southern Shiawassee County where Coldwater is mapped, really found the Coldwater formation directly beneath the drift. The presence of Marshall formation on both the northeast and southwest flanks of the structure is also fairly certain from scattered deep wells. Many shallow water wells penetrate the bedrock in western Livingston County and eastern Ingham County, and these wells if properly interpreted are an aid to accurate mapping. The faulted zone on the southwest flank is postulated on subsurface evidence and the proofs of the Howell structure are presented in Part II, Chapter IV. The type of faulting is not well understood but it must have been complex and covered a zone of some width. The disturbance may not continue to the surface along its entire mapped trend as there is local evidence of the disconformable overlap of the younger beds. The narrowing of the Marshall formation outcrop on the flanks of the structure is probably due to both the steep dip and formation overlap originating at the time of deposition. The feathering out of the Grand Rapids outcrop to the north of the structure must be due to overlap almost entirely and the reentrant in the "Red Beds" contact in southeastern Gratiot County may have some bearing on the northwestern extension of the Livingston County structure.

CROSS SECTIONS

The conditions of overlap and the amount which the beds thicken toward the central part of the State is illustrated by stratigraphic cross sections. Sections A-A′ (see fig. 20) and B-B′ (see fig. 21) show the correlation of a number of wells across the Michigan synclinal basin. The horizontal scale is necessarily exaggerated for purposes of reproduction, so that the amount of dip can only be determined by relative comparison. The sections do not include rocks very far below the Devonian in the central counties, and the thickening of the Silurian beds is illustrated in other cross sections. (See figs. 10 and 11). The section A-A′ is intended to indicate conditions parallel to the long axis of the synclinal basin; the section B-B′ is drawn to represent conditions transverse to the long axis.

In section A-A′, the rate of regional dip, the thickening of beds, and the changes in character of the rocks toward the center of the "basin" are shown. The changes in thickness to the northwest are not well shown because there is a long gap where Lake Michigan crosses the line of section. Some of the important overlaps and disconformities are very evident. The variable thickness of the Dundee formation, the westward change in facies of the Berea-Bedford, and the overlap of the Napoleon sandstone and Lower Marshall formation are especially noticeable. The erosion surface at the base of the Pennsylvanian strata is indicated by the variable thickness of the Parma sandstone. The "Red Beds" in Isabella, Clare, and Osceola counties are evidence of the previously mentioned northwestward tilt which took place after Saginaw time, and it may be noted in this area that red colors also occur well down in the Saginaw formation.

The scale of the section is so small that only the larger structural features can be shown and these but diagrammatically because they do not lie in favorable position with the line of section. The size of the Howell structure, Livingston County and the Mount Pleasant structure, Isabella County is roughly indicated.

Section B-B′ is drawn to the same scale as section A-A′, and if superimposed upon the latter, it shows the stronger regional dip into the central part of the "basin" area. This is proof that the basin is synclinal in character and elongated along a major northwest-southeast axis. The westward thinning and overlap of the Dundee, Bell, and Traverse formations is clearly indicated by the section. The Devonian salt in the deepest part of the "basin" is also shown. The westward overlapping Berea and Bedford formations occur similarly to Section A-A′. The Napoleon sandstone and Lower Marshall formations change laterally in thickness and character, but the Parma sandstone is more regular in thickness. The "Red Beds" are located centrally with respect to the basin, but the red facies of the Saginaw formation appears to the westward as before. No pronounced structural features are found along the line of section except a slight terracing in the central part of the State.

REGIONAL STRUCTURE

The synclinal nature of the basin was one major controlling feature of the region. It has been observed for several periods of sedimentation how the Michigan "basin" simulated a geosyncline with a general northwest-southeast direction of elongation. Many years ago, James Hall[2] maintained that "the minor axes of foldings must be essentially parallel to the great synclinal axis and the line of accumulation." These characteristics seem to persist in Michigan, as shown by the regional subsurface structural contour map of the southern peninsula. (See pl. III).

This map is limited by the structural control points which are available and is hypothetical in many areas, particularly in the northern counties of the peninsula. The contours are drawn with a contour interval of 100 feet on the base of the Antrim or the top of the Traverse formation. This contact is used for contouring because of the ease with which it can be identified, the absence of a pronounced angular unconformity, and the importance of the Devonian rocks as petroliferous formations. The disconformity at the top of the Traverse may locally distort structural interpretations made from this horizon, but this should not materially affect the regional aspects of the structural picture. The datum plane is mean sea level so that there are both positive and negative contours, and the range of elevation on the Upper Traverse beds is from over 1300 feet above sea level to more than 2400 feet below sea level. The regional structural relief of the Upper Traverse beds in Michigan is, therefore, in excess of 3700 feet.

The various periods of folding which affected the Michigan Basin region in early Paleozoic time are not well understood. The mountain making disturbances[3] taking place in the eastern United States in late Ordovician (Taconic), late middle Devonian (Brunswickian), and Permian (Appalachian) were probably felt extensively as far west as the Michigan region. Other minor disturbances also seem to be recorded in the rocks of the State.

[2] Hall, James, Organic Remains of the Lower Helderberg Group and the Oriskany Sandstone: Nat. Hist. Survey of New York, Pt. IV, Vol. 3, p. 73 (1859).
[3] Blackwelder, Eliot, A Summary of the Orogenic Epochs in the Geologic History of North America: Jour. Geol., Vol. 22, pp. 633-643 (1914).

PERIODS OF FOLDING

The structure of the Trenton (Ordovician) limestone does not conform to Devonian folding, and this can probably be explained by the intervening movements which took place during late Ordovician time. Slight deformation may also have taken place in pre-Sylvania time or at the close of Silurian because the Sylvania is extremely irregular in thickness. Evidently, it was deposited on a very uneven surface, because anomalous water conditions show the presence of individual catchment basins. That there was post-Monroe folding is shown in Monroe County where several gentle folds[4] with dips of 50 to 60 feet per mile do not persist upward into the Dundee strata. These folds seem to trend about north 60° east. Further evidence of the persistence of the lower Devonian movement is the abnormally rapid thickening of the Detroit River beds into the center of the State. Grabau[5] believed that this folding "was incidental to the larger deformation which produced the Michigan basin and the Cincinnati anticline." Post-Dundee warping is suggested by the extensive Middle Devonian[6] unconformity in southwestern Michigan and the apparent relation between buried Dundee land surface relief and lines of structural deformation. In oil field areas where extensive drilling has been carried on, the Dundee is usually thicker on the "highs" than on the "lows." This condition would indicate that folding was in progress at the time that post-Dundee erosion took place and either climatic conditions or later shifting of the axes made the present anticlines correspond more closely to the post-Dundee ridges than the valleys. A small amount of movement probably also occurred at the close of Traverse time, but this seems to have been simply in the nature of northward tilting. The tilting of the basin which took place during early Mississippian time (p. 79) was another important movement of this type. Numerous other gentle Devonian and Mississippian warpings have been shown by means of the thickness maps (See figs. 7, 8; 12-16, 18, 19). The irregularities of the Napoleon land surface and the variations in the lower part of the Michigan series suggest that some rather extensive deformation must have occurred at the end of Marshall time. The deformation seems to have taken place along the general trend of Devonian folding, because the structure of the Napoleon sandstone persists downward through the Devonian rocks. Post-Mississippian folding was much the same, for the Parma sandstone is deposited in the topographic valleys which conform more or less to the structural "highs." Most of the structural features in the Michigan area were probably sharpened, and the earlier movements were revived and accelerated during the Appalachian Revolution when the great eastern mountain chain was built. Since that time there is little evidence of deformation, but some normal faulting might have taken place from the eastern Triassic disturbance which affected a few of the Atlantic coast states. The "Red Beds" of central Michigan may be Triassic instead of Pennsylvanian or Permian as postulated, but this is doubtful. Although the rocks in the eastern part of the United States show scarcely any Tertiary deformation, a final post-Pleistocene uplift on the northeast side of the Michigan Basin is registered by the

[4] Grabau, A. W., and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, p. 57 (1910).
[5] Grabau, A. W., Op. cit., p. 58.
[6] Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. America, Vol. 41, pp. 725-738 (1930).

differential elevation of glacial lake beaches some distance inland from the shores of the present Great Lakes. This differential tilting of lake beaches is apparently an index of deformation that is still active.

DISCONFORMITIES

The reservoir conditions of oil producing formations and the local structural features of several oil fields in the Michigan Basin have been greatly influenced by disconformities. A disconformity, unconformity, or sedimentary break is a contact between beds giving evidence of a lapse in deposition. This evidence may indicate simply non-deposition, non-deposition and erosion, or erosion followed by tilting and folding before other beds were laid down. Disconformities have aided in the development of porosity by solution and secondary cementation by infiltration. Known structural conditions have been found changed at depth because of them. The structure developed in the shallow rocks in one field (pp. 142-144) has been shifted or almost entirely eliminated beneath a disconformable sequence of beds. The important sedimentary breaks which have been observed in Michigan are the Niagara-Salina; the Bass Island-Sylvania; the Detroit River-Dundee; the Dundee-Traverse; the Traverse-Antrim; the Berea-Coldwater; the Marshall-Grand Rapids; and the Grand Rapids-Parma. Other minor interruptions in sedimentary history have not been so well worked out.

NIAGARA-SALINA BREAK

The Niagara-Salina and Bass Island-Sylvania breaks are very pronounced in the southern and western counties of the State. These disconformities probably account for the Muskegon anticline losing all semblance of its shallow structural form at depth. In fact, the dome with about 70 feet of structural closure on the Traverse and Dundee formations was not found in the beds beneath the Salina. A well drilled through the Salina strata on the top of the anticline, as mapped on the "Dundee," was lower structurally when the Niagaran was reached than a well drilled in a less favorable position fairly well down the flank of the structure to the northwest. This loss of structure may be interpreted in a number of ways, but the most logical explanation seems to be found in the stratigraphic breaks which separate the Dundee and Niagaran beds. The rate of increase in the Monroe-Salina interval (see fig. 11) between the two wells in question was sufficient to take up more than the amount of structural relief in the "Dundee" and higher beds. The result was that the Muskegon anticlinal fold lost all recognizable character in the deeper rocks.

BASS ISLAND-SYLVANIA BREAK

The Bass Island-Sylvania break in southeastern Michigan has been described by Grabau and Sherzer[7], and a number of examples are cited where various strata overlap the Sylvania sandstone. The character and thickness of the Sylvania is variable over most of the State. Two wells were drilled to this formation in northeastern Oceana County and where the one struck strong sulfur brine in the Sylvania, the other found no water whatever. Similar conditions have been encountered in several other localities of the State.

[7] Grabau, A. W., and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, pp. 55, 56, (1910).

DETROIT RIVER-DUNDEE BREAK

The Detroit River-Dundee break has also been discussed by Grabau and Sherzer[8] for Monroe and Wayne counties where these beds are widely exposed. This disconformable contact is marked by the zone of the "black water" of the drillers, which is commonly found in wells penetrating the horizon. The water usually possesses a characteristic dark blue or black color and a very strong hydrogen sulfide (H_2S) odor. In most wells, this water horizon is from 30 to 50 feet below the contact of the two formations. The Detroit River series changes in thickness basinward from less than 100 to over 1,060 feet, and the Dundee rests successively on different members of this series.

DUNDEE-TRAVERSE BREAK

The Dundee-Traverse break[9] of western Michigan has recently been described and the rate of change in the thickness of the beds is shown diagrammatically in Figure 22. The weathering of the Dundee beds is indicated by the "solution" porosity which is found in the Muskegon oil field. Post-Dundee erosion apparently caused considerable surface relief, for in the central part of the State the formation may vary as much as 200 feet in thickness within a comparatively short distance and some of the upper beds seem locally absent. This disconformity is important in controlling the direction and speed of "edge-water" encroachment in the Mount Pleasant oil field. It also seems to explain[10] the almost total absence of "edge-water" in some parts of the field, for there is apparently very little water encroachment up the west side of the structure in western Midland and eastern Isabella counties. The pronounced Dundee-Traverse break is an important modifying structural factor throughout a large part of the Michigan synclinal basin.

TRAVERSE-ANTRIM BREAK

As pointed out by Kirkham[11], an important unconformity is present at the top of the Traverse formation:

"This unconformity is best illustrated in adjacent wells by notable discrepancies in the interval between the top of the Traverse and the surface of the producing horizon, and also by equally important discrepancies in the interval between the top of the Antrim formation and the top of the Traverse formation in wells in the same local area.

"In a large number of well studies, where discrepancies have been noted, it was observed that where the Antrim formation is thicker than normal the Traverse formation is thinner than normal and in other wells the opposite is true. A further study of the logs of these wells indicates, however, that the interval from the top of the Antrim to the top of he producing horizon is in all cases nearly the same.

"This important break has been shown in several areas in Michigan where extensive drilling has been carried on, and the relief at the top of the Traverse is at once evident from a careful study of well records."

[8] Op. cit., pp. 54, 55.
[9] Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. America, Vol. 41, pp. 734-735 (1930).
[10] Thomas, W. A., Oral communication.
[11] Kirkham, Virgil R. D., Unconformity at the top of the Traverse Formation in Michigan: (Abstract) Bull., Geol. Soc. America, Vol. 43, pp. 136-137 (1931).

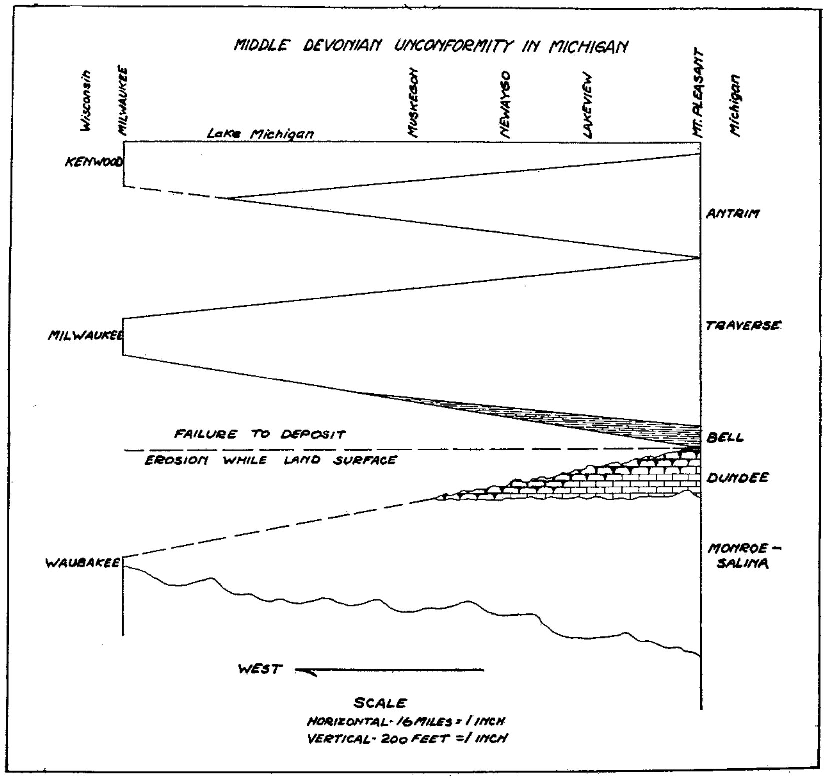


Figure 22. Diagrammatic sketch of the Middle Devonian Unconformity in Western Michigan.

BEREA-COLDWATER BREAK

As shown in Figure 15, the Berea-Coldwater break represents a time when the southeastward tilted basin was brought back to a position where the deepest part was again nearly in the center of the State. The Berea sandstone beds are almost entirely absent in western Michigan, and apparently rather extensive erosion and wearing down of adjacent limestone lands had been going on in the interim between Ellsworth and Coldwater times. The red shaly limestone which formed is fairly good evidence of this break in western Michigan. The porous nature of this shaly limestone member is brought out by the fact that it contains commercial quantities of oil in some parts of the Muskegon field. In accordance with the prevalent notion of the origin of limestone porosity by solution before the deposition of successive beds, this would indicate a considerable period of exposure before the Coldwater was laid down. Because the fact that it restricts oil and gas production from the Berea and other important Mississippian rocks in western Michigan, this break is an important one.

MARSHALL-GRAND RAPIDS BREAK

The Marshall-Grand Rapids break in deposition represents a period of considerable erosion and reworking of the Upper Marshall sandstone. The stratigraphic evidence for the break has been reviewed by Thomas[12] and Kirkham[13] and the reworked Upper Marshall material is recognized from the study of well cuttings in the Central Michigan Area. The westward overlap of both the Upper Marshall (Napoleon) and Lower Grand Rapids (Michigan Series) has been illustrated by the diagram (see fig. 17) showing the progressive change to the west of both thickness and lithologic character of these formations. The structural importance of this overlap is the feathering out and appearance higher in the section of the local lower sandstone lenses of the Michigan series as they grade laterally westward into more shaly members. This is probably due to either the westward retreat of the sea which deposited them or a combination[14] of two invasions and one retreat. The sandstone lenses in the lower part of the Michigan series are stratigraphically higher to the west irrespective of the major folds caused by deformation. These sandstone members, therefore, carry gas in the central portion of the State farther down the northwest flanks of structures than would be expected from folding observed in the lower beds.

GRAND RAPIDS-PARMA BREAK

The Grand Rapids-Parma break is at the Mississippian-Pennsylvanian contact, which is a zone of considerable erosional relief throughout much of the eastern United States. That a large amount of erosion took place is shown by the fact that locally the Parma sandstone rests directly on the Upper Marshall (Napoleon) sandstone. In these cases, the two are not easily separated in well sections without the aid of samples of the cuttings. The structural significance of this break is that average sized anticlines in the Pennsylvanian rocks do not persist with like

[12] Thomas, W. A., A Study of the Marshall Formation in Michigan; Papers, Michigan Acad. Sci., Vol. XIV, pp. 487-498 (1930).
[13] Kirkham, Virgil R. D., Unconformity at the top of the Marshall Formation in Michigan: (Abstract) Bull., Geol. Soc. America, Vol. 43, pp. 137-138 (1931).
[14] Grabau, A. W., Principles of Stratigraphy: A. G. Seiler & Company, p. 738 (1913).

characteristics to any depth in the underlying beds. The local deposition of the Parma sandstone in channels has resulted in pockets of gas being trapped, but these occurrences of gas seem very limited in extent. Some of this gas might be in the upper part of the Grand Rapids formation. The only recorded commercial pool of this kind is near Ashley in southeastern Gratiot County. There seems to be no direct relation between this small gas pool and local structure, although it is situated along a general regional "high." The Mississippian-Pennsylvanian disconformity seems to remove almost all direct correspondence between the shallow surface structures and the more deep seated deformation. However, the Bayport limestone is usually thin or absent on producing structures.

Chapter VI

THEORY OF ORIGIN AND GROWTH OF THE MICHIGAN BASIN

The origin of the Michigan Basin was obviously complex and its growth involved numerous stages in which there must have been many potent factors. Any conception of the origin and growth of the "basin" is, therefore, hypothetical to a large degree, and must stand the test of future discoveries or else be changed to accommodate newly found facts. The theory outlined in this chapter is merely a framework on which one may build or remodel with new facts and interpretations. However, in order to best understand the local structural features of the region, some useful hypothesis of the origin and growth of its major structural features is necessary. In full recognition of the possible inadequacies and errors of interpretation, a theory is advanced which, in the light of our present meager knowledge of stratigraphy and structure in Michigan, seems more or less practical and at least partially satisfies conditions as revealed.

GENERAL STRUCTURAL FEATURES

The structural features of a sedimentary basin are reflected in the distribution and concentration of its deposits. According to Ulrich[1], the oscillating earth movements shift the areas of deposition, and the causes for this warping are (1) the marginal effects or orogenic factors that build mountains, and (2) the local differential movements of the lithosphere. Because of these, the features of deposition already outlined should be a guide to a better understanding of the structures peculiar to the Michigan Basin. A knowledge of the rocks formed and the thickness, distribution, and age relationships of the beds are necessary for a clear conception of the major phases of structural history.

The fundamental ideas concerning the relation of the downwarping of the crust of the earth to areas of thick sedimentary deposits originated with James Hall[2], who also maintained that within the larger synclines numerous smaller anticlines and synclines of lesser rank would develop. Folding within regions of great sedimentation would finally take place when the stresses built up became greater than the strength of the earth's crust. These movements would give rise to the pronounced folding and faulting which are typical of the great mountain chains of the earth. To such areas of sedimentation, Dana[3] gave the name "geosyncline," which is now fixed in the terminology of geological literature.

Structurally, the Michigan Basin is not a geosyncline in the true sense of the term, although some characteristics are strikingly similar. It probably was more typically a geosyncline during some of the earlier periods of its formation. Coarse clastic deposits, like conglomerates and thick sandstones, are comparatively scarce, unless they are present

[1] Ulrich, E. O., Major Causes of Land and Sea Oscillations: Washington Acad. Sci. Jour., Vol. 10, No. 3, p. 68 (1920); also published in Smithsonian Inst., Ann. Rept. 1920, pp. 321-337 (1922).

[2] Hall, James, Descriptions and Figures of the Organic Remains of the Lower Helderberg Group and the Oriskany Sandstone: New York Geol. Survey, Pal. Vol. 3, p. 70 (1859).

[3] Dana, James D., On Some Results of the Earth's Contraction from Cooling, Including a Discussion of the Origin of Mountains, and the Nature of the Earth's Interior: Am. Jour. Sci., 3d Ser., Vol. 5, p. 430 (1873).

in the deeply buried Cambrian or pre-Cambrian sedimentary series. Assuming a normal thickening of these deeper rocks into the center of the State, the maximum thickness of all Paleozoic deposits would amount to between 12,000 and 15,000 feet.

The great thickening of many deposits into the "basin" area, the asymmetrical nature of the downwarped region through several important periods of sedimentation, the elongation of the "basin," the important parallel lines of folding which extend across the center of the State in approximate alinement with the direction of elongation, and the indications of strong faulting movements in the central district point to the geosyncline-like characteristics of the Michigan "basin." Temporary upward movements to the south so restricted the area from invading seas that the region became isolated, and deposits typical of shrinking, dessicating basins were formed. At these stages, Michigan was a basin in the strictest sense of the word. According to our present knowledge, the complete isolation occurred four times during geological history; in late Silurian, in early Devonian, in late Mississippian, and in "Permo-Carboniferous (?)." These periods characterize the Michigan Basin but are not typical of its major structure. They represent simply the results of limiting factors which were only temporarily operative.

ORIGIN OF THE SYNCLINAL BASIN

The Michigan Basin is a synclinal region so vaguely known that no one* has attempted to trace its structural history in any complete detail. The great downwarped area has long been recognized, but the "when and where" of its origin has never been discussed because of the scarcity of information relative to stratigraphic succession and the intimate structural features. Many other facts must be known before the entire story of how the "basin" originated can be told. A number of observed relationships in the province seem to agree with a plan of origin which will be outlined below. Several of the links in the chain of evidence supporting this proposed hypothesis must necessarily be supplied or reinforced. The background of structural events involved in its formation and the analogy with many of the characteristics of the Appalachian geosyncline are, however, apparently logical and clear.

The structural provinces surrounding the region must have borne some relation to the great sinking area of the synclinal basin in lower Michigan. The Wisconsin land mass on the west, the Wabash arch of Indiana on the southwest, the Cincinnati anticline on the southeast, and the Laurentian land mass on the northeast were the known positive structural elements affecting the region. The Illinois-Indiana coal basin and the Logansport "sag" on the southwest, the western part of the Appalachian coal basin in Ohio on the southeast, and the Lake Superior geosyncline on the north were the known areas of predominant negative tendencies that maintained periodic connections with the sinking Michigan "basin." Among these structural provinces, the oldest positive

*Before this report went to press, an article by George W. Pirtle appeared in the American Association Petroleum Geologists Bulletin, Vol. 16, No. 2, pp. 145-152, on the Michigan Structural Basin and its Relation to Surrounding Areas. In the article, he discussed the origin of the "basin" and also the folds within the "basin" and presented a map of the regional structure of the Michigan Basin and adjacent areas, contoured on the Trenton limestone. The studies in connection with this report were carried on at approximately the same time, and it is interesting to note how somewhat similar conclusions were reached from entirely different modes of attack.

areas were the Laurentian and Wisconsin land masses; the oldest negative area was probably the Lake Superior geosyncline.

The Lake Superior geosyncline probably originated in about Middle Keweenawan time[4], although an earlier Huronian sedimentary basin of wider extent was mapped in 1883 by Irving[5] who showed the essential structural characteristics as then known. The folding of the basin was practically complete at the end of the Keweenawan period, but in post-Cambrian time and possibly in post-Cretaceous time, the region suffered the effects of great strike faulting[6]. Martin has cited the necessity of modifying the hypothesis of the origin of the Lake Superior basin as a geosyncline to include the possibility of graben or rift faulting[7]. The idea of torsional warping which resulted from unequal foundering in the geosynclinal area has recently been introduced by Aldrich[8] to explain the local structural features in the Gogebic Iron Range of Wisconsin.

