# STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

Thesis for the Degree of M. S.

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NOBLE F. LEWALLEN II

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This is to certify that the

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STRUCTURAL GEOLOGY OF THE NORTHWESTERN
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presented by

Noble F. Lewallen II

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of the requirements for

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James H. Fisher
Major professor

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ABSTRACT

STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

By

Noble F. Lewallen II

Previous studies have proposed that the Michigan Basin subsided on basement faults, and that these faults controlled structure in the overlying sediments. The findings of this study support such a theory, based on structural mapping of various horizons in northwestern lower Michigan. These maps reveal that the major structural trends of this area have a northwest-southeast orientation and that the structural features become more pronounced with depth. Such observations are interpreted to result from northwest-southeast trending basement faults which parallel the Mid-Michigan Gravity Anomaly - a proposed rift zone.

Cross-sections of two fields in Missuakee County reveal little or no structural effect of salt solution or flowage associated with these structures. However,

salt movement may be more significant nearer the depositional limits of the various salt units.

Future hydrocarbon exploration in northwestern Michigan will be directed toward fault related anticlines and associated porosity zones, or Niagaran pinnacle reefs.

# STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

By

Noble F. Lewallen II

A THESIS

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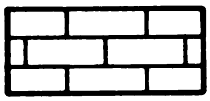

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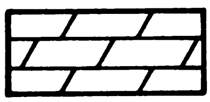

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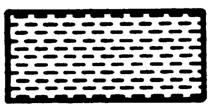

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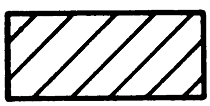

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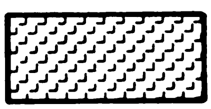

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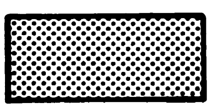

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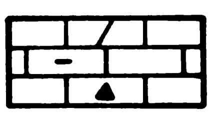

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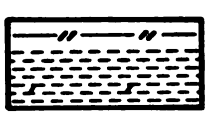
ARGILLACEOUS } LIMESTONE
CHERTY



ANHYDRITIC } SHALE
DOLOMITIC

# INTRODUCTION

The Michigan Basin is an intracratonic basin whose mode of origin is poorly understood. Similarly, the origin of the Basin's folded and faulted structures is unclear. An important key to solving such problems is a detailed study of the structures within the Basin. A number of workers have proposed that the Michigan Basin subsided on faults in the Precambrian basement and that these faults have controlled structure in the overlying Phanerozoic sediments throughout the evolution of the Basin. It follows then that by studying the location and orientation of the structures within the Basin sediments, this model can be tested. Additionally, because much of Michigan's petroleum is produced from structural traps, a study of this nature can shed valuable insight on the potential of future exploration efforts. The Albion-Scipio oilfield, Michigan's largest, produces from a fault-controlled structural trap, and some workers have suggested that similar traps may be the most likely prospect for future large fields in Michigan.

Mescher (1980) and Fisher, J.A. (1981) studied the structural geology of southeastern Michigan which contains the best deep well control in the state, and related the structures to complex faulting in the Precambrian basement. They, and many others, also related the Mid-Michigan Gravity Anomaly to a rifted graben-like structure that probably filled with Keweenawan basalts. These studies however, do not address the possible factors that could modify structure, such as salt solution and flowage.

The area for this study was chosen in order to further test the work of Mescher and Fisher. It is well suited for such a study because of its recent deep drilling activity, the presence of the Mid-Michigan Gravity Anomaly, and the presence of thick Devonian salts which may possibly alter structures if they have flowed.

## Purpose of Study

Since the drilling of the Dart-Edwards 7-36 discovery well in Reeder Township of Missaukee County in 1980 (tested 12 MMCFPD of gas) numerous deep tests have been drilled in northwestern lower Michigan. This deep well control makes this area the best suited for deep structural studies outside the area studied by Fisher in southeastern Michigan. As in southeastern Michigan, the Mid-Michigan Gravity Anomaly extends through northwestern Michigan. Thus, structural mapping of northwestern Michigan will determine the location and orientation of anticlines, synclines, and faults, as well as the relationship of these structures to the Mid-Michigan Gravity Anomaly.

Salt solution and flowage are important modifiers of structure in Allegan County of southwestern Michigan, and this has led to speculation that similar modification of structure may occur in other areas of the basin. Further, salt solution may indicate the presence of faults or fractures in the area and therefore be an important exploration tool in locating dolomitized reservoirs such as the Northville oilfield which produces from the dolomitized Trenton Limestone and exhibits extensive salt solution and thinning. Northwestern Michigan might be particularly prone to salt modified structure due to the presence of thick Devonian salts which are not present in the southern half of the basin. Good control on both Devonian and Silurian salts is possible in northwestern Michigan because of the hundreds of wells drilled to the Middle Silurian Niagara Formation along the northern Niagara reef trend.

This good well control, the presence of the Mid-Michigan Gravity Anomaly, and Devonian salts, make the northwestern portion of the Michigan Basin a good location to study structures within the basin and their possible modification. Knowledge of the cause, location and trends of structural features and how these features have changed through time is of great economic value, for such knowledge can guide future oil and gas exploration efforts.

## Area of Study

The area selected for this study is the northwestern portion of the lower peninsula of Michigan in an area bounded by the eastern boundary of Emmet, Charlevoix, Antrim, Kalkaska, Missaukee, Osceola, and Mecosta Counties, and by the southern boundary of Mecosta, Newaygo (less the eight southernmost townships), and Oceana Counties (Figure 1).

## Method of Study

Because a thick mantle of glacial drift covers virtually the entire basin, data collection for this study was limited to information obtained from oil and gas exploration wells. Approximately 7000 wells lie within the study area. Data for wells were examined at the State Geological Survey in Lansing, Michigan. Selection of wells for use in this study was made by choosing only dry holes wherever possible. This was done in order to eliminate the localized structural effects that pinnacle reefs have on the overlying formations. Also, wells with mechanical logs were preferred to wells without such logs because of the better

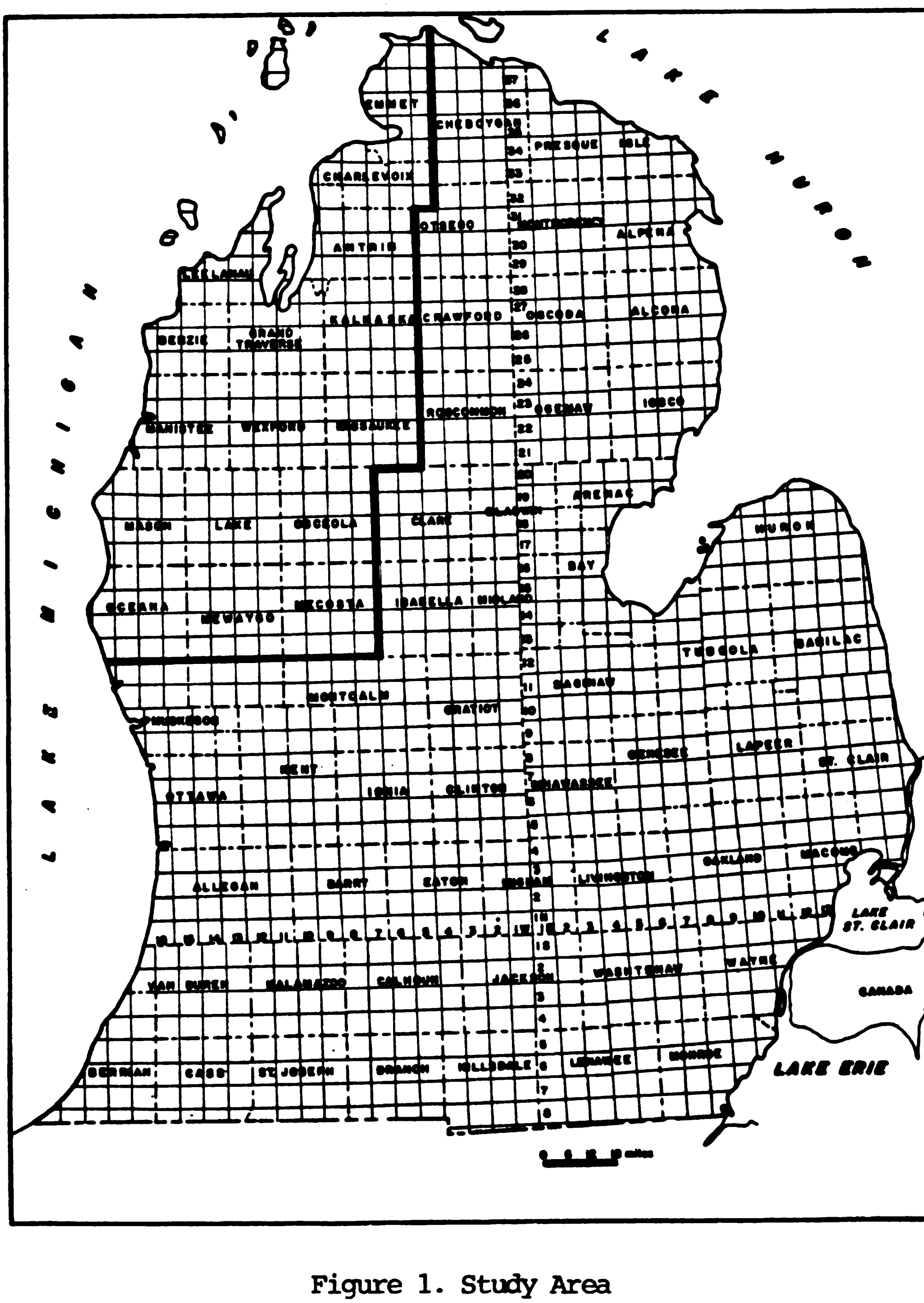



Figure 1. Study Area

reliability of correlations between these wells. Where no mechanical logs were available, driller's logs were used.

