AN INVESTIGATION OF SUBSURFACE REEF CONDITIONS IN THE TRAVERSE GROUP OF MICHIGAN

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

William Waldo Henry

1949

This is to certify that the

thesis entitled

An Investigation of Subsurface
Reef Conditions in the Traverse Group
of Michigan

presented by

William Waldo Henry

has been accepted towards fulfillment
of the requirements for

M. S. degree in Geology

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Date November 15, 1949

AN INVESTIGATION OF SUBSURFACE REEF CONDITIONS

IN THE TRAVERSE GROUP OF MICHIGAN

By

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A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology and Geography

THESIS

ACKNOWLEDGEMENTS

To Dr. W. A. Kelly of Michigan State College, the writer expresses thanks for directing the study, use of laboratory space and criticism of the manuscript. Acknowledgements are made to Mr. E. J. Baltrusaitis and Mr. K. A. Gravelle of the Gulf Refining Company, Mr. W. W. Turnbull of the Carter Oil Company and Mr. K. G. Walsworth and Mr. G. W. Straight of the Michigan Geological Survey for assistance in obtaining samples, maps, electric logs and diamond-cut cores so essential to the accomplishment of the study. The manuscript has been read by Dr. S. G. Bergquist and Dr. B. T. Sandefur, both of whom offered helpful suggestions for its improvement.

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INTRODUCTION

Reef limestones are becoming increasingly important to the petroleum geologist and present interesting problems in stratigraphy. Twenhofel, (1949, p. 61) suggests that future exploration for oil in the United States and Canada will place much emphasis on the finding and development of oil-bearing reefs. The organic structures known as reefs have been built somewhere in every geologic period since the beginning of the Huronian. During Paleozic time many such reefs were formed in the areas of our present mid-western states. This is particularly true for the Silurian and Devonian periods.

As early as 1901, A. W. Grabau (1903, p. 340), reported reefs in the Traverse Group (Middle Devonian) of Michigan. His account was based on observations in the Traverse outcrop area in the northern part of the Lower Peninsula, specifically, in the vicinities of Alpena, Charlevoix and Petoskey (Fig. 1).

Grabau's diagram of an Alpena reef (1913, p. 427), however, leaves some doubt as to what he actually saw and to what he inferred to be present.

So far as the writer is aware, the subsurface occurrence of reefs in the drift-covered part of Michigan has never been substantiated. In Central Michigan, Hake and Maebius (1938, p. 454) interpret several thick zones of dense, even-textured, light-colored limestone as reefs but their observations, based on lithology alone, are insufficient to establish the zones as reefs.

Records of wells in Southwestern Michigan make frequent reference to reef-like material in samples, and much of the oil production in this

Michigan area is believed to be from reef reservoirs. This belief however remains unproven due largely to a paucity of information.

Oil companies are constantly studying their oil reservoirs, to most efficiently extract the oil. The reef-like producing zones are studied as any other, but are not necessarily examined for reef criteria, due to time limitations, as has been done in this investigation.

This thesis is a report of research and laboratory study of subsurface "reefs" in the Traverse Group of Michigan with emphasis on the Pentwater Oil Field of Oceana and Mason Counties (Fig. 1). When possible, examinations were made at Michigan State College but additional time was spent in the Gulf and Carter laboratories examining samples and electric logs not available for loan.

PURPOSE OF THE STUDY

The purpose of the investigation is to examine the Traverse Group in the Pentwater Field, where a possible reef structure exists, to search particularly for reef criteria, and to cite other areas in the same stratigraphic horizon where similar conditions are likely to occur. A comparison with known reef producing fields outside of Michigan is also made.

The study is timely and should prove of economic value in view of recent interest for Traverse production in Western Michigan by major oil companies. Kimball Lake, Newago County, Pentwater and Stoney Lake, Oceana County, are termed reef-like producing pools in company reports submitted to the Michigan Geological Survey. To establish or disprove these porous zones as Devonian reefs would be of consequence to the producer as well as to the student of stratigraphy. If the porous zones prove to be reefs, a pattern should be expected that would serve as a guide in future exploration.

It is hoped this study may serve as a step toward further research on the problem.

DEFINITION OF REEF

The frequent use of reef in this paper warrants a slight digression to clarify the often misused term.

According to Twenhofel (1949, p. 61), a reef represents a deposit that is mainly of organic origin and has been built upward at a more rapid rate than the contemporaneous sediments deposited about its margins. He recognizes two types of reef building organisms: (1) those that build the framework of the core (colonial corals, algae and sponges, some crinoids), and (2) those which fill the space within the framework (non-colonial algae, corals, sponges, mollusks, brachiopods, bryozoans and foraminifera). He adds that ancient reefs were mostly in the form of isolated ridges of somewhat limited dimension and unlike modern reefs of great length and limited width and should be sought in every great calcareous formation.

Cumings (1932, p. 337) defines the reef core as follows:

> "A ridge-like, mound-like or tower-like unstratified mass made up of fragments of organisms, embedded in a matrix of triturated and macerated sand and mud; and often so completely diagenized and dolomitized that most of the original organic structures have been destroyed."
>
> He continues, "It has a massive, rough and porous, often cavernous or loose appearance and usually a pronounced vertical cleavage or jointing. In composition it is either a pure carbonate of lime or dolomite. In fact, any unbedded pure calcareous rock with minute insoluble residue may be suspected of being reef rock."

Cumings and Shrock, (1932, p. 333), working with Silurian reefs of Northern Indiana, introduced the term bioherm for organic accumulations having the conventional form and internal structure of a reef, and biostrome for stratified organic accumulations which are not in the form of mounds or ridges and do not have noteworthy differences in thickness from marginal accumulations. Specifically, they suggest the use of bioherm for reef-like, mound-like, lens-like or otherwise circumscribed structures of strictly organic origin, embedded in rocks of different origin.

The above defined terms are seldom used by petroleum geologists. They prefer the descriptive term "build up" to denote the form of a bioherm.

In writing about the Alpena outcrop area, Warthin and Cooper, (1943, p. 586) explain bioherms by the following paragraph:

> "During the time of deposition of the upper part of the Alpena Limestone conditions still favored the growth of corals and stromatoporoids, but this growth did not proceed evenly over the entire bottom. In areas of limited extent the organisms grew in abundance and to large size, but otherwise the colonies were few and small. The cause of this condition is not definitely known. A slight deepening of the water may have killed off all but a few scattered colonies which were able to survive and grow upward into their customary depth. A slight shoaling of the water might produce the same effect, the increased wave action destroying many of the colonies and burying others beneath debris. Whatever the cause, it fostered growth of the colonies in scattered groups, producing small knobs on the sea floor. Each knob, together with its immediately flanking sediments, is a bioherm, and the aggregation of knobs is probably best called a reef. It has not been demonstrated, however, that the platform on which the knobs grew was actually raised above the general sea bottom, as is usual in present day reefs.
>
> Within the core of the bioherm there is no definite bedding of the limestone, this being obscured by the jumble of coral and stromatoporoid colonies and their debris. As this material is in the nature of a breccia it naturally follows that the unbedded core is more porous than the flanking sediments. This porosity is increased by the abundant natural openings within the fossils themselves."

Two descriptive terms, detrital and lithographic, are used in referring to the character of encountered limestones. Rice (1949, p. 103) defines detrital rock as a rock made up of the debris of other rock. According to Van Ingen (p. 6), lithographic limestone is fine-grained, homogeneous, conchoidal-fracturing, pure limestone, with few organic remains.

CRITERIA FOR THE IDENTIFICATION OF REEFS

Many criteria have been used for establishing the existence of subsurface reefs. Notable among these are the following:

(1) Lack of bedding within the reef core.

(2) Irregular form of the reef proper.

(3) An existence of a "build up".

(4) A change in facies of contemporaneous marginal sediments.

(5) Inclined flanking strata with well-defined bedding which grade radially into the crudely stratified peripheral margins of the core.

(6) High porosity of the central core, the result of fossil voids, its original brecciated nature and later leaching by percolating waters which in many cases have favored complete dolomitization.

(7) Abundant fauna of all classes of organisms but few individuals.

(8) Random orientation of corals in the flank deposits of the reef.

Positive evidence for a lack of bedding in Unit Two is not cited because only two drill cores were available. The lack of bedding in the cores examined does not preclude the possibility that a study of additional cores might prove or disprove this criterion. Lowenstam (1948, p. 174) in describing the Marine Pool, Madison County, Illinois, employs this criterion and writes that the reef core rocks are massive and lack recognizable bedding. Layer (1949, p. 592) describes the D-3 zone of Devonian age in the Leduc Field, Alberta, Canada, as a uniform, massive, highly porous dolomite with a complete lack of bedding.

The irregular form of a reef connotates both vertical and lateral expressions of irregularity. Pentwater's exhibition of this criterion is best shown in Figure 8. Abrupt vertical changes in all directions are noted in Unit Two from Well 9, functioning as the axis of the drawing. Vertical irregularity is best shown between Wells 9 and 10; 10 and 11; 15 and 16; and Wells 1 and 2. An approximate slope of three percent between Wells 9 and 10 is noted. Lateral irregularity is shown in Figure 4a where the -920 foot contour approximately delineates the present producing area of Unit Two.