The Lake Superior geosyncline has been an intensely deformed region since its beginning and has been subject to innumerable faulting and cross bending movements as well as periodic downwarping. That sedimentary rocks younger than Cambrian constitute a part of this lake basin is entirely conjectural, but downdropped blocks of Paleozoic are probably present beneath the water cover. A possible early connection of this geosyncline with the Michigan "basin" has been suggested by Robinson[9], who explains the later separation of the two downwarped regions by differential erosion in Paleozoic and perhaps Tertiary time. He postulates early Paleozoic erosion of the Michigan Basin area by drainage which removed many of the older Paleozoic rocks from the southern peninsula but did not similarly affect the Lake Superior area. Afterwards, possibly in Tertiary time, deep erosion of the Lake Superior basin took place, and Paleozoic rocks were removed by drainage which did not affect the Michigan "basin". As a result of this later erosion, a cuesta or ridge developed not far north of the present south shore of Lake Superior, separating the new Superior drainage from the Michigan "basin" area.

This argument is very plausible and has many points in its favor, but the ingenious erosional history required to fulfill the physiographic conditions is rather exacting. The conception of a direct relation between the origin of the Michigan "basin" and the Lake Superior geosyncline is a very significant contribution, and with the background which Robinson has furnished, a new tentative hypothesis is proposed. The purpose of this hypothesis is (1) to explain the sedimentary and structural history of the Michigan synclinal basin, and (2) to show the cause of the forking of the Cincinnati arch.

The largest exposed zone of extensive deformation due to faulting in the vicinity of the "basin" is the Keweenaw fault, which was probably the result of an upthrust from the northwest in about late Keweenawan

[4] Van Hise, C. R., and Leith, C. K., The Geology of the Lake Superior Region: U. S. Geol. Survey, Mon. 52, p. 421 (1911).

[5] Irving, R. D., The Copper Bearing Rocks of Lake Superior: U. S. Geol. Survey, Mon. 5, pp. 410-418, Plate XXVIII (1883).

[6] Van Hise, C. R., and Leith, C. K., Op. cit., p. 423.

[7] Idem, p. 112, Chap. IV, by Lawrence Martin.

Martin, Lawrence, Physical Geography of Wisconsin: Wisconsin Geol. & Nat. Hist. Survey Bull. 36, Ec. Ser. No. 4, pp. 401-402 (1916).

[8] Aldrich, H. R., The Geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geol. & Nat. Hist. Survey, Bull. 71, Ec. Ser. No. 24, p. 132 (1929).

[9] Robinson, W. I., Unpublished manuscript: Michigan Geol. Survey files.

time[10] and was a region of recurrent movement thereafter. The displacement along this great structural feature has been estimated[11] to be possibly from a few thousand feet to three miles, depending on the accepted causal events leading up to its formation. The major fault zone strikes in a general northeasterly direction, parallel to the direction of elongation of the Lake Superior syncline in this particular area. The strike seems to change to the southeastward near the tip of Keweenaw Point, and the Keweenawan beds are recognized at Stannard's rock, an island to the southeast of the point in the same general line of strike. This change of strike to the southeast is a significant condition in determining the possible origin of the broad synclinal basin to the south, and the problem of tracing this zone of fault movement beyond Stannard's rock remains unsolved. The great Murray fault[12] which begins north of Sault Ste. Marie and extends for nearly 115 miles southeast along the north channel of Lake Huron in Ontario may be the continuation of a related movement. The vertical displacement along the Murray fault is estimated between 5,000 and 6,500 feet in a nearly vertical direction, the age late pre-Cambrian, and the downthrow largely to the north. The trace or surface course of the fault is parallel to the main axis of Killarnean folding and some of the movement probably accompanied Killarnean deformation. In some respects, such as intensity of movement and relative age, this fault feature compares with the southeast extension of the Keweenaw fault, but the apparent direction of the movement along the fault is almost opposite. There is a remote possibility that the Murray fault may be simply a movement accompanying the Keweenaw fault, and the actual extension of the Keweenaw fault is buried under Paleozoic cover approximately parallel to the topographic basin of Lake Huron. The direction of folding and downwarping in the Michigan Basin seems to partly support such a structural hypothesis.

The cause and time of formation of the Keweenaw fault has long been in dispute among geologists. In summarizing the various opinions on this subject, Butler and Burbank[13] state that "Van Hise and Leith regard the faulting as post-Cambrian, possibly post-Cretaceous. Lane believes that it started in Keweenawan time and continued 'ages later.'" They postulate the origin of the thrust from the north, starting as a fold which broke when the elastic limit was reached and show by means of descriptive diagrams two different possible conditions. These conditions include (1) the formation of the entire Keweenawan series prior to the formation of the Lake Superior basin, and (2) the contemporaneous formation of the basin at the same time that the Keweenawan series of interbedded lava flows and sediments was accumulating. They support the second assumption and conclude that "the movement of the fold and subsequent fault began in Keweenawan time and continued after the Jacobsville ("Eastern") sandstone was laid down, possibly for a long time after. The thrust movement from the interior of the basin suggests that the cause of the Keweenaw fault was probably closely allied to the formation of the Lake Superior syncline and the intrusion of the

[10] Butler, B. S., and Burbank, W. S., and Others, Copper Deposits of Michigan: U. S. Geol. Survey, Prof. Paper No. 144, pp. XI and XII (1929).
[11] Butler, B. S., and Burbank, W. S., and others, Op. cit., p. 51.
[12] Collins, W. H., North Shore of Lake Huron: Canada Dept. Mines, Canada Geol. Survey, Mem. 143, p. 106 (1925).
[13] Op. cit., pp. 50, 51, 52, 53.

laccolith. It seems possible that successive upward thrusts alternating with outpouring of lava and settling during igneous activity produced the folding and finally the faulting along the margin of the area."

Lane[14] believed that the Keweenaw fault began as a block fault in an interior basin like those of the Great Basin region, that it was also a line of volcanic activity, and that an overthrust movement took place at the time of the Appalachian Revolution to bring about the present form and general hade of the fault. The idea of "block faulting" would agree somewhat with the conception of a rift valley that was mentioned by Martin.

The arcuate trace of the Keweenaw fault, including the southwest extension determined by Aldrich[15] and the above mentioned possible southeast extension, partly encloses the Michigan synclinal basin to the south. If the source of movement along this arcuate trend was from the north, then there is a logical and feasible explanation for the origin and structural development of the Michigan Basin. Assuming this surface course of the fault and source of movement, the major structure of lower Michigan probably attained its present general form during the time of the late Keweenawan faulting movement.

An objection to this conclusion arises because Van Hise and Leith[16] contended that the Lake Superior Basin was essentially the general location of a shore zone lapping up against the continental area to the north. They stated that in the formation of the Lake Superior basin, the thrust came from the south toward this northern continental region and gave rise to the asymmetrical structure of the basin. This source of pressure would show that possibly the Lower Peninsula basin was a "deep" parallel to the old northern pre-Cambrian shore line.

Although the pressure downwarping the Michigan Basin might have been applied from either the north or south, according to the idea of Suess that such movements originate from the land, the source of pressure forming the synclinal basin of the southern peninsula of Michigan originated to the north and was applied principally from the northeast. The comparatively gentle regional dip into the center on the southwest margin of this basin, its asymmetrical shape, the persistent deep troughs on the east and northeast sides of the Lower Peninsula (see figs. 23 and 24), and the type of local folding with steep dips to the southwest indicate that the source of pressure was mostly from the northeast. It is apparent that the basin may have formed prior to Keweenawan, but its present character and shape was probably not developed until after that time.

If the structural and depositional history of lower Michigan is now traced on this basis, the various major structural features of the region seem to fit into the picture in rather logical order. In considering the origin and causes of structure in the "basin," one should include rotational shear.[17] Forces of this type were probably active and localized minor structures in the area. The stresses affecting the major synclinal basin, must have operated from the east and northeast throughout a great part of Paleozoic time. The separation of the Lake Superior and the lower Michigan basins was probably brought about by the Kewee-

[14] Lane, A. C., Keweenaw Fault: Bull. Geol. Soc. America, Vol. 27, p. 93 (1916).
[15] Aldrich, H. R., Op. cit., p. 123.
[16] Op. cit., page 623.
[17] Mead, M. J., The Mechanics of Geologic Structures: Jour. Geol., Vol. 28, pp. 505-523 (1925).

nawan movement. Upon this assumption it is possible to draw an interesting analogy between the Michigan "basin" and the Appalachian trough.

The sinuous character of the Keweenawan structural front is comparable to the Appalachian structural front, and the asymmetrical cross section and variable thickness of deposits in the Michigan basin is very similar to the cross section and thickness of deposits in the Appalachian basin[18]. The relation of the Appalachian trough to the Cincinnati anticline is similar to the Michigan synclinal basin and the Wabash arch—"Wisconsin island" positive structural element. On this supposition, the Wabash arch was formed much earlier than the Cincinnati anticline and now represents a downwarped southeast extension of the old Wisconsin land mass. At least, the Wabash arch seems to be a preliminary remote southwest upward element of the Keweenawan movement, similar to the Cincinnati anticline, which was probably an early result of the westward stresses (Suess' conception) which ended in the Appalachian movement.

This relation can be carried still farther in comparing the minor cross effects of the Keweenawan and Appalachian movements. The trend of folding in the Michigan Basin seems to change in direction from northwest-southeast to more nearly north-south in the northern part of the southern peninsula. The axes of folding in the Appalachian trough veer sharply from a northeast-southwest trend to the east in its northern portion and to the west in its southern portion. Cross buckling[19] is common along the axis of the Appalachian trough; cross folding is common along the major axis of the Michigan "basin." The east-west faulting of central Kentucky is comparable to the east-west faulting in eastern Wisconsin[20] which extends into western Michigan in the form of sharp east-west folds.

The adoption of the isopachous or equal thickness maps, used previously in the discussion of the evolution of the synclinal basin to show the depositional as well as the structural history of the province, is patterned somewhat after the comprehensive study made by Cheney[21] on the history of Carboniferous sediments of the Mid-Continent oil fields. Structurally, the Michigan synclinal basin is a much more limited area and includes one structural province rather than several connected structural provinces. The isopach contour interval used for Michigan has been either 50 or 100 feet of thickness and, whenever possible, the figures have been compiled accurately for an individual formation. The results and the important deductions are similar to those of Cheney in the entirely remote Mid-Continent area, although no attempt is made to explain the causes for shifting of the basin by the transfer[22] of the subcrustal plastic material as did Cheney. An effort has been made, however, to indicate the origin of stresses causing the movement and consequent shifting of the location and elongated direction of individual troughs in the sinking sedimentary basin. It seems preferable in the

[18] Price, Paul, The Appalachian Structural Front: Jour. Geol., Vol. 39, No. 1, p. 40 (1931).
[19] Keith, Arthur, Outlines of Appalachian Structure: Bull. Geol. Soc. America, Vol. 34, pp. 313, 326 (1923).
[20] Chamberlin, T. C., Geology of Wisconsin: Wisconsin Geol. Survey, Vol. 4, Pl. 8 (1882). Thwaites, F. T., The Buried pre-Cambrian of Wisconsin: Bull. Geol. Soc. America, Vol. 42, p. 729 (1931).
[21] Cheney, M. G., History of the Carboniferous Sediments of the Mid-Continent Oil Fields: Bull. Am. Assoc. Petroleum Geologists, Vol. 13, No. 6, pp. 557-594 (1929).
[22] Cheney, M. G., Op. cit., pp. 569, 588-594.

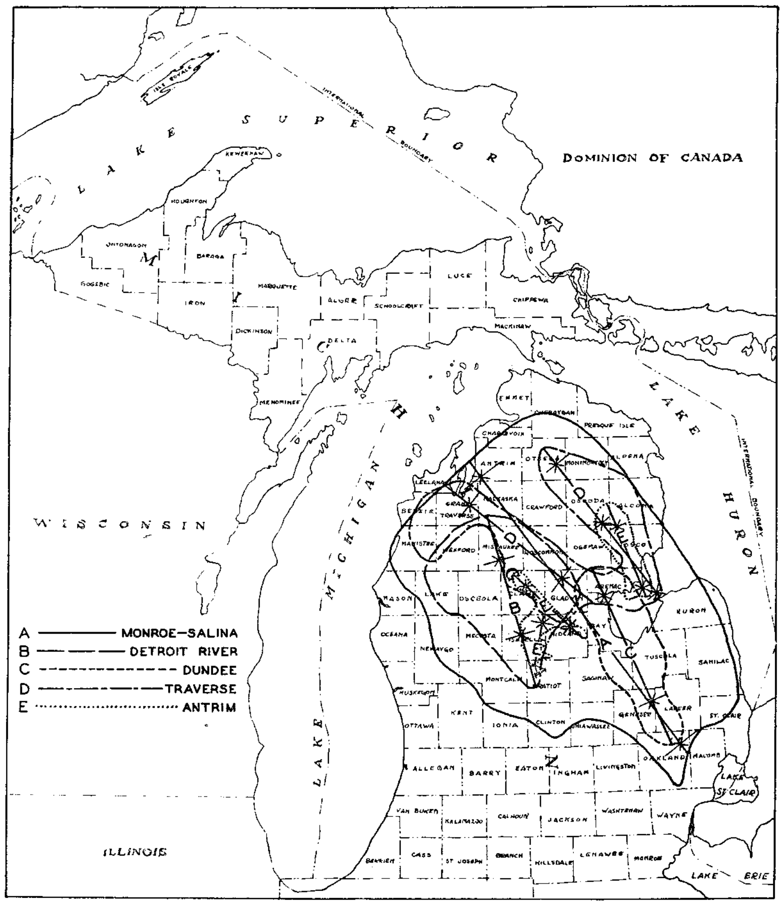
Michigan region to explain the differential subsidence or downwarping of the basin by the change in predominant directions from which tangential stresses were applied through different periods, rather than simply by the shifting of subcrustal material. The transmission of tangential stresses by strong or competent beds may not have been of the order that is commonly understood to cause folding in connection with mountain building. The conception is rather that built up stresses were transmitted horizontally through the deeper seated rocks (not in the zone of plastic flow) and that the resulting strains were resolved into components and released by movements along preexisting lines or zones of weakness, which had been caused during earlier times of grand deformation. It would seem that the transfer of plastic material is actually an effect rather than a cause, and that the real cause for the shifting of downwarped areas in an individual sedimentary basin are the strains which exist within the crust of the earth. The source of these strains would be the accumulating pressures which later give rise to the major mountain making disturbances in the areas of greatest sinking.

Apparently Cheney[23] is partly in accord with this idea for he says:—"Structural trends developed during successive periods may vary in direction. The pre-Carboniferous trends seem to have been mainly west-north-west, as already noted. The Ouachita basin and *orogeny must have largely controlled structural development* throughout much of the Mid-Continent area during most of the Mississippian and Pennsylvanian epochs, producing northeast trends of folding. The Ardmore basin evidently accentuated the pre-Carboniferous lines of folding within its sphere of influence. Permian basins necessitated adjustments from diverse centers of subsidence, and post-Jurassic embayments and tiltings add further complications."

The ability of rocks above the zone of flow to transmit stresses over long distances is questioned by many geologists, but the influences which caused progressive downwarping of the Michigan synclinal basin seem to have been remotely controlled. During the Appalachian disturbances, Keith[24] is of the opinion that although the limit of strong folds does not reach westward beyong central Pennsylvania and West Virginia, the lesser structures caused by the movement were formed as far west as central Minnesota and northwestern Iowa. Cheney[25] believes that the epi-continental accumulations of unequal thickness in downwarped areas are "just as convincing evidences of crustal movements as are thousands of feet of uplift and consequent erosion," and "it is as improbable that basins subside evenly as it is that uplifts rise uniformly." The series of thickness maps (see figs. 7, 8; 12-16; 18, 19) for the Michigan synclinal basin very clearly emphasizes the significance of these relationships. By outlining the areas of the various deep basins of Michigan during the stages of Devonian and Mississippian deposition, it has been possible to develop comparative evidence which illustrates the directional relation of tilting and warping movements that took place during these periods.

The several stages of configuration in the development of the "basin" during the Devonian period are shown together on one map in Figure

[23] Cheney, M. G., Op. cit., p. 588.
[24] Keith, Arthur, Structural Symmetry in North America: Bull., Geol. Soc. America, Vol. 39, p. 330 (1928).
[25] Cheney, M. G., Op. cit., p. 586.



DEVONIAN

Figure 23. Map showing the axes and areal extent of the regions of greatest downwarping in Michigan in late Silurian and Devonian times.

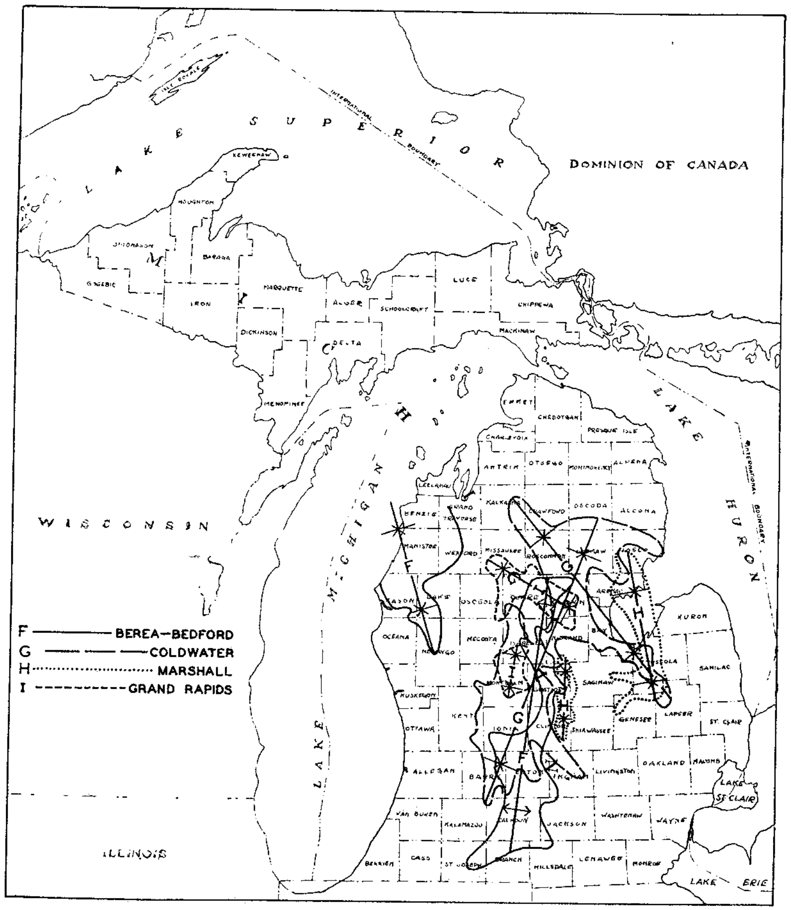
23. The predominance of the northwest-southeast direction is very striking, and the continuance of warping parallel to this general axial trend is explained by the controlling effect of dominant movement along lines of weakness which originated in Keweenawan time. The stages of the synclinal basin during Mississippian times are similarly indicated in Figure 24. This map shows a marked change in the principal elongation of the basin from the preceding period. The change of the long direction to northeast-southwest is considered evidence that there was pressure from a new source controlling the downwarping of the basin. Apparently, the growing strains which culminated in the Appalachian Revolution or the building of the Appalachian Mountains during the Pennsylvanian and Permian, commenced during Ellsworth-Bedford times. The effect of the new stresses was to temporarily counterbalance the controlling influence of the older Keweenawan lines of weakness and bring about warping parallel to the general direction of the present Appalachian mountain chain.

It is evident from this map (see fig. 24) that the controlling movement from the Appalachian center was not continuously dominant during the Mississippian period. From time to time, warping took place along the northwest-southeast direction, and apparently when the two dominant directions were more or less in balance, an almost perfect basin formed. During these periods, the "basin" became practically isolated, and conditions of evaporation set in. The evaporite series prior to Mississippian times was probably also brought about by similar circumstances.

This explanation of the depositional conditions and some of the movements affecting the basin seems to satisfy the relationships indicated by the isopachous maps. The details of interpretation are probably open to question, but the general reasoning seems borne out by the relationships of the major structural features. These comparisons seem more than a mere coincidence and strongly suggest a genetic relation between the Keweenawan movement and the Michigan "basin" that is similar to the Appalachian revolution and the Appalachian trough. The intersection of these two stress zones in middle and late Paleozoic was probably the controlling factor which brought about periodic isolation of the Michigan sedimentary basin and the consummation of evaporite conditions in the formation of thick deposits of salt, anhydrite, and gypsum. It was evidently in the Mississippian that the growing stresses forecasting the Appalachian revolution were first felt in Michigan. A marked shifting of the direction of the components of downwarping in the Michigan basin and the accentuation of the Logansport "sag" in northern Indiana took place at this time.

The forking tendency of the Cincinnati anticline into two divergent arches profoundly affected the sedimentary history and the migration of fauna into Michigan. It seems from the theory of origin outlined for the Michigan "basin" that the separate arches constituting the northerly extension of this structural feature were not formed at once but at different times. This division of the Cincinnati anticline into two branches was a product of complex factors in structural evolution.

The downwarping of the Michigan synclinal basin was probably the composite result of the weight of sediments and periodic subsidence due to horizontal stresses from mountain making disturbances. The chang-



MISSISSIPPIAN

Figure 24. Map showing the axes and areal extent of the regions of tilting and greatest downwarping in Michigan in Mississippian time.

ing trends of the downwarping are conclusive evidence that its causes were not always acting vertically. The type and distribution of the sediments played an important part in the amount of sinking. That tilting movements also took place is indicated by the shifting of the deep portion of the basin from one side to the other in almost parallel position. These tiltings of the land allowed the sea to transgress and retreat, bringing in different types of sediments and life in various stages of evolution. The importance of this class of earth deformation has been emphasized by Ulrich[26], Schuchert[27], and Grabau[28] for the great sedimentary basins of eastern North America. These writers have not discussed the Michigan Basin to any large degree because of the scarcity of stratigraphic data in the region. However, a study of recent well data reveals much about the tilting and oscillatory movements that took place. The relation of the regional aspects of the Michigan Basin to contiguous major basins of deposition brings out some interesting comparisons. These may have a bearing upon the origin of the larger structural features of the area. The basin seems to be connected with the Appalachian trough by a saddle or downwarp along the Cincinnati anticline where it crosses the Ontario peninsula in the vicinity of Lake St. Clair. This connection suggests that the two provinces were possibly associated structurally. The control of Appalachian folding over conditions in the Michigan region has been previously postulated. Richardson[29], in discussing the regional structure of the Pittsburgh-Huntington basin (a division of the Appalachian trough), states that the minor structures show the effect of "the dying out of the forces that produced the major features of the Appalachian structure farther east." The temporary joining of the Michigan basin with this province would offer further evidence in support of the premise that forces connected with Appalachian folding exerted a marked control over deposition and structure in Michigan.

The similarity of folding in the southern peninsula with well known structural features like the LaSalle anticline in Illinois is particularly striking. The Howell structure (see plate III) is similar in size, trend, and basinward steep dip to the LaSalle anticline and, although the two are far removed, some sort of genetic connection is suggested by this comparison. The lines of weakness originating in Keweenawan in the Michigan synclinal basin may have been affected by the Devonian movement which developed numerous faults on the northeast side of the Ozark dome. According to Keith[30], the same movement formed gentle anticlines and synclines in northern Illinois, Wisconsin, and Iowa, which

[26] Ulrich, E. O., Revision of the Paleozoic Systems: Bull. Geol. Soc. America, Vol. 22, pp. 281-680 (1911); Index Vol. 24, pp. 625-668 (1913).

———, Major Causes of Land and Sea Oscillations: Washington Acad. Sci. Jour., Vol. 10, No. 3, pp. 57-78 (Feb. 4, 1920); also Smithsonian Inst., Ann. Rept., pp. 321-337 (1920).

———, and Schuchert, Chas., Paleozoic Seas and Barriers in eastern North America: New York State Mus., Bull. 52 (Paleont. 6, Rept. of State Paleontologist), pp. 633-672 (1902).

[27] Schuchert, Chas., Paleogeography of North America: Bull. Geol. Soc. America, Vol. 20, pp. 427-606 (1910).

———. The Nature of the Paleozoic Crustal Stability in eastern North America: Am. Jour. Sci., 4th Ser., Vol. 50, No. 300, pp. 319-414 (December, 1920).

———, Sites and Nature of the North American Geosynclines: Bull. Geol. Soc. America, Vol. 34, pp. 151-230 (June, 1923).

[28] Grabau, A. W., Types of Sedimentary Overlap: Bull. Geol. Soc. America, Vol. 17, pp. 567-636 (1906).

[29] Richardson, G. B., Structure-Contour Maps of the Pittsburgh-Huntington Basin: Geol. Soc. America, Bull., Vol. 39, p. 544 (1928).

[30] Keith, Arthur, Structural Symmetry in North America: Geol. Soc. America, Bull., Vol. 39, p. 327 (map), p. 360 (1928).

are slightly unconformable with the overlying Mississippian beds. Similar movements probably took place in the contiguous Michigan Basin. If this is true, then the principal folding which determined the structures in the middle Devonian rocks of the State must have occurred during the later part of the Devonian epoch, and subsequent deformation simply modified or accentuated the results of this movement.