Because of the large study area, and the scale used for regional mapping (one inch equals six miles), only wells in every other section were used in order to avoid cluttering. When more than one well was present in the desired section, the deepest, most recently drilled well was chosen. From these data, formation tops were identified and used to prepare a series of structure contour maps.

Five regional structure maps were made in order to delineate the structural configuration at different levels within the stratigraphic column. (Figure 2) The selected formations were the Sunbury Formation (Early Mississippian), Traverse Limestone (upper Middle Devonian), Dundee Formation (Middle Devonian), A-2 Carbonate (Middle Silurian), and the Trenton Formation (Middle Ordovician). Unfortunately, data for formations deeper than the Trenton were too sparse to be of use in the study area. Correlations of these tops were based on the stratigraphic cross-sections prepared by Lilienthal (1978).

All five of these formations produce easily recognizable patterns on geophysical well logs. Additionally, the

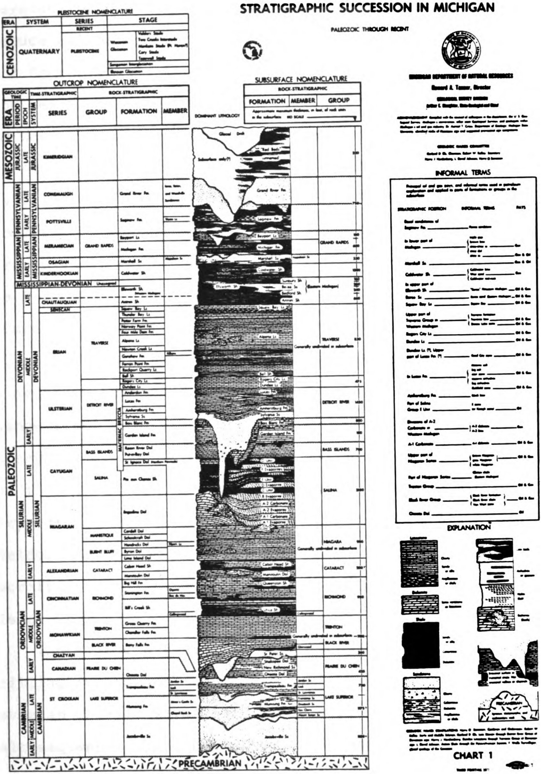



Figure 2. Stratigraphic Succession in Michigan

Traverse, Dundee, A-2 Carbonate, and Trenton Formations produce oil and gas, making them economically interesting.

Four detailed (one inch equals one mile) structure maps were constructed to show the structure in Missaukee and Oceana Counties, which have the best well control in the study area. Additionally, Missaukee County contains the Falmouth and Enterprise fields on which stratigraphic cross-sections were constructed. In Missaukee County, structure was mapped on the Dundee, and on the Trenton in the Falmouth field area. In Oceana County, Dundee and A-2 Carbonate Formation structure maps were prepared.

Six stratigraphic cross-sections were constructed in order to determine whether or not salt thicknesses change significantly near structure. The Falmouth and Enterprise fields of Missaukee County were selected for use in this study. Two cross-sections approximately perpendicular to one another, were constructed for both fields. Additionally, two detailed cross-sections of the Detroit River Salts unit were prepared for the Falmouth field.

The Falmouth field was chosen because recent deep drilling in and near the field penetrated not only the Devonian Detroit River Salts, but also the entire Salina salt sequence. The Enterprise field was chosen because it was the only other non-reef field in the study area with sufficient well control to allow construction of cross-sections of the Detroit River Salts. Niagaran reef fields were not selected for cross-sections because of their relatively small size and the fact that salt thicknesses near such reefs vary depositionally rather than post-depositionally.

In summary, it is proposed that most structures within the Michigan Basin were developed, and controlled by an ancient pattern of faults in the Precambrian basement rock. Therefore, the location and orientation of these structures in the overlying sediments should exhibit characteristics that reflect such basement influence. The major characteristic of such influence would be an increasingly subdued displacement of sediments upward in the stratigraphic column. Thus, the Trenton Formation should show the greatest relief, followed by the A-2, Dundee, Traverse, and Sunbury Formations, respectively. Basement structure might also be evident in the overlying sediments along the Mid-Michigan Gravity Anomaly, thus revealing important clues as to the nature of this feature.

It is further proposed that movement of salt can significantly modify structure. Determination of the extent to which salt movement has affected known oil producing structures can provide important clues to locating other salt modified structures. Therefore, stratigraphic cross-sections were constructed for the known structures associated with the Falmouth and Enterprize fields of Missaukee County. Anomalous thickening or thinning of salt horizons near these fields would indicate a need for further study of the effects of salt solution and flowage.

## Error Analysis

Data collection procedures for this study were subject to three potential sources of error. First, and most importantly, inaccurate drillers' logs can introduce significant errors in formation top elevations. This is particularly true in the older wells which were drilled early in the exploration history of Michigan before the stratigraphy of the basin was well understood. Where data from drillers' logs were obviously in error, the data were omitted. Another problem with drillers' logs was the lumping of several formations under one heading. Commonly, the Sunbury Shale was not differentiated from the overlying Coldwater Shale, nor the Traverse Limestone separated from the overlying shales of the Traverse Formation. Therefore, some wells in this study were not useful for the shallow formations such as the Sunbury and Traverse Limestone, yet yielded good data for deeper formations such as the Dundee.

Secondly, correlation of formation tops in poorly recorded or poorly printed geophysical logs can introduce errors. Formation tops can also be inaccurate where the borehole has been deviated from vertical (which exaggertes the thickness of formations). To minimize this error, only non-directional boreholes were utilized in this study. However, most wells are not perfectly vertical and thus introduce minor errors.

Finally, contouring of well data is an individual interpretation, and is therefore subject to error. In areas of sparse well control, interpretations by different workers can vary significantly. In areas of good control, interpretations vary less and accuracy is improved.

In this study, the best control, and therefore the greatest accuracy, is obtained in those portions of Kalkaska, Grand Traverse, and Manistee Counties where the Niagaran reef trend has been extensively drilled. Good control is also present in the counties south of the reef trend. Control is sparse north of the reef trend in Leelanau, Antrim, Charlevoix, and Emmet Counties, and is absent for the Sunbury and Traverse Limestone Formations where they have been eroded. Control on the Trenton Formation is sparse throughout the study area.

## Previous Work

The Michigan Basin area has been studied geologically for more than one hundred and forty years. Consequently, much has been written about the geology of the region. Part of this information has been published and is well known throughout the geological community. However, much of the geological knowledge of the Michigan Basin is contained in the files of the many companies that have explored here for a variety of resources. Such information is unavailible to the public and is obviously not reported here. Likewise, much of the published work on the region is out of date. Therefore, only the most important published works, relevant to this study, are included here.

In 1923, Robinson suggested that the structural elements in the Michigan Basin were folds that resulted from vertically acting forces rather than compressional forces. He described five fold types that could be formed by such vertical forces as subsidence and downwarping.

Pirtle (1932) stated that the major structural elements did not result simply from subsidence, but rather were controlled by trends of folding or lines of structural weakness in the basement rocks. He proposed that a system of Precambrian mountains extended southeastward from central Wisconsin to northwestern Indiana, the remains of which are the Wisconsin and Kankakee arches. Paralleling these mountains, Pirtle suggested a geosyncline which later became the Michigan Basin. Such a geosyncline would have an axis and structures parallel to the mountain ranges. Thus, Pirtle explained the dominant northwest-southeast trending structural elements of the basin by relating them to basement features that moved throughout time as horizontal forces were applied to affect the overlying sediments.

Despite the time of Newcombe's (1933) work, "Oil and Gas Fields of Michigan," his study provides an excellent account of the geology of the Michigan Basin. Many of the predictions and hypotheses put forth by Newcombe have been proven correct by the data provided by about thirty-five thousand wells drilled since 1933. One such hypothesis is that the Lake Superior Basin is a rift valley that connects with the Michigan Basin. This idea was later supported by geophysical surveys conducted by Hinze in 1963. Like Pirtle, Newcombe believed that the basin originated during the Precambrian and that the structure was related to zones of weakness in the basement rocks.

In 1945, Landes, Ehlers, and Stanley wrote the first comprehensive report exclusively about the geology of the northern part of the southern peninsula of Michigan.

Of particular interest to this study is their work concerning the relationship between salt solution and the Mackinac Breccia. They proposed that the Mackinac Breccia resulted from the leaching of the Salina salts near the edge of the basin and the subsequent collapse of the overlying sediments. They further proposed that the Detroit River Evaporites are the reprecipitated Salina salts which were transported in solution to their present position south (i.e. down-dip) from the Mackinac area.

Lockett (1947) related the formation of the basin and its structures to the positive areas around it. Like Pirtle, Lockett suggested that the Wisconsin and Kankakee arches lie along an ancient mountain range. As these mountains eroded, the sediment load collected in the surrounding low areas, causing the basin to sink. Lockett argued that the northwest-southeast structural trends of the basin resulted when fractures occurred parallel to the positive areas to the west.