The Marine Pool reef is expressed on a Silurian isopach map by Lowenstam (1948, p. 167) as an insular area of abrupt thickening, thus utilizing the "build up" criterion in his study. Layer (1949, p. 591) finds it probable that Leduc's D-3 zone thins from 600 feet to 200 feet in a distance of two and one-half miles, again suggesting a "build up". The same criterion applies to Unit Two. Figure 8 shows definite thinning in all directions from Well 9 toward the margins except at Well 13 where the eastward extension continues to be structurally high.

Verhoeven (1948, p. 25) cites the presence of a reef in the Afton-

Onaway area of Michigan as an explanation of the change in facies of contemporaneous sediments. The lagunal deposits are sublithographic, light-colored, dense and stylolitic limestone. On what is believed by Verhoeven (1948, p. 25) to be the seaward side, the limestone is dark-colored and detrital in character as a result of wave action upon the reef. Grabau (1913, pp. 437-442), cites this condition to be true in the Solenhofen region of Bavaria. An unsuccessful attempt to delineate the Pentwater Unit Two on the basis of these lithologic changes was made by the writer. Verhoeven's method remains as a possible attack if adequate marginal wells are drilled in the Pentwater Field.

Three facies complexes are recognized by Lowenstam (1948, p. 159) in the Marine Pool. Two are regional. A third, and local facies, is the reef complex, which, in the pool area entirely replaces the upper regional facies, and partially the lower regional facies.

Another characteristic of the Marine Pool reef deposits is found in the bedding relationship. All of the reef-flank beds are inclined, with dips ranging from 20° to 45°. Slopes of this magnitude are not found in Pentwater's Unit Two. The greatest probable slope in this zone would be in the vicinity of Well 10 (Fig. 8) where a 26-foot vertical thinning in a 330-foot horizontal distance approaches eight percent. (See Fig. 4a)

Unit Two's high porosity is shown by Figure 9 and is substantiated by studies of the Gulf Refining Company (1949, Personal Communication). The porosity appears similiar to that of the Marine Pool which is principally developed around fossil cavities that were enlarged by solution and along numerous intersecting fractures. The Marine and Pentwater Pools differ because the sediments in the former are completely dolomitized and are not in the latter. According to Layer (1949, p. 590), the D-3 zone of the Leduc pool is dolomitized with many vugs and intercrystalline porosity and numerous open fractures.

Few individuals but many classes of organisms is a criterion of reefs suggested by Van Ingen. However, Lowenstam (1948, p. 174) finds the fossil constituents of the Marine Pool reef facies contrasting sharply in size, physical appearance, and abundance with those of the normal facies surrounding the reef. Aside from their physical appearance the reef fauna can be recognized in cuttings by the relative abundance of colonial corals such as _Favosites_ and _Halysites,_ of stromatoporoids, and of heavy-shelled pentameriod brachiopods. This is true to a lesser extent in Unit Two where stromatoporoids and _Favosites_ only can be called abundant.

Lowenstam (1948, p. 174) cites the random orientation of many fossils in the flank deposits as a diagnostic feature of cores, the dip slope of the reef flanks commonly being shown by the inclined colonial corals. This criterion was observed in one Unit Two core but is hesitatingly offered as positive evidence because core examination was limited.

Cuming's (1932, p. 337) suggestion that any carbonate rock with minute insoluble residue might be suspected of being reef rock led to an investigation of all the samples from two wells (Figs. 10 and 11) by means of insoluble residues. It was thought that such a study might correlate with the graphic and electric logs and consequently substantiate by a third means the validity of the unit divisions.

The Gulf Refining Company's Mary Paulsen No. 4 Well (Fig. 10) was selected for its location high on the Unit Two structure; The Carter Oil Company's W. Johnson No. 2 Well (Fig. 11) for its structurally low position.

In general, the method used by Eddy (1933, p. 347-348) was employed in this investigation. Tests were limited to two grams of sample for each 10 foot vertical interval. Results are shown by bar graphs (in black) in

Figures 10 and 11.

For control, two samples from Michigan outcrops were tested. One from a reef of the Alpena Formation left no measurable residue from 20 grams. The other sample, of detrital origin, was from the Norway Dam Formation. The insoluble portion of this sample amounted to 75 percent. The residue was predominently silicified fragments of brachiopods; crinoids, and corals, with a minor portion being clay-sized material containing minute pyrite crystals.

Results of these tests of Pentwater well cuttings reveal little correlation with electric and graphic logs. No notable difference in the insoluble residues were detected by examination under the binocular microscope despite their differing structural locations.

Unit Two is characterized by less insoluble material than any of the lithologic zones above or below it. In both wells, the residue was entirely argillaceous except low in the unit where a slight amount of delicate siliceous aggregate was noted. The percentage of insolubles in the unit varies from less than one percent to 22.6 percent.

No distinguishable difference is shown by percentage representation in Units Three and Four. They do differ, however, in the character of their residue. Unit Three left aggregates of quartz crystals and sub-angular quartz grains; Unit Four contained much light-colored clay with gray to brownish-gray chert being noted stratigraphically lower in the unit. Unit Five's insoluble was entirely anhydrite and ran as high as 40 percent of the total sample.

The stratigraphically highest zone, Unit One, showed in general, a progressive decrease in percentage residue with depth. Here the residue was transitional from black shale and pyrite, typical of overlying beds, to a light-colored clay and pyrite.

THE PENTWATER FIELD

LOCATION AND EXTENT

The Pentwater Oil Field, (Fig. 1), discovered in May, 1948, is located two miles northeast of Pentwater village and 12 miles southeast of Ludington. It is in Secs. 35 and 36, Summit Township, Mason County, Secs. 1, 2, and 12, Pentwater Township, and Secs. 5, 6, 7, and 8, Weare Townships, in Oceana County, (Fig. 3). Although complete delineation of the field awaits further development, its present extent is three and one-fourth miles long and one mile wide. The field trends in a general northwest-southwast direction as do the majority of Michigan's oil fields.

HISTORY OF DEVELOPMENT

The Pentwater Field was Michigan's most important 1948 oil discovery in adding new reserves. It also helped end a five year period of declining production. Discovery of this field was made by extensive test drilling using the Coldwater "redrock" (Fig. 2) of Mississippian age as the marker bed. May 12, 1948, the Roosevelt Oil Company's McMillan No. 1, Sec. 6, T.16N., R.17W. (Fig. 3), produced oil from the Dundee formation at a depth of 2088 feet to become the field's initial producer. Traverse production, was initiated August 4, 1948, with the completion of the Leon McMillan No. 3 (Fig. 3) by Augie Busk at a depth of 1591 feet. Welsh Oil Company's Dundee completion of the Wright No. 1, Sec. 35, T.17N., R.18W. (Fig. 3) at a depth of 2106 feet extended this field one and one-half miles to the northwest. Activity during the first half of 1949 was to the southeast in Secs. 5 and 8, R.17W., T.16N. (Fig. 3) where a porous coralline zone, called Unit Two (Fig. 8) in this study, is proving to be an excellent Traverse reservoir.

STRATIGRAPHY

The term "Traverse Group" as defined by Warthin and Cooper (1943, p. 573), will be used in this study to designate the series of beds from the bottom of the Bell shale upward to the base of the Antrim black shale. Warthin and Cooper exclude the transition zone immediately underlying the Antrim and overlying the "Traverse Limestone".

For purposes of discussion in this thesis, the strata encountered in the Upper Traverse of the Pentwater Field are divided into five recognizable lithologic units. Unit Five is the oldest and is discussed first since it is the datum used in this paper. All of these units (Fig. 8) are described in the following paragraphs:

Unit Five, a thin bed of massive anhydrite, is used as a datum from which to build a column and study the structural relationships of all units. This evaporite facies is suited for the purpose since it suggests a local period of uniform conditions and its top serves as a time line. Weaver (1949, Speech) substantiates the soundness of using an evaporite bed for a datum by stating that evaporites are deposited instantaneously, geologically speaking, and have no stratigraphic equivalent.

Observed thicknesses vary from 8 to 15 feet and the anhydrite exhibits slight permeability and an increase of resistivity on the electric log (Figs. 10 and 11).

Older strata, designated as "underlying beds" (Fig. 8), serve no function except as a base upon which Unit Five was deposited.

Figure 6 is a contour map drawn on the Unit Five top using the data shown in Table 1.

Unit Four is dense and detrital in character and exhibits various shades of gray limestone. Brachiopod fragments have been recognized from well cuttings in this unit. Low permeability and high resistivity on the electric log are in sharp contrast to overlying Unit Three and underlying Unit Five (Figs. 10 and 11).

Unit Four is nearly of uniform thickness, varying from 72 to 85 feet in examined wells.

Figure 5 is a contour map drawn on the top of Unit Four using the data of Table 1.

Unit Three is predominantly a coarsely crystalline brown dolomite but contains some fine-grained high calcium limestone embedding dolomite "rhombs". The upper contact (Unit Two-Unit Three) cannot be reliably picked from all the electric logs and therefore is not used by the writer for a contouring horizon as was the case in Units Four and Five. However, a continuous high permeability is noted for the unit with minor permeability and resistivity fluctuations depending perhaps upon the amount of dolomitization and water. The occurence and origin of dolomitization is not within the scope of this paper since the primary study is devoted to undolomitized Unit Two. Dolomitized units are brought into the study only as an aid in establishing structural relations above and below Unit Two.