FOLDING IN THE SYNCLINAL BASIN

CONTROLLING FEATURES OF THE FOLDING

The recognition of folding in the Michigan synclinal basin dates back to the time of the earliest geologists who made observations in the region. In 1865, Alexander Winchell[31] compared Michigan with the Ontario peninsula and at that time was favorably inclined toward the future oil possibilities of the Michigan Basin. He stated in this article: "Whatever differences exist between the geological indications observed in the two regions are rather in degree than in kind; and the advantages are undoubtedly on the side of the Michigan region." The extent of structural deformation in the State has been summarily discussed by various later writers[32] who have presented new conceptions about the details and causes of folding.

The idea that the principal forces causing the folding of the sedimentary rocks of southern Michigan had been those forces which acted vertically[33] prevailed for some time. The early structures discovered in Michigan seemed to pitch toward the central part of the State, and the prevailing notion that the "basin" was almost circular afforded evidence for this theory. The results of the intensive drilling from 1925 to the present time have revealed conditions indicating that this view of the importance of vertical structural causes will have to be somewhat

[31] Winchell, Alexander, On the Oil Formation in Michigan and Elsewhere: Am. Jour. Sci., 2d Ser., Vol. 39, pp. 352, 353 (1865).

[32] Lane, A. C., The Geology of Lower Michigan with Reference to Deep Borings: Geol. Survey of Michigan, Vol. V, Pt. 2, pp. 1-100, pls. I-LXXIII (1895).

——————, and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept. State Geologist for 1908, pp. 43-46 (1909).

Grabau, A. W., Physical and Faunal Evolution of North America during Ordovicic, Siluric, and early Devonic Time: Jour. Geol., Vol. 17, pp. 246-249 (1909).

——————, and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, pp. 55-58 (1909).

Sherzer, W. H., Detroit Folio No. 205: Field addition, pp. 91-94 (1916).

Smith, R. A., Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 8, Geol. Ser. 6, pp. 366-397 (1911).

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Robinson, W. I., Possibilities of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 32, Geol. Ser. 26, pp. 103-118 (1922).

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Carlson, C. G., Geology of the Saginaw Oil Field, Michigan, and a Discussion of Michigan's Oil Prospects: Am. Assoc. Petroleum Geologists, Bull., Vol. 11, No. 9, pp. 359-365 (1927).

Newcombe, R. B., Structural Influences on recent Michigan Oil Development: Michigan Acad. Sci., Arts and Letters, Papers, Vol. 10, pp. 209-215 (1928).

——————, Oil and Gas Development in Michigan: Michigan Geol. Survey, Pub. 37, Pt. 3, pp. 141-299 (1928).

——————, Characteristics of Geological Structure in Michigan: Nat. Pet. News, Vol. 22, No. 34, pp. 53-56 (August 20, 1930).

Pirtle, George W., Michigan Structural Basin and Its Relationship to Surrounding Areas: Am. Assoc. Petroleum Geologists, Bull., Vol. 16, No. 2, pp. 145-152 (February, 1932).

[33] Robinson, W. I., Folds Resulting from Vertically Acting Forces: Jour. Geology, Vol. 31, pp. 336-343 (1923).

revised. It seems that Hedberg[34] has concluded, "while low ill-defined folds of gentle dip may frequently be due to settling, it must be rarely and only under special conditions that large, well-defined, surface structures may be attributed solely to compaction over topographic features separated from them by thousands of feet of rock." The causes of folding in Michigan are now thought to have been complex and varied with many controlling elements effective in different parts of the sedimentary basin.

SECONDARY CAUSES OF FOLDING

The original causes of folding in Michigan have been outlined previously in discussing the development of the structure of the synclinal basin (pp. 102-112). In addition to the great regional stresses, a number of other causes of deformation must be considered. Rotational shear due to faulting in the pre-Cambrian basement rocks, vertical compaction over buried hills, and the strains set up in overlying beds by the solution of underlying weaker, more soluble rocks are other possible sources of folding stresses. Probably, these forces were active either together or separately at different times.

DEEP SEATED FAULTING

The presence of a somewhat deeply buried regular fault system in the pre-Cambrian rocks beneath the area is practically certain. Thwaites[35] has recently mapped the major subsurface faults of eastern Wisconsin and described these faults in some detail. Faulting is known to be present in the Paleozoic of the western part of the Ontario[36] peninsula adjoining Michigan, and Carman[37] has definitely proved the faulted nature of the west flank of the Cincinnati anticline in northwestern Ohio. The Howell structure in Livingston County, Michigan, is faulted on the steep southwest flank, although the details of this zone of faulting have not been well worked out. The uniform, sharp, west dip of nearly all structures in the central part of the State strongly suggests deep seated faulting as a cause for the location of these structures. The en echelon or staggered arrangement of local domes in Midland and Isabella counties indicates (see pls. IV and V) the effects of shearing due to movements along deeply buried faults in the basement complex, as previously demonstrated by Chamberlin[38] and Thom[39] for central Montana and Fath[40] for certain localities in northeastern Oklahoma and southeastern Kansas. The more likely method by which shearing took place was through differential movement along the two sides of a fault plane or zone, giving rise to torsional warping in the surficial rocks. This type of deformation was first illustrated by Mead[41] with a thick piece of rubber which was coated with paraffin and then twisted

[34] Hedberg, Hollis D., The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Am. Assoc. Petroleum Geologists, Bull., Vol. 10, Pt. 2, p. 1066 (1926).

[35] Thwaites, F. T., Buried Pre-Cambrian of Wisconsin: Bull., Geol. Soc. America, Vol. 42, p. 729 (1931).

[36] Harkness, R. B., Oral communication.

[37] Carman, J. Ernest, Geology of Lucas County: Ohio Geol. Survey, Unpublished manuscript; also oral communication.

[38] Chamberlin, R. T., A Peculiar Belt of Oblique Faultings: Jour. Geol., Vol. 27, pp. 602-613 (1919).

[39] Thom, W. T., Jr., The Relation of Deep-seated Faults to the Surface Structural Features of Central Montana: Am. Assoc. Petroleum Geologists, Bull., Vol. 7, No. 1, pp. 1-13 (1923).

[40] Fath, A. E., The Origin of Faults, Anticlines, and Buried Granite Ridge of the Northern Part of the Mid-Continent Oil and Gas Field: U. S. Geol. Survey, Prof. Pap. 28-C, pp. 75-84 (1921).

[41] Mead, W. J., The Mechanics of Geologic Structures: Jour. Geol., Vol. 28, pp. 505-523 (1920).

to show the effects of torsional movement. The same results may be obtained by simply twisting an ordinary hard rubber eraser. Sherrill[42] favored this type of movement, supplemented by a broad uplift, to explain the origin of the en echelon faults in north central Oklahoma, formerly studied by Fath[43] and Foley[44]. Aldrich[45] used this same explanation in accounting for the regular, systematic cross faults in the Gogebic Iron Range of Wisconsin and Michigan. Link[46] has recently suggested in supporting a former paper by McCoy[47] that faults of this type can be commenced by feeble tensile stresses which arise when sediments settle irregularly over a low arch or ridge. The incipient en echelon fissures thus formed develop into normal faults by later adjustment. A theory similar to that propounded by Sherrill for Oklahoma and Aldrich for Wisconsin and stated more generally by Cheney[48] for the entire Mid-Continent region, seems to explain the en echelon folding in central Michigan. Cheney states that "en echelon folding and faulting may be the natural result of the local features along an older line of weakness being accentuated by potent forces coming from a new direction." The idea thus expressed is in line with the statement of Bailey Willis[49] that "the orientation of shear planes in any but a homogeneous body is governed by lines of weakness." The interior of the "basin" was very likely subject to unequal subsidence, and the recurrent tilting movements caused by pressures from various directions completed the shearing effects along deep seated faults which resulted in the en echelon arrangement of the folds. The faults in the crystalline basement rocks were probably not the direct cause of deformation, but the "rudders" which determined the localization of nearly all movements throughout geologic time in lower Michigan. Abnormal initial dips and unequal sedimentation which Willis[50] considers so important in the commencement of folding would normally be concentrated along these zones by previous deep seated displacements. The perfection of pattern shown by Hobbs[51] to be the usual condition for nearly all earth features is clearly illustrated by the directions of folding in Michigan and the regular interval between parallel zones of folding. (See pl. III). These relations constitute further evidence of the control of pre-Cambrian basement faults upon the directions of folding in the Michigan Basin.

VERTICAL COMPACTION

The compaction theory has been stressed greatly in explaining the characteristics of many folds in the Mid-Continent oil region. The con-

[42] Sherrill, R. E., Origin of the En Echelon Faults in North Central Oklahoma: Bull., Am. Assoc. Petroleum Geologists, Vol. 13, Pt. 1, pp. 31-37 (1929).

[43] Fath, A. E., Op. cit.

[44] Foley, L. L., The Origin of the Faults in Creek and Osage Counties, Oklahoma: Bull., Am. Assoc. Petroleum Geologists, Vol. 10, No. 3 (with discussion), pp. 293-303 (1926).

[45] Aldrich, H. R., The Geology of the Gogebic Iron Range of Wisconsin: Wisconsin Geol. & Nat. Hist. Survey, Bull. 71, Ec. Ser. 24, p. 132 (1929).

[46] Link, Theodore A., En Echelon Tension Fissures and Faults: Bull., Am. Assoc. Petroleum Geologists, Vol. 13, Pt. 1, pp. 627-637; Discussion pp. 637-643 (1929).

[47] McCoy, A. W., Discussion: Bull., Southwestern Assoc. Petroleum Geologists, Vol. 1, p. 110 (1917).

——————, A Short Sketch of the Paleogeography and Historical Geology of the Mid-Continent Oil District and its Importance on Petroleum Geology: Bull., Am. Assoc. Petroleum Geologists, Vol. 5, No. 5, pp. 541-544 (1921).

[48] Cheney, M. G., History of the Carboniferous Sediments of the Mid-Continent Oil Field: Bull., Am. Assoc. Petroleum Geologists, Vol. 13, No. 6, p. 588 (1929).

[49] Willis, Bailey, Folding or Shearing, Which?: Bull., Am. Assoc. Petroleum Geologists, Vol. 11, Pt. 1, p. 34 (1927).

[50] Willis, Bailey, The Mechanics of Appalachian Structure: U. S. Geol. Survey, 13th Ann. Rept., pp. 253, 262 (1893).

[51] Hobbs, W. H., Repeating Patterns in the Relief and in the Structure of the Land: Bull., Geol. Soc. America, Vol. 22, pp. 123-176 (1911).

ception that folds were formed from vertical compaction of sediments invokes the factor of differential settling over a topographic irregularity as a primary cause for structural warping. Blackwelder[52] made one of the first extensive applications of this theory to explain a number of unusual anticlinal structures in central Kansas, and Monnett[53] applied the same idea to several other domes in the Mid-Continent region. The exposition of the subject by Sidney Powers[54] brought the notion of gravitational compaction into still wider application. Monnett[55] and Powers[56] have entered into further discussion of this kind of deformation. In recent years, exhaustive research has been carried on by Hedberg[57], Nevin and Sherrill[58], Beckstrom and Van Tuyl[59], Athy[60], and Trask[61] in an effort to show more exactly by experimentation and research the factors controlling this type of folding and the quantitative relations involved. Although accepting the gravitational compaction theory in part, Rubey[62] continually emphasizes that loss of porosity by burial is simply one phase of the process and, therefore, the quantitative application of the idea must be critically analyzed. He reasons from both field observation and experimental data that the stretching and squeezing of strata by landslides of soft material over buried hills and also tilting, or actual stretching of the beds due to the tensional movements on anticlines resulting from horizontal compression, must be considered in the analytical examination of structures thought to have been primarily formed by vertical compaction. The change in the attitude of sediments caused by unequal settling and compaction over topographic irregularities on the sea floor was, however, probably an important factor in the origin and growth of numerous Michigan structures. Robinson[63] showed that folds resulting from dominantly downward, vertically acting

[52] Blackwelder, Eliot, The Origin of the Central Kansas Oil Domes: Bull., Am. Assoc. Petroleum Geologists, Vol. 4, No. 1, pp. 89-94 (1920).

[53] Monnett, V. E., Possible Origin of the Structures of the Mid-Continent Oil Field: Econ. Geology, Vol. 17, No. 3, pp. 194-200 (1922).

[54] Powers, Sidney, Reflected Buried Hills and their Importance in Petroleum Geology: Econ. Geology, Vol. 17, No. 4, pp. 233-259 (1922).

[55] Monnett, V. E., The "Buried Hills" as a Structural Agency: Oklahoma Acad. Sci., Proc., Vol. 6, Pt. 2, pp. 268-272 (1927).

[56] Powers, Sidney, Structural Geology of the Mid-Continent Region. A Field for Research: Geol. Soc. America, Bull., Vol. 36, pp. 379-387. Discussion by K. C. Heald and Sidney Powers, pp. 389-392 (1925).

——————, Buried Ridges in West Texas: Bull., Am. Assoc. Petroleum Geologists, Vol. 11, No. 10, pp. 1109-1115 (1927).

[57] Hedberg, Hollis D., The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: Bull., Am. Assoc. Petroleum Geologists, Vol. 10, Pt. 2, pp. 1035-1072 (1926).

——————, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: A Reply to a discussion by W. W. Rubey; Bull., Am. Assoc. Petroleum Geologists, Vol. 11, No. 7, pp. 875-886 (1927).

[58] Nevin, C. M., and Sherrill, R. E., Studies in Differential Compaction: Bull., Am. Assoc. Petroleum Geologists, Vol. 13, Pt. 1, pp. 1-22 (1929).

[59] Beckstrom, R. C., and Van Tuyl, F. M., Compaction as a Cause of the Migration of Petroleum: Bull., Am. Assoc. Petroleum Geologists, Vol. 12, No. 11, pp. 1049-1055 (1928).

[60] Athy, L. F., Density, Porosity, and Compaction of Sedimentary Rocks: Bull., Am. Assoc. Petroleum Geologists, Vol. 14, No. 1, pp. 1-24 (1930).

——————, Compaction and Oil Migration: Bull., Am., Assoc. Petroleum Geologists, Vol. 14, No. 1, pp. 25-35 (1930).

[61] Trask, Parker D., Compaction of Sediments: Bull., Am., Assoc. Petroleum Geologists, Vol. 15, No. 3, pp. 271-276 (1931).

[62] Rubey, W. W., Determination and Use of Thickness of Incompetent Beds in Oil Field Mapping and General Structural Studies: Econ. Geology, Vol. 21, No. 4, pp. 333-351 (1926).

——————, The Effect of Gravitational Compaction on the Structure of Sedimentary Rocks: A Discussion: Bull., Am. Assoc. Petroleum Geologists, Vol. 11, No. 6, pp. 631-632; No. 12, pp. 1333-1336 (1927).

——————, Lithologic Studies of Fine Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region: U. S. Geol. Survey, Prof. Paper 165-A, pp. 1-54 (1930).

——————, and Bass, N. W., The Geology of Russell County, Kansas, with special reference to Oil and Gas Resources: State Geol. Survey of Kansas, Bull. 10, Pt. 1 (discussion of origin of structure by W. W. Rubey, pp. 72-86) (1925).

[63] Robinson, W. I., Folds Resulting from Vertically Acting Forces: Jour. Geology, Vol. 31, pp. 336-343 (1923).

forces were represented in the rocks of Michigan and gave a rather complete analysis of folds of this type.

The unevenness of the pre-Cambrian land surface has been recognized in Ontario and Wisconsin, where the maximum relief exceeds 800 feet. The relation between the structure of the Paleozoics and the pre-Cambrian floor in Wisconsin has been analyzed by Thwaites[64], who ascribes the origin of a number of Wisconsin folds to settling over the uneven land surface of the underlying pre-Cambrian. According to Collins[65], the pre-Cambrian relief in the area contiguous to the Paleozoic rocks north of Lake Huron in Ontario is between 500 and 800 feet. Ehlers[66] described abnormal offshore dips on Sulphur Island in the same general region. From these observations, it seems almost definite that structural features of the same type are present in the Michigan synclinal basin, but none of the sharp folds seem to have been caused in this manner. It is altogether possible that peneplaination had gone on so far before the Paleozoic sediments were laid down that the structures derived from deposition and compaction on an uneven floor are for the most part broad and unimportant in causing oil accumulation. This supposition does not preclude the possibility that monadnocks of considerable size might have remained, but there seems to be no evidence of this condition unless the broad structural feature in Livingston County (see pl. III and fig. 38) is an example.

SOLUTION

Folding brought about by solution is difficult to determine from subsurface data, but evidence of fracturing and faulting due to this cause has been shown by the presence of recemented breccia, fractured rock, and fissures in exposures and in cores from the beds of the various evaporite series containing salt and gypsum. There is further evidence of displacements from this cause in the local sharp parallel reentrant cross noses and structural ravines on the crests of the Muskegon and Mount Pleasant folds. (See figs. 27 and 28; pls. IV and V). Some of the concentric terrace folds like those parallel to the margins of the "basin" described by Robinson[67] may have resulted in this manner.

ALINEMENT OF FOLDS

The general parallel alinement of folds across the State is obvious (see pl. III), although the perfection of this arrangement may be somewhat exaggerated by incorrect interpretation where no wells have been drilled. The principal directions of the major lines of folding seem to be closely allied to the general strike of the rocks. There are four dominant directions of folding: northwest-southeast, northeast-southwest, north-south, and east-west. These are the ones which Hobbs[68] cited as the dominant directions characterizing practically all earth movements. The northwest-southeast folding seems to be the most pronounced and widespread in the eastern, southeastern, and central portions of the southern peninsula. The north-south flexures are present locally in the southern part of the State, but they seem to be more prominent in the north central part. Many of the northwestward trending folds may join with the north-south axes in an arcuate fashion, but more drilling will be necessary to prove this. Northeast-southwest folds occur in the southwestern part of the State, and apparently these constitute broad, gentle flexures compared with the sharper ones in central Michigan. Prospecting for oil and gas in this region has not been particularly successful. As shown by the regional map (see pl. III), structures that trend almost east-west are the most prominent in several of the western counties where extensive drilling has taken place. These districts seem to include Muskegon and Oceana counties, and the western part of Newaygo County.

[64] Thwaites, F. T., Buried Pre-Cambrian of Wisconsin: Geol. Soc. America, Bull., Vol. 42, pp. 739, 740 (1931).
[65] Collins, W. H., North Shore of Lake Huron: Canada Dept. of Mines, Canada Geol. Survey, Mem. 143, pp. 9, 10 (1925).
[66] Ehlers, G. M., An Ordovician Reef on Sulphur Island, Lake Huron: Papers, Michigan Acad. Sci., Arts and Letters, Vol. 4, pp. 425-429 (1925).
[67] Robinson, W. I., Op. cit., p. 340.
[68] Hobbs, W. H., Repeating Patterns in the Relief and in the Structure of the Land: Bull., Geol. Soc. America, Vol. 22, pp. 148-176 (1911).

The principal directions of joints in the Paleozoic rocks of the northern peninsula also conform to this same general pattern. Robinson[69] has observed that in the Niagaran rocks of northern Michigan the most pronounced joint direction trends N.50°W. Another series of joints occurs approximately at right angles to this set, and the two directions form the master joint system of the region. He found also that another less common set trends almost north and south. According to Robinson, these fracture systems show the characteristic features of compression joints and were probably formed by forces acting in a nearly north-south direction.

The central basin area of Michigan is deeply furrowed with troughs which trend northwest-southeast. These local basins are broad in comparison to the "highs" which cross the same part of the State and seem to be more or less flat, although this apparent absence of structural relief may be due to incomplete information because of the lack of wells. This condition is locally a real one because the Dow Chemical Co. operating wells in Midland, Isabella, and Gratiot counties, has drilled in the structural "lows" which would otherwise be avoided. These structural features of central Michigan, including sharp, narrow, asymmetrical anticlines and broad flat bottomed synclines, indicate again that deep seated faults were potent factors in determining the localization of folding in the Michigan synclinal basin.

MODIFYING STRUCTURAL FACTORS

Among the factors which modify the structures resulting from folding processes are faulting, solution, expansion, and the occurrence of reefs. These factors are often inter-related and may also exercise a dominant control over one another. Some of their important influences are in forming secondary structures, creating porosity in the beds, and controlling the general lines of structural deformation. The influences act jointly, and the dominance of any one of the structural factors largely determines the characteristics of the resulting deformation. There are several examples of such modifying structural factors within the Michigan Basin.

FAULTING

Faults with large displacements have not been observed in the surface rocks of the southern peninsula of Michigan, although the results of

[69] Robinson, W. I., Oral communication—observations made on private survey, summer of 1930.

small movements have been found in several localities[70]. The presence of larger faults is indicated by the distribution of the rocks in Presque Isle County and, according to Hindshaw[71] these fault zones can be traced for some distance. Faulting has been recognized in several coal mines and displacements of from 50 to 100 feet have been reported.

The most important zone of faulting which has been found in the southern peninsula of the State is in Livingston County near the city of Howell. (See fig. 38) The type of faulting and amount of displacement has not been determined, but a total throw of several hundred feet is indicated. The evidence substantiating this important fault zone is convincing. (See Pt. II, Chap. IV). The location and general trend of the faulted area is indicated in Plate III, and apparently the zone of movement extends across Livingston and portions of Shiawassee and Clinton counties. The displacement seems to have occurred along a zone including several subsidiary faults which may be partly normal and partly reverse. Drag folding and brecciation has taken place along the general line of faulting and some cross faults may be present. Well data suggest the cross faults, but drilling operations have not proceeded far enough to definitely prove the exact relationship of individual faults.

SOLUTION

Faulting which is caused by the dissolving of salt beds is probably a widespread type of displacement in the rocks of the State. The margins of the Detroit River and Salina salt basins as previously outlined (see fig. 9) are general belts of extensive solution and slumping resulting from that cause. Detailed structure maps of the Muskegon and Mount Pleasant oil fields show many sharp reentrants. (See figs. 27 and 28 and pls. IV and V). The minor steep cross folds which crenulate the crests of the anticlines suggest that faults of small displacement have occurred. Monoclinal flexures and small reverse faults originating in this manner have been extensively described from several New York localities, particularly in the vicinity of Syracuse[72]. Newland[73], in discussing the conditions resulting from solution along the Salina outcrop in northern New York, states that "salt measures are only found in strength some eight or ten miles back from their former place on the outcrop where the overlying strata attain a thickness of 800 feet as a minimum; the collapse of the cover following solution of the heavy salt seams has further promoted disintegration." The nearness of the Muskegon structure to the margin of the area underlain by salt deposits offers a basis for thinking that the peculiar structural features on the crest of this particular dome may have originated in a manner similar to the faults in north central New York state.

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[70] Sherzer, W. H., The Detroit Folio No. 205: U. S. Geol. Survey Atlas, Field Addition, p. 93 (1916).
Pohl, E. R., The Middle Devonian Traverse Group of Rocks in Michigan: A Summary of Existing Knowledge: U. S. Nat. Mus., Proc., Vol. 76, Art. 14, pp. 18, 19 (1929).
Personal observation in Sanilac and Wayne counties.

[71] Hindshaw, Henry H., Oral communication.

[72] Schneider, P. F., A Geologic Fault at Jamesville near Syracuse, New York: Am. Jour. Sci., Vol. 3, pp. 458-459 (1897).
——————, The Marcellus Fault: Onondaga Historical Assoc. Sci., Ser. No. 2, pp. 1-7 (1899).
——————, Preliminary Note on some Overthrust Faults in Central New York: Am. Jour. Sci., Vol. 20, pp. 308-312 (1905).
Gwynne, Chas. S., A Study of the Structural Features south of the Helderberg Escarpment in the Vicinity of Syracuse, New York: Master of Science Thesis, Syracuse Univ. Library, Syracuse, New York.

[73] Newland, D. H., The Gypsum Resources and the Gypsum Industry of New York: Bull., New York State Museum, No. 283, p. 38 (1929).

Solution must have taken place not only in the salt strata but also in the beds of anhydrite and gypsum as well. The exposures of gypsum show, by their fluted surfaces, that these minerals can easily be removed by percolating waters and other weathering agents. The structural effects which result from solution can only be postulated, but the total movement caused by adjustments brought about by solution in Michigan rocks is probably large.

EXPANSION

Anhydrite (calcium sulfate rock) also gives rise to movements derived from the expansion which takes place when it is converted into gypsum by hydration. This source of movement has been suggested by Kraus[74] to explain the origin of caves which are found on Put-in-Bay Island off the shore of Lake Erie in northern Ohio. The occurrence of abundant deposits of different varieties of calcium sulfate in all the Michigan rocks from Silurian to post-Pennsylvanian indicates strongly the activity caused by this type of movement. The doming effect of the anhydrite-gypsum reactions at depth against the high confining pressures of the great load of rocks above is not well understood and is probably insignificant below the zone of actively circulating waters. However, the deforming action near the surface from this cause is important. In northern New York, according to Newland[75], the present rock topography determines the gypsum zone, and a four-foot bed of gypsum has been found thinning to thirty inches of anhydrite down the dip. A slight rise of ground has resulted where the gypsum zone has reversed the natural northward slope. It has been determined[76] that under shallow cover anhydrite undergoes alteration to gypsum and expands in the process 50 to 60 per cent. This amounts to an exerted pressure of about 120 pounds per square inch for each 100 feet of depth. Movement of this type doubtlessly took place in that part of the Michigan synclinal basin where deposits of anhydrite and gypsum were frequently formed.