Both Pirtle and Lockett overlooked the lack of geosynclinal-type sediments in the Michigan Basin. If the erosion of the Wisconsin range was associated with the initiation of subsidence, a coarse conglomerate should be present in the basin. No such conglomerate is known in Michigan. A further problem with the sediment load-subsidence theory is that sediment loading by itself appears to be insufficient to cause the entire subsidence of the basin based on geophysical studies (Sleep, 1976 and Sleep, Nunn, and Chou, 1980).

Cohee (1944-1948) prepared a series of maps and cross-sections of the Michigan Basin for the U.S. Geological Survey. Cohee and Landes (1958) summarized this work and acknowledged the northwest-southeast structural trends of the basin. They also compared different structural horizons over the Howell anticline in southeastern Michigan and showed that the axis of the structure had migrated one and one-half miles west from Niagaran time to Dundee time.

Migration of structural axis through time has obvious importance to the exploration for oil and gas. If a migration pattern could be found in the Michigan Basin, it would greatly aid the extrapolation of shallow fields to deeper horizons. Such a migration pattern is closely examined in this study.

Cohee and Landes proposed a late Silurian origin of the basin with the major period of folding occurring during Late Mississippian time.

Based on gravity and magnetic maps of the southern peninsula of Michigan, Hinze (1963) examined the regional structure of the Michigan Basin Precambrian basement. The most pronounced feature of the study was the anomalous gravity and magnetic high transecting the Basin from northwest to southeast. Hinze proposed a mass of mafic rock in the basement as the probable cause of such an anomaly. This suggested a link between the anomaly and the exposed mafic rocks of the Keweenawan rift zone in the Lake Superior Basin. Additionally, the anomaly is strikingly similar to the Mid-Continent gravity high in form and magnitude and thus Hinze suggested a relationship to this feature.

Sanford (1965) briefly reported the geology of the Salina salt beds of southwestern Ontario. He described the structures associated with leaching of salts and the subsequent collapse of the overlying sediments or the gradual filling during the deposition of the overlying Bass Islands Formation. Apparently, leaching first occurred near the margin of the basin soon after salt deposition and moved basinward through post-Upper Devonian time. Leaching was most intense above structural irregularities such as patch reefs, or along joints and faults. Sanford reported that most of Ontario's Devonian oil fields produce from dome structures associated with salt leaching and collapse.

Ells (1967) summarized much of what was known about Michigan's Silurian oil and gas fields. Although written prior to the discovery of the northern Silurian reef trend, the paper provides valuable information on the geology of the rocks of the Silurian group based on data from the southern reef trend. Of particular interest to this study is the analysis of reef associated structures and salt structures.

Ells stated that structural closure is formed in nearly all Salina units overlying Niagaran pinnacle reefs, with some reef fields showing closure in formations as young as Mississippian age. Reef height, and the thickness of overlying sediments apparently control the degree of closure in formations above reef structures. Thus, the most structural closure is encountered in basin margin reef structures where the overlying sediments are thinner; closure decreases basinward as the overlying sediment thickness increases.

Ells attributed anomalous salt thicknesses and the occurrence of small salt-cored structures to either the result of solution and collapse, or by flowage of salt. The Mackinac Breccia apparently resulted from salt solution and collapse of the overlying sediments, while the salt-cored anticlines of Allegan County appear to be due to salt flowage and subsidence rather than solution and collapse. Both the Mackinac Breccia and the Allegan County salt-cored anticlines occur along the depositional edge of the salt. This is true of the other known salt-related structures in the Michigan Basin. Figure 3 is a cross-section of the salt-cored "pseudoanticline" of the Overisel Field in Allegan County showing the anomalous thickness of A-1 Evaporite salt causing a doming of the overlying sediments.

In 1969, Ells summarized much of the previous structural work done in the Michigan Basin. He discussed the Basin's origin and framework based on his analysis of the Howell anticline of southeastern Michigan. He suggested that structure in this area is controlled by three major fault blocks which have moved relative to one another through time, and that other similar fault blocks may control structure throughout the basin.

Fisher, J.H. (1969) used isopach maps to show that the Michigan Basin began during Cambrian time and evolved into its present size and shape during the Ordovician. The most rapid subsidence occurred during the Salina period. He suggested that the structure of the basin is controlled by a pattern of faulting in the basement rock that changes direction regionally. Such a pattern is evident in the exposed Canadian Shield north of the basin (Figure 4). Examination of Figure 4 reveals that the fault pattern of the Shield is predominantly northwest-southeast with a lesser northeast-southwest trend.

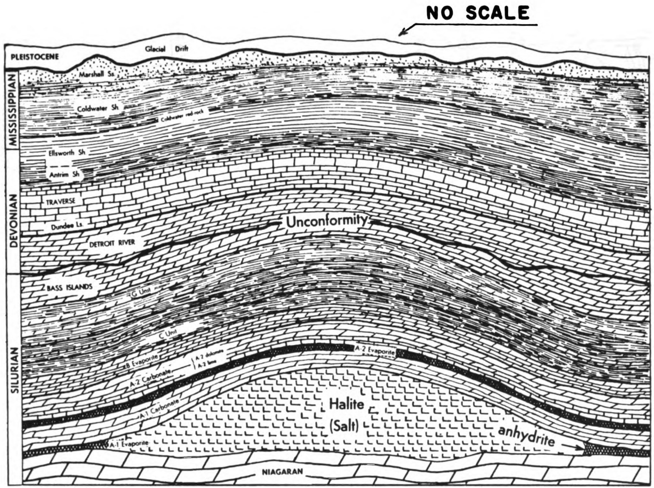



Figure 3. Salt Cored Anticline, Overisel Field, Allegan County. (From Ells, 1967.)

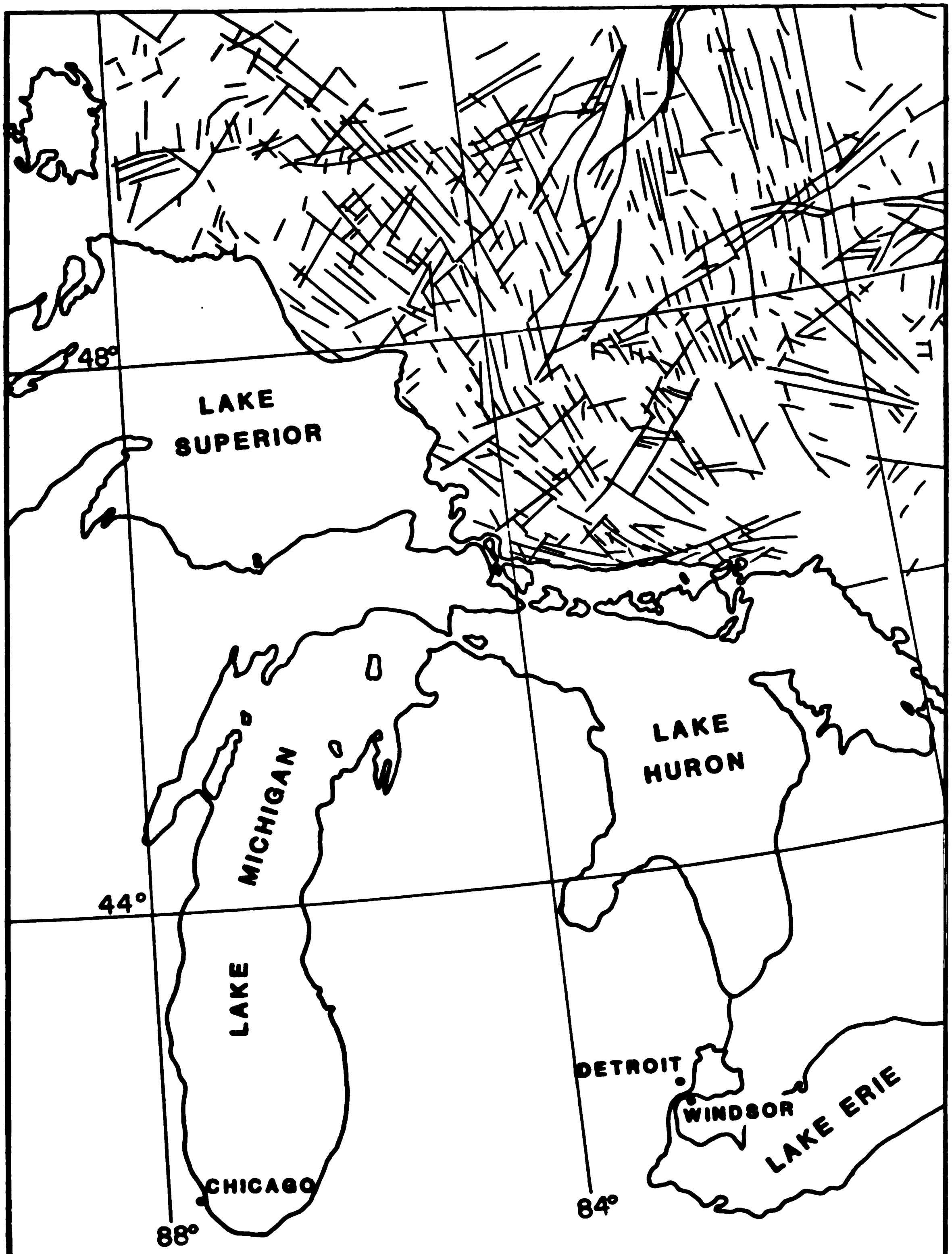



Figure 4. Rectilinear Pattern of Faulting in the Canadian Shield. (Adopted from Tectonic Map of Canada, 1969.)