Unit Two, the major concern of this paper, is a finely crystalline, buff, stylolitic limestone containing fossils, and exhibiting a high porosity uncommon in other Michigan oil fields. In thickness, Unit Two varies far more than the other units, from 28 to 79 feet, and is characterized by high permeability and, in general, a low resistivity. The low resistivity may be attributed to the high water content in all but the top few feet of the zone. This is marked even in the structurally highest wells.

Whether this porous coralline horizon is a Devonian coral reef or not has been the subject of much discussion among petroleum geologists. Since Dundee wells are adjacent to many of those which end in the Traverse, an opportunity for studying underlying beds is offered in the Pentwater Field which is not offered in other reef-like fields of Michigan.

Unit Two is the lowest and most prolific of three Traverse oil pays. The two upper producing zones are in Unit One.

Unit One is an alternating series of dense limestone and dolomitized limestone zones. Dolomite "rhombs", embedded in a light-colored calcitic limestone matrix appear to be transitional between the two extremes. By samples and by the electric logs the top of Unit One is readily determined. The abrupt increases in both curves of the electric log are particularly characteristic (Fig. 10 and 11). The resistivity curve decreases at the bottom contact while little notable change is evidenced in the permeability. A break in lithology between Units One and Two is distinctive, the former being normal marine limestone and the latter a buff coralline limestone.

Oil comes from two dolomitized pays in this unit but none of the wells make their proration of 100 barrels per day.

The shale above Unit One provides a lithologic break which is easy to recognize at the top of the Unit. The horizon is therefore used for contouring by the writer as well as company petroleum geologists. Figures 4a and 4b are contoured on this top, usually referred to as the top of the "Traverse Limestone" by Michigan petroleum geologists.

Strata designated as overlying beds (Fig. 8) are a series of gray shales with a few limy beds of Upper Traverse referred to as the overlying transition zone by Hake and Maebius (1938, p. 457). Common usage is to call this section the Traverse Formation in Western Michigan. Cohee (1947, pp. 90-92) believes the Traverse Formation is the equivalent of the Milwaukee Formation of Wisconsin which has no equivalent in Eastern Michigan because of either non-deposition or erosion.

No attempt is made to correlate the above five units with formations into which the Traverse has been divided by Warthin and Cooper and others, because lateral and basinward changes make them difficult to recognize. Whether or not any or all of the five subsurface units possess sufficient lateral extent to qualify as formations is not known and therefore justifies the exclusion of an attempt to correlate with outcrops.

PRODUCTION

Cumulative oil production of the Pentwater Field to July 31, 1949, was 1,014,871 barrels according to figures of the Michigan Geological Survey. Of this, 192,397 barrels was 38.4° A.P.I. gravity oil from three Traverse pays and 28 producing wells. Unit Two, of this paper, is by far the most prolific of the Traverse multiple pays. Wells produce from the top few feet of the Unit. The oil-water contact is at an approximate elevation of 950 subsea. This indicates a maximum pay of 12 feet for the highest wells. Structurally low wells carry water in this pay and produce from the two upper zones, both in Unit One.

Upon completion, Traverse wells are prorated at 100 barrels of oil per day; Dundee wells are limited to half that amount.

Pressure history of the Unit Two reservoir indicates an active water drive. Gas-oil ratios are extremely low, measuring 68 cubic feet per barrel, according to Michigan Geological Survey reports (1949, Oral Communication).

The well spacing at present is one well to each twenty acres, the wells being drilled in the center of the northeast and southeast ten acres of each forty. When wells are to be drilled to both Traverse and Dundee formations the same spacing pattern is used but the wells are drilled about 50 feet apart. All Dundee production to date is believed to be from a single pool.

The upper two Traverse pays are thin members of dolomitized limestone in Unit One whose producing sections are seldom more than two feet thick. None of these wells make their proration of 100 barrels per day.

Oil recovery in the Pentwater Unit Two is expected to approach 70 percent, on the basis of present reservoir studies by the Carter Oil Company (1949, Personal Communication), the major acreage holder in the area. The Michigan Geological Survey opines 75 percent recovery (1949, Personal Communication). Estimates of total recoverable oil are incomplete and not available.

METHOD OF INVESTIGATION

The absence of outcrops in Mason and Oceana Counties dictated an investigation of Pentwater's upper Traverse section based on the following sources:

(1) Subsurface samples from wells drilled for oil.

(2) Electric logs from these wells.

(3) Diamond-cut cores from the zone of corralline material (Unit Two).

(4) Personal communications.

(5) Publications and maps applicable to the problem.

In attacking the problem, original "Traverse Limestone" elevations were obtained from abbreviated scout reports of the Michigan Geological Survey. After contouring on these elevations (Fig. 4a), wells were selected for study on the basis of their relation to the Traverse structure. If data could not be obtained for one of the selected wells, another of similar relation to structure, for which data was available, served as a substitute. Table 1 lists the final selection of wells.

Through the courtesy of E. J. Baltrusaitis of the Gulf Refining Company, two diamond-cut cores of the Unit Two pay were made available for study. One is pictured in Figure 9. Examinations of the other were made from both thin-sections and polished sections and Lemberg's solution was used on the former to readily distinguish between calcite and dolomite. Results of this study are discussed under "The Investigation of Unit Two".

In all, 41 sets of Pentwater drill cuttings were on file and available for study. Cuttings of six wells, complete through Unit Five, were examined in detail under the binocular microscope and the graphic logs of these were compared with electric logs for the same wells. Acid and staining fluid was used for confirmatory tests to bring out the textural and mineralogical compositions of the rock. The Units, One through Five, were set aside as distinct lithologic members by this study. Samples and electric logs of an additional 18 wells were examined, but the cuttings were incomplete for these wells. In most cases they were complete through the coralline horizon (Unit Two); electric logs were intact for all desired wells.

Samples were incomplete in the above instances because of extensive coring and oil company practice to save from wells drilled in a proven field only those cuttings immediate to pay zones and marker beds. Electric logs were the sole source of information if samples were missing. Picking unit contacts by this method was validated by previous study where cuttings were also available.

Copies of the official records for wells of the Pentwater Field now on file with the Michigan Geological Survey were scrutinized but proved of no material assistance in the solution of the problem. Records for six wells have been published and are available from that source.

Insoluble residues of Unit Two were used to check for the criterion suggested by Cumings (p. 3), that any pure carbonate rock with minute insoluble residue might be suspected of being reef rock. Results are discussed under the "Investigation of Unit Two".

INVESTIGATION OF UNIT TWO

Examination both by thin and polished sections of the Unit Two core from the Gulf Refining Company's Mary Paulsen No. 3 well reveals the member to be high in organic matter. Stromotoporoids and branching Favosites are abundant; ostracod shells were found in a finely crystalline, even-textured, stylolitic, buff limestone matrix. The fossils present agree with those classed by Twenhofel (p. 3) as reef building organisms but the matrix does not conform with Warthin and Cooper's (1943, p. 586) observed bioherm cores which they describe as "a jumble of coral and stromatoporoid colonies and in the nature of a breccia". No evidence of bedding was observed in the Unit Two core.

High porosity is characteristic of the Unit Two matrix. In most cases the cavities are completely lined with clear calcite crystals. The irregular nature of the openings suggests that they are solution cavities.

Landes (1946, p. 314) states that without doubt ground water solution, either above or below the water table, is of utmost importance in producing porosity in carbonate rocks. A reef rock of nearly pure carbonate content would be no exception.

The writer believes that the original porosity was primarily due to pore spaces within the calices of the corals and between the valves of bivalved organisms. The matrix is believed to have been dense originally with fractures accounting for the entire porosity in this sublithographic ground mass.

Geikie (1903, p. 426) has pointed out the importance of fissures in supplying channelways for dolomitizing waters. The writer suggests a like assistance from fractures in creating the abnormal porosity in Pentwater's Unit Two, except the percolation waters in this case were leaching waters containing carbon dioxide rather than magnesium-rich solutions.

Two possible interpretations of the Unit Two structure are offered in this paper depending upon whether or not there is a collapse of Unit Two in SW$\frac{1}{4}$, NW$\frac{1}{4}$, NW$\frac{1}{4}$, Sec. 8, T.16N., R. 17W. (Fig. 3). The Carter Oil Company's Dumaw No. 1, at this location, may be 25 feet lower than any of the five surrounding wells within a maximum radius of 1320 feet and does present an abrupt drop-off.

The writer's preference is to contour the horizon as shown in Figure 4a, an interpretation used by Lowenstam (1948, p. 181) in his illustration of the Marine Pool in Illinois. Figure 4a and that of Lowenstam are essentially mirror images of one another.

A second interpretation (Fig. 4b) is that of assuming a collapse of Unit Two in the area of the Dumaw well. It should be considered a possibility for The Gulf Refining Company reports, on the basis of laboratory studies, porosities approximating 30 percent which approaches the theoretical limit of limestone before collapse (1949, Personal Communication).

The above interpretations are secondary to the fact that Unit Two does exhibit notable slopes and an unpredictable nature not uncommon in known reef fields cited by Stormont (1949, p. 57).