REEFS

Coral reefs are strongly developed in the Silurian and Devonian rocks of the State and bring about local structural irregularities because of unequal deposition of sediment on their uneven surfaces. Beds when consolidating naturally conform to the irregularities caused by the more compact masses of fossils such as *Stromatopora, Prismatophyllum* (more commonly called *Acervularia*) and other types of reef-forming organisms. The size of the individual areas involved in this kind of deformation is relatively small, although some of the Traverse reefs of northern Michigan and the Niagaran reef mounds which are exposed around the margin of the synclinal basin have remarkably steep dips over a short distance. The coral reef structures are very seldom reflected upward to any degree and no oil fields that can be ascribed to them alone have been found in Michigan. The principal effect of these structural features is the influence which they have on local porosity in an oil producing area. This kind of porosity may be original in part but is mostly developed

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[74] Kraus, E. H., On the Origin of the Caves of the Island of Put-in-Bay, Lake Erie: Am. Geologist, Vol. 35, pp. 167-171 (1905); Abst., Bull. Geol. Soc. Am., Vol. 16, p. 563 (1906).

[75] Newland, D. H., Op. cit., pp. 68-70.

[76] Newland, D. H., The Geology of Gypsum and Anhydrite: Econ. Geology, Vol. 16, p. 399 (1921).

by the unequal solution and possibly some dolomitization of the reefs. The local original and secondary porosity of reefs explains erratic oil production in the fields of Michigan where much of the oil is obtained from the Traverse formation. This same condition of local structure and porosity accounts for the frequent, unusual occurrence of noteworthy oil shows in regions that are structurally "low" or synclinal. Many unsuccessful drilling operations in Michigan have been prompted by these "shows" of oil and gas from locally porous zones of coral reefs in the upper part of the Traverse formation.

PERSISTENCE OF STRUCTURAL TREND LINES

The frequent recurrence of physiographic features which reflect the structural pattern[77] of the underlying rocks may act as a quasi-reliable guide in the search for hidden deeply buried faults and anticlines. When the surface rocks are covered with glacial material as in Michigan, the physiographic expression of structure is often concealed by the cover or somewhat masked by the topographic features from glaciation. In some places the influence of subsurface structure in determining the direction of drainage, shore lines, and other surface features seems stronger than in others. Caution must be used in too wide application of the principle of control of physiography by structure. A general summary of some structural and physiographic relationships, however, may suggest new lines of attack in solving problems concerning deformation in the Mchigan Basin.

ANGULARITY OF SHORE FEATURES

The angular outline of the coastal boundaries of the southern peninsula may be significant structurally. The points and promontories are particularly sharpened on the Lake Michigan shore where Little Sable Point, Big Sable Point, and Betsie Point, together with the irregular shore line in the Grand Traverse bay regions, display a remarkable conformity in shape and spacing. Thwaites[78] has recently illustrated how the shore features across the Lake on the Wisconsin side are influenced by the known subsurface faults. Some of the lines from his map when projected across Lake Michigan seem to show a rough alinement with the coast on the Michigan side of the Lake.

The northwest-southeast shore line direction of both the north and south shores at the western end of Lake Erie show a remarkable parallelism with the axial trend of the principal folding in the southeast part of the State. This correspondence in direction appears still more real when the controlling joint directions observed by Cook[79] in the vicinity of Pelee and neighboring islands are considered. He found that the principal joint directions fall into three sets that were approximately N.45°E. and N.45° W.; N.15°E. and N.75°W.; and N.75°E. and N.15°W. The N.45°W. direction corresponds almost exactly to the northwest-southeast trend of the Howell anticline in Livingston County. (See pl. III and fig. 38).

[77] Hobbs, W. H., Repeating Patterns in the Relief and in the Structure of the Land: Bull., Geol. Soc. America, Vol. 22, pp. 123-176 (1911).
[78] Thwaites, F. T., The Buried Pre-Cambrian of Wisconsin: Bull., Geol. Soc. America, Vol. 42, p. 729 (1931).
[79] Cook, C. W., The Influence of Joints in the Formation of the Islands at the Western End of Lake Erie: Papers, Michigan Acad. Sci., Arts and Letters, Vol. 5, pp. 243-251 (1925).

Saginaw Bay has an angular outline which cannot be explained by the strike directions of the rocks, and the relation of the Bay to a synclinal area is shown in Plate III. The southwest shore of the Bay near Bay City possesses a northwest-southeast elongation somewhat parallel to the major structural features of the region. The points and islands on the opposite sides of Saginaw Bay are well oriented with the mapped lines of folding and structural disturbances (see pl. III), but their origin is also related to the distribution of hard and soft rocks. The general trend of one anticlinal fold is from the vicinity of Stony Island to Point Aux Gres and another probably from Sand Point to Point Lookout.

Thunder Bay in Alpena County seems to show a much closer relation to the strike and is probably due mostly to the erosion of the softer rocks rather than to a structural cause. Little Traverse Bay is also approximately along the strike of the rocks, but the contours indicate some kind of unusual structural feature in this region. That certain shale beds in the Alpena region may have played a big part in aiding erosion and sapping down the dip is illustrated in the vicinity of Grand and Long lakes.

ELONGATION OF LAKES FRINGING LAKE MICHIGAN SHORE

The position of many lakes which fringe the Lake Michigan shore may be related in some way to structure. The minor east-west axis of the Muskegon anticline is just north of Muskegon Lake, which is elongated in a similar east-west direction. Black Lake, near Holland, seems to be alined with a sharp syncline, and Spring Lake, north of Grand Haven, is in a district that is apparently folded. A broad syncline is headed toward Pere Marquette Lake, near Ludington, and Manistee Lake is crossed at a small angle by the axis of an anticline. Portage Lake, north of Manistee, also seems to be in the general direction of an anticlinal fold. A possible structural disturbance along a general north-south direction in the vicinity of Grand Traverse Bay may also have caused the approximate parallelism of Elk Lake and Torch Lake. Pine Lake, near Charlevoix, is apparently in a structural depression, and the region near Walloon Lake is upwarped. It is suggested by the lakes in western Michigan that when the direction of the predominant structural axes change from northeast-southwest to northwest-southeast, the elongation of the lakes changes accordingly. The seeming orientation of these lakes with structure may be simply accidental because most of the region is thickly covered with drift material, but the examples are somewhat striking and should be considered in making structural studies.

DRAINAGE NETWORK PATTERN

The drainage network and small physiographic features in a glaciated area are usually very haphazard[80] in pattern. Locally, this condition holds true in Michigan, but the diagonal pattern of physiographic features in the State was long ago recognized by Winchell[81]. This diagonal arrangement is illustrated remarkably well in maps showing the areas of the various drainage systems by means of different colors. The prin-

[80] Hobbs, W. H., Earth Features and Their Meaning: The MacMillan Company, p. 309 (1912).
[81] Winchell, Alexander, The Diagonal System in the Physical Features of Michigan: Am. Jour. Sci., 3d Ser., Vol. 6, pp. 36-40 (1873).

cipal divide takes a zig-zag course north and south through the southern peninsula with changes in direction which closely correspond to some of the known structures in the underlying rocks. The Grand River-Saginaw River systems divide through the central part of the State along a line strikingly parallel to the northwest prolongation of the Howell structure although this parallelism is imperfect in detail.

GLACIAL FEATURES

Although glacial deposits practically hide the structural features of the State, still some of the pronounced morainic ridges in the north central part are curiously parallel to the trends of the known folds. If the regions where the various morainic systems sharply change their directions are lined up, these changes in direction seem remotely related to structure. Another relationship that is singular though perhaps accidental is the apparent concentration of glacial features caused by water flowing from the front of the ice (outwash, kames, eskers, etc.) in some of the areas of folding. This does not seem to be a general condition, but there was apparently a certain amount of control of this kind in the Livingston[82] County region and parts of the "Thumb" district.

Lines of glacial drainage seem to have been affected locally along their courses by belts of structural disturbance, as indicated by the Grand River channel. Leverett[83] calls this "the largest and most deeply trenched glacial river channel in Michigan and one of the finest in the glaciated area of North America." The place where the Imlay outlet [84] joins the Grand River channel is near Maple Rapids in the area of the northwest prolongation of the Howell structure. (See pl. III). This important glacial feature seems to have some relation to the structure of the region. Farther to the west near Grand Rapids, the Grand River makes a sharp northward bend for several miles. The apparent association of this feature with structure can be observed on a few of the previous maps. (See figs. 13, 14 and 18; pls. I and III).

PHYSIOGRAPHICAL FEATURES OF THE BEDROCK SURFACE

The bedrock surface beneath the glacial drift is furrowed into ridges and valleys (see pl. I) which closely parallel the directions of lines of folding in the rocks themselves. (See pl. III). In most cases the bedrock ridges are in the approximate locality of the steep dips off the flanks of well known structures. One of these ridges seems to correspond to the steep southwest dip on the west side of the Howell structure and extends from Wayne County to the central part of the State. A faint topographic expression carries across central Mecosta and Lake counties to southern Manistee County. A sharp ridge on the bedrock surface marks the general locality of the Mount Pleasant structure and the 400 foot (see pl. I) contour indicates the en echelon or staggered arrangement of the structures of the district. The Saginaw anticline shows a broad bedrock ridge that veers sharply northward. There is a blunt east-west rock ridge in the immediate locality of the Muskegon structure, and a long northeast-southwest ridge projects southwestward through Newaygo County into Muskegon County.

[82] Leverett, Frank, and Taylor, F. B., The Pleistocene of Indiana and Michigan and the History of the Great Lakes: U. S. Geol. Survey, Mon. 53, pp. 211-214; 270-271 (1915). (Compare the maps on the pages in Mon. 53 with plate III of this report).

[83] Op. cit., p. 255.

[84] Idem, pp. 255-261.

An unusually large north-south bedrock ridge in western Kent County corresponds to a broad structural "nose" in the same area. The topographic "low" on the rock surface in central Berrien County conforms approximately to the supposed structural "high" in the same region. The comparatively sharp ridge of bedrock across central Manistee County is in the same general vicinity as a mapped nose, and the northwest-southeast trend of the ridge seems to be associated with the structural trend in the central part of the State. The sharp ridge crossing Arenac and Ogemaw counties is elongated in about the same direction and seems to line up with similar topography on the west side of the State. It is probably related to the steep dip on the West Branch structure, Ogemaw County.

The topography of the bedrock surface in the "Thumb" area of eastern Michigan has pronounced relief northwest of Port Huron, but the ridges are broken by the northeast-southwest topographic high region in the center of the "Thumb" district. The rough correspondence between bedrock surface features and folding across Shiawassee and Genesee counties seems to suggest the southeastward trend of the line of deformation forming the Mount Pleasant structure in the central part of lower Michigan.

Comparisons of this kind emphasize the similarities and neglect the differences, but the approximate parallel correspondence of bedrock topography to structure is locally definite enough to be considered in prospecting for oil structures. The prevailing trend of the minor bedrock ridges and valleys controlled by folding and faulting in the State is shown to be largely in a northwest-southeast direction. A curious fact is that the folds aline more exactly with the ridges than with the valleys. This correspondence suggests that faulting may be possibly more widespread than the available subsurface evidence indicates. The area near Howell, Livingston County, mapped in greater detail, seems to support this supposition. (See figs. 37 and 38).

MINING DISTRICTS OF NORTHERN MICHIGAN

Most of the mining regions of the Upper Peninsula have been more or less thoroughly surveyed by various means of prospecting and geological study, and the structural conditions are well understood over limited districts. The structural trend lines of these areas may have some bearing on the direction of folding in the Lower Peninsula, but any definite relationship is difficult to determine. The prevailing folds in the different ranges do not trend uniformly, although east-west is usually considered the predominant direction by many workers in the Lake Superior district. The usefulness of these trends for interpreting subsurface folding in lower Michigan seems very limited.

HINGE LINES OF POST-GLACIAL UPLIFT

The approximate parallelism of structural trend lines to the various hinge lines marking the stages of post-glacial uplift in the Michigan Basin is most striking. As the ice retreated from the region of lower Michigan, a series of ice dammed lakes occupied depressions in front of the different ice lobes. These lakes in general were at higher elevations than our present Great Lakes. As the ice fronts slowly melted back, new and lower outlets were successively uncovered and the level of each lake dropped to the level of its new outlet. While at these different levels, beaches and other shore features were formed. The fact that these beaches are now at higher elevations progressively northward shows that the land has undergone a peculiar type of uplift. A hinge line is an imaginary line from whence the general northward tilt of the beaches took place. The trend of most of the hinge lines is northwest-southeast and roughly parallel to some of the principle lines of folding. The deformation of shore lines in the region has been fully discussed by Taylor[85] and Hobbs[86].

The hinge lines intersect at an acute angle with the trend lines of subsurface structural deformation in the western part of the State. This lack of parallelism may possibly be explained by the fact that many of the folds in western Michigan and eastern Wisconsin are elongated east and west. The hinge line for beaches of Algonquin time seems closely parallel to the southeast extension of the Keweenaw fault and the Murray fault and this may have some bearing on the alinement of hinge lines in general.

The principal zones of structural weakness in the central and eastern parts of the Michigan Basin seem to be roughly defined by the lines along which this upward tilting took place. (See pl. III). These zones are spaced somewhat uniformly northeastward across the State and trend northwest-southeast with a swing to the west across some of the western counties. The correspondence of the zones of weakness to the hinge lines may prove to be a valuable guide in the future forecasting of subsurface conditions and result in a fuller knowledge of the causes of post-glacial movements.

SUMMARY AND CONCLUSIONS

The features of deposition and structure of the Michigan Basin, as worked out from comparison of drill records, tend to place it in a new category. Although embodying many characteristics of a typical sedimentary basin, the region has acted structurally like a geosynclinal area throughout many periods of geological history. The basin has been progressively downwarped. The beds thicken markedly into the central area, the outline of the course of the outcropping rocks is roughly oval, and the minor structures are mostly parallel to the longer diameter of the downwarp. These are features of geosynclines. On the other hand, the

[85] Leverett, Frank, and Taylor, F. B., The Pleistocene of Indiana and Michigan and the History of the Great Lakes: U. S. Geol. Survey, Mon. 53, pp. 502-518, Map, p. 503 (1915).
[86] Hobbs, W. H., The Late Glacial and post-Glacial Uplift of the Michigan Basin: Michigan Geol. & Biol. Survey, Pub. 5, Geol. Ser. 3, pp. 11-68, Map, p. 35 (1910).

basin has been isolated and subjected to periods of evaporation at various times. The absence of thick series of coarse clastic sediments is conspicuous in the post-Cambrian rock column of Michigan. These conditions are more characteristic of a major structural basin.

The origin of the lower Michigan synclinal basin is probably related to the Keweenawan disturbance which formed the Lake Superior geosyncline and caused the Keweenaw fault. The structural relationships of the province suggest that the principal source of the movement which originally warped the lower Michigan synclinal basin came from the northeast. These earth forces acting against the Wisconsin land mass and its southeast extension in the region of the present Wabash arch caused and developed the great downwarp in Michigan, which is comparable in many respects to the Appalachian geosyncline of a much later mountain making disturbance. The uplift of the positive element known as the "Wisconsin island" probably was going on at the same time as this downward movement.

The evolution of the Michigan "basin" in its present form and the cause of its frequent isolation is related to the younger movements which brought about the east branch of the Cincinnati arch and ended in the Appalachian Revolution. These later stresses caused warping more or less at right angles to the zones of weakness developed by the previous Keweenawan deformation. These modified the original structure of the older geosyncline into the present synclinal basin of Michigan and adjoining regions.

The minor anticlines and synclines of the State can best be understood with this background of structural history even though it may be incomplete and wrong in some details. The principal zones of folding seem to be alined along the older lines of geosynclinal weakness. Certain characteristics of many of the folds indicate that the deformation in the shallow rocks is related to deep-seated faults in the basement complex. The arrangement of the folds displays the regular pattern and the three dominant directions common to deformation which results from shearing, as illustrated by Mead[87]. The movement was probably torsional downbending. Downward warping of the basin by forces applied from almost opposite directions would cause torsion, and shearing would result. This shearing movement might be localized along lines of preexisting weakness, but the individual domes would take on the curved outlines brought about by these new stresses. Shearing and unequal subsidence seem to explain the staggered or en echelon arrangement of anticlinal structures in the central part of the "basin" area.

Oil and gas accumulation in the local domes has been somewhat controlled by the important disconformities. The principal oil producing strata in Michigan are limestones or dolomites and the porosity in these reservoir beds is largely the result of solution and leaching, both before and after the burial of the rocks. The porous zones are, therefore, concentrated near places in the stratigraphic section where breaks in deposition have occurred. The disconformities have also aided in modifying

[87] Mead, W. J., Notes on the Mechanics of Geologic Structures: Jour. Geol., Vol. 28, pp. 512-513 (1920).

deformation and trapping pools of oil and gas. Unequal settling over hills or ridges beneath a disconformable contact has both changed the location and amount of folding. Thickening of the beds toward the central area of the "basin" has caused the alteration of structure at depth. Oil and gas have been locally trapped because overlapping and lenticular sediments prevented lateral migration. Porosity beneath old buried erosion surfaces often varies laterally because deep valleys have cut out the beds most susceptible to solution. These factors have had a very effective control on the accumulation of petroleum in Michigan.

The nature of deposition and the development of structure in the "basin" are closely interrelated. The features of deposition and structure in the Michigan synclinal basin are the bases for theories of origin and growth which may explain some of the important problems of the geological history of the region. These features give rise to some of the possible hypotheses for future studies of this important isolated structural province.

PART II—ECONOMIC GEOLOGY

Chapter I

OIL AND GAS STRUCTURES

PRINCIPLES OF OIL AND GAS ACCUMULATION

Although the fundamental principles that govern oil and gas accumulation are now rather common knowledge, it seems appropriate at this point to outline briefly some of these principles. The anticlinal theory of accumulation had its inception among American geologists in 1859, when T. Sterry Hunt[1] recognized in Ontario that there was a direct relationship between oil and gas pools and anticlinal folds. Independently, E. B. Andrews[2] in West Virginia, F. W. Minshall in Ohio, and H. Hoefer in Austria arrived at similar conclusions and added new evidence from the districts with which they were most familiar. During the period from 1859 to 1885, the theory was developed and elaborated until in the latter year, I. C. White[3] came out with a clear and concise statement of the principles which stamped him as the "father of the anticlinal theory".

The practical application of this theory that structure controls oil and gas accumulation was not greatly developed until the discovery of oil pools in the plains area of the Southwest. Drilling in the Mid-Continent region of Kansas, Oklahoma, Arkansas, Louisiana, and Texas was largely guided by studies of geologic structures, and the period from 1910 to 1920 proved to operating oil companies that the search for domes and anticlines was an important factor in reducing prospecting risks. A voluminous literature on structure and accumulation grew out of these studies, and the works of E. R. Lilley[4] and W. H. Emmons[5], and others have summarized the geology of oil and gas fields.

The röle of geological structure in the accumulation of oil and gas has been excellently and briefly stated by F. H. Lahee[6] in a recent article:

"An oil pool is strictly and wholly a geological phenomenon. It occurs within some kind of porous reservoir rock. It is definitely associated with some type of geological structure, which, in most cases, comprises strata inclined from the horizontal. It exists because, in its relations to this structure, the upward and lateral escape of the petroleum is prevented by impervious rocks which seal the reservoir. Within the reservoir the oil is commonly associated with gas and water. Gas occurs dissolved in the oil and if, under the conditions, there is an excess of gas, it may occur in a free state. These three fluids, water, oil and

[1] Hunt, T. Sterry, On some points in Chemical Geology: Canadian Nat., Vol. 4, pp. 414-425 (with additions) (1859).
———, Notes on the History of Petroleum or Rock Oil: Canadian Nat., Vol. 6, pp. 241-245 (1861).
———, Contributions to the chemical and geological history of bitumens and pyrochists or bituminous shales: Am. Jour. Sci., 2d series, Vol. 35, pp. 157-171 (1863).

[2] Andrews, E. B., Rock oil, its relations and distribution: Am. Jour. Sci., 2d series, Vol. 32, pp. 85-91 (1861).

[3] White, I. C., The Geology of Natural Gas: Science. Vol. 5, pp. 521-522 (June, 1885); Vol. 6, pp. 43-44 (July 1885).
———, Petroleum and Natural Gas: West Virginia Geol. Survey, Vol. 1, pp. 167-175 (1899).

[4] Lilley, E. R., The Geology of Petroleum and Natural Gas: D. VanNostrand Company, Inc. (1928).

[5] Emmons, W. H., Geology of Petroleum: McGraw-Hill Book Co., Inc. (1931) 2d edition.

[6] Lahee, F. H., Importance of Geology in New Conception of Unit Pool Development: Oil and Gas Jour., Vol. 31, No. 2, pp. 38, 39 (June 2, 1932); Oil Weekly, Vol. 65, pp. 27-29 (June 6, 1932); Am. Pet. Inst. Production Bull. No. 209, Proc. A. P. I., pp. 4-7 (June 1932).

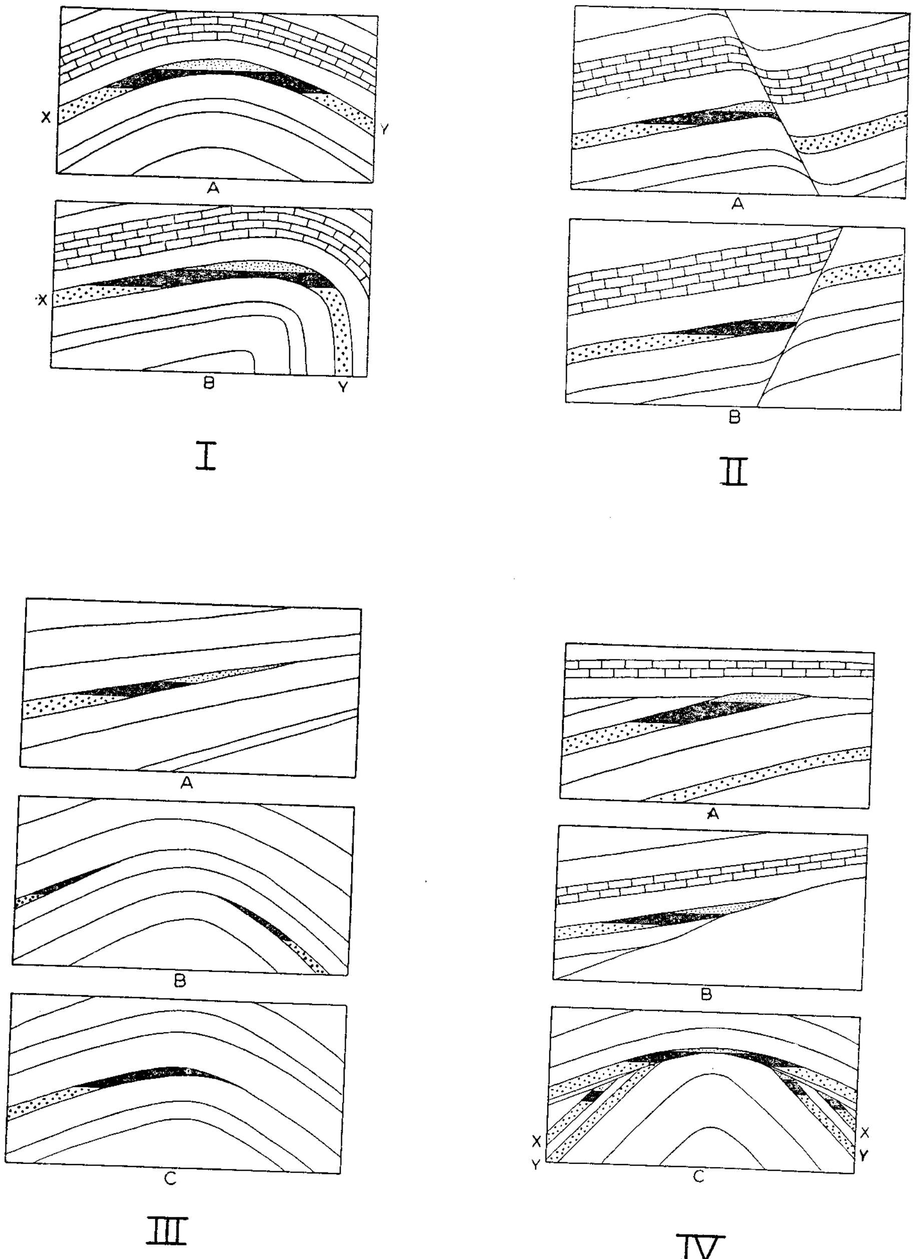

Figure 25. Generalized cross-sections of different classes of oil and gas producing structures (after Lahee).

free gas, are distributed in the reservoir in the order of their specific gravities, the gas above or updip from the oil, and the water below or downdip from the oil. They are under the influence of certain forces of compression, due chiefly to the weight of the column of rock overlying the pool and to hydrostatic pressure within the reservoir rock, operating from some distant region. These several conditions which pertain to the oil pool, namely, the geologic structure and the reservoir rock, the oil, gas and water, and the pressures acting on these fluids within the reservoir may be classified as rock factors, fluid factors, and energy factors, all of which are of primary importance. Together they constitute the geological framework of the oil pool.