Hinze and Merritt (1969) and Hinze, Kellogg, and O'Hara (1975) related the Mid-Michigan Gravity Anomaly to a rift zone. Such a rift zone would contain dense mafic rocks (basalt) that would give a positive gravity anomaly.

Haxby, Turcotte, and Bird (1976) suggested the subsidence of the basin was related to a heating event caused by diapiric penetration of the lithosphere by hot asthenospheric mantle rock. This heating transformed the rocks of the lower crust, metastable gabbroic rocks, to a more dense rock, eclogite. The basin then subsided under the load of the eclogite.

Lilienthal (1978) prepared the first extensive series of cross-sections of the Michigan Basin based on geophysical well logs. Picks for formation tops in this study were the same as those used by Lilienthal.

Sleep, Nunn, and Chou (1980) reviewed many of the theories of intracratonic basin formation, particularly as they related to the Michigan Basin. They examined such mechanisms as sediment loading, thermal contraction, phase changes, crustal stretching and loading, and sublithospheric processes. They favored a thermal contraction model to explain intracratonic basin formation, not because of strong positive evidence, but by analogy to subsidence along Atlantic margins and mid-oceanic ridges.

Mesher (1980) studied the structural evolution of southeastern Michigan. Using a series of structure contour and isopach maps, he concluded that an irregular, highly faulted basement played a major role in forming the structures visible in the overlying sediments.

Fisher, J.A. (1981) also studied southeastern Michigan with structure contour and isopach maps. She showed that the faults and folds of this area parallel the Mid-Michigan Gravity Anomaly and are probably controlled by a combination of vertical movements of basement fault blocks and a horizontal shearing force derived from outside the basin. She concluded that structure in the Michigan Basin as a whole is controlled by a rectilinear pattern of faults and fractures in the Precambrian basement. Such a theory is evaluated in this study.

## STRATIGRAPHY

The Michigan Basin contains sediments with an estimated maximum thickness of 15,000 feet. All periods from Cambrian to Pennsylvanian are represented. Jurassic red beds are present in the central portion of the basin, however Permian and Triassic rocks are not known to exist within the basin (Figure 2). The rocks are predominantly carbonates, with lesser amounts of shale, evaporites, and sandstones. The entire Southern Peninsula is covered with glacial drift which averages 200-300 feet thick, however, it reaches over 1000 feet in some areas. What follows is a brief description of those sedimentary units which were mapped or contained within the cross-sections of this study.

The Trenton Formation of Middle Ordovician age is the oldest formation examined in this study. It consists of light brown to brown and grey, fossiliferous, fine to medium crystalline limestone (Cohee, 1945) (Fisher, J.H. et al, 1969). It contains thin beds of carbonaceous shale which increase in number near the base of the formation in the northern part of the basin. Dolomites occur locally and seem to be confined to the axes of folds and faults. The largest oil field in Michigan, the Albion-Scipio field, produces from a dolomitized zone in the Trenton. The formation ranges from 200-475 feet in thickness.

The Middle Silurian age Niagaran group is the oldest formation shown on the cross-section of the Falmouth field. The Niagaran consists of carbonate beds in the upper portion and carbonates, argillaceous carbonates, shales and chert in the lower section (Lilienthal, 1978). Niagaran rocks consist of thick barrier reef and pinnacle reef buildups along the margin of the basin. Basinward, the Niagaran group thins considerably. The pinnacle reefs have been a major exploration target for oil and gas in Michigan. This intense exploration effort is reflected in the dense well control along the reef trend seen in the structure contour maps.

The A-1 Evaporite overlies the Niagaran group and is the lower-most formation of the Salina group of Middle Silurian age. In the center of the basin the A-1 reaches a thickness of 475 feet and is predominantly salt, which grades into anhydrite and pinches out near the reef complex along the margin. It is generally absent over the crests of pinnacle reefs. Its absence over the reef appears to be due to lack of deposition rather than a post-depositional alteration and is therefore not examined here.

Overlying the A-1 Evaporite is the A-1 Carbonate. It is typically a dark colored dolomite in the margin areas and a limestone in the basin center. The unit sometimes contains thin beds of anhydrite near the shelf margins and adjacent to pinnacle reefs. These so-called "rabbit ears" are sometimes indicative of a nearby reef. The A-1 Carbonate is thickest near the basin margins where it reaches 160 feet, and is thinnest in the basin center where it is about 60 feet thick. Oil and gas are produced from a few A-1 Carbonate fields in Michigan. Some are associated with Niagaran pinnacle reefs, others are associated with folds and faults where the unit is dolomite or where A-1 Salt flowage has resulted in doming of the unit. The overlying A-2 Evaporite is the cap rock for such fields.

The A-2 Evaporite is very similar to the A-1 Evaporite. It reaches a thickness of 475 feet in the basin center and consists almost entirely of pure salt. Salt changes to anhydrite near the basin margins and pinches out. The A-2 Evaporite often thins drastically and changes to anhydrite over pinnacle reefs.

The A-2 Carbonate consists of grey to brown limestones and dolomites. Where the unit overlies the reef complex, it is usually dolomite. Near the center of the basin, the A-2 Carbonate reaches a maximum thickness of 150 feet, and may contain some poorly developed shale and anhydrite beds. The unit generally thins to 50-75 feet near the reef complex, except in localized areas, where it may thicken to as much as 275 feet. Oil and gas have been produced from the A-2 Carbonate, especially in southwestern Michigan where the unit is dolomite.

The B-Unit overlies the A-2 Carbonate and is of late Middle Silurian age. It consists predominantly of salt, however in the upper portion of the unit, interbedded shales, anhydrite, and dolomite also occur. The unit is 475 feet thick in the center of the basin, but thins to

50 feet along the basin margins as the lower salt pinches out. In southeastern Michigan, the distribution of the B-Unit is irregular, probably as a result of solution (Fisher, J.A. 1981). The B-Unit is overlain by the early Late Silurian age C-Unit.

The C-Unit is a greenish-grey dolomitic shale noted for its variation in thickness (50-200 feet) and extremely widespread nature. Irregularities in its thickness have been related to the solution of the underlying B-Unit by Fisher,J.A. (1981).

In contrast to the underlying C-Unit, the D-Evaporite has the smallest areal extent of all the evaporite units of the basin. It is found only in the basin interior and averages about 40 feet in thickness (Lilienthal, 1978). It consists of salt and is usually split by a thin dolomite bed.

The D-Evaporite is overlain by the E-Unit which is composed of a series of grey, greenish-grey and red shales interbedded with thin dolomites (Lilienthal, 1978). In the western portion of the basin the unit contains a porous dolomite near its base which has produced some oil. The E-Unit has a fairly constant thickness of 90-120 feet.

The F-Evaporite overlies the E-Unit and shows a variation in thickness of 0-970 feet within the basin.

It consists of a succession of salt, thin anhydritic shale, dolomitic shale and dolomite beds. The shales are generally grey, reddish or greenish-grey, while the dolomites are grey or brown. Thinning is due mostly to depositional thinning of the salt beds, however it has been completely removed by erosion in parts of the basin (Ells, 1967).

The G-Unit is the uppermost formation of the Salina Group. It consists of a grey dolomitic shale in the basin center which grades into a thinner dolomite at the edges of the basin. Overlying the Salina Group is the Bass Islands Group of late Late Silurian age.

The Bass Islands Group is composed of the Raisin River and Put-In-Bay Dolomites, but these formations are rarely separated in the subsurface. The rocks consist of typically dense buff dolomites which are sometimes oolitic in the upper portion. The lower portion is more argillaceous, and in the basin interior contains thin anhydrites and salt beds (Lilienthal, 1978). In the northern part of the basin, the Bass Islands rocks are 350 feet thick and thicken to 500 feet in the center of the basin.

The Silurian and Devonian rocks of the Michigan Basin are separated by an unconformity in most areas of Michigan. The Bois Blanc Formation is the basal formation of the Devonian. It is a cherty carbonate which is interbedded and gradational with the Sylvania sandstones or the Amherstburg, where the Sylvania is absent (Lilienthal, 1978). The central basin contains 800 feet of Bois Blanc which thins toward the margins of the basin. To the northwest, it thins to 300 feet in Leelenau County, and to the southeast it disappears completely in Monroe County. The Bois Blanc forms much of the well-known Mackinac Breccia which has been discussed previously (Landes et al, 1945).

Rocks of the Detroit River Group overlie the Bois Blanc Formation. The group is composed of the Lucas, Amherstburg, and Sylvania Formations. The Sylvania Sandstone is the basal formation of the Detroit River Group and is composed of well-rounded and sorted, fine to medium grained sandstone, with lesser amounts of silt, chert, and carbonate (Landes, 1951; Lilienthal, 1978). Not found everywhere throughout the basin, the Sylvania is located in northwestern, central and southeastern Michigan (Landes, 1951). The Sylvania reaches a maximum thickness of 300 feet in the central basin, and pinches out in all directions.

The Amherstburg Formation lies stratigraphically above the Sylvania Formation and is present everywhere in the Southern Peninsula except in the southeast and southwest corners of the state, where it has been eroded. It consists of mostly limestone in the north and east, but is nearly all dolomite in the western and southern portions of the basin. The Amherstburg has been termed "The Black Lime" because of its very dark brown to black color. The thin Filer sandstone is contained within the Amherstburg in western Michigan. The Amherstburg Formation produces hydrocarbons in Michigan and is the productive formation of the Enterprise field which is examined in this study.

