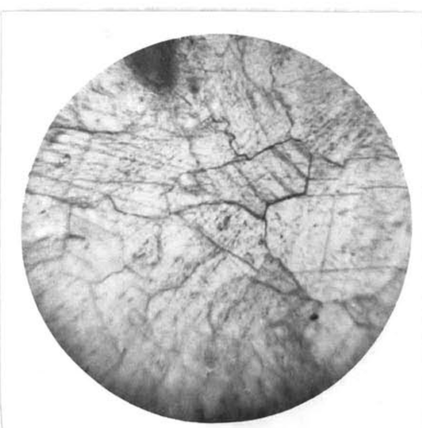
ACID RESIDUE:

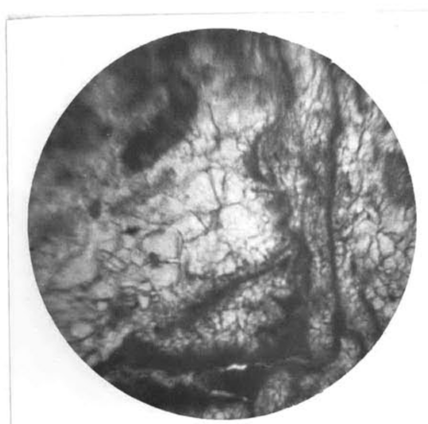
2-3% of dark gray clay; little to no oil.

CORE ANALYSIS DATA:

Permeability is 0. Porosity is 1.2%

PHOTOMICROGRAPHS:





15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 190

WELL ELEVATION: 2445 ft. DEPTH: 6865 ft.

MACROSCOPIC DESCRIPTION:

A very fossiliferous, loosely-cemented, brachiopod limestone (probably a former coquina). There are several types of brachiopods, one a small species of the Productid type. The larger specimens are about 5/8" by 1/2". All shells are set in a slightly argillaceous, dense matrix giving the rock a mottled appearance on a polished surface. The rock is tan-gray in color and contains numerous vugs and cavities, some up to ½" diameter.

MICROSCOPIC DESCRIPTION:

The rock is 20-25% shell fragments. The interiors of the shells and former pore space is largely filled by coarsely crystalline calcite. The matrix is finely crystalline. There are numerous oolites and psuedoolitic masses. Some shells have or had an old mud fillings making these areas slightly darker in color.

ACID RESIDUE:

1-2% gray clay; moderate amounts of oil.

CORE ANALYSIS DATA:

Permeability is 1.8 md. Porosity is 11.1%

PHOTOMICROGRAPH:

15X. Ordinary light.

WELL: M.J. Womack #2 CORE: # 203

WELL ELEVATION: 2445 ft. DEPTH: 6883 ft.

MACROSCOPIC DESCRIPTION:

A light tan-gray, fossiliferous limestone with many small vugs. Some of the vugs are lined with small calcite crystals. The rock is considerably fractured and has a brecciated appearance. Porosity estimated at 5-8% with permeability low to fair. Excellent stylolites with small openings irregularly developed along them. The brecciated appearance is due to a close packing of fossil fragments, $\frac{1}{4}$-$\frac{1}{2}$" in size.

MICROSCOPIC DESCRIPTION:

Rock is about 75% fossil debris; forams are the most prominent and are about 35% of the rock, bryozoa 20% and echinoderms 20%. An old solution channel has been filled by small rounded grains of calcite sand. There are occasional areas of coarsely crystalline calcite. Rock is very heteroegenous in overall appearance.

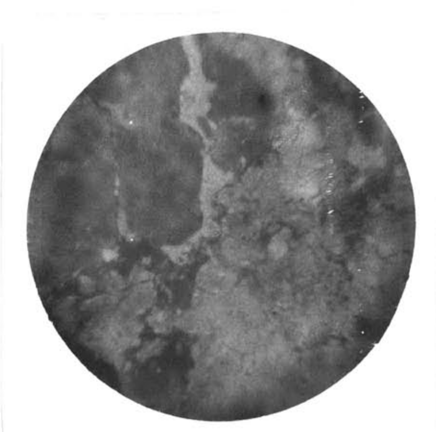
ACID RESIDUE:

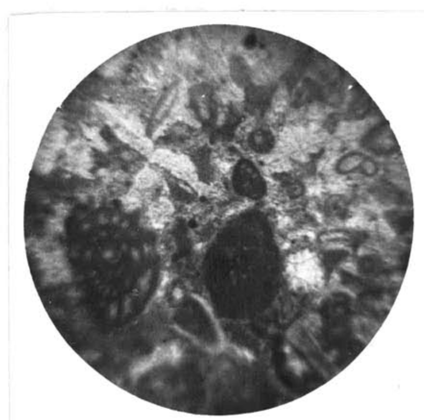
2-3% of a dark gray-brown clay; moderate amounts of oil.

CORE ANALYSIS DATA:

Permeability is 10 md. Porosity is 9.0%

PHOTOMICROGRAPHS:





15X. Ordinary light.