"...... A majority of the known producing structures fall under one or another of these four classes: (1) Domes and closed anticlines; (2) fault structures; (3) lensing reservoir rocks; and (4) unconformities. In Figure 25 I is a dome in cross section. It may be symmetrical like A, or asymmetrical, like B. The arch may be relatively high or low. The main point is that any vertical cross section through the top will show the beds bent in an arch. Assuming that the reservoir rock, X, Y is uniformly porous throughout, oil, free gas, and water will be distributed in this type of structure as indicated.

"Figure 25 II illustrates cross sections of fault structures. Oil, gas and water are represented in their usual relations. In A retention of petroleum is accomplished by downward bedding (drag) and sealing of the reservoir rock at the fault. In B, accumulation of oil and gas depends wholly on sealing of the reservoir bed in the fault, since the structural relations are such as to facilitate escape up the fault plane. ....

"Figure 25 III shows three examples of lensing reservoir rocks. In A, the reservoir pinches out updip in a series of tilted beds. In B, pay sands pinch out on an anticline, but some distance below the crest. In C, the reservoir rock passes over the top of an anticline and pinches out downdip, but at a level higher than the water-oil contact on the structure.

"In Figure 25 IV are several conditions which may be encountered in association with unconformities .... An unconformity is simply an old erosion surface, like our present land surface, covered up and deeply buried by a later series of deposits. In Figure 25 IVA, a porous reservoir bed is unconformably overlain by an impervious layer in the lower part of the younger rock series. In B, the reservoir rock is in the younger series. Its updip edge is sealed where it abuts against the uneven surface at the top of the older series. In Figure 25 IV C more complicated relations are shown. Bed X is capped by an impervious layer on each side of the anticline. Bed Y is similarly capped on the right, but on the left it is in contact with porous basement sand in the overlying series, thus permitting escape of oil and gas into this basement sand. For purposes of demonstration we may suppose that closure both above and below the plane of the sketch has allowed accumlation in bed Y on the right.*

"In the four figures outlining geologic structures, we have assumed that the reservoir rock is uniformly porous; but this is almost never true of pay beds in actual experience. In the first place the reservoir

* In using any of these diagrams one should remember that they represent only one section across the structure. Vertical sections taken in other directions might reveal somewhat different relations.

may be a true sand, composed of granular particles of quartz and other hard minerals, or it may be a limestone or a dolomite. Rarely it is some other kind of rock. Within a sandstone or a limestone or dolomitic reservoir the pore spaces may differ in size, in distribution within the rock, and in continuity. We need not go into the causes of these differences. The significant facts to bear in mind are that such variations in porosity are common and that they have a very definite bearing (1) on the distribution of oil and gas on a structure and (2) on the permeability of the reservoir rock.

"Permeability, in this connection, refers to the ability of the rock to yield the fluids within its pores. There is a most important distinction beween porosity and permeability. A fine sand composed of small grains of equal size and a coarse sand composed of large grains of equal size may both have the same porosity, or total pore space, but the permeability of the coarse sand may be many times that of the fine, due to the freer movement of fluids through the large open spaces. Permeability is sometimes called 'effective porosity'. The efficiency of the energy available within the reservoir is largely dependent on the permeability of the pay rock."

In discussing structure in the accumulation of petroleum, Clapp[7] has given eight criteria which he considers fundamental if a locality is to be geologically favorable for commercial oil pools:

"1. Are the rocks of sedimentary origin?
2. Is the age of the strata (in part at least) similar to that of oil-field strata in some known oil or gas field?
3. Does a possible source of origin exist? If this be not apparent, may it nevertheless be present?
4. Do porous beds or 'reservoirs' exist in which oil may be held in commercial quantity?
5. If so, does sufficient cover exist above the reservoir beds to prevent the oil or gas from escaping to the surface and being lost?
6. Are the strata so slightly metamorphosed by heat or pressure that the oil has presumably not been driven out?
7. Does 'geologic structure' exist suitable for concentrating oil in commercial quantity?
8. Are the hydrostatic conditions such as will not prohibit the accumulation of oil in pools?"

It will be observed at once from the discussion of both Lahee and Clapp that favorable structure is only one of the conditions that must be fulfilled before commercial pools of oil and gas can form. There must be a source, a reservoir, and a barrier to migration—these three additional factors are also necessary. Source rocks are generally shales dark in color but may be certain types of bituminous, fossiliferous limestones. Reservoirs are strata containing communicable openings and may be porous honeycombed limestones and dolomites, sandstones, or fractured rocks of any type. Barriers to migration may be any dense rock bed which prevents escape of the oil and gas into other rocks less porous than the reservoir bed or to the surface.

[7] Clapp, F. G., Fundamental Criteria for Oil Occurrence: Bull., Am. Assoc. Pet. Geol., Vol. 10, pp. 1227-60 (1926).
————————, Role of Geologic Structure in the Accumulation of Petroleum: Structure of Typical American Oil Fields; A Symposium; Vol. II, pp. 669-670 (1929).

However, the search for oil and gas is still essentially a search for favorable structures. This is the starting point from which other types of geological investigation in oil finding must begin. The classification by Clapp[8] gives very fully the different kinds of structures in which oil and gas have been found:

"I. Anticlinal structures
 (a) Normal anticlines
 (b) Broad geanticlinal folds (or 'regional uplifts')
 (c) Overturned folds.
II. Synclinal structures
III. Homoclinal structures
 (a) Structural 'terraces'
 (b) Homoclinal 'noses'
 (c) Homoclinal 'ravines'
IV. Quaquaversal structures or 'domes'
 (a) Domes on anticlines
 (b) Domes on homoclines and monoclines
 (c) Closed salt domes
 (d) Perforated salt domes (or *'diapir'* structures)
 (e) Domal structures caused by igneous intrusions
V. Unconformities
VI. Lenticular sands (on any type of structure)
VII. Crevices and cavities irrespective of other structure
 (a) In limestones and dolomites
 (b) In shales
 (c) In igneous rocks
VIII. Structures due to faulting
 (a) On the up-thrown side
 (b) On the down-thrown side
 (c) Overthrusts
 (d) Fault blocks (or *horsts*)"

OIL AND GAS STRUCTURES OF MICHIGAN

The concentration of explorations for oil and gas in areas where productive domes were discovered has locally furnished detailed subsurface structural information. The producing oil fields in Michigan are near Saginaw, Saginaw County; Mount Pleasant, Isabella and Midland counties; and Muskegon, Muskegon County. These fields are called the Saginaw Field, Mount Pleasant Field, and Muskegon Field. The center of activity at the present time is the Mount Pleasant Field where developments have spread out to include a district in central Michigan covering portions of several counties. This entire producing district has come to be known as the Central Michigan Area.

Oil in small quanties has been found near Port Huron, and Blaine, St. Clair County; Dundee, Monroe County; Howell, Livingston County; Owosso, Shiawassee County; Bannister, Gratiot County; Union, Cass County; Decatur, Van Buren County; Allegan, Allegan County; White

[8] Clapp, F. G., The Use of Geological Science in the Petroleum and Natural Gas Business: Proc., Eng. Soc. W. Pennsylvania, Vol. 26, pp. 87-120 (1910).
————————, Revision of the Structural Classification of Petroleum and Natural Gas Fields: Bull., Geol. Soc. America, Vol. 28, pp. 553-602 (1917).
————————, Röle of Geologic Structure in the Accumulation of Petroleum: Structure of Typical American Oil Fields. A Symposium, Vol. II, pp. 671, 672 (1929).

Cloud, Newaygo County; Hart, Oceana County; Walhalla, Mason County; and Manistee, Manistee County. Gas wells have been found near Ashley, Gratiot County; St. Clair, St. Clair County; north and west of Mount Pleasant, Isabella County; near Clare, Clare County; Barryton, Mecosta County; Evart, Osceola County; and Walhalla, and Freesoil, Mason County. These showings of oil and gas have not yet been developed into large sized fields, but they indicate the widespread favorable structural conditions which may afford accumulations of commercial importance.

The largest known anticlinal structures which have not been adequately developed are the Howell structure, Livingston County, and the West Branch structure, Ogemaw County. The northwest and southeast trends of the known "highs" in Isabella and Midland counties are also areas where prospecting will be necessary to determine the location of new producing domes. The regional structural contour map drawn on the top of the Traverse formation (see pl. III) gives some idea of the possible extensions of proved structures. This map, although provisional in many details, may assist in guiding future "wildcat" drilling.

Some of the important characteristics of local anticlinal structures in Michigan are the small width (usually 1½ to 2 miles), the asymmetrical cross section, the steep dip generally toward the basinward side, the sharp cross-folding along the crest, the arcuate or "pistol-shape" outline, the irregular porosity of the "pay" zones, and the thinning or absence of Michigan series (Lower Grand Rapids) and Napoleon (Upper Marshall) beds on the crest. The synclinal structures are wide and flat in comparison to the anticlines and thick deposits of gypsum in the Michigan series are concentrated in these "lows." Faulting has probably taken place along the steep side of some of the larger anticlinal structures.

The Port Huron, Deerfield, and Saginaw anticlines and the Allegan structure have been previously described[9] and geological maps of these districts have been published. Detailed progress maps for the Muskegon, Mount Pleasant, and Howell structures have been released in blueprint form by the Michigan Geological Survey, but the folds have only been partially described in published reports[10]. For this reason, these three districts will be discussed in detail.

[9] Smith, R. A., The Occurrence of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 14, Geol. Ser. 11, pp. 50-67; 170-176; 126-135 (1912).
Newcombe, R. B., Oil and Gas Development in Michigan: Michigan Geol. Survey, Pub. 37, Pt. 3, pp. 166-186; p. 203 (1928).
Carlson, C. G., Geology of the Saginaw Oil Field, Michigan, and a Discussion of Michigan's Oil Prospects: Bull., Am. Assoc. Petroleum Geologists, Vol. 11, No. 9, pp. 359-365 (1927).

[10] Newcombe, R. B., Op. cit., pp. 215, 255.

Chapter II

MUSKEGON STRUCTURE

INTRODUCTION

The Muskegon structure is in the west-central part of Muskegon County, which borders Lake Michigan about one hundred miles from the south line of the State. The highest part of the fold is on the north side of Muskegon Lake, a large harbor extending inland 4 miles long east and west. The producing structure extends around the northeast corner of the lake in an arcuate fashion and has a length of approximately 6 miles. The region of the dome is confined to Muskegon and Laketon townships, and a part of the field is within the city limits of North Muskegon.

The city of Muskegon is accessible to Chicago by rail, water, and excellent paved roads. Direct connections may also be made with Grand Rapids and Detroit by the Pennsylvania and Grand Trunk Western lines. Three different paved highway routes lead to Grand Rapids, which is 40 miles away. According to the 1930 census, Muskegon had a population of 41,390, but "Greater" Muskegon, including suburban cities, has more than 58,000 inhabitants. Cultural facilities are entirely adequate for the needs of a growing industry. The city is the county seat and the location of several important manufacturing plants, including the Continental Motors Corporation and the Brunswick-Balke-Collender Manufacturing Company.

PHYSIOGRAPHY

The area of the Muskegon structure is included in the Muskegon, Twin Lake, and Montague topographic quadrangle sheets, which were surveyed in 1929, soon after the oil field was discovered. The base for these maps was compiled from airplane photographs and ground control. These photographs show many of the features of the oil field and the base map used for subsurface structural contours has been corrected in conformity with the aerial pictures.

The topography shows 70 feet of relief, with well elevations ranging from 586 to more than 650 feet. The immediate region of the oil field is relatively flat, the variation in relief being caused entirely by a terrace, which has an elevation ranging from 40 to 50 feet above the level of Muskegon Lake and the valley flat formed by the flood plains of Muskegon River and Cedar Creek.

The surface of the region is almost entirely composed of sandy lake beds which form poor soils and the land is only infrequently farmed. The valley flat is mucky and celery raising is carried on locally. The only hills of the region are the high dunes which form an almost continuous scalloped topped sandy ridge that fringes the Lake Michigan shore.

The land is not heavily timbered. The typical growth consists of scrub oak which is in some places very thick. There are also a few small coniferous second growth trees. The side roads are generally sandy, but the main roads are in good repair and suitable for heavy trucking.

HISTORY

At one time Muskegon was the leading lumber center on the west side of Michigan. Early drilling operations in the State were largely fostered by the lumber industry, because the waste material from the saw mills afforded ready fuel for the evaporation of brines in the manufacture of salt. Rominger[1] records in 1876 that several deep borings had been made in Muskegon and mentions that the Whitney well was 1,230 feet deep. Lane[2] states that this same boring was the oldest in the community and that it possibly reached 1,600 feet. Rominger[3] comments that another hole at Muskegon penetrated to 2,627 feet, the deepest well in the State at that time. The drill never reached sufficient depth in these first operations to strike rock salt; therefore, the attempts were fruitless.

Several of the first wells, including the Mason well drilled during 1872-1875, were described by Lane, who mentioned the discovery of small quantities of oil in the region. At that time, Lane[4] recognized the flattening of the dip indicated by the Ryerson well at the east end of Muskegon Lake. In 1903, Lane[5] again mentioned the structural irregularities in the vicinity of Muskegon and suggested the possibilities of oil and gas in the Dundee horizon in an anticline which might exist in the area north across the lake. In these recommendations, he was fundamentally correct, but the sections mentioned (Secs. 15 and 16, Laketon township) were proved later unproductive. Geological conditions and oil possibilities at Muskegon were further discussed by Smith[6] in 1914.

The discovery well in the field (Chas. Reeths No. 1, NW.¼ NW¼ sec. 9, T.10N., R.16W.) was located by Hugh D. Crider, then resident geologist for the Dixie Oil Company, Inc. This well came in on December 8, 1927, at 1,640 feet in the upper part of the Traverse formation, making 494,000 cubic feet of gas per day. On December 21, deepening was continued and an initial production of 300 barrels of oil per day resulted. The ensuing field was developed rapidly[7] and in 1928 a more prolific oil horizon was discovered in the Dixie Oil Company's A. and O. Becker No. 1, SE.¼ SW.¼ sec. 4, T.10N., R. 16W., from porous beds considered by many to be of Dundee age. The large producing oil and gas wells obtained from this formation brought many operators to the scene of development and by August, 1929, the field had reached its peak of production of 18,570 barrels daily. In May, 1932, the average production of the Muskegon district had declined to 1,160 barrels per day. The largest oil well produced about 3,000 barrels daily and the largest gas well had an initial flow of over 25,000,000 cubic feet.

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[1] Rominger, Carl, Geology of the Lower Peninsula: Geol. Survey of Michigan, Vol. 3, Pt. 1, p. 84 (1876).
[2] Lane, A. C., Deep Wells and Prospects for Oil and Gas: Geol. Survey of Michigan, Ann. Rept. for 1901, p. 232 (1902).
[3] Op. cit., p. 84.
[4] Lane, A. C., Op. cit., pp. 232-34; The Geology of Lower Michigan with reference to Deep Borings; Geol. Survey of Michigan, Vol. V, Pt. 2, pp. 27, 71; Pl. 43 (1895).
[5] Lane, A. C., Deep Borings for Oil and Gas: Geol. Survey of Michigan, Ann. Rept. for 1903, pp. 275,276 (1905).
[6] Smith, R. A., The Occurrence of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 14, Geol. Series 11, pp. 186-190 (1914).
[7] Newcombe, R. B., Oil and Gas Development in Michigan: Michigan Geol. Survey, Pub. 37, Pt. 3, Geol. Ser. 31, pp. 244-55 (1928).

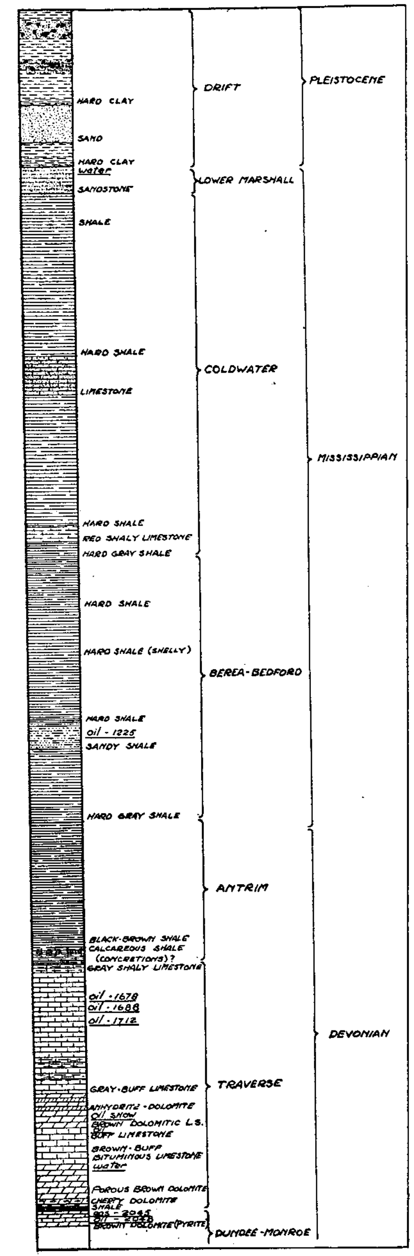


Figure 26. Typical well record in Muskegon oil field. (Dixie Oil Company's A. and O. Becker well No. 1, sec. 4, T.10N., R.17W., Muskegon township, Muskegon County. Elevation 631.8 feet).

STRATIGRAPHY

The rock formations penetrated in wells in the Muskegon field include beds ranging from the Lower Marshall formation of Mississippian age to the St. Peter sandstone of Ordovician age, encountered at a depth of 4,710 feet. The upper formations to about 2,050 feet are best known because most of the wells do not go below this depth. This section, as previously described[8], is as follows:

"The record of the discovery well drilled by the Dixie Oil Company on the A. and O. Becker farm (Fig. 26) may serve as a type section for the Muskegon area. Generalized data furnished by other wells in the field are included in this figure in order to show variations in thickness and conditions peculiar only to certain wells. The bedrock is covered by 190 to more than 300 feet of glacial drift, which consists largely of lake clay and dune sand. The first beds encountered are the fine-grained gray and pink sandstones of the Lower Marshall formation. This formation is everywhere water-bearing, and the water is usually brackish.

"The Lower Marshall sandstone is underlain by the blue-gray shales and calcareous shales of the Coldwater formation. One calcareous phase of the Coldwater is a gritty granular limestone, which is persistent throughout the field at a depth of about 270 feet below the top of the formation. At many places, it contains oil and gas and here and there some water. In the lower part of the Coldwater there is a bed of red, shaly fossiliferous limestone, which can be so easily recognized that it is the most useful horizon marker in the field. It has not yet yielded determinable fossils. Oil and gas are found in considerable quantities at this horizon in some parts of the producing area.

"The Berea can not be definitely identified at Muskegon. The varicolored greenish gray and gray beds of sandy shale found about 30 feet below the red limestone probably represent beds nearly equivalent to the Berea-Bedford (*Ellsworth shale*) of eastern Michigan. In their porous parts in the Muskegon field, they contain small quantities of oil. Near the bottom of the group, these beds become less sandy and their color changes to a darker gray.

"The Antrim shale, which overlies the Traverse, is usually considered Upper Devonian, but the exactness of this correlation is still in controversy. The formation consists of brown and black pyritous shale containing abundant *Sporangites huronensis*. A concretionary zone near the bottom of the Antrim shale generally logged by drillers as limestone is probably nearly equivalent to a like zone observed at Kettle Point, in Ontario; at Paxton, in Alpena County; and at Norwood, in Charlevoix County, Michigan.

"The Traverse group at Muskegon includes an average of about 430 feet of strata. Of this thickness, 60 to 70 feet should be classified as Upper Traverse (Thunder Bay), 200 to 210 feet as Alpena-Petoskey limestone, 160 feet as Lower Traverse, (Long Lake), and from 5 to 10 feet as Bell shale. The Bell shale is at many places split into two beds by a layer of limestone from 3 to 12 feet thick. At the top of the Lower Traverse, there is a 30-foot bed of anhydrite and dolomite. This bed was probably formed at the end of Long Lake time, when the sea was shallow and the land was a desert in which there was considerable evaporation and con-

[8] Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. America, Vol. 41, pp. 732-33 (1930).

TABLE VIII.—*Record of Muskegon Oil Corporation's (Muskegon Deep Well Syndicate's) H. Heinz No. 5*

Location: NE. ¼ of NE. ¼ sec. 8, T. 10 N., R. 16 W., Muskegon County. Permit No. 309. Elevation: 636 feet above sea level. Drilling Contractor: Buckeye Drilling Co. and K. S. & W. Drilling Co. Record compiled by O. F. Poindexter and R. B. Newcombe from driller's log and samples. Completed to "Dundee" March 29, 1929; began deepening August 6, 1930; completed as dry hole February 27, 1931. Casing: 245 feet of 12½; 335 feet of 10; 2,231 feet of 8¼; 4,675 feet of 6⅝-inch.

Formation.	Thickness.	Depth.
	Feet.	*Feet.*
Pleistocene:		
Sand	245	245
Mississippian:		
Lower Marshall and Coldwater Formations:		
Shale, blue	355	600
Limestone	50	650
Shale, blue	201	851
Limestone, red	20	871
Ellsworth Formation:		
Shale, blue	309	1,180
Sandstone, limy	10	1,190
Shale, blue	62	1,252
Shale, blue	128	1,380
Devonian:		
Antrim Formation:		
Shale, brown	220	1,600
Traverse and Dundee Formations (Undivided):		
Shale, light	47	1,647
Limestone	53	1,700
Limestone	75	1,775
Limestone, gray	165	1,940
Limestone	60	2,000
Shale	5	2,005
No record	8	2,013
Shale	3	2,016
Shale and limestone	2	2,018
No record	5	2,023
No record	15	2,038
Detroit River (Upper Monroe) Formation:		
Dolomite, brown	32	2,070
Dolomite, light brown	30	2,100
Dolomite, buff gray and brown, sandy	6	2,106
Dolomite, light brown	54	2,160
Dolomite, buff, brown and gray; little anhydrite	40	2,200
Dolomite, brown and gray; little anhydrite	20	2,220
Dolomite, brown and brownish buff, variegated	15	2,235
Dolomite, light brown (show gas 2,244—2,265)	35	2,270
No sample	3	2,273
Dolomite, gray; anhydrite	8	2,281
Dolomite, brown; anhydrite	19	2,300
No sample	10	2,310
Dolomite, brown; anhydrite	20	2,330
Dolomite, limy, brown and buff	5	2,335
Dolomite, gray and light brown; anhydrite	10	2,345
Dolomite, brown and buff	10	2,355
Anhydrite; little gray, buff and brown dolomite	73	2,428
Anhydrite; buff, gray and brown dolomite	27	2,475
Dolomite, buff; anhydrite	5	2,480
Anhydrite; brown, variegated dolomite	15	2,495
Dolomite, brown, variegated; anhydrite	45	2,540
Dolomite, brown, variegated	35	2,575
Bass Island (Lower Monroe) Formation:		
Dolomite, gray, argillaceous	25	2,600
Dolomite, gray, argillaceous; a little pink gypsum	30	2,630
Dolomite, gray and brown, argillaceous; little anhydrite	15	2,645
No sample	5	2,650
Dolomite, gray, argillaceous; little anhydrite	5	2,655
No sample	5	2,660
Dolomite, brown and gray; little anhydrite	15	2,675
Dolomite, brown and gray; argillaceous	20	2,695
Dolomite, gray and brown, argillaceous; a little gypsum and anhydrite	15	2,710
Dolomite, brown and gray	20	2,730
Dolomite, gray and brown, argillaceous	60	2,790
Dolomite, gray and brown, argillaceous; little pink gypsum	25	2,815
Dolomite, gray and brown, argillaceous; with a little reddish dolomite and pink gypsum	25	2,840
Dolomite, gray, argillaceous	5	2,845
Dolomite, brown and gray, variegated, argillaceous	40	2,885

TABLE VIII.—*Record of Muskegon Oil Corporation's (Muskegon Deep Well Syndicate's) H. Heinz No. 5*—Continued

Formation.	Thickness.	Depth.
	Feet.	*Feet.*
Salina Formation:		
Salt	45	2,930
Dolomite, brown and gray	10	2,940
Limestone, light brown	15	2,955
Limestone, brownish buff	10	2,965
Limestone, brown	5	2,970
Limestone, dark gray brown, semi-lithographic	65	3,035
Dolomite, gray, argillaceous	20	3,055
Limestone, gray, buff and brown, argillaceous	25	3,080
Salt	260	3,340
Dolomite, brown to dark brown (show oil 3,370-3,375)	50	3,390
Salt	200	3,590
Limestone, brown, salty	5	3,595
Limestone, brown, variegated (show oil 3,601)	5	3,600
Limestone, buff gray and brown	10	3,610
Limestone, buff gray	5	3,615
Burnt Bluff Formation:		
Limestone, buff gray with red oolites (?)	35	3,650
Limestone, buff gray	30	3,680
Limestone, buff gray and dark red	15	3,695
Limestone, dark red and buff gray	5	3,700
Limestone, dark red, buff and dark gray	15	3,715
Limestone, buff, gray and dark red	5	3,720
Limestone, buff, brown, dark gray and red	5	3,725
Limestone, brownish gray and light gray	5	3,730
Limestone, buff to brownish gray, to grayish brown cherty	45	3,775
Limestone, grayish brown	15	3,790
Limestone, grayish brown and gray shaly	15	3,805
Mayville Formation:		
Limestone, dolomitic, grayish buff to grayish brown	5	3,810
No sample	5	3,815
Limestone, dolomitic, buff to brown	5	3,820
Cataract Formation:		
Cabots Head Shale Member:		
Shale, dark red ferruginous	15	3,835
Shale, dark red ferruginous and gray	10	3,845
Manitoulin Member:		
Shale, gray	5	3,850
Shale, gray; dolomite, gray shaly	70	3,920
Dolomite, gray shaly and white	25	3,945
Dolomite, gray shaly and white, sandy; shale, gray	10	3,955
Dolomite, gray shaly, white, and brown crystalline	5	3,960
Dolomite, brown, crystalline	15	3,975
Ordovician:		
Cincinnatian Series (Undivided), Richmond in part:		
Dolomite, brown crystalline, and hard sandy dolomite	5	3,980
Dolomite, hard gray sandy	5	3,985
Dolomite, hard gray, sandy; gray shale	5	3,990
Shale, hard gray; and hard gray dolomite	20	4,010
Dolomite, gray; shale, gray	10	4,020
No samples	15	4,035
Dolomite, gray; shale, gray	25	4,060
No sample	20	4,080
Shale, gray; dolomite, gray	30	4,110
Shale, gray; some gray dolomite	25	4,135
No samples	30	4,165
Shale, gray	65	4,230
Utica Formation:		
Shale, darker gray	85	4,315
Trenton Formation:		
Dolomite, brown: shale cavings	5	4,320
Limestone, brown dolomitic	5	4,325
Limestone, brown	15	4,340
Limestone, brown, variegated; shale cavings	25	4,365
Limestone, brown, variegated	165	4,530
Limestone, gray brown, variegated	30	4,560
No sample	5	4,565
Limestone, brownish buff to brown	10	4,575
Limestone, brown and buff	5	4,580
Limestone, brownish buff to brown (water at 4,575—2,500 feet in hole).	15	4,595
Limestone, light brown; no sample	5	4,600
Limestone, gray and white; no samples	68	4,668
Limestone, brown; no samples	17	4,685
Limestone, brown and black sandy	25	4,710
St. Peter Formation:		
Sandstone, white (hole full water)	25	4,735
Total depth	....	4,754

sequent concentration of sulphate. The re-working of the Monroe-Salina deposits may also have contributed to this concentration.