It is interesting to note a probable reflection of a Dundee structure (Fig. 7) in beds as high in the stratigraphic column as Unit One. Particular interest is focused on that portion lying in Sections 5 and 8. A structure is shown on Unit Five (Fig. 6) at this point. The same is true for Unit Four (Fig. 5). However, contouring on the Unit One top (Fig. 4a) reveals additional relief not shown on previously mentioned horizons. The writer proposes that this change is due to a "build up" within the coralline unit and that observed reflection from lower units was present in Unit Two. The initial reflection is believed by the writer to have served as a platform more favorable for the growth of reefs than the surrounding bottom. This was a factor in determining the location of the reef.

That Pentwater's Unit Two does "build up" is shown in Figure 8. A thinning of this unit in all directions from well number nine, high on the structure, can be noted and in some cases, the thinning is quite abrupt.

Random orientation of branching Favosites was observed in the core from the Gulf Refining Company's Mary Paulsen No. 3. Lowenstam (1948, pp. 174-175), recognizes this criterion to be of diagnostic value in the flank deposits of the Marine Pool. These deposits are dolomitized in contrast to the undolomitized Pentwater Unit Two. Reef occurences in the Alpena area are likewise limestone deposits.

To test whether or not Unit Two satisfied the requirements of a reef rock set forth by Cumings (p. 3), insoluble residues were applied to the investigation. The procedure outlined by Eddy (1933, pp. 347-348) was generally followed. Samples varied from one gram in weight to as much as 15 grams depending upon the amount of rock available. The study was not an extensive one, but ten samples, considered to be representative of Unit Two were tested and found to be in excess of 99% pure carbonate. The only appreciable residue noted was from the pay zone. The residue in this case was primarily "dead oil" that had remained within the pore spaces of the rock.

ORIGIN OF UNIT TWO

A satisfactory picture of the origin and development of the Pentwater Traverse strata is far from complete. The presence of little clastic material in all examined zones, however, suggests remarkably clear waters in this portion of the Traverse sea. Hake and Maebius (1938, p. 459) recognize this as characteristic of all Traverse strata in Western Michigan and name reefs as the possible deterrent in preventing the transportation of clastic material from the littoral zones.

The change in lithology of the Traverse Group from evaporites, dolomites and limestones in Western Michigan to a predominance of calcareous, siliceous and argillaceous material in central and eastern Michigan has never been satisfactorily explained. Knapp (1947, p. 6) postulates that the Porter-Winterfield uplift of pre-Dundee time formed a shoal or bar with open sea to the east and a restricted sea to the west. A separation of the west portion of the Traverse sea as a result of such a barrier or a series of barriers persisting into Traverse time certainly must be considered a possibility.

If limestone, gypsum and salt are assumed to be the normal succession of precipitation from a restricted sea as the concentration on the waters is increased, Pentwater's three lower units (Three, Four and Five) are readily explained. At the conclusion of Unit Three time, suppose subsidence took place on either a local or regional scale. Increasing subsidence would have increased water depths and lessened the concentration of the sea enough to favor abundant organic growth. Assuming this growth to take place as outlined by Warthin and Cooper (1943, p. 586), it may have continued until unfavorable conditions again prevailed and killed all life. Uplift and consequent concentration could have once again prevailed with normal marine limestone (Unit One) being precipitated. This environment existed until the final withdrawal of the sea at which time Traverse deposition ceased.

CONCLUSIONS

The Pentwater Field is producing oil from a porous Traverse pay believed by some petroleum geologists to be a Devonian reef. Some evidence supports this belief but conclusive proof is lacking. The possibility still remains, therefore, that Unit Two is not a reef. Only future drilling and coring operations may provide enough data to decide.

If Unit Two proves to be a reef, as other data does avail itself for study, a pattern of reefs might be present that would aid in future exploration. Considerable oil may be locked up in such untapped reservoirs.

The random orientation of fossils and sublithographic matrix in the examined Unit Two core lead the writer to a tentative conclusion that the rock was from the lagunal side of the Unit, if it is a reef, where marginal sediments would normally be expected to grade into the reef proper. If this is a true interpretation, then one should expect to find detrital limestone on the seaward side of the structure as suggested by Verhoeven (1948, p. 25).

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ASG'D NO. (FIG.8)	FARM NAME AND WELL NUMBER	NEGATIVE ELEVATIONS (IN FEET) OF UNIT TOPS AND OBSERVED THICKNESSES UNIT NO. 1	UNIT NO. 2	UNIT NO. 3	UNIT NO. 4	UNIT NO. 5
1.	A. Demokos No. 1	-948 (38)	-986 (28)	-1041 (81)	-1095 (74)	-1169 (12)
2.	O. G. Jensen No. 1	-936 (35)	-971 (45)	-1016 (77)	-1093 (75)	-1168 (13)
3.	W. Johnson No. 2	-944 (37)	-981 (49)	-1030 (58)	-1088 (76)	-1164 (15)
4.	A. M. Astrouski No. 1	-944 (42)	-986 (44)	-1030 (61)	-1091 (79)	-1170 (9)
5.	W. G. Leversey No. 1	-929 (34)	-963 (50)	-1013 (80)	-1093 (77)	-1170 (8)
6.	M. Paulsen No. 2	-923 (30)	-953 (65)	-1018 (75)	-1093 (77)	-1170 (9)
7.	E. Osborn No. 1	-921 (34)	-955 (79)	-1034 (69)	-1103 (72)	-1175 (10)
8.	M. Paulsen No. 3	-914 (29)	-943 (67)	-1010 (83)	-1093 (76)	-1169 (9)
9.	M. Paulsen No. 4	-908 (30)	-938 (73)	-1011 (78)	-1089 (77)	-1166 (10)
10.	A. J. Dumaw No. 1	-934 (33)	-967 (45)	-1012 (78)	-1090 (74)	-1164 (9)
11.	A. J. Dumaw No. 4	-910 (31)	-941 (65)	-1006 (80)	-1086 (76)	-1162 (11)
12.	S. Warner No. 3	-909 (31)	-940 (63)	-1003 (83)	-1086 (75)	-1161 (8)
13.	S. Warner No. 1	-908 (32)	-940 (63)	-1003 (83)	-1086 (75)	-1161 (8)
14.	A. Adams No. 5	-936 (31)	-967 (34)	-1001 (86)	-1087 (77)	-1164 (8)
15.	A. Adams No. 4	-951 (35)	-966 (42)	-1008 (78)	-1086 (77)	-1163 (10)
16.	A. Adams No. 1	-908 (29)	-937 (73)	-1010 (78)	-1088 (72)	-1160 (10)
17.	J. Lauber No. 1	-915 (29)	-944 (67)	-1011 (80)	-1091 (78)	-1169 (10)
18.	J. Adams No, 4	-919 (32)	-951 (58)	-1009 (82)	-1091 (85)	-1176 (11)
19.	J. Adams No. 2	-924 (31)	-955 (61)	-1016 (78)	-1094 (78)	-1172 (9)
20.	M. Thamasauky No. 1	-939 (28)	-967 (58)	-1025 (79)	-1104 (74)	-1178 (9)
21.	J. Padzunnas No. 1	-929 (37)	-966 (43)	-1009 (84)	-1093 (82)	-1175 (10)

TABLE 1. Data obtained from the study of well samples and electric logs of the Pentwater Pool. This data has been utilized in Figure 8.