The Lucas Formation comprises the uppermost rocks of the Detroit River Group. The formation consists of beds of dolomite, anhydrite, salt, limestone, and sandstone. It varies in thickness from 20 feet in southwestern Michigan to over 1000 feet in the central basin area. In the central basin area, much of the section is composed of salt and anhydrite, making the Lucas a candidate for possible salt solution or flowage. Such a possibility is examined in this study.

Salt in the Lucas is usually confined to the upper portion of the evaporite sequence in the central basin area, where it reaches 400 feet in thickness. Anhydrite, like salt, is more prominent in the central basin area, but it extends further marginward than does the salt. The greatest abundance of anhydrite is found in the lower half of the evaporite sequence, particularly in the zone termed "the massive anhydrite". Lilienthal (1978) made no attempt to correlate the individual salt beds of the Lucas. In this study, the individual salt beds were correlated in the cross-sections of Falmouth and Enterprise fields in order to analyze whether thickening or thinning of salt beds occurs across these fields.

A group of argillaceous dolomite beds separated by anhydrites is present below the Detroit River Salts in northern and central Michigan and is termed DR-2. The unit is correlated together with the "massive anhydrite" as the unnamed unit directly overlying the Richfield in the cross-sections of this study.

The Richfield member of the Lucas Formation is a dolomite which contains several porosity zones which produce hydrocarbons. These porosity zones seem to be best developed in northern Michigan (Lilienthal, 1978). In central and western Michigan, the Richfield contains beds of sandstone which are sometimes called the Freer Sandstone.

Besides the Richfield member of the Lucas Formation, several other zones produce oil and/or gas, including the "sour zone" and the "Reed City" zone (if the Reed City zone is placed in the Detroit River Group). Additionally, the Lucas has produced significant quantities of salt and brine, making this formation a valuable economic resource.

The Dundee Limestone is the most prolific producer of oil and gas in the Michigan Basin. This Middle Devonian formation consists predominately of brownish-grey, fine to coarsely crystalline limestone. Dolomite is present with limestone in the central basin area, and the Dundee is entirely dolomite in the west and south (Lilienthal, 1978). The formation varies considerably in thickness, from less than 40 to more than 475 feet. It is present everywhere except in the extreme southwestern portion of the state. For this study, the Reed City zone is included in the Dundee rather than the Detroit River group.

The Dundee is overlain by rocks of the Traverse group which consists of the Traverse Formation, Traverse Limestone, and Bell Shale. The Traverse Limestone is predominantly shale in eastern Michigan, but grades progressively to nearly a pure limestone or dolomite in western Michigan. Small reefs have been found in Alpena County quarries and others probably exist in the subsurface in other parts of the state (Lilienthal, 1978). In fact, some Traverse Limestone oil fields seem to produce from small bioherms. Most Traverse fields are located in the southwest quandrant of the state where they have produced a significant portion of Michigan's oil and gas.

The youngest formation examined in this study is the Early Mississippian Sunbury Shale. The Sunbury is a brown to dark grey or black pyritic shale. It ranges in thickness from 0 feet in western Michigan, where it pinches out or grades into the Ellsworth Shale, to 120 to 140 feet in the eastern portions of the state (Lilienthal, 1978). The Sunbury is locally thick in the southern portion of Newaygo County (Newcombe, 1933).

## STRUCTURE

The Michigan Basin has been variously classified in the past, but is probably best described as a shallow, intracratonic basin. It is similar in shape and magnitude to the Illinois and Williston Basins; it is nearly circular, encompasses approximately 122,000 square miles, and contains a maximum thickness of about 15,000 feet of gently dipping strata.

Figure 5 shows the shape of the basin and its relationship to the surrounding positive structures. The basin includes the entire Southern Peninsula, the eastern part of the Northern Peninsula, eastern Wisconsin, northeastern Illinois, northern Indiana, northwestern Ohio, and western Ontario. It is surrounded by the Canadian Shield to the north, the Algonquin Arch to the east, the Findlay Arch to the southeast, the Kankakee

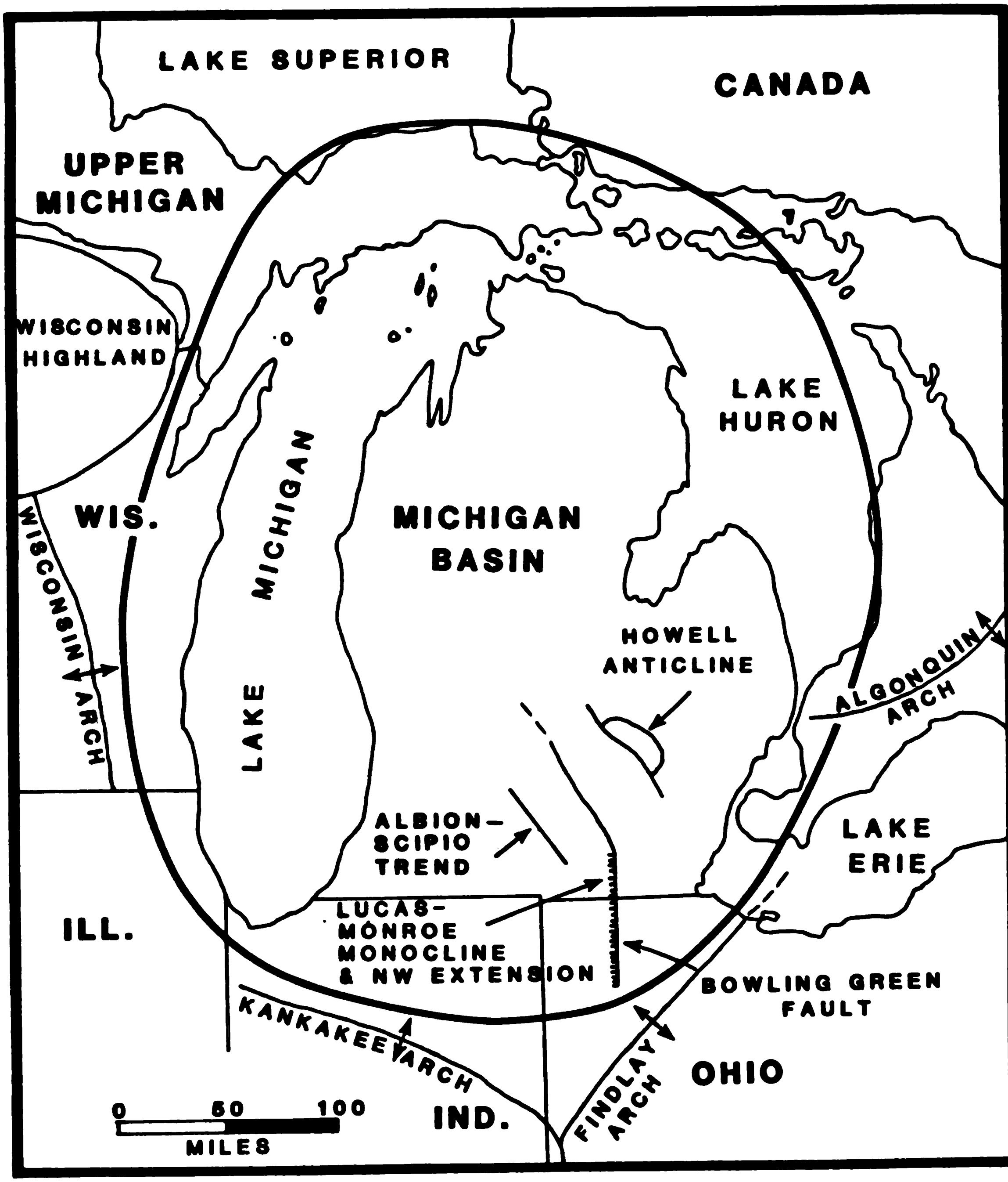



Figure 5. Michigan Basin and Surrounding Structural Features.

Arch to the southwest, and the Wisconsin Arch and Dome to the west.

The nearly circular shape of the basin shows a slight northwest to southeast elongation. Dominant structural trends of the basin parallel the elongation trend as shown by the Dundee trends of Figure 6. The Mid-Michigan Gravity Anomaly also transects the basin from northwest to southeast (Figures 7 and 8). Associated with this gravity high is a magnetic anomaly as shown in Figure 9.

Sedimentary rocks of the area dip toward the center of the basin which lies just west of Saginaw Bay. Dips average about 25 to 60 feet per mile (Ells, 1969), but folding, faulting, solution and removal of salt layers, erosion, and other factors greatly modify the uniformity of the rock sequence. It is these first three factors which are examined in the data analysis portion of this study.

Before analyzing the data, however, it is worthwhile to review some of the proposed models of basin subsidence. Some of the factors to be considered in basin subsidence are: the location of the basin within the continental plate, the time and amount of subsidence, the size and shape of the basin, the structures around and within it, and its relation to other basins on the continental plate.