"The oil-bearing beds include one (20 to 30 feet thick) in the Alpena-Petoskey limestone; one at the top of the Lower Traverse, below the bed of anhydrite; and one (ranging in thickness from a few inches to several feet) below the base of the Bell shale. The water-bearing beds are associated with the oil-bearing beds and are also about 100 feet below the top of the Lower Traverse.

"The base of the so-called Dundee has not been distinguished clearly enough to show accurately the thickness of that formation, which is probably variable but may at some places reach 20 or even 30 feet. It was once supposed that the water found about 100 feet below the top of the Lower Traverse (see fig. 26) represented the base of the Dundee and that the Bell was absent, but studies covering a wide area, a close observation of the pay horizon, and the discovery of some fossils in the Bell shale furnish evidence that is strongly adverse to this supposition. It is possible, however, that the lowest fossiliferous productive bed beneath the Bell shale may be the Anderdon limestone, of Detroit River age."

The deeper rocks in the Muskegon district are known from the well drilled by the Muskegon Deep Well Syndicate in 1930 (see table VIII). This boring encountered gas in a horizon of the Detroit River dolomite at approximately 200 feet from the top of the formation. The top of the Salina salt was penetrated at 2,885, the top of the Niagaran series at 3,600, the Trenton limestone at 4,315, and the hole was abandoned at a total depth of 4,754 feet. A showing of oil occurred in the Salina dolomite beds at 3,370, and in the Manistique formation at 3,601 feet, brine in the Trenton limestone at 4,575, and in the St. Peter sandstone at 4,735 feet.

STRUCTURE

General Features—Muskegon County is on the west side of the Michigan synclinal basin, where the general regional dip is northeastward. The approximate strike of the beds is N.40°W., although in the northwest corner of the county the strike veers almost to north. The district is evidently in a broad regional syncline which is marginal to the larger basin including the entire southern peninsula of Michigan. This regional syncline causes the dip of the rocks to change from northeast in the southern part of the county to east in the northern part. The Muskegon anticline seems to be a product of the structural factors which control the change in the direction of the regional dip.

As rocks are not exposed in Muskegon County, our knowledge of conditions of structure is based on subsurface data obtained from drilling. Two contour maps have been prepared to show the size and outlines of the anticline in the vicinity of the city of Muskegon. In the first of these, (see fig. 27), the persistent fossiliferous shaly red limestone in the lower part of the Coldwater strata is used as the key bed. This bed is present throughout the field and, though in few places no more than 20 feet thick, it can be recognized easily. The discovery of the field resulted from deductions made from comparisons between wells with this horizon as a basis.

"Coldwater" structure—The anticline is elongated east and west, although the axis or top of the fold is an arc which bends southeast. There

are several small domes on the fold, and the amount of closure is between 60 and 70 feet. The steeper flank of the structure is on the northeast side. It has a maximum dip of slightly over 100 feet per mile, and the other limb dips approximately 50 feet per mile.

The highest part of the Muskegon anticline is in sections 8 and 9, Muskegon township, near the intersection of two axes of folding. The arch with the northwest-southeast axis shows the sharpest dip and is probably the controlling feature. The east-west axis is narrow and this cross fold probably trapped the largest quantity of oil, as shown by the more productive wells on the west side of the structure. The largest Dundee gas wells were on the highest parts of the structure, but local porosity determined some of the largest Traverse wells.

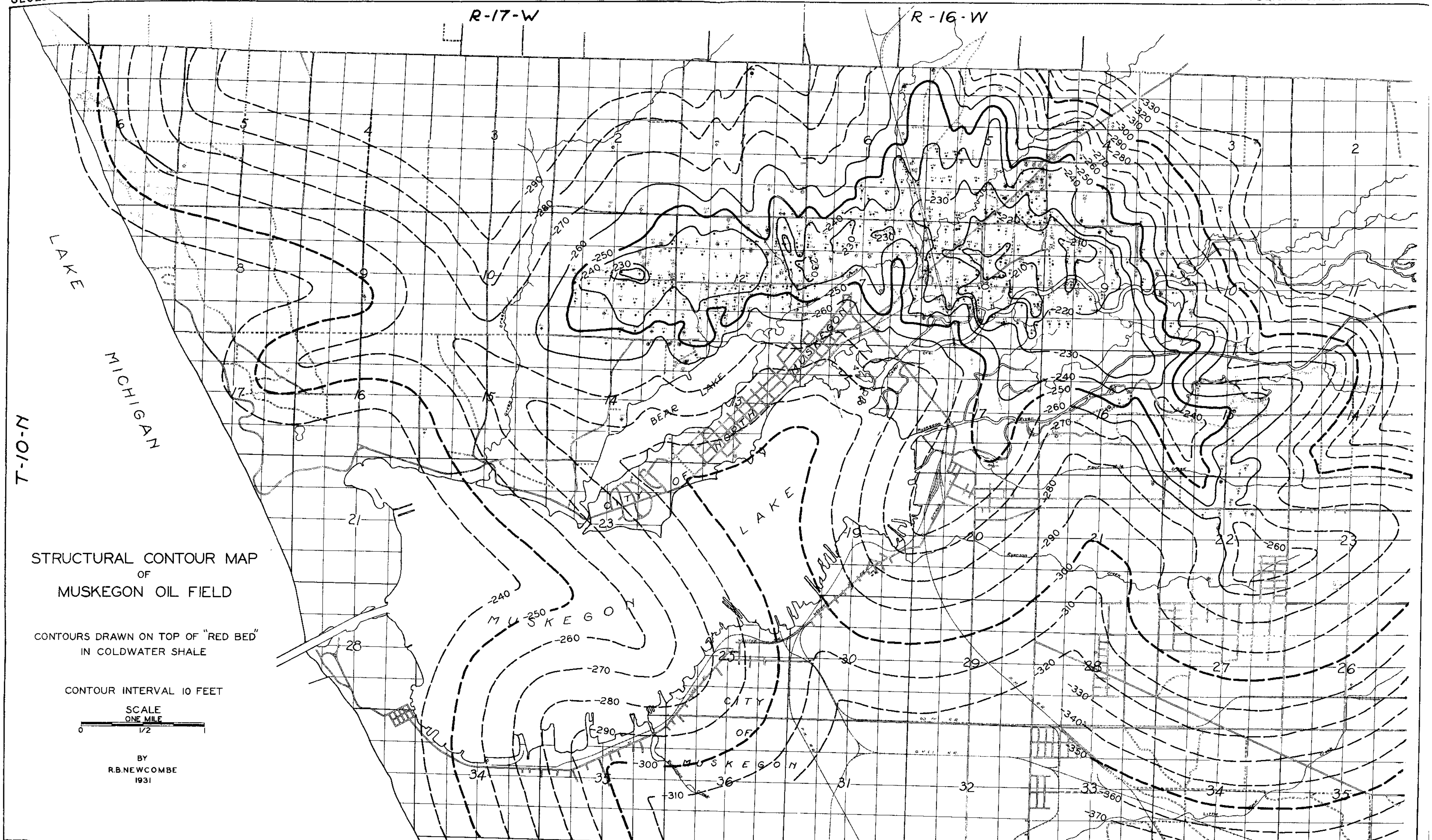
The numerous sharp reentrants shown by the structural contours indicate that secondary movement occurred along the crest of the fold. The regularity of the occurrence of these reentrants suggests a relation to jointing or faulting. At first they were considered to be the product of erosion at a surface of disconformity. The persistence of these features through the deeper beds, however, suggests that they may have been caused along the directions of prominent joints by slump faults resulting from solution of rock salt in the Salina formation beneath. Structure of this type has been observed in many places in New York.

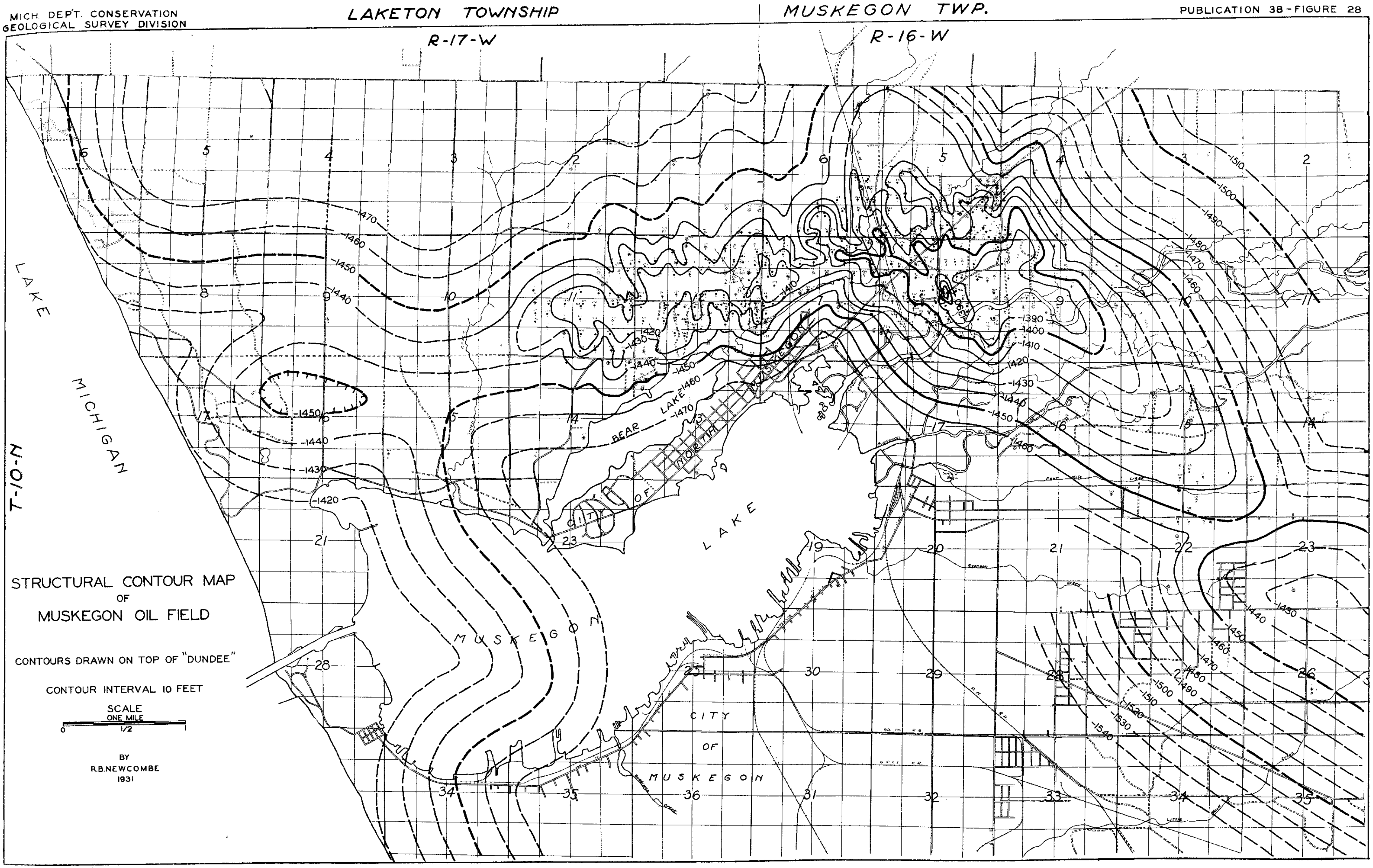
"Dundee" structure—The structure in the Devonian rocks conforms closely with that of the Mississippian beds above. The Muskegon anticline, contoured on the base of the Bell shale or the top of the so-called "Dundee" formation, is shown in Figure 28. The similarity between this map and the previous one on the "Red bed" is striking. The sharp reentrants do not correspond exactly, but their direction is very similar. The highest parts of the structure are nearly the same, and the dips are about the same intensity on the northeast limb. The dips on the south side of the anticline are somewhat steeper than shown by the contours drawn on the top of the Coldwater red horizon. This apparent sharpening of folding in the deeper beds may be due to the recurrence of deformation along the same axis and possibly to some compaction of the beds. The structural closure in the "Dundee" beds is not much more than 60 feet. This suggests that the steepening of the fold in the deeper rocks is only local and that there is actually very little difference between the effects of deformation in the Mississippian and the Devonian strata.

"Niagaran" structure—There is a pronounced change in the amount and localization of folding beneath the Salina beds. The nature of this change is not known because only two wells have been drilled deep enough to go through the Salina section. One of these wells (K. Savacool No. 1, SW.¼ SW.¼ sec. 2, T.10N., R17W., Laketon township) is low on the "Dundee" structure, and the other (H. Heinz No. 5, NE.¼ NE.¼ sec. 8, T.10N., R.16W., Muskegon township) previously described, is structurally high, as shown by comparing the "Dundee" elevations. In spite of the fact that the Heinz well is 60 feet higher than the Savacool well, as contoured on the "Dundee," (see fig. 28), the Niagaran beds are 60 feet lower, making a total difference of 120 feet in structural elevation. The correct explanation of this change of structure with depth is of vital importance in problems of the persistence of folding beneath the Devonian rocks elsewhere in Michigan.

LAKETON TOWNSHIP

MUSKEGON TWP.




LAKETON TOWNSHIP
MUSKEGON TWP.
R-17-W
R-16-W
T-10-N
LAKE MICHIGAN
BEAR LAKE
NORTH MUSKEGON
CITY OF
LAKE
MUSKEGON
CITY OF MUSKEGON
STRUCTURAL CONTOUR MAP
OF
MUSKEGON OIL FIELD
CONTOURS DRAWN ON TOP OF "DUNDEE"
CONTOUR INTERVAL 10 FEET
SCALE
ONE MILE
0
1/2
1
BY
R.B.NEWCOMBE
1931

The thick salt beds and important stratigraphic "breaks" between the "Dundee" and Niagaran rocks probably explains the structural discrepancy, but several hypotheses might possibly account for the change with depth. These include the following:

1. The mechanical adjustment of structure with depth because of the thickening of the Monroe-Salina rocks, including the salt beds, toward the center of the "basin." This condition might cause a shallow fold to be represented in the lower beds by a terrace or plunging nose with insufficient closure to trap any oil and gas. It might also shift the anticline one way or another in the deeper rocks.

2. The deposition of sediments over a hill formed during an erosion period in some of the beds above the Salina. This hill might result either from erosion of the beds themselves or solution of the rock salt beneath. The natural dip of the beds away from the hill would be sufficient to form a dome or anticlinal structure, but differential settling around and over the hill would increase the height of the structure. This theory would account for the seeming absence of the fold at depth and the thinning of the salt beds off the flanks of the structure.

3. The existence of a fault beneath one of the formational "breaks" between the Dundee limestone and the Niagaran series. The resulting escarpment would probably be on the downthrown side of the fault and the topographic ridge would be structurally low rather than high. Deposition over this ridge might cause a fold which would be synclinal on the upthrown side of the fault.

4. The solution of salt along planes of faulting and fracturing at some time after salt deposition, but before the overlying load was very great and the beds were sufficiently competent to hold cavities. This process might result in a slight arching which would increase in intensity by the additional amount of solution.

5. Flowage of relatively weak incompetent salt beds as the result of the folding of competent beds above, thus accounting for the thickening of the salt series "on structure" and the decrease in the amount of folding at depth. If the salt beds accommodated themselves to the warping by flowing rather than bending, the structural disturbance occurring beneath the salt would be different from that above it.

Lane[9] has also suggested the possibility that, in the warping of the strata, they acted like a downward bent beam in which the upper beds were slightly folded due to compression while the lower beds were in tension; thus, less affected. The first hypothesis seems more plausible. Theories 2 and 3 give conditions requiring a compaction fold in the shallow rocks in which folding increases in intensity at depth. The two structure maps (see figs. 27 and 28), showing approximately the same amount of closure in the Mississippian and Devonian rocks, suggest that the deformation is not due wholly to compaction. This evidence tends to refute theories 2 and 3. The conditions of theory 4 would result in secondary faulting, for which some proof exists, but the conditions of the hypothesis are so exacting that the theory seems untenable. The circumstances required by theory 5 probably exist to a certain extent. The "salt plugs" of southeastern Utah and southwestern Colo-

[9] Lane, A. C., personal communication.

rado show some of the conditions[10] resulting from the sharp arching of strata containing salt beds. Nevin[11] states that salt layers observed in the mines near Ithaca, New York, show ample evidence of the flowage of salt, and the formation acts as a very plastic, incompetent bed. Gliding planes parallel with the faces of some of the crystals are present in the rock salt obtained from Michigan at the Oakwood mine of the Detroit Rock Salt Company. These facts seem sufficient evidence to show that some flowage has probably occurred. The presence of thick competent beds of dolomite beneath the salt and the gentleness of the folding seem to discount the significance of the explanation given in theory 5.

The thickening of the salt beds and the Silurian-Devonian rocks from Muskegon into the central part of the Basin area is very great. The rate of thickening of these beds between the two Muskegon County wells (K. Savacool No. 1 and H. Heinz No. 5) practically accounts for the loss of structure in the deeper beds. The general change in attitude of the lower strata caused by disconformity and overlap apparently explains the absence of folding in the deeper rocks similar to that in the shallower formations.

Muskegon County is close to the border of the salt-bearing rocks and this region in post-Salina time must have been an area of great solution and slumping. This may explain the change in the strike of the rocks across the county. The east-west downwarp in the northern part (see pl. III) suggests some relation between the regional structure and the south border of the region underlain by Salina salt beds.

Comparison with other Michigan folds—The generalized features of the Muskegon anticline are similar to those of most of the other domes found in the State. The major axis, almost parallel with the regional strike, the steep dip on the basinward side of the arch, and the wide comparatively flat-bottomed syncline adjoining are features typical of Michigan folding. The sharp northeast dip is similar in intensity to that on the southwest flank of the Saginaw structure in eastern Michigan. A strong narrow east-west cross fold on the gentler dip side of the dome is also found on the Mount Pleasant structure in Greendale township, Midland County, central Michigan. (See pls. IV and V.) The northwest-southeast axis of the structure is parallel with the trend of other folds in the State and suggests that this direction is the more important of the two lines of folding which contributed to the formation of the dome. The occurrence of large quantities of gas is typical of anticlines near the margin of a major basin. Greater earth pressures because of nearness to the old rising land mass of the "Wisconsin Island" may have also aided in the formation of the relatively large quantities of gas in this field. Another explanation would be the possible long distance up dip migration of the gas in the "Dundee" reservoir rock which pinches out westward until it is absent at Milwaukee.

WATER CONDITIONS

The chemical properties of the oil field waters from Muskegon show some interesting comparisons. In Table IX, the "Dundee" brines in

[10] Harrison, Thomas S., Colorado-Utah Salt Domes: Bull., Am. Assoc. Pet. Geol., Vol. 11, No. 2, pp. 111-33 (February, 1927).
Prommel, H. W. C., and Crum, H. E., Salt Domes of Permian and Pennsylvanian Age in Southeastern Utah and their Influence on Oil Accumulation: Bull., Am. Assoc. Pet. Geol., Vol. 11, No. 4, pp. 373-93 (April, 1927).
[11] Nevin, C. M., written communication (1931).

TABLE IX.—**Oil Field Brines of Muskegon Field*

	1	2	3	4	5	6	7	8	9	10
Total Solids	260,000	257,000	400,000	365,280	333,800	348,920	415,000	253,000	276,000	272,000
Specific Gravity			1.200	1.197			1.200		1.188	1.181
SiO_2			104				160			
Fe_2O_3	5.0			86	42		0.4			
Ca	17,340	19,510	28,600	25,700	28,250	27,650	29,200	23,810	36,000	33,000
Mg	3,730	4,260	5,600	5,450	1,120	1,058	5,900	4,620	8,360	6,280
Na+K	76,038	72,012	63,400	104,000	77,266	93,000	75,700	65,006	54,627	59,385
Cl	158,000	157,000	164,000	222,000	172,000	195,000	185,000	154,600	172,000	168,000
SO_4	201	277	411.4	366	675	403	321	282	422	390
HCO_3	14	23	82	33.5	80	102	58	38	48	28
CO_3							48			
Bromine	630	580						600	1,293	1,228
Iodine	1	1						1	5.8	6.3
Strontium	580	610						670		

1. Johnson Oil Co.—Cihak No. 1—Upper Traverse water
2. Muskegon Pipe Line Co.—Cook No. 1—Upper Traverse water
3. Johnson Oil—Adams No. 1—Dundee Water
4. Reed Oil—Torrent No. 1—Dundee water
5. Goldboss—Marquart No. 1—Dundee water
6. Dixie Oil Co.—Becker No. 1—Dundee water
7. Johnson Oil—Savacool No. 1—Dundee water
8. Johnson Oil—Grotefeld No. 1—Dundee water
9. Muskegon Deep Well Synd.—Heinz No. 5—Trenton water
10. Muskegon Deep Well Synd.—Heinz No. 5—St. Peter water

*Analyses shown in parts per million.

general have a higher concentration of total solids than the shallower Traverse brines, but the deep waters from the Trenton and St. Peter horizons are less concentrated than those from the "Dundee." The total solids in ten samples range from 253,000 to 415,000 parts per million and the specific gravity in five of them from 1.181 to 1.200. A certain composition-depth relationship seems to persist as in the brines from other parts of Michigan. (Compare table XV). The chemical composition of waters in the deeper horizons show a downward increase in calcium and magnesium, a decrease in sodium plus potassium, and an increase in both bromine and iodine. According to the analyses of brines from other parts of the State, potassium would probably also show an increase if it were calculated separately from sodium. A few of the samples are radioactive and some contain small quantities of strontium. The primary salinity of the brines varies from 60 to about 80 percent, secondary salinity from 20 to 30 percent, chloride salinity usually over 99 percent, and primary alkalinity normally less than 1 percent.

The edgewater in the "Dundee" followed up the sides of the structure with the depletion of the oil and gas, and coning sometimes resulted where large wells were produced at full capacity. In some places along the margin of the field, the water drive exercised a certain amount of pressure control over the remaining gas in the reservoir because the rock pressure in a few edge wells toward the end of the decline was higher than normal. The water encroachment did not take place regularly up the flanks of the structure because the porosity of the limestone was irregular and the water followed the more porous channels. During the early life of the field the water level, however, was comparatively uniform. On the south edge of the structure, it stood at about 1,459 feet below sea level and, before extensive encroachment set in, it was from -1,453 to -1,462 feet on different sides of the producing district. Later, after the decline of pressure from "pulling" the wells had brought about channeling and abnormal water conditions, it was from -1,433 to -1,448 feet. Regionally higher on the west side of the structure, several wells penetrated water in the "Dundee" at -1,444 to -1,450 feet.