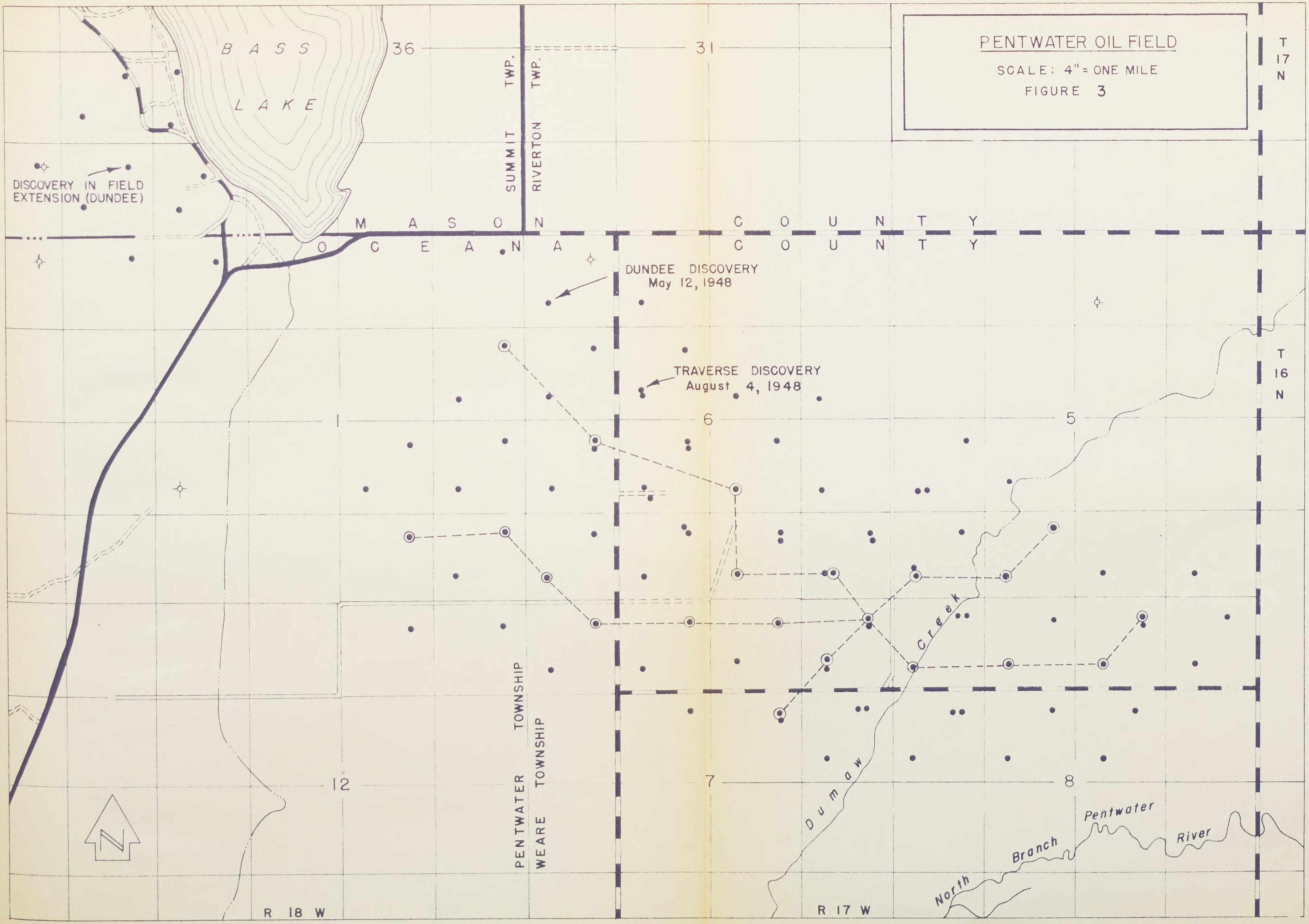
FIGURE I. INDEX MAP

SYSTEM	FORMATION	COLUMNAR SECTION	MAXIMUM THICKNESS	DESCRIPTION
PLEISTOCENE			680'	GLACIAL DRIFT
MISSISSIPPIAN	COLDWATER ELLSWORTH		1004'	SHALE, BLUE-GRAY
DEVONIAN	ANTRIM		780'	SHALE, BLACK, BITUMINOUS
	TRAVERSE FM		78'	SHALE, GRAY-BLACK, LIMEY
	TRAVERSE LM		462'	LIMESTONE, GRAY, DOLOMITE, ANHYDRITE
	BELL		85'	SHALE, BLACK
	DUNDEE		435'	DOLOMITE AND LIMESTONE
	DETROIT RIVER		539'	DOLOMITE AND ANHYDRITE
SILURIAN	BASS ISLAND		310'	DOLOMITE, ANHYDRITE, ARGILLACEOUS
	SALINA		930'	SALT, DOLOMITE, LIMESTONE
	NIAGARAN		220'	LIMESTONE
	CATARACT		155'	SHALE AND DOLOMITE
ORDOVICIAN	CINCINNATIAN		335'	SHALE, SOME DOLOMITE
	TRENTON		490'	LIMESTONE
	ST. PETER			SANDSTONE