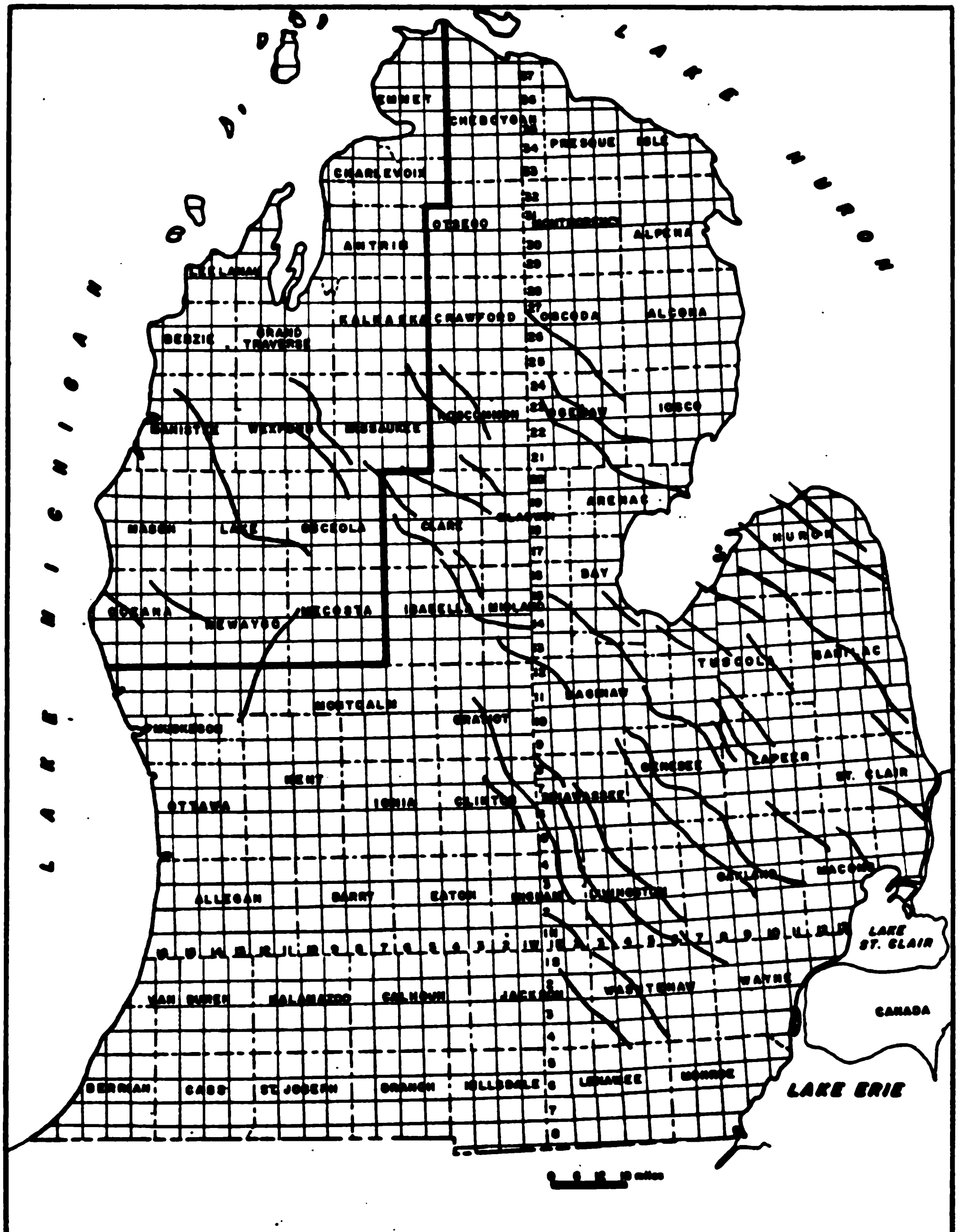



Figure 6. Structural Trends of the Dundee Formation.

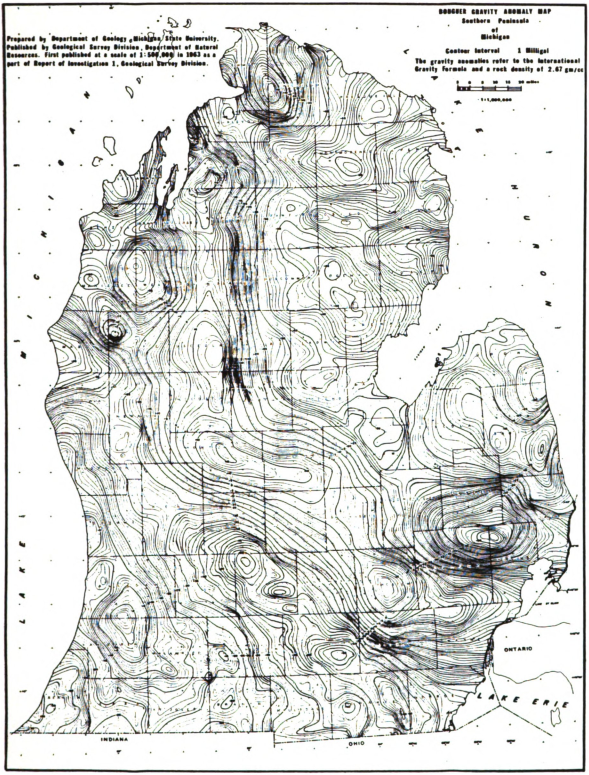



Figure 7. Bouguer Gravity Anomaly Map.

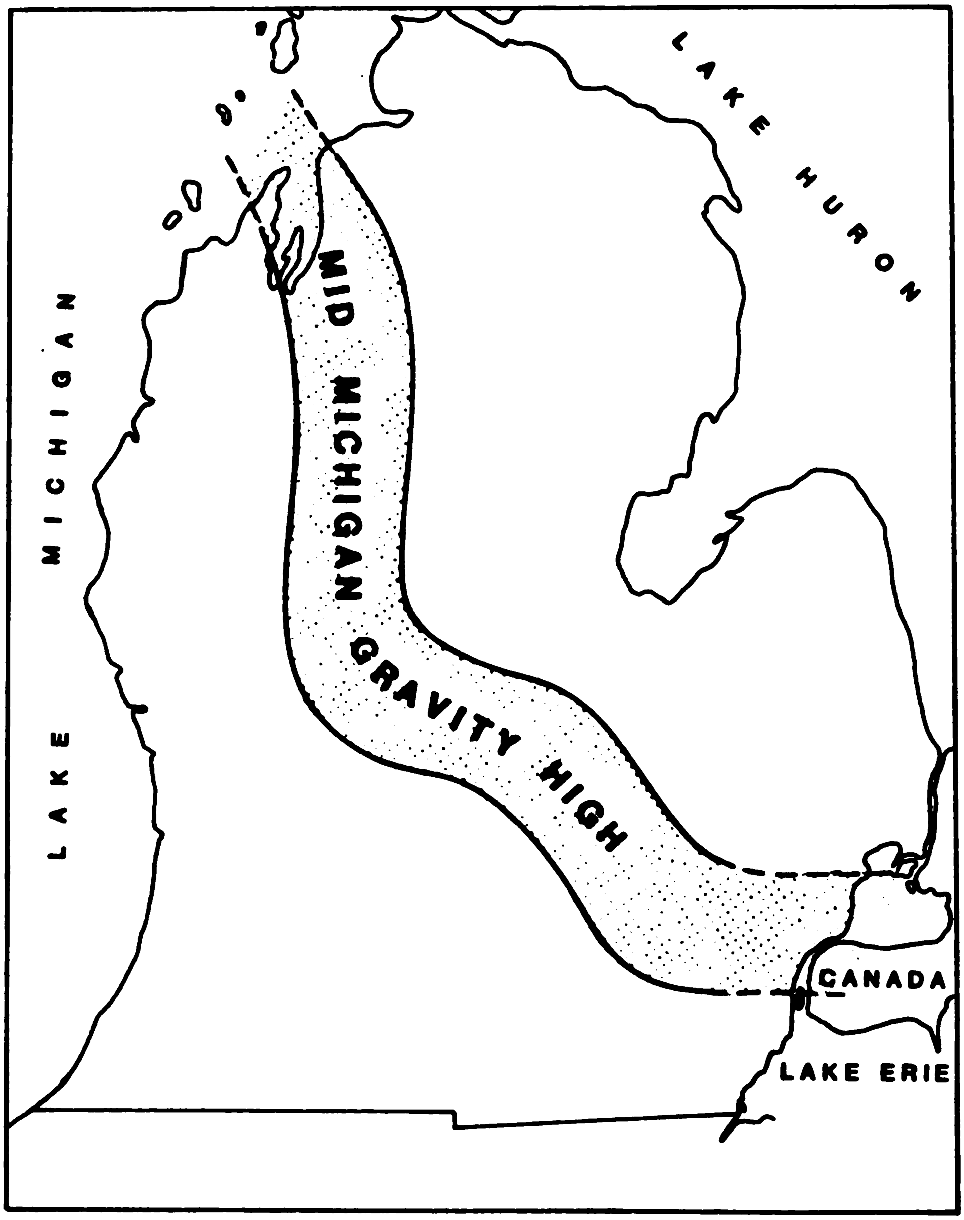



Figure 8. Schematic Diagram of Mid-Michigan Gravity High.

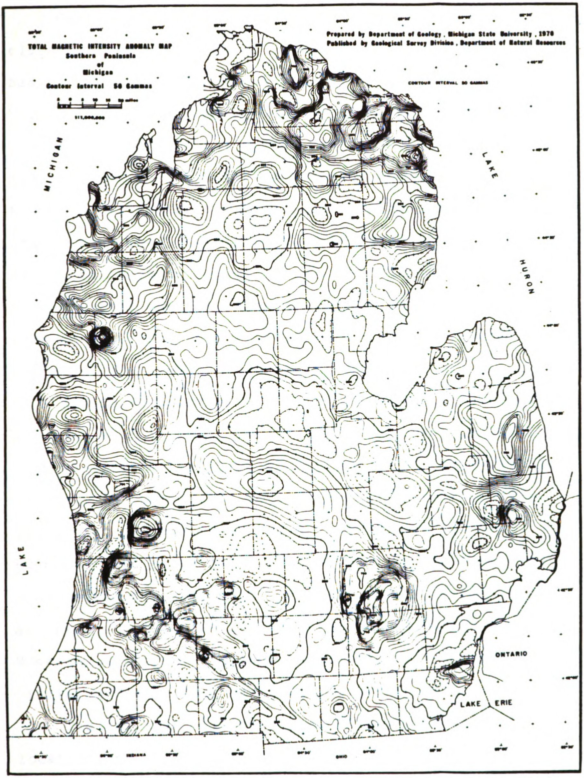



Figure 9. Total Magnetic Intensity Anomaly Map.