OIL AND GAS DEVELOPMENT

The Muskegon field is now in the last stages of development. Drilling operations largely include deepening of old wells to the later discovered gas horizon in the Detroit River (Upper Monroe) formation. The productive horizons, in the order of their importance, are the "Dundee," Upper Traverse, Lower Traverse, and Upper Monroe porous members. These "pay" zones are entirely in limestones or dolomites, and most of the porosity probably has been formed by solution below surfaces of disconformity.

The limits of production in the field may be determined from Figure 29, which shows graphically the areas where oil and gas were obtained from the different horizons. The continuity of "Dundee" porosity evidently is much greater than that of the other "pay" zones. The Upper Traverse areas seem to be in small patches which strongly suggest that local factors determine the porous parts of the formation.

The field was extensively over-drilled because town-lot subdivision permitted unusually close spacing of the wells. The acre yield is com-

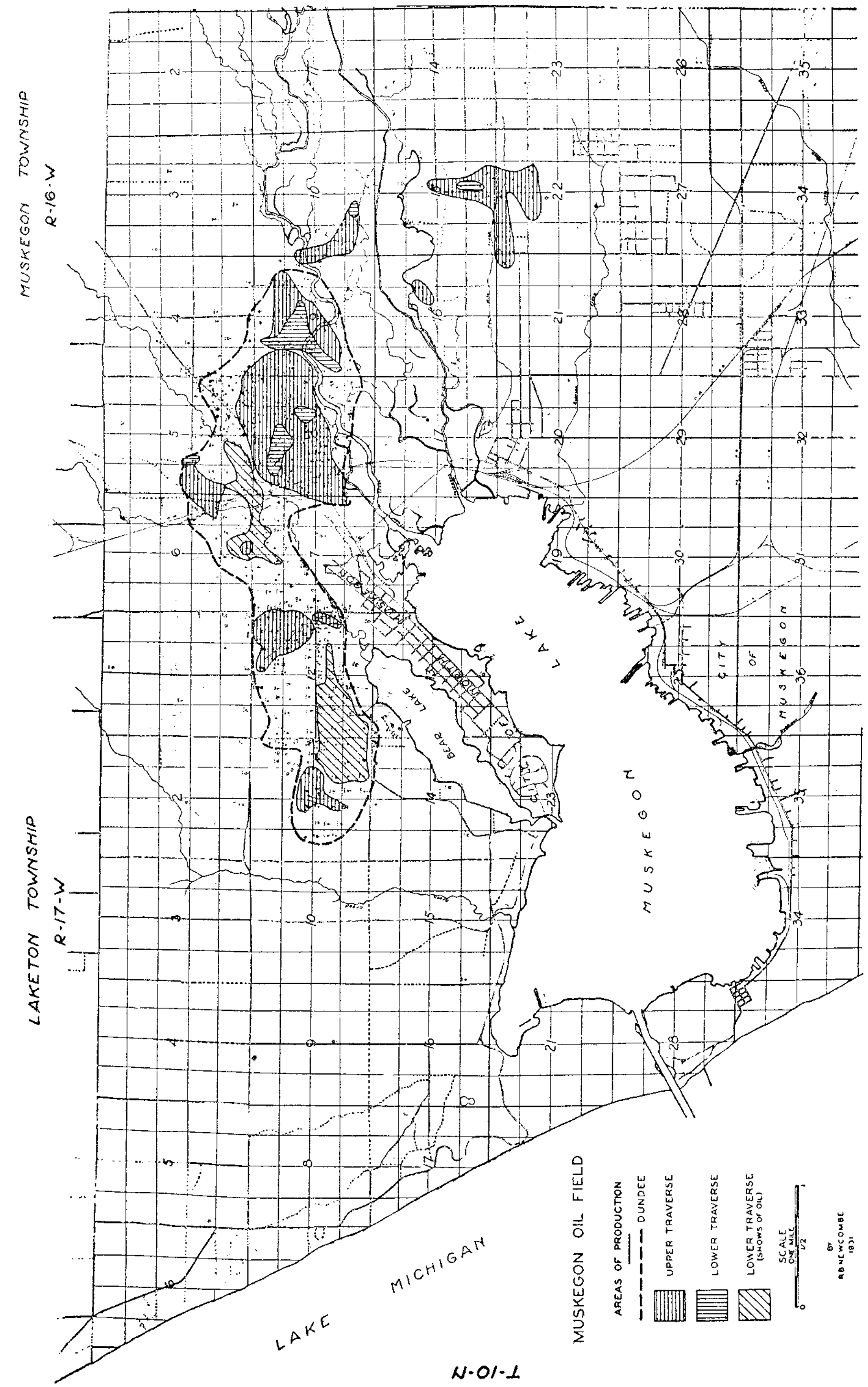


Figure 29. Map of Muskegon field showing approximate limits of areas of production from different producing horizons.

paratively small because of early loss of gas pressure and the rapid edge-water encroachment. On January 1, 1933, the Muskegon pool had produced 2,072 barrels per acre, and until accelerated late in 1932 by the use of acid, the yield was being increased at the rate of about 10 barrels per acre per month. Its yearly output was 1,928 barrels in 1927; 334,601 barrels in 1928; 3,157,668 barrels in 1929; 1,297,962 barrels in 1930; 531,147 barrels in 1931; and 478,728 barrels in 1932. The fluctuation of both oil and gas production is shown on the graph in Figure 30, and the decline curve of the "Dundee" rock pressure has been added for comparison. The monthly peak of gas production was reached in March, 1929, with 427,863,671 cubic feet, (measured on an 8 ounce basis), and the highest monthly output of oil was 557,140 barrels in August of the same year.

The gas withdrawals from the Muskegon field were somewhat uniform, considering the normal decline of the pool. The large percentage of industrial users probably contributed to this condition. However, the pipelines were not common carriers and due to the different capacities and individual demands of the lines, the various wells were not pulled regularly or uniformly. After the field was practically depleted, the percentage withdrawal of gas from individual wells was restricted by law, but this action came too late to stop the wasteful and uneconomical development of the area. The reserves of gas in the "Dundee" were calculated to be 3,760,000 cubic feet per acre, but because of careless operation, blowing of gas into the air, and waste of gas in the production of oil, the total actual recoveries for all pay horizons did not reach this figure. On the basis of 2,800 acres in the pool, only about 2,493,000 cubic feet of gas per acre for all horizons had been produced and sold up to January 1, 1933.

Four pipelines have transported gas out of the Muskegon field for use in the city. The Muskegon Gas Company line, consisting of 5.7 miles of 8, 6, and 4 inch pipe, delivered gas to domestic consumers in Muskegon for two and one-quarter years. The Continental Motors Corporation operated a 6 inch line during the boom period from the field to their plant on the southeast side of Muskegon Lake. The third line, built by the Muskegon Pipe Line Company, was made up of 6.9 miles of 10, 8, and 6 inch. The largest and longest line still in operation belongs to the West Michigan Consumers Company, whose distribution system includes, together with a treating and compressor plant, 10.7 miles of 12, 8, 6, and 4 inch pipe line. The pipeline transportation system for oil includes two principal lines built by the Stanolind Oil and Gas Company and the Simrall Pipeline Company. These lines lead from leases in the field to 30,000 and 55,000 barrel storage tanks near the Muskegon Sanitorium, thence to the Old Dutch Refinery on the east side of the city, and to loading docks on Muskegon Lake. The Simrall pipe line and storage has recently been taken over by the Old Dutch Construction Company.

Although several refineries were operated at Muskegon while the field was being actively developed, only two are now running. The Henry H. Cross Company erected a small topping plant of 1,000 barrels capacity which has become obsolete. The Michigan Central Refining Company of North Muskegon moved their equipment to Mount Pleasant and became the Roosevelt Refining Company. The Naph-Sol Refining Company

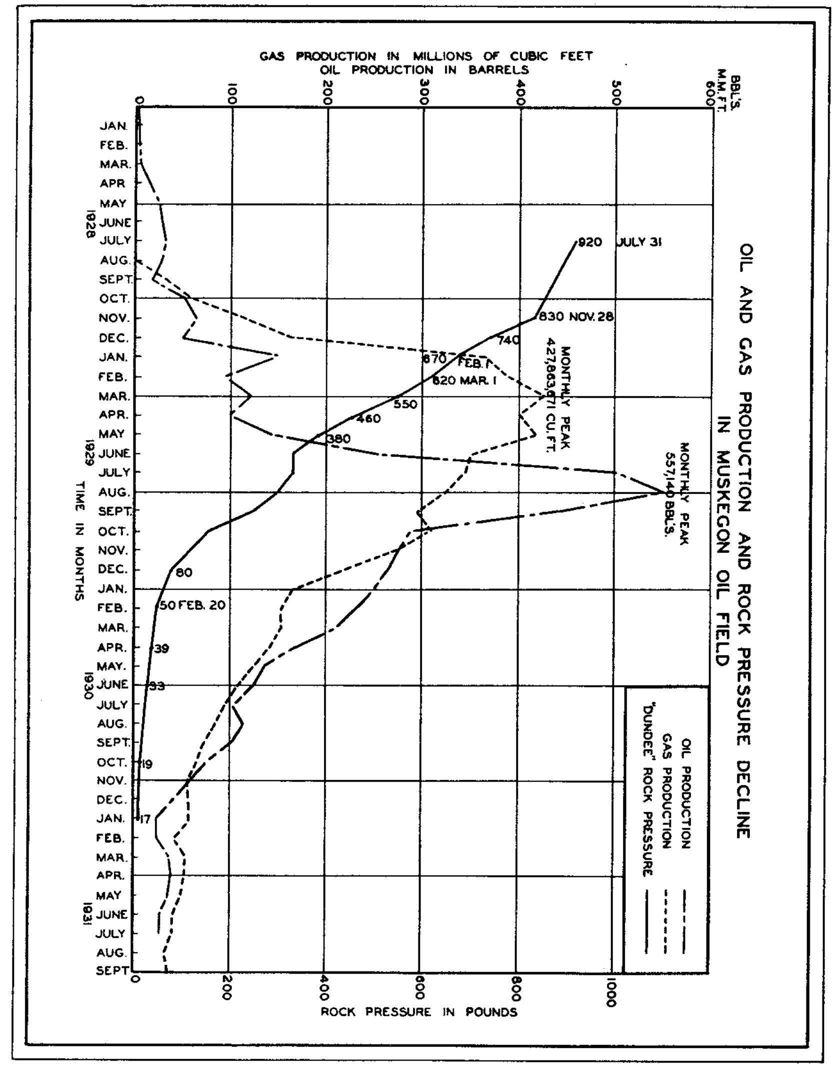


Figure 30. Graph showing fluctuation of oil and gas production and rate of rock pressure decline in Muskegon field.

refinery of about 2,000 barrels capacity in the middle of the field north of the Pere Merquette tracks, and the Old Dutch refinery of 2,500 barrels crude oil capacity are still operating and marketing naphthas, mineral solvents, kerosene, and fuel oil.

The crude oil from the Traverse has an average gravity of approximately 37° Be., and is a high-grade paraffine-base, sweet oil (sulfur 0.336 percent). The gasoline content ranges from 34 to 35 percent; the kerosene content is 14 percent; and the remainder is crackable residuum. The "Dundee" crude ranges from 37° to more than 39° Be. gravity, but it is a sour oil (sulfur, 0.98). The gasoline content varies from 26 to 29 percent; the kerosene, from 23 to 24 percent; the gas oil is 10 percent; the lubricating distillates, 16 percent; and the residuum, approximately 23 percent. The current prices paid for the Muskegon crude oils, except once when Dundee crude went to 50 cents a barrel, have been the same as the Mid-Continent gravity scale and fluctuated accordingly.

The composition of the natural gases (see table X) shows considerable variation in the Muskegon field, partly because of the different stages during the life of the field when samples were taken and partly because of the methods of analysis. The percentage of oxygen is from 0.19 to 1.29 percent, while nitrogen and other inert constituents range from 0.4 to 19.24 percent. Several analyses of the gas from Muskegon show helium from 0.19 to 0.24 percent, which is very small. The gases from the Traverse and Dundee horizons are nearly all sulfurous and analyses reveal from 1.54 to 3.05 grains per 100 cubic feet, but the Monroe gas is "sweet." Of the inflammable gas in the natural gas mixture, ethane ranges from 10.40 to 23.22 percent and methane from 58.10 to 81.0 percent. The heating value varies from 912 to 1,153 B.T.U., and the moisture content is usually small. The prices paid for gas at the well ranges between 7 and 12 cents per thousand cubic feet.

TABLE X—*Analyses of Natural Gas from Muskegon Field*

	1	2	3	4	5
Hydrogen sulfide	0.25	0.09	0.24	....	....
Carbon dioxide	0.27	0.21	Trace	....	....
Oxygen	1.07	0.19	1.29	....	0.7
Methane	61.95	59.78	58.10	81.00	79.3
Ethane	22.04	23.22	21.13	10.40	19.6
Propane	....	....	....	....	....
Butanes	....	....	....	....	....
Unsaturated hydrocarbons	....	....	....	.10	....
Hydrogen	....	....	....	....	....
Nitrogen	(Residue) 14.42	(Residue) 16.51	(Residue) 19.24	8.50	0.4
Total	100.00	100.00	100.00	100.00	100.00
Sulfur—Grains per 100 cubic feet	....	....	....	3.05	....
Moisture per 100 cubic feet	....	....	....	1.296	....
Sp. gravity—Air=1	....	....	....	....	.657
Heating value B. T. U.	1,016.00	1,015.00	912.00	1,005.3	1,153.00

1. Dixie Oil Co.—C. Reeths No. 1D, Muskegon County, Dundee gas.
2. Dixie Oil Co.—F. Figge No. 11D, Muskegon County, Dundee gas.
3. Joliet Morris—J. B. Nichols, No. 3, Muskegon County, Dundee gas.
4. Johnson Oil Refining Co., Smith No. 1, Muskegon County, Dundee gas.
5. Muskegon Oil Corp.—Daniloff No. 1, Muskegon County, Monroe gas.

Natural gas is no longer used for domestic purposes at Muskegon and industrial gas which is still being burned under steam boilers and consumed in gas engines, core ovens, and dry kilns is diminishing in quantity. This may be eventually replenished with central Michigan gas if pipeline projects under consideration materialize. The increased gasoline content in the Muskegon gas has brought its heating value from approximately 1,000 to over 1,400 B.T.U. At the time when the supply of gas was large, about 1,750,000 cubic feet were handled daily by an absorption plant which had an output capacity of 5,000 gallons of natural gasoline per day. The gasoline recovery from this plant, which has now been moved to the Mount Pleasant area, was about one gallon per thousand cubic feet. The present gas withdrawal from the entire Muskegon field is less than a million cubic feet per day.

At the close of December, 1932, the area had produced 5,802,034 barrels of oil and close to 6,981,347,000 cubic feet of gas. On October 1, 1932, 466 wells had been completed in the field, of which 244 were still producing, 37 were idle, 184 abandoned and plugged, and one drilling. Of 214 producing oil wells, 149 were in the "Dundee," 43 in the Upper Traverse, and 22 in the Lower Traverse. The 30 gas wells included 13 in the Monroe, 11 in the "Dundee," four in the Lower Traverse, and two in the Upper Traverse. The daily gas production at that time was 783,188 cubic feet, including 581,086 cubic feet of casinghead gas and 202,102 cubic feet from dry gas wells. The daily oil production was 2,460 barrels, of which 1,996 barrels were from the "Dundee," 330 barrels from the Upper Traverse, and 134 barrels from the Lower Traverse. The average output per producing well was 11.5 barrels of oil and 20,740 cubic feet of casinghead gas. The 122 wells treated with acid were averaging 15.6 barrels of oil per well in comparison to 6.05 barrels per well from the 92 wells untreated, and approximately 90 per cent of the wells were making water with an average of 11.95 barrels per well.

Chapter III

CENTRAL MICHIGAN STRUCTURE

INTRODUCTION

The Central Michigan Area is treated as a single structural province, although it includes two distinct "highs" on which several distinct and separate structures have been partially outlined. These structures vary in shape, size, and depths at which the various producing horizons are found. Conditions of production also vary from field to field. Since these pools are in the vicinity of the lowest part of the "basin," they are grouped together. Drilling and operating conditions in the different pools of the area are essentially the same, and the depths to the same formations do not vary more than two or three hundred feet.

Mount Pleasant is the center of the area, and it is about midway between the two separate lines of folding. The Mount Pleasant structure, as originally outlined, is in the approximate geographic center of the southern peninsula with about two-thirds in Isabella County and one-third in Midland County. In 1931, new production was found east of the original field and later drilling showed this to be on the same structure. The field as now defined is about one-fourth in Isabella County and three-fourths in Midland County.

Since the finding of oil on the Mount Pleasant structure, new discoveries have been made until the Central Michigan Area now includes 7 producing fields in Midland, Isabella, and Clare counties. These are called the Mount Pleasant, East Extension, Leaton, Vernon, and Porter pools, and Clare and Broomfield gas fields. The business and supply center of nearly all operations is Mount Pleasant, a city of over 5,000 people, and the county seat of Isabella County.

Mount Pleasant is not an industrial city, but living conditions are adequate to furnish accommodation for a large transient class of people. It is the trading center for a considerable area of good farming territory and the seat of the Central State Teacher's College and the United States Indian School. The city is served by the Ann Arbor railroad of the Wabash system, affording direct connections with Toledo and junction points to Detroit. A branch line of the Pere Marquette railroad goes to Coleman, where it joins with the main line to Saginaw and Bay City. A paved highway leads southward to Lansing, about 70 miles distant, and improved gravel and paved roads connect with Bay City and Saginaw. The side roads in some parts of the district are well maintained, but in the area of poor land east of Mount Pleasant, near the Isabella-Midland county line in which the original oil field is located, many of the roads are sandy and swampy.

Other towns in the vicinity of the Mount Pleasant field are Midland, Alma, St. Louis, and Clare. Midland is 27 miles east of Mount Pleasant and twelve miles east of the nearest producing oil well in the East Extension pool. The city is the center of a large mineral and chemical industry carried on by the Dow Chemical Company, who also operates a branch plant at Mount Pleasant. Many wells put down by this company for brine are located in parts of the area not included in the oil and gas fields.

Small refining plants which operate on Central Michigan crude have sprung up in Mount Pleasant, Midland, Big Rapids, and Saginaw. Large tank farms have been constructed by the Pure Oil Company in the field and at a terminal in Bay City. A six-inch oil pipe line built by the same company connects the field with water transportation facilities at Bay City. Gas lines have been laid to Midland, Mount Pleasant, Clare, and also connect with an older line from Midland to Zilwaukee near the city of Saginaw.

The Central Michigan Area is about 25 miles wide and 40 miles long. Although many dry holes have already been drilled and much of the district will be found barren of oil and gas, still several new pools along these "highs" are very probable. Prospecting to date has shown that the structural "lows" are unfavorable for commercial pools of oil or gas. Cross folds in different directions to the main trends and lenticular "sand" conditions seem to bring about the accumulation of natural gas in the shallow Mississippian formations at lower structural levels than have produced oil at greater depths. The area in which immediate future prospecting can be expected includes over 1,000 square miles.

PHYSIOGRAPHY

The surface features of the region are largely the result of Pleistocene glaciation, either from the melting of ice or the stages of glacial Lake Saginaw. Midland County and eastern Isabella County are covered by deposits of lake clay, sandy lake beds, and deltas formed by streams flowing into the glacial lakes which covered the district at different times during the retreat of the ice. The waters of glacial Lake Saginaw reached as far west as Mount Pleasant, and the shore features of that lake are fairly well defined at an elevation of 780 feet extending northward and southeastward from the city. The soil of these lake deposits is usually poor in quality, land is comparatively flat with little relief, and swamps are frequently present. The surface elevations in the vicinity of the oil field vary from 670 to something over 740 feet above sea level. The ground surface is comparatively flat with occasional sandy crescentic bar or beach ridges and low sand dunes that rise a few feet above the surrounding country. Some of this lake bed country is underlain with clay, particularly in southern and northwestern Midland County, but much of the area is sandy. The vegetation consists of low bush, tamaracks, and scrub oak.

The land rises in a series of ridges to the west and northwest of Mount Pleasant in two pronounced rows of hills that attain elevations in excess of 1,060 feet. The first hills west of the city range between 860 and 890 feet high, and the Bundy Hills, between 4 and 7 miles farther west, rise from 950 to over 1,000 feet above sea level.

The glacial features besides the terminal moraine are till plain and outwash. The moraines are members of the West Branch-Gladwin group along the western edge of the Saginaw ice lobe. Southward from Clare County, where the West Branch morainic system is separated into several members, the relief of each ridge is less than 100 feet except in northwestern Isabella and eastern Mecosta counties, where it is 200 feet or more. In Gratiot, Montcalm, and central Isabella counties,

the moraines are separated by broader strips of fertile till plain, which lie on the inner or eastern slopes of the moraines. The sandy and swampy areas of old glacial drainage channels lie on the outer or western slopes. One prominent line of glacial drainage which gave rise to these swampy and sandy areas is continuous from southern Clare County southward across western Isabella County to the outlet of glacial Lake Saginaw, a distance of about seventy miles. It heads near Hatton and passes southwestward, leaving Farwell at its east border and enters the Chippewa Valley drainage in northwestern Gilmore township, Isabella County. This series of drainage channel, moraine, and till plain constantly repeats itself across the region west of Mount Pleasant.

The larger ridges of terminal moraine west of Mount Pleasant extend northwest-southeast and during the Ice Age, the position of the ice front at this point was apparently controlled in part by pre-glacial topography, a reflection of the structure of the underlying rocks. Near the western margin of Isabella County, the surface is extremely rough and the hills are high and steep. The moraines are composed chiefly of boulder clay, with some sand and gravel. The land north and west of the city of Mount Pleasant is of much better quality than to the east, and the border between the two classes of soils is more or less governed by the extent of the sandy glacial lake deposits.

The principal rivers of the region are the Pine, Chippewa, and Salt, tributaries of the Tittabawassee which empties into Saginaw River near the city of Saginaw. The Chippewa flows in a general eastward course across Isabella and Midland counties and is the most important stream of the oil field area. The divide which separates the eastward and westward flowing streams of the State crosses the northwestern corner of Isabella County and central Clare County in a northeast-southwest direction. The Muskegon River drainage is on the west side of this divide, and the tributaries of this river system serve the remainder of the district.

HISTORY

Drilling for brine in conjunction with the lumber and chemical industries furnished structural data and led to the discovery of several Michigan oil fields. The first well belonging to the Dow Chemical Company, Midland, Michigan, was put down soon after the concern started operations in 1890. As the chemical plant grew, the company spread its drilling activity out into the surrounding territory. The new wells were scattered at irregular intervals along the Chippewa and Pine rivers, until the locations of holes put down for brine extended over several of the townships west of Midland. The more recent Dow brine wells have been spotted with greater regularity at approximately half mile intervals along the section lines.

For a long time, the records of most of the wells of the Dow Chemical Company were withheld, and since the rocks were deeply buried by glacial drift the anticlinal fold with its several individual domes was not recognized. Some of the holes drilled for brine found showings of oil and gas, and the drillers who worked at the wells and the people of the surrounding community remembered these. The Saginaw oil field was discovered in July, 1925, and with the influx of men trained and experienced in the petroleum industry, new interest was aroused in the oil and gas possibilities of the Central Michigan Area.

The Pure Oil Company obtained from the Dow Chemical Company the records of their many wells which had been previously held confidential. Close study of these well logs revealed a strong arching of the rocks in the same general locality where small quantities of oil and gas had been found years before. A deep well was drilled at a favorable place on the structure and this test hole, completed on February 8, 1928, was the discovery well of the Mount Pleasant oil field. The hole was situated on the Laura Root farm, NE. ¼ of the SE. ¼ of sec. 18, T. 14 N., R. 2 W., Greendale township, Midland County, and W. A. Thomas, geologist for the Pure Oil Company, made the location.

The Root well was not an unusual producer. It commenced at about 30 barrels and increased to about 100 barrels per day when later drilled a few feet deeper into the "sand" or pay horizon. This deepening of the hole definitely established that the water was at some distance below the "pay" and that the discovery had been made well up on the structure. Soon afterwards drilling became active, and other holes were put down which showed that the field would cover a wide area. The most sensational development occurred on May 8, 1931, when the so-called East Pool or the East Extension was discovered with the bringing in of the Kalamazoo Improvement Company, George Harnick No. 1, SW. ¼ of the NW. ¼ of the NW. ¼ of sec. 15, T. 14 N., R. 2 W., Greendale township, Midland County, good for 820 barrels initial production. In 1930, the Mount Pleasant district had become the leading oil producing area in Michigan, and the large output of the East Extension with several wells having over 3,000 barrels initial production brought the pool into national prominence. On June 1, 1932, it was believed that the original Mount Pleasant Pool, together with the East Extension, would include a potential productive area of approximately 9,000 acres.