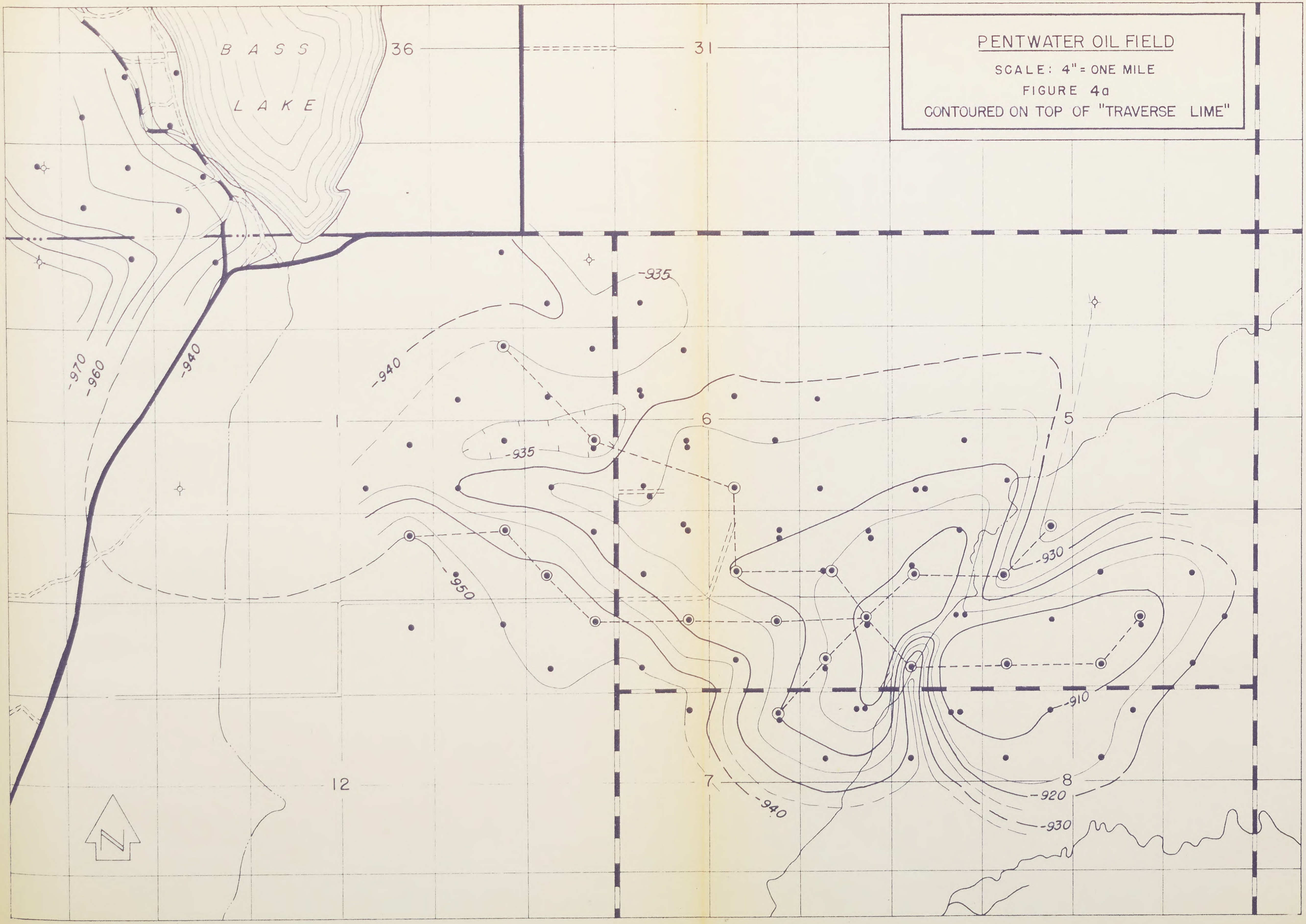
FIGURE 2. GENERALIZED STRATIGRAPHIC SECTION OF WESTERN MICHIGAN

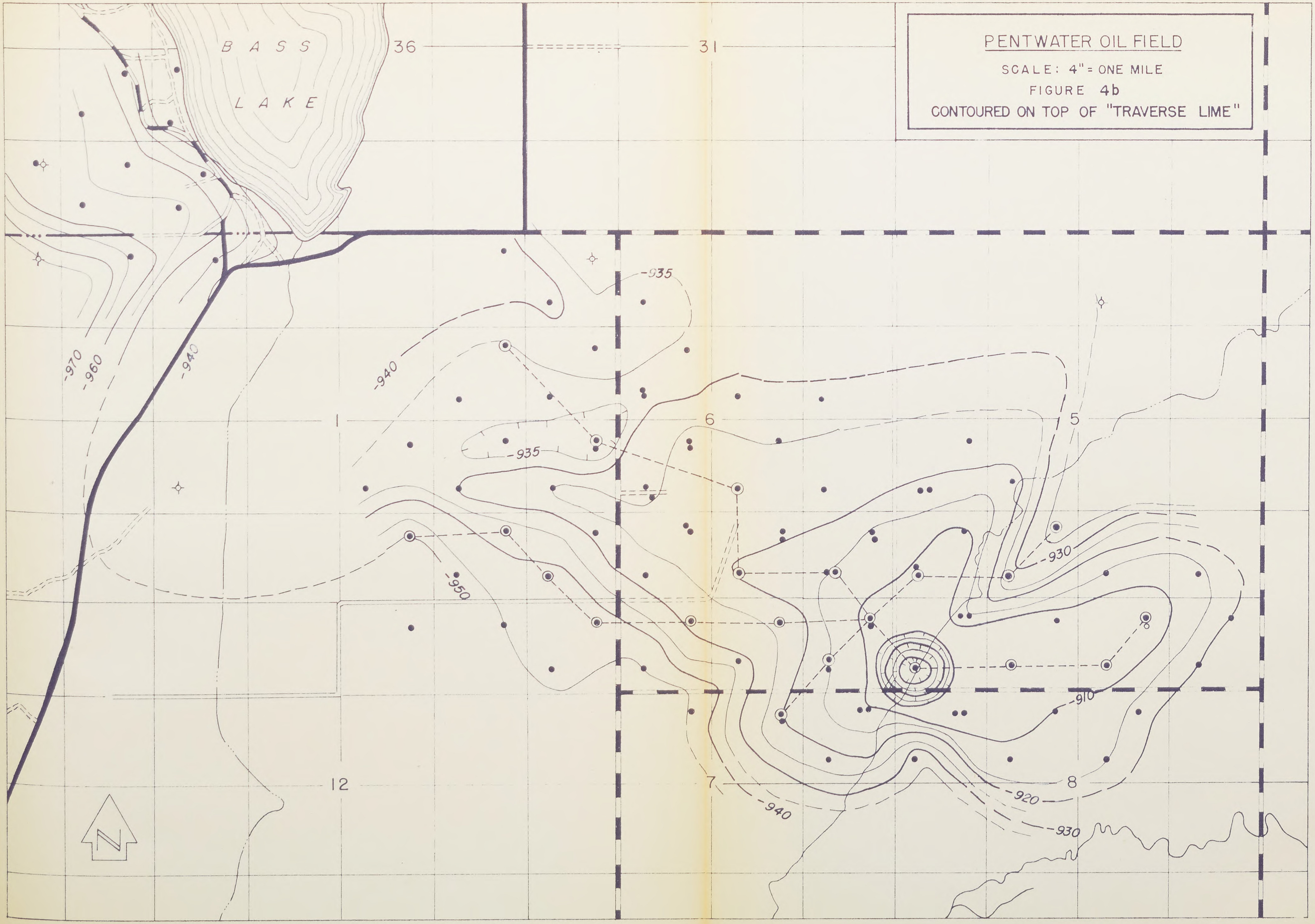
VERTICAL SCALE

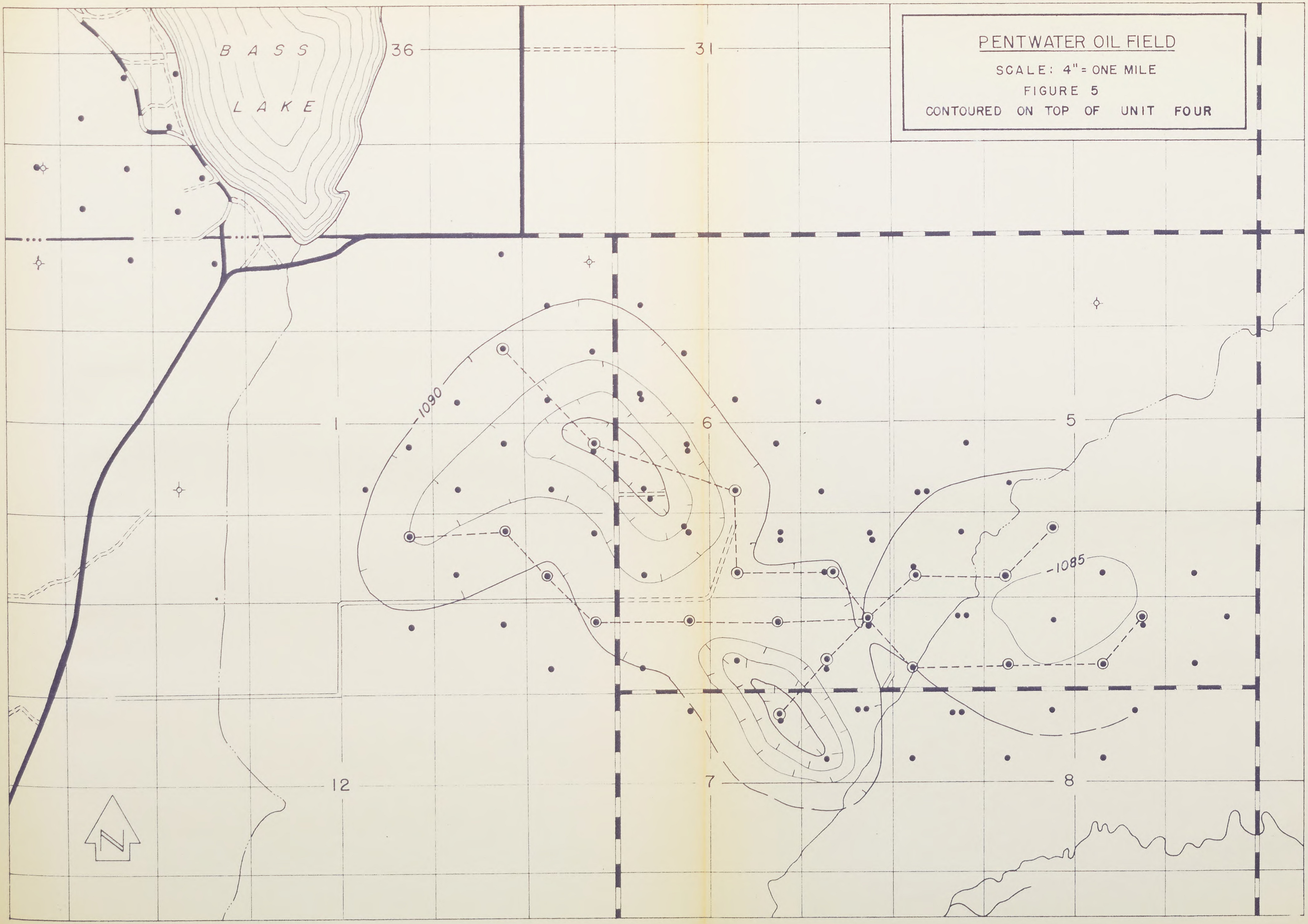
0 — 1000 FEET

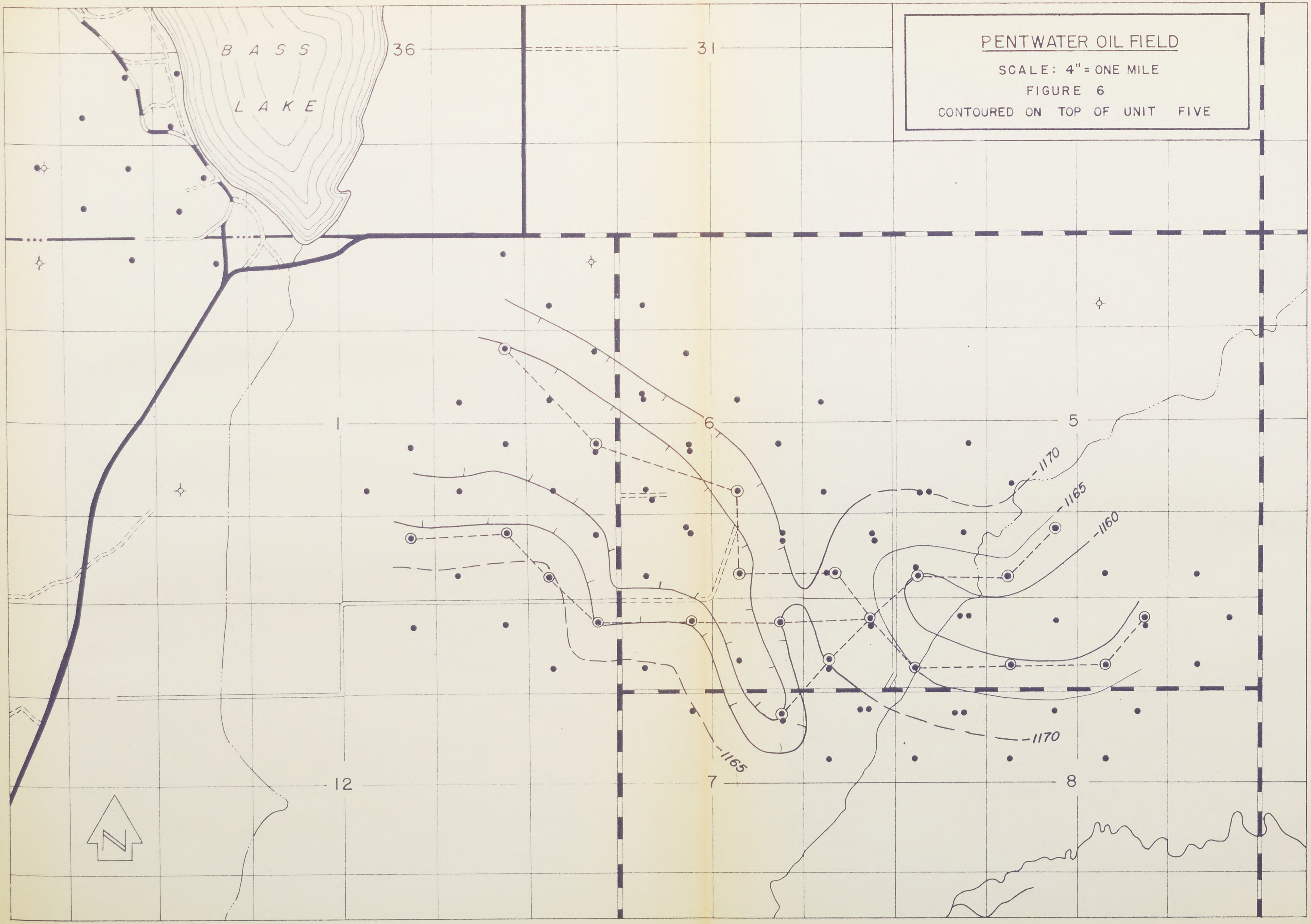


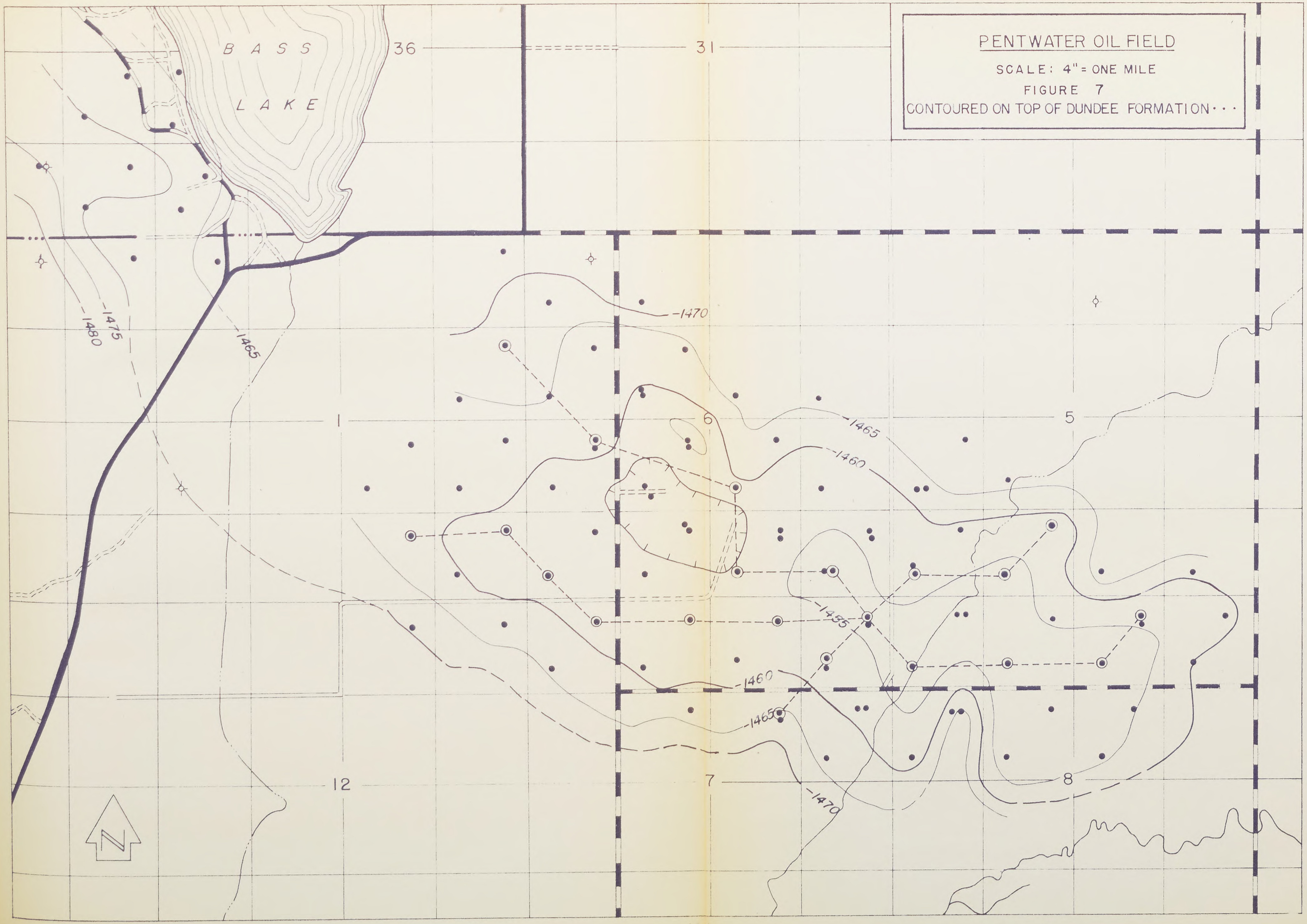
PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 3
BASS LAKE
36
31
SUMMIT TWP.
RIVERTON TWP.
T 17 N
T 16 N
DISCOVERY IN FIELD EXTENSION (DUNDEE)
MASON COUNTY
OCEANA COUNTY
DUNDEE DISCOVERY May 12, 1948
TRAVERSE DISCOVERY August 4, 1948
1
6
5
12
7
8
PENTWATER TOWNSHIP
WEARE TOWNSHIP
Dumaw Creek
North Branch Pentwater River
R 18 W
R 17 W
N


PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 4a
CONTOURED ON TOP OF "TRAVERSE LIME"
BASS LAKE
36
31
1
6
5
12
7
8
-935
-940
-970
-960
-950
-930
-920
-910
N


PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 4b
CONTOURED ON TOP OF "TRAVERSE LIME"