Basins within the continental crust have been classified by Sleep, et al (1980) into (a) Atlantic marginal basins, such as the eastern continental shelf of the United States, (b) fault controlled or rift basins such as the Triassic grabens of the eastern United States, and (c) interior platform (intracratonic) basins such as the Michigan, Illinois, and Williston Basins. Fault controlled basins have been clearly related to horizontal stresses in the lithosphere (Sleep, et al, 1980). Subsidence of Atlantic-type margins seems adequately explained in relation to plate tectonics. However, no plate tectonic explanation of interior basins is obvious.

Widespread similarity of the geology of the craton requires that a theory for intracratonic basin subsidence must be examined in light of all the major intracratonic basins. In much of his work, Sloss (1963, 1966, 1972, 1976) examined the synchrony of sedimentary-tectonic events on the North American platform. He related events recorded in the sediments over large areas of the craton and even extended the similarities to the European and Russian platforms. Indeed, the Michigan, Illinois, and Williston Basins show great similarity.

The Michigan, Illinois, and Williston Basins are located just south of the Canadian Shield. Each basin began subsiding in its present size and shape during the

Ordovician, ceased to subside in Pennsylvanian time, and reached a maximum depth of about 15,000 to 16,000 feet. All three basins are of similar size and are roughly circular with a slight northwest-southeast elongation. Dominant structural trends in the basins are also northwest-southeast, for example: the Howell Anticline and Albion-Scipio fields of Michigan, the La Salle Anticline of Illinois, and the Cedar Creek Anticline of the Williston Basin. Such similarities in the evolution of these basins caused Sleep and Sloss (1978) to suggest that some major influence must have affected these basins in a concerted sequence of subsidence and deformation. No mechanism for such influence over all three basins is known. Further, no theory has adequately explained the subsidence of any one of the three basins. What follows is a brief summary of the major theories on the evolution of the Michigan Basin.

Most of the early theories regarding the subsidence of the basin suggest that the weight of the sediments eroded from a nearby mountain range accumulated in a topographic low and created sufficient force to downwarp the basin. Pirtle (1932) and Lockett (1947) and others postulated an ancient mountain range along the Wisconsin Arch and Dome and Kankakee Arch, which supplied the early basin sediments.

This theory fails to explain the presence of the Michigan Basin both geologically and geophysically. Geologically, the basin does not contain a thick sequence of conglomerates and arkose that would be expected if nearby mountains had been eroded. Further, it is unlikely that the early clastic sediments of the basin have a western provenance. Geophysically, the theory fails because sediment weight alone does not appear to be a sufficient driving force to cause the entire subsidence of the Michigan Basin (Sleep, et al, 1980).

Sleep, et al (1980) show that sediment load does greatly amplify subsidence. They state that if an initial depression of one kilometer was present, the current sediment thickness of the basin could have caused the observed subsidence.

Both Pirtle and Lockett proposed that folds within the basin are orogenic and that the basin is actually a geosyncline bordering the ancient Wisconsin mountains. There are three problems with this proposed model for the folded structures of the basin. First, orogenic folds are asymmetric away from the major deforming force. Michigan Basin folds show no pattern of eastward asymmetry (Fisher, J.A. 1981). Secondly, tectonic basins such as the Powder River Basin contain intense orogenic folds around the margin of the basin, but are virtually undeformed near their centers. The Michigan Basin shows the converse of this, with the structural trends being best developed in the central basin area. Finally, there is no known Paleozoic orogenic force from the northeast or southwest that could produce the observed northwest-southeast structural trends of the basin.

Hinze (1963), based on gravity surveys, postulated the addition of dense mafic rocks to the Precambrian basement which casued subsidence to occur to restore isostatic equilibrium. Hinze, et al (1975) refined the theory and suggested that the addition of mafic rocks (basalt) occurred along a rift zone. They based this on the similarity between the Mid-Michigan Gravity Anomaly, the Mid-continent Gravity High, and the outcropping Keweenawan rift zone of the Lake Superior Basin.

This theory has two problems: the proposed Keweenawan rift is apparently too old, and the pattern of basin subsidence is too irregular. If the basin subsided because of the weight of the Keweenawan basalts (1.05-1.15 billion years ago), subsidence was delayed until Late Cambrian or Early Ordovician time (500-600 million years ago). This seems too long a period between addition of weight and initiation of subsidence. Once subsidence started, it is likely that the basin would have subsided in a gradual, fairly constant manner. However, the

Michigan Basin appears to have been subsided and uplifted in a highly irregular pattern throughout the Paleozoic.

It is noteworthy that although there are no basalts known which would support the rift theory, the McClure-Sparks, et al #1 well did encounter more than 5000 feet of Precambrian redbeds. Fowler and Kuenzie (1978) suggest these redbeds represent a shallow marine turbidite sequence deposited within a failed Keweenawan rift valley.

Fisher, J.H. (1969) suggested the dominant structural trends of the basin are controlled by a faulting pattern in the Precambrian basement. This theory is supported by numerous factors; structural trends of the basin parallel the proposed rift; trends are similar to features and faults of the Precambrian Canadian Shield; extrapolation from Ontario and Ohio where deep well control shows basement faulting; and structures such as the Howell Anticline and Albion-Scipio field which appear to be fault controlled.

Haxby, et al (1976) proposed that hot mantle diapirs penetrated the crust and altered meta-stable gabbro to eclogite. With cooling, the eclogite became increasingly dense and caused the area to subside. Like the rift origin of the basin model, this phase change model suffers because the expected regular uninterrupted pattern of subsidence is not exhibited in Michigan. Further, no conclusive evidence of high heat flow has been found in the basin. However, Moyer (1982) suggested that a higher thermal gradient or thicker sediment column was once present based on his analysis of the thermal alteration of spores and vitrinite reflectance.

Mescher (1980) and Fisher, J.A. (1981) concluded that structure in southeastern Michigan is controlled by faults in the basement. They suggested from structure contour and isopach maps that vertical movement of fault blocks and horizontal shearing force on these blocks derived from tectonic events outside the basin controlled structures in southeastern Michigan and probably throughout the entire basin. It is this thesis that is tested in the following data analysis section.

## DATA ANALYSIS

### Regional Structure Maps-General

Five regional structure contour maps were constructed using the tops of the Sunbury, Traverse Limestone, Dundee, A-2 Carbonate, and Trenton Formations as datum. As stated earlier, control for the Sunbury, Traverse and Dundee is good throughout most of the study area, except where these formations are missing. Control for the A-2 Carbonate is good along the northern Silurian reef trend, but poor everywhere else in the study area. Control on the Trenton is extremely limited throughout the area. The contour interval for the Sunbury, Traverse, and Dundee Formations is 50 feet, and for the A-2 Carbonate and Trenton Formations, 100 feet.

The dominant features seen on the structure contour maps are the large areas of nosing which interrupt the otherwise smooth arc of the contours, and the anticlinal structures which show closure. Where control was inadequate to shape the contours of a closed structure, the contours were shaped according to the map of Michigan Oil and Gas Fields (Figure 10). No faults are directly evident at the scale and contour intervals used in this study.

Sunbury Structure Map (Plate 1)

Although the Sunbury is the youngest formation to be mapped and thus expected to have the best control, the control is not as great as the older Traverse Limestone and Dundee Formations because the Sunbury is absent in the western and northern portions of the study area. Sunbury control also suffers because many of the driller's logs do not report the Sunbury top, while the other formation tops are more commonly reported.

Deflections of contour lines to form a nosing pattern are the prominent feature on the Sunbury structure contour

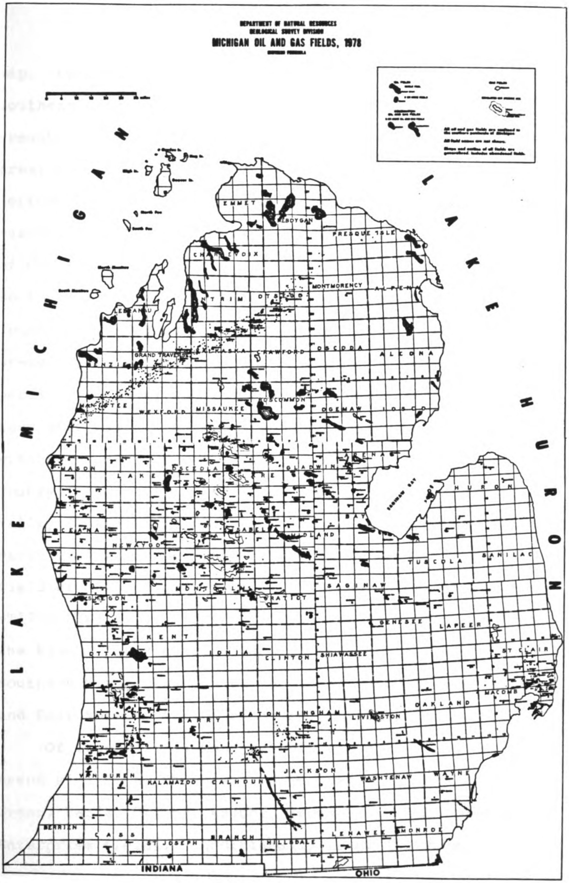



Figure 10. Michigan Oil and Gas Fields.

map. For the most part, these "noses" trend northwest-southeast, and are associated with similar trending troughs. Beginning in the southern portion of the study area, the most prominent "noses" are located in: the northwestern portion of Newaygo County extending north-westward into Oceana County; the southeastern portion of Osceola County extending to northeastern Lake County; south-central Missaukee County to southeastern Wexford County; and northwestern Missaukee County to southeastern Grand Traverse County. Many of these "noses" have troughs parallel to them, and together, these noses and troughs have many oil and/or gas producing anticlines associated with them. For example: the Huber field of Newaygo County (T14N, R14W), Pentwater (T16N, R17W) and Crystal Valley (T16N, R16W) fields of Oceana County, Green and Paris fields of Mecosta County (T16N, R10W), the Sauble field of Lake County (T19N, R14W), the Orient, North Fork (T17N, R7W) and Evart (T18N, R8W) fields of Osceola County, the Riverside, Reeder, Falmouth, and Prosper fields of southern Missaukee County, and Enterprise, Cannon Creek and East Norwich fields of northern Missaukee County.