STRATIGRAPHY

The general stratigraphy of the Mount Pleasant oil field is known in the structurally high places to a depth of 4,600 feet and in the lowest part of the district to 4,821 feet. The deepest wells have penetrated the Sylvania formation, but none have gone completely through it. The area as a whole shows considerable stratigraphic similarity, but several members change markedly from place to place. In most cases, these lithologic and thickness changes are related to unconformities. Bedrock does not crop out anywhere in the central part of the State, and the descriptions of the various formations are entirely from well logs, samples of cuttings, and cores. A well record from the northwest part of the Mount Pleasant Pool on the Dixie Oil Company's N. Davis lease is shown as typical of the Central Michigan Area. (See table XI.)

PLEISTOCENE

The glacial drift materials of Pleistocene age are the surface deposits of the region. They consist of sand, gravel, and clay, either in beds or in heterogeneous, unevenly distributed deposits. The thickness of the drift is variable, but in the immediate vicinity of the Mount Pleasant Pool it averages 300 feet. In this part of the area, the materials are sand and lake clay. Some of the sand is cemented by infiltration of

TABLE XI—*Record of Dixie Oil Company's (Stanolind Oil and Gas Company's) N. Davis No. 1*

Location: SE. ¼ of SE. ¼ of SW. ¼ sec. 2, T. 14 N., R. 3 W., Isabella County. 330 feet from north and 330 feet from east property line. Permit No. 816. Elevation: 716 feet above sea level. Record compiled by John D. Lamont and R. B. Newcombe from driller's log. Commenced: December 10, 1929. Completed: March 4, 1930. Initial production: 130 bbls. oil. Casing: 331 feet of 14; 810 feet of 10; 1,424 feet of 8¼; 3,208 feet of 6⅝-inch.

Formation.	Thickness.	Depth.
	Feet.	*Feet.*
Pleistocene:		
Sand	65	65
Sand; white clay, soft	55	120
Clay, white, soft	28	148
Sandstone, hard	7	155
Red rock, soft	27	182
Sandstone	30	212
Sandstone and gravel	38	250
"Permo-Carboniferous" (?):		
"Red Beds:"		
Red rock	2	252
Limestone shell, hard	2	254
Red rock	13	267
Ionia Sandstone (?):		
Sandstone, red	56	323
Pennsylvanian:		
Saginaw Formation:		
Sandstone, white, hard	129	452
Shale, black, soft	46	498
Clay, black, soft; shale	94	592
Limestone; "shell," hard	10	602
Clay, black, soft	118	720
Sandstone, white	34	754
Sandstone	27	781
Clay, blue, soft; shale	6	787
Sandstone, white, hard	3	790
Shale, gray	41	831
Parma Formation:		
Sandstone; (water)	11	842
Sandstone, white, hard	28	870
(Bayport apparently eroded)		
Mississippian:		
Michigan Formation:		
Shale, light, soft	72	942
"Shell," hard	5	947
Shale, dark, soft	23	970
Shale, dark, medium hard	45	1,015
Limestone, white, hard	10	1,025
Shale, dark	55	1,080
Limestone, white	10	1,090
Shale, dark	30	1,120
Sandstone, white	5	1,125
Shale, dark	17	1,142
Sandstone (show of oil 1,148-1,153)	39	1,181
Napoleon (Upper Marshall) Formation:		
Sandstone	131	1,312
Lower Marshall Formation:		
Sandstone, red	28	1,340
Red rock	44	1,384
Sandstone, red, medium hard	32	1,416
Coldwater Formation:		
Shale, white, hard	8	1,424
Shale, blue, soft	299	1,723
Shale, white, soft	682	2,405
Sunbury Formation:		
Shale, brown	15	2,420
Berea Formation:		
Sandstone, "grit"	40	2,460
Devonian:		
Antrim Formation:		
Shale, brown	440	2,900
Traverse Formation:		
Limestone	30	2,930
Limestone, hard	298	3,228
Limestone, hard, "broken" (steel line measurement 18 feet difference)	50	3,278
Bell Formation:		
Shale, white, medium hard	55	3,333
Shale, white, soft	182	3,515

TABLE XI.—*Record of Dixie Oil Company's (Stanolind Oil and Gas Company's) N. Davis No. 1*—Continued

Formation.	Thickness.	Depth.
	Feet.	*Feet.*
Dundee Formation:		
Limestone, dark, hard	3	3,518
Limestone, dark, hard	2	3,520
Limestone, gray, very hard	2	3,522
Limestone, gray, hard	11	3,533
Limestone, dark gray, hard	12	3,545
Limestone, gray, soft porous	3	3,548
Limestone, blue gray, hard	2	3,550
(show of oil-gas 3,546, hole filled 200 feet with oil at 3,548 feet)		
Limestone, gray, hard	5	3,555
Limestone, gray, soft	3	3,558
Limestone, gray, hard	2	3,560
Limestone, light gray, porous	3	3,563
Limestone, brown ("pay" from 3,560 to 3,564)	1	3,564
(well commenced to flow when drilled to 3,560 feet)		
Limestone, brown, soft	1	3,565
Limestone, brown, soft	½	3,565½
Limestone, gray, hard	5	3,570½
Limestone, dark, soft	½	3,571
Limestone, dark, medium hard	1	3,572
Limestone, light gray, hard	½	3,572½
Limestone, light gray, hard	1	3,573½
Limestone, gray, hard	1	3,574½
Limestone, gray, hard	1	3,575½
Limestone, gray, medium hard	3	3,578½
Limestone, gray, hard	2	3,580½
Limestone, dark gray, hard	1	3,581½
Limestone, brown, hard	2	3,583½
Limestone, gray, hard	4	3,587½
Limestone, light gray, hard	1	3,588½

lime and in certain wells this cemented sand aggregate has caused much trouble in landing the drive pipe. The thickness increases, and the character of the drift changes to the north and northwest. In Isabella County, Denver township, it is 320 to 350 feet thick; Vernon township, 415 to 430 feet; Broomfield township, 500 to 650 feet; and in the Clare gas field, Clare County, 450 to 540 feet. Some of this thicker morainic drift is sandy too, but much of it is of bouldery clay or till. Artesian flows have been encountered from the drift in some parts of the Leaton Pool, Denver township.

"PERMO-CARBONIFEROUS" (?)

The "Red Beds" are not reported in all wells of the district, but they are apparently very generally present. These beds, where thin, may be often logged with the glacial drift. It is evident from samples that the reworked red material is represented in some of the basal Pleistocene clays. The red sandstone which is usually found at the base of the series probably correlates with the Woodville (Ionia) member as shown in Figure 6, Part I, Chapter III.

PENNSYLVANIAN

The individual beds of the Saginaw formation cannot be easily correlated between wells over long distances. Sometimes dark shales, coals, or sandstone members are traceable from well to well if they are close enough together. The thickness of the formation depends on pre-glacial topography and the position of the drilling location in respect to regional and local structure. In the Central Michigan Area, there are usually from 300 to over 600 feet of Pennsylvanian rocks.

The Parma sandstone generally occurs at depths of about 800 feet throughout the Mount Pleasant field. It is not recognized in all the wells of the field and often has unusual physical characteristics. The typical milky to clear white sandstone carries water and is usually the first important water bearing stratum after bedrock is penetrated. Frequently, the sandstone is limy and interspersed with reworked Bayport, making it difficult to identify in well logs. The Parma, having been laid down on the uneven surface of the Grand Rapids group, may vary greatly in thickness from 20 to over 100 feet. It may rest on shale or sandstone but is more commonly found on the Bayport limestone, which is also extremely variable. The average amount of Parma is from 50 to 80 feet.

MISSISSIPPIAN

The Bayport limestone may be cut out by pre-Pennsylvanian erosion, and this is probably the explanation for its absence in the Davis No. 1 well. (See table XI). Where present, it is gray to buff limestone and usually sandy and impure in the upper part. The recorded thickness ranges from 12 to over 100 feet but from 40 to 80 feet is most common.

The Michigan series is similar to the Saginaw formation in that the individual beds cannot be traced easily between wells, although sometimes correlation is possible in a limited area. The gray and black shales, the dolomitic bituminous limestones, the anhydrite and gypsum beds, and the lenticular sandstones characterize the formation. A rather persistent sandstone bed from a few feet to 30 or 40 feet above the base usually carries gas or heavy oil. This member, sometimes broken by shale partings, is similar in character to the Napoleon sandstone and seems to be a reworked phase of the Marshall formation. Northward and northwestward from Mount Pleasant the strata separating this horizon from the Napoleon sandstone frequently contain gypsum beds. Early records miscorrelated this sandstone as Marshall, but the gypsum layers between the upper sandstone and the typical Napoleon has made the present correlation more plausible. A thin, bituminous, brown limestone may overlie this upper sandstone, and a similar brown limestone nearly always overlies the thicker and more uniform Napoleon sandstone below. Therefore, unless a "wildcat" hole is drilled for some distance into the Marshall, it is difficult to know from the character and order of the beds whether the "stray" sandstone in the lower part of the Michigan series has been penetrated.

The Napoleon (Upper Marshall) sandstone is normally from 130 to 150 feet thick and present everywhere in the Mount Pleasant field. It is the principal horizon from which the Dow Chemical Company obtains the heavy brine for extraction of chemicals and the nature of this sandstone section is thoroughly known from the many scattered wells of this company. South and southeast of the oil field the Upper Marshall beds become thinner. In Jasper township, Midland County they are 105 to 115 feet thick; Porter township, Midland County, 75 to 125 feet; Mount Haley township, Midland County, 90 to 120 feet; and Bethany township, Gratiot County, 75 to 90 feet. East of the field in Lee township, Midland County, they are 90 to 115 feet thick; Homer township, Midland County, 85 to 125 feet; and Midland township, Midland County, 100 to 120 feet. North and northwest of Mount Pleasant, the Upper Marshall attains a thickness of from 160 to 170 feet. The formation generally consists of gray, white, yellowish, and light greenish sandstones with a few limy or gray shaly streaks and partings. The important unconformity at the top has caused local and regional changes in the character of the beds which are sometimes confusing. Among these changes are alternating red and gray sandstones in some of the top beds, a "broken" or shaly condition in some of the upper members, a red shale bed in the middle of the massive Napoleon sandstone, and a red sandstone at the base. The changes are localized as follows: the alternating red and gray top beds in the district north and northwest of Mount Pleasant; the "broken" or shaly upper members in the structurally high region along the southeast trend of the anticlinal fold in Jasper and Porter townships; the red shale in the middle of the Napoleon (Upper Marshall) in the region south of Midland and in the Leaton Pool; and the red sandstone at the base in scattered parts of the field. The red color in the Upper Marshall is probably related to the reworking of exposed red Lower Marshall rocks in Napoleon time and the reincorporation of this material with the coarser sand. These unusual Napoleon sandstone beds are generally pink instead of red, and much of the color is due to cementing matter as evinced by the way this color fades or disappears when the cuttings are thoroughly washed.

The Lower Marshall formation includes several beds of pink to red sandstone and red shale, aggregating from 80 to over 100 feet in thickness. The red color is darker than the Napoleon and the texture finer. It is micaceous, silty, and shaly, and more sharply differentiated from the Napoleon sandstone above than from the Coldwater below.

The Coldwater shale is gray and light blue in color. Although the shale may be either soft or hard, it is for the most part uniform. In many wells, a series of dark beds have been found near the top of the formation. The thickness ranges from about 960 to 1,050 feet.

The Sunbury brown shale can usually be distinguished from cuttings, but many drillers do not recognize its dark color when the samples are wet. This shale contains pyrite and breaks up under the drill as large chips. It is an important marker at the base of the thick Coldwater shale section.

The Berea is not well represented as a definite sandstone and the beds are mostly sandy and limy shale. These sandy beds and the underlying gray Bedford shale are from 30 to 80 feet thick in the west part of the field and 30 to 125 feet in the east part. The Berea is better developed to the east and shows from 20 to 50 feet of "sand." The oil and gas in the formation increases eastward in the localities where rather favorable showings have been found.

DEVONIAN

The Antrim shale, as correlated in central Michigan, exceeds 400 feet in thickness and is largely brown to black shale. It contains abundant pyrite and *sporangites* (yellow-brown spore cases). The upper beds of this shale may represent a dark gray facies of the Ellsworth formation of western Michigan. The cause of the change in physical character and color of the beds in this part of the stratigraphic column between

the western and the central counties of the State is not well understood. The abnormally thick section of dark colored shale is probably due to lateral variation in the Ellsworth beds. A series of gray and brownish limy beds occurs about 60 to 80 feet above the base of the Antrim. In some instances, these limestones are partly concretionary and usually from 5 to 25 feet thick. The basal beds of the Antrim may be transitionary with the upper gray shales of the Traverse, but the contact between the two formations is fairly sharp.

The Traverse group consists of gray to blue shales and gray, buff, and brown limestones and averages about 600 feet in thickness throughout the entire field. A porous zone that occurs from about 100 to 130 feet though usually about 120 feet below the top of the formation may contain oil, gas, or water. These porous strata are probably near the top of the Alpena limestone member. A basal shale series, which is usually about 60 feet thick, is correlated with the Bell shale. The lower beds of this shale are black and this indicates nearness to the top of the Dundee formation.

The Dundee limestone contains the important oil producing horizons of the Mount Pleasant field. The beds are buff to gray and often cherty or fossiliferous. The first porous layers are in horizons struck from 25 to 35 feet in the Dundee, and a certain degree of porosity is found for 25 or 30 feet. The beds then become more dense and, on the highest parts of the structure, water is not found until about 95 feet of Dundee has been penetrated. The productive part of the formation does not extend more than 70 feet beneath the top and drilling operations are generally stopped at that point.

The porosity of the Dundee beds is attributed to solution. Cores of the "pay" strata have cavities characteristic of those made by percolating water and many of these vugs contain recrystallized calcite. The porous beds are full of stylolites and many of the openings are adjacent to the stylolitic sutures. A stylolite is a small, short, columnar structure transverse to the bedding and commonly filled with a thin residual film of carbonaceous clayey material. If one is to accept the conclusion[1] that stylolites are caused by solution, then this relationship should serve as rather positive evidence that the openings originated by solution. Some have advanced the explanation that the unusual porosity in the East Extension is a result of the presence of coral reefs. Cores which have been examined show openings caused by the dissolving out of the internal structure of cup corals, but no reef forming corals were observed. Reefs have not been found in the Dundee where exposed; therefore, it would not seem plausible that they would be present in this area.

Only two wells in the Mount Pleasant Pool proper have gone through the Dundee limestone, so the data on the thickness of the formation are meager. One was on the top of the structure and the other was just off the southeast flank. The Dundee was 224 feet thick in the first well and 189 feet thick in the second. These figures seem to indicate a discomformable relief of over 35 feet on the top of the Dundee formation for the Mount Pleasant Pool proper, but the possible error due to

[1] Stockdale, Paris B., Stylolites, Their Nature and Origin: Indiana Univ. Studies, Vol. IX, pp. 1-97 (1922).

———, The Stratigraphic Significance of Solution in Rocks: Jour. Geol., Vol. 34, No. 5, pp. 399-414 (1926).

the unconformity at the base must not be overlooked. A well west of Rosebush, Isabella County, showed 128 feet of Dundee, and a hole in the south part of sec. 9, Lee township, Midland County, also penetrated the entire formation. If the production in the Vernon Pool is coming from the Detroit River beds instead of the Dundee, then the topographic relief of the pre-Bell land surface for the entire Central Michigan Area is more than 224 feet.

The Detroit River series is abnormally thick, exceeding 1,050 feet in the central part of the State. The beds are largely dolomite and anhydrite, with a few thin salt seams. They are porous near the top of this series where the "black water" is encountered and the water horizon is about 5 feet in the formation. There are also several other water horizons which include zones 200 to 225 feet; 410 to 440 feet; and 500 to 550 feet from the top. In two wells, the deepest of these porous zones carried oil and the water below this "pay" zone contained sulfur. It is interesting to note that one of these wells was high on the structure and the other was low.

The Sylvania strata are the deepest rocks penetrated in the region. They are made up of fine grained sandstone and buff, cherty, sandy dolomite. The sand grains are more angular than those typical of the same formation in the southeastern corner of the State. The upper part of the Sylvania carries a heavy brine, which in one well was supersaturated. The approximate depth to the first Sylvania beds on the top of the Mount Pleasant anticline is about 4,700 feet.

STRUCTURE

The anticlinal fold which was discovered by drilling for brine and later outlined by wells put down for oil in the Mount Pleasant Pool has been traced across Midland and Isabella counties, and into Clare County. The position of the arch is much better known in some places along the general axis than in others. Contour maps drawn on two subsurface horizons indicating structural conditions, as of January, 1933, are shown in Plates IV and V. The contours are drawn on the top of the Lower Marshall (Red rock) of Mississippian age and on the Dundee limestone of Devonian age. The contour interval is 20 feet, and the elevations on the datum beds are below sea level. Dashed lines are used in most instances and indicate the uncertainty of the structure as drawn. Future drilling may greatly change the local picture, but the regional aspects of the structure as represented are probably more certain.

Two important parallel "highs" are outlined on these maps. They are traced from Gratiot and Saginaw counties on the southeast into Clare and Osceola counties on the northwest. At somewhat regular intervals, they are interrupted by cross folding which changes their size, shape, and trend. These cross folds give rise to domes with sufficient closure to trap oil and gas in pools. There seems to be two series of these cross folds, one with an east-west and the other with a northeast-southwest direction. North-south folds with large dimensions seem infrequent. A third northwest-southeast "high" is suggested on the northeast as an extension to the northwest of the Saginaw structure. Further drilling is necessary to determine this.

These lines of folding have been termed in the field, the Mount Pleasant "high," and the Broomfield "high," but, as shown by the maps, the name given to the "high" east of Mount Pleasant is somewhat misleading. It is suggested that discovery be made the basis for naming them and they be called in order from east to west, the Saginaw "high," the Greendale "high," and the Broomfield "high." The lows in between these trends of anticlinal folding could be called the Midland trough and the Mount Pleasant trough. The domes on these anticlines are from 1¼ to 2 miles across and the deepest part of the synclines 4 to 4½ miles wide. The maximum structural relief off the Greendale "high" into the Mount Pleasant trough is 270 to 280 feet and off the Broomfield "high" about 300 feet. The relief is essentially the same on both the Mississippian and Devonian rocks and in its major features the structure is largely conformable for both ages.

Several regional features of structure should be emphasized. The deepest part of the Michigan "basin" is in the Mount Pleasant trough west of the village of Rosebush and the two principal highs of the district are on each side of this deep trough. The troughs beyond on the outer side of these lines of folding are narrower and shallower than the central one. The comparatively steep dip like the west flank of the Greendale "high" does not seem to be present off the Broomfield "high" and the latter is more symmetrical in cross section than the former. This may be partly due to the lack of structural information on the Broomfield fold since wells are scarce in most of that region except in Broomfield township.

It may be observed on both maps (see pls. IV and V) that the structures seem to broaden out and the noses become less sharp up the regional dip to the southeast beyond a line between Alma and Saginaw. This is evident, particularly because the pitch of the Mount Pleasant trough flattens appreciably in northwestern Saginaw and northeastern Gratiot counties. A possible explanation for this seeming regional terracing is a deep syncline which parallels the long direction of Saginaw Bay. This transverse syncline (see pl. III) may be the result of a regional downwarp of sufficient magnitude to extend into the central part of the State and form terraces, gentle dips, and flattened structural noses.

The regional dip is difficult to determine in most of the Central Michigan Area, because it is interrupted by the local structures and is changed in short distances. The central trough and the major parallel highs affect the whole district. The axes of the Greendale "high" north of the Vernon Pool and of the Broomfield "high" north of Barryton seem to bend more to the north. This may possibly be due to a change in the trend of the axis of the basin itself, or to a local cross fold.

The individual structures along the trend of the Greendale "high" apparently have some characteristics in common. They are arcuate in shape and the closures are somewhat regularly spaced along the axis. The gas in the Mississippian rocks is more or less confined to the regions of northeast-southwest cross folds. The map on the Lower Marshall (see pl. IV) seems to indicate a similarity between the Leaton Pool structure and the southwest plunging nose in secs. 13, 23, and 24, Jasper township, Midland County. The arc concave to the northeast, which traces the axis of the Mount Pleasant Pool (Chippewa-

Greendale townships), may possibly be duplicated again to the southeast but there is some evidence that the axis will swing to the south across Jasper township. Any similarity of structural pattern along the axis would be an invaluable aid to future prospecting.

MOUNT PLEASANT STRUCTURE

The Mount Pleasant anticline proper in Chippewa township, Isabella County, and Greendale township, Midland County, extends about 5 miles in a northwest-southeast direction. It is separated from the Leaton dome to the northwest by a saddle with a north-south axis which changes direction toward the northeast on the north side of the arch. The Mount Pleasant structure swings more to an east-west direction at the southeast end and joins with a subsidiary, more or less continuous structure, called the East Extension. This extends eastward into Lee township and is about 4 miles long. It is partially separated on the south from the northwest-southeast trending main fold by a small saddle coming in across section 20, 21, and 29, Greendale township. The Mount Pleasant anticline along its major direction is about 8½ miles long. The elongated dome is about 1½ miles across where widest and the steeply dipping flank is on the southwest, or basinward side of the arch. This steep dip varies from about 180 to 240 feet per mile, and the inclination of the beds on the gentle side of the fold does not greatly exceed 50 feet to the mile. The plunge of the fold to the northwest varies from 80 to 90 feet to the mile and from the nose of the structure, the north dip decreases eastward until on the north side of the East Extension it averages between 26 and 27 feet per mile.

The asymmetrical character of the fold compares very closely with the other known anticlines in Michigan. The East Extension of the Mount Pleasant Pool indicates an east-west direction of folding which, together with the arcuate (pistol-like) outline of the structure, is also characteristic of Muskegon. In a similar manner to the Muskegon field, the most productive area is found on this narrow east-west fold in sections 9, 10, 15, and 16, Greendale township. A somewhat gentle east-west syncline coming in from the east across the south part of sections 13, 14, and 15 seems to cut off production on the south side of the structure. The 560 foot contour suggests (see pl. IV) that in the southeastern corner of section 16, the Mount Pleasant anticline proper is joined by means of a saddle in the vicinity of Stearns to another anticline regionally higher to the southeast along the same trend.

The anticline has between 40 and 50 feet of closure on the northwest-southeast trending dome and between 20 and 25 feet of closure on the east-west trending dome. Oil occurs more than 10 feet below the level of the lowest closing contour on the west side and more than 20 feet below this level on the east side of the dome. The absence of normal edgewater on the steeply dipping side of the structure may possibly account in part for this. The wells on the steep side of the fold have generally shown a very slow, regular decline in production, and the disconformity at the top of the Dundee limestone may possibly explain these unusual characteristics. The variable thickness of the Dundee on and off structure and the nature of the porosity tend to support this conclusion.

The structure displays numerous minor irregularities, particularly on the south side. Several narrow saddles indent the crest at about right angles to the axis of the fold. Small local domes extending from a quarter of a mile to more than a mile are scattered along the crest and rise 20 to 30 feet. These, together with small depressions of like magnitude on top the structure, are seemingly due to the topography representing the erosion surface existent at the close of both Lower Marshall and Dundee times. The north side of the structure forms a broad nose northward and northeastward into western Geneva township. The nature of this nose and its relation to other nearby structures is difficult to explain, but it is significant that small quantities of free oil were found in the Dundee on this nose as far down the dip as sections 19 and 20, Geneva township. Possibly, there may be another parallel subsidiary structure on this side of the Greendale "high."

LEATON STRUCTURE

The Leaton structure is named from the small town of Leaton, Denver township, Isabella County. This dome is a much smaller structural feature than the Mount Pleasant anticline and, although the major axis seems to trend in a northeast-southwest direction, the contours on the Dundee show it to be nearly circular. Apparently, it is the result of the cross buckling which caused the saddle between the Chippewa and Vernon township parts of the fold. The east-west and north-south diameters of the dome are each about a mile and a quarter in length. The dip is very sharp on both the southern and western sides of the dome but it flattens out to the north and east. Westward, it is from 140 to 200 feet per mile and southward 50 to 60 feet per mile on top the Dundee.

Two small closures are indicated by the Lower Marshall map (see pl. IV), and the structure seems to be elongated in a northeast-southwest direction. The total amount of closure on these shallow beds is between 25 and 30 feet, but on the Dundee it is apparently greater, amounting to 35 or 40 feet. (See pl. V). The circular shape of the dome is more clearly defined on the Dundee beds, and there seems to be only one restricted closure in the vicinity of the section corner between sections 24 and 25, Isabella township, and sections 19 and 30, Denver township. The saddle joining the Leaton dome with the Mount Pleasant anticline crosses the middle of section 29, Denver township and, in this direction as well as down the gentler south dip of the dome, production is found from 10 to 15 feet lower than on the other sides. The depositional and structural importance of the northeast-southwest cross folding in the Mississippian rocks is indicated by the presence of large quantities of "Michigan Sand" gas on this dome. The uneven surface of the Lower Marshall is shown by the irregular contour lines and the small closures.

VERNON STRUCTURE

The Vernon structure is situated on the Greendale "high" in Vernon township, Isabella County, northeast of the Leaton dome, and about half way between Rosebush and Clare. Its developed area consists of two parts, outlined by the oil wells in sections 22, 26, and 27 and the "Michigan Sand" gas production in sections 26, 35, and 36. The limits and the characteristics of this structure are not well understood. The