BASS
LAKE
36
31
1
6
5
12
7
8
-970
-960
-940
-935
-950
-930
-920
-910


PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 5
CONTOURED ON TOP OF UNIT FOUR
BASS LAKE
36
31
1
6
5
12
7
8
1090
1085
N


PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 6
CONTOURED ON TOP OF UNIT FIVE
BASS
LAKE
36
31
1
6
5
12
7
8
1170
1165
1160
1170
1165
N


PENTWATER OIL FIELD
SCALE: 4" = ONE MILE
FIGURE 7
CONTOURED ON TOP OF DUNDEE FORMATION
BASS LAKE
36
31
1
6
5
12
7
8
-1470
-1465
-1460
-1455
-1475
-1480
N

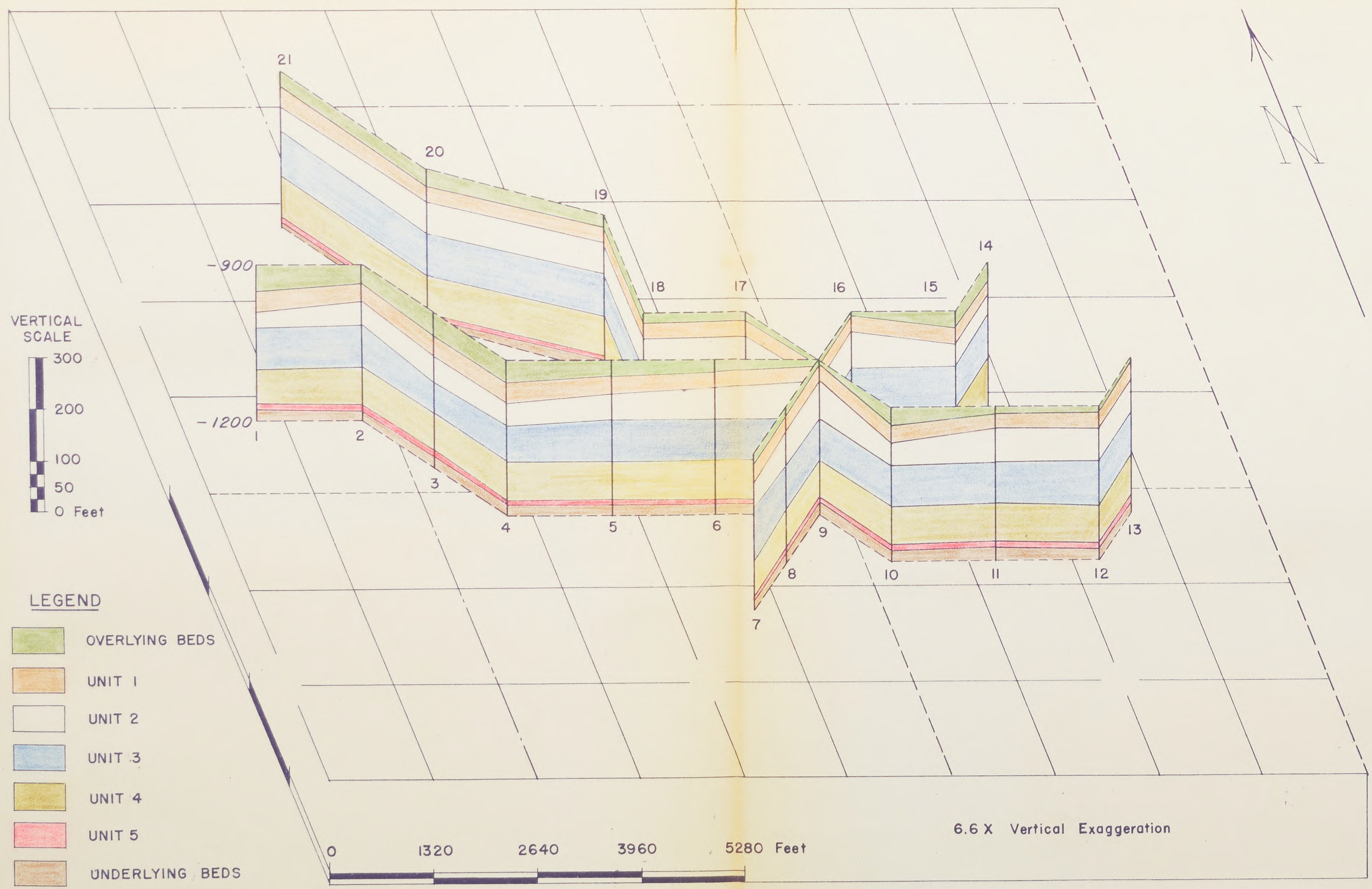


FIGURE 8. ISOMETRIC DIAGRAM SHOWING RELATIONSHIPS OF UPPER TRAVERSE STRATA IN THE PENTWATER OIL FIELD, MASON AND OCEANA COUNTIES, MICHIGAN · · 1949

END VIEW

SCALE IN INCHES

0 1 2 3 4 5

SIDE VIEW

FIGURE 9. DIAMOND - CUT CORE OF "UNIT TWO" FROM GULF NO. 3 MARY PAULSEN AT THE DEPTH OF 1588 FEET SHOWING HIGH [redacted] POROSITY.

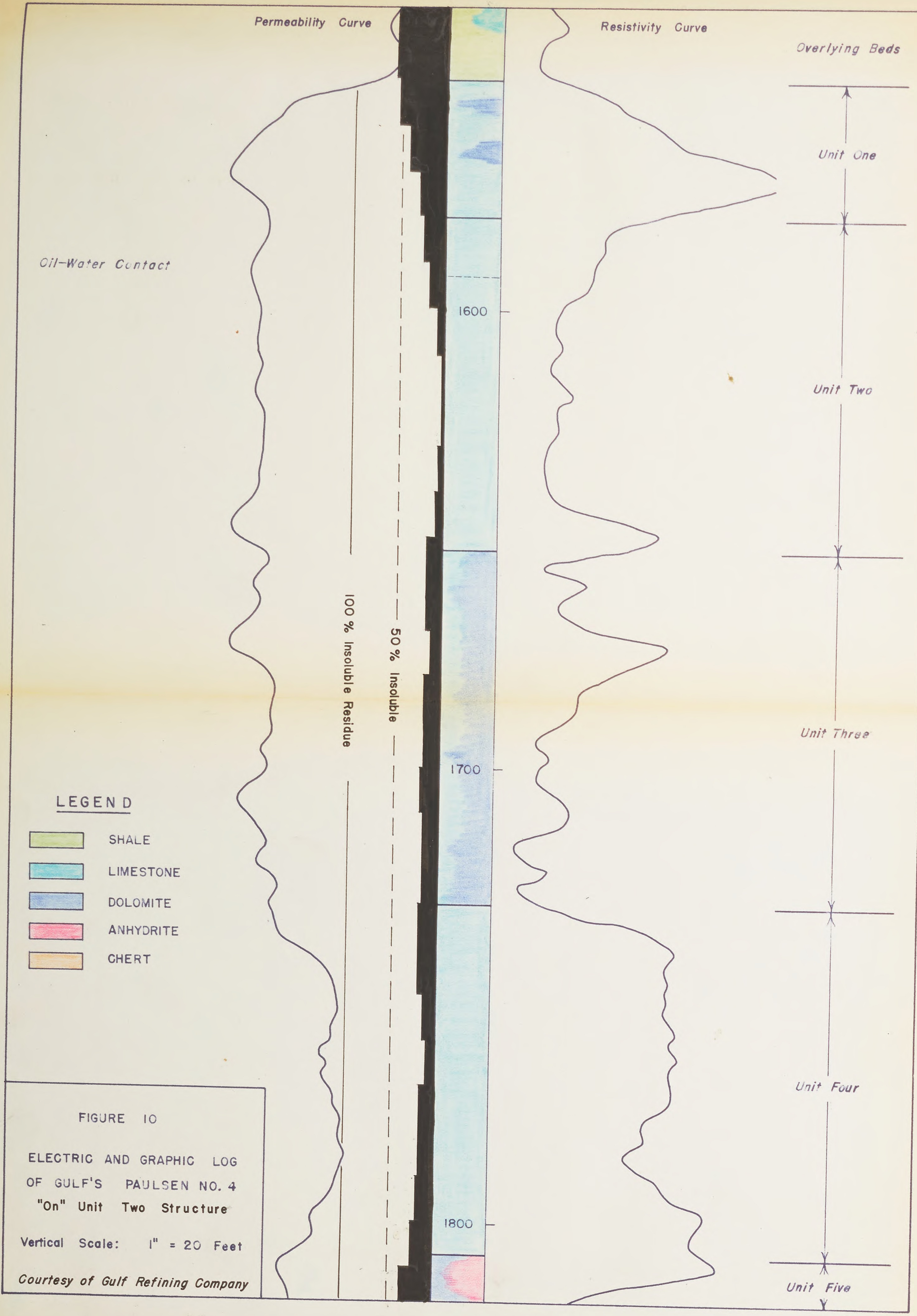


FIGURE 10

ELECTRIC AND GRAPHIC LOG OF GULF'S PAULSEN NO. 4 "On" Unit Two Structure

Vertical Scale: 1" = 20 Feet

Courtesy of Gulf Refining Company

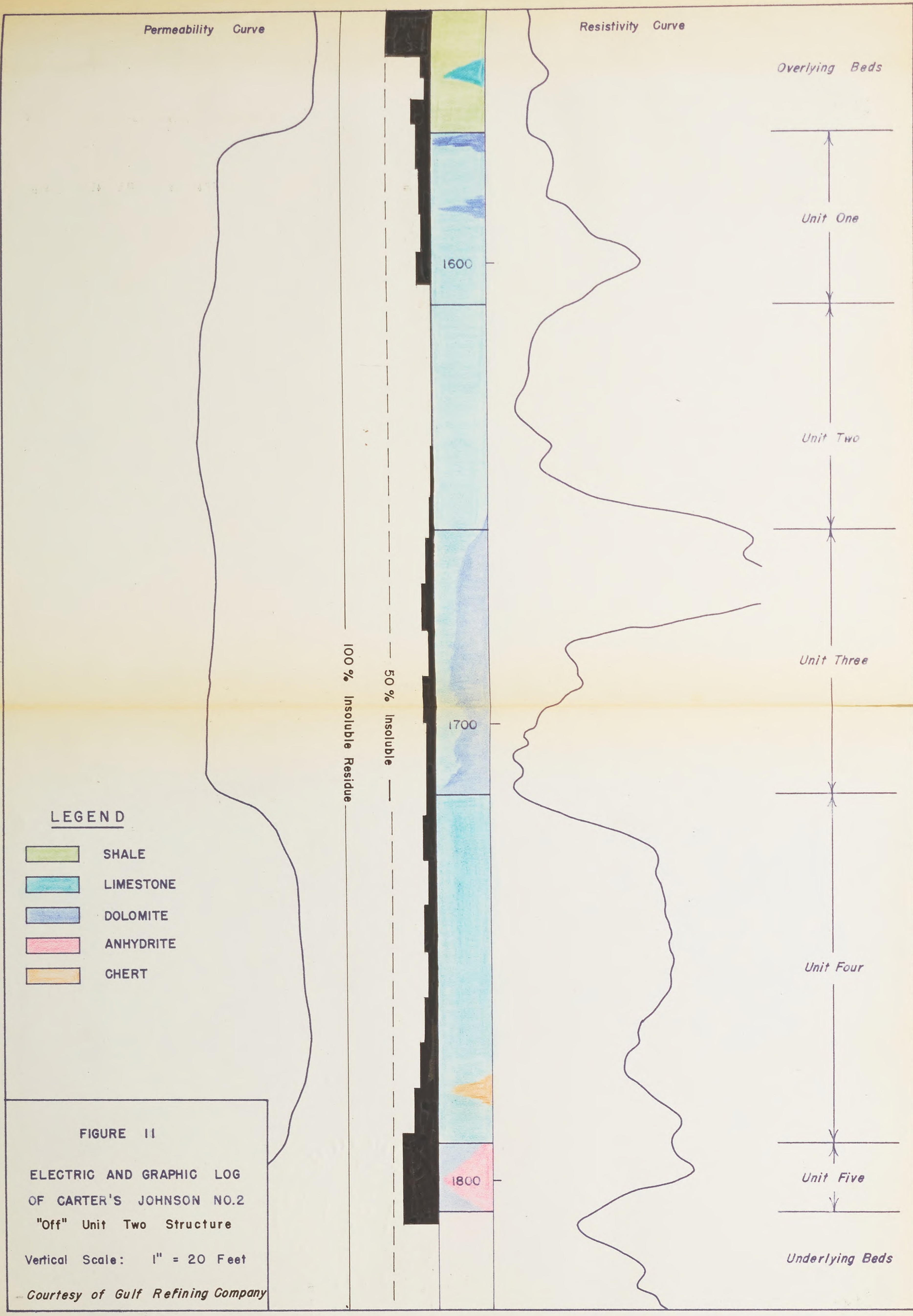


FIGURE 11

ELECTRIC AND GRAPHIC LOG
OF CARTER'S JOHNSON NO.2
"Off" Unit Two Structure

Vertical Scale: 1" = 20 Feet

Courtesy of Gulf Refining Company