Of these fields many exhibit a northwest-southeast trend similar to the nose-trough trend: Huber, Pentwater, Green, Paris, Orient, Reeder, Prosper, Cannon Creek and Enterprise fields. Additionally, many fields not associated with the nose-trough features show the same northwest-southeast or north-south trend. These fields include Goodwell and East Goodwell (T14N, R11W), Woodville (T15N, R11W), Hardy Dam and Reynolds (T13N, R10W), Austin (T14N, R9W) and Reed City (T18N, R10W).

Traverse Limestone Structure Map (Plate 2)

The Traverse Limestone Formation structure contour map generally mimics the Sunbury map. However, it contains some important differences. Most obvious is the better control of the Traverse in the western and northern portions of the study area. The Traverse is present everywhere except for Emmet County, where its top is eroded. Better control also allows more definintion of the nosing and anticlinal features of the area.

Apart from differences in control between the Sunbury and Traverse maps, the Traverse map shows more closure on the anticlinal fields in almost every instance. For example, the Huber field of Newaygo County (T14N, R14W) shows 150 feet of closure on the Traverse map, but only 50 feet of closure on the Sunbury map. Other fields show similar increases in closure with depth: Woodville (T15N, R11W), Goodwell (T14N, R11W), Reed City (T18N, R10W), and Evart (T18N, R8W) fields for example.

Another difference between the Traverse and Sunbury maps is in the orientation of the nosing trends. The Traverse trends show a very slight counterclockwise rotation from their position on the Sunbury map.

Dundee Structure Map (Plate 3)

The Dundee Formation structure contour map closely resembles the Traverse map. It shows the same nosing pattern and anticlinal features as the Traverse map but gives more definition to the features. In most cases, mapped closure on the Dundee is the same as in the Traverse. However, several fields show closure at the Dundee level which did not show closure at the Traverse level; for example the Peacock field (T19N, R13W) of Lake County and the Dayton field (T13N, R14W) of Newaygo County.

A-2 Carbonate Structure Map (Plate 4)

Control for the A-2 Carbonate map is good along the reef trend but is poor everywhere else in the study area. This lack of control is evident in the gentle sweeping nature of the contours and the numerous dashed contour lines in the large areas where no wells penetrate the A-2 Carbonate top. Because of poor well control, a 100 foot contour interval was used in this map. Despite the poor control, the A-2 Carbonate map still exhibits many of the broad trends shown in the shallower formations. For example, the nosing features seen on the Sunbury, Traverse, and Dundee maps in Mason and Lake Counties, and in Missaukee County, are visible on the A-2 Carbonate map. The only anticlinal structure mapped on the A-2 Carbonate is the Falmouth field (T22N, R7W) of Missaukee County where eight deep wells offset the Dart-Edwards 7-36 Prairie du Chien discovery well and delineate the closure. The Falmouth field shows 100 feet of closure at the A-2 Carbonate level as opposed to the 50 feet of closure seen at the Dundee, Traverse and Sunbury levels. The areal extent of this closure however, is smaller than at the shallower depths.

Trenton Structure Map (Plate 5)

The Trenton Formation structure contour map contains the least control of the five maps, and therefore exhibits the least detail and the most potential error. Like the A-2 Carbonate map, the Trenton map consists mostly of gently arcing dashed contours. The nosing features in Oceana County and in Missaukee County persist in the Trenton map despite the lack of control. Structural closure is evident in the Falmouth field of Missaukee County and in the Crystal Valley field of Oceana County (T16N, R16W).

Detailed Structure Maps - General

In order to further investigate the subtle nosing trends in Oceana and Missaukee Counties, and the structure of the Falmouth field, detailed structure contour maps were constructed in Missaukee and Oceana Counties. Both of these counties contain some of the best well control in the study area, particularly at the Trenton Formation level. Expanded well control was used in these county maps and a contour interval of 20 feet was utilized in order to better delineate the structures in these areas.

Missaukee County - Dundee Structure Map (Plate 6)

The detailed Dundee structure contour map of Missaukee County better defines the structural features seen on the regional Dundee map. The nosing features of the southwestern and northwestern portions of the county seen on the regional maps are also evident in this map. The southwestern nose trends directly into the Riverside oil and gas fields. Similarly, the northwestern nose trends into the Cannon Creek field and leads directly toward a northwest-southeast trending area of very closely spaced contours. The rate of dip in this area based on the contour map is approximately 70 to 90 feet per mile as compared to 30 to 40 feet per mile in most other areas of the county. This northwest trending area of high dip runs between the northwest-southeast trending Enterprise and Falmouth fields. It is interesting to note that the trend of the streams in this county is also northwest-southeast; for example the West Branch Muskegon River system flows from northwest to southeast, as do the Haymarsh Creek, Butterfield Creek, Mosquito Creek, and Clam River systems. Hopkins and Ham Creeks flow northwest into the Manistee River.

The additional detail on this map compared to the regional map shows that the Riverside field is actually composed of several distinct highs instead of a single high as shown in the regional map. This detail also defines a definite northwest-southeast trend in the Falmouth field that is not clearly seen in the regional maps.

<u>Falmouth Field - Trenton Structure Map (Figure 11)</u>

Figure 11 is a structure contour map on the Trenton Formation in the Falmouth field area of Missaukee County. Deep well control in Missaukee County is limited to the Falmouth field area and therefore only that portion of the county is mapped at the detailed 20 foot contour interval. Although this limited well control restricts the comparison between the shallow and deep structure in the county, one difference is strikingly clear; the

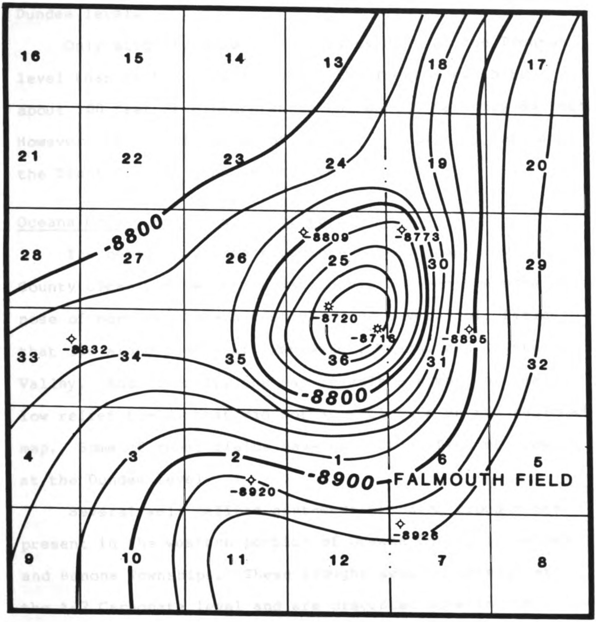



Figure 11. Trenton Formation Structure Map of Falmouth Field Area, Missaukee County. (Scale: Approximately 1"= 1 Mile)

structural trend of the field is northeast-southwest as opposed to the northwest-southeast trend seen at the Dundee level.

Only slightly more closure is evident at the Trenton level than at the Dundee level. The Trenton exhibits about 100 feet of closure while the Dundee has only 80 feet. However, the areal extent of closure is slightly less at the Trenton level than at the Dundee level.

Oceana County - Dundee Structure Map (Plate 7)

The detailed Dundee structure contour map of Oceana County clearly shows the relationship between the prominent nose of northern Oceana County to the several oil fields that lie along the nose: Pentwater, Weare, and Crystal Valley. Additionally, the map reveals a number of small low relief fields that did not show closure on the regional map. Some of these fields have only 20-30 feet of closure at the Dundee level.

Several well defined east-west trending troughs are present in the western portion of Oceana County in Golden and Benona Townships. These troughs seem to persist at the A-2 Carbonate level and are discussed more in the section on the A-2 Carbonate.

As in the Missaukee County map, the dominant direction of stream alignment is northwest-southeast. The Pentwater

River and its south branch flow to the northwest into Lake Michigan, as does the Pere Marquette River of northeastern Oceana County. Newman Creek, Sand Creek and Carlton Creek, as well as a portion of the North Branch of the White River flow from northwest to southeast. It should be noted, however, than many streams in both Oceana and Missaukee Counties trend in directions other than northwest-southeast.

Oceana County - A-2 Carbonate Structure Map (Plate 8)

Well control for the A-2 Carbonate in Oceana County is limited to the western portion of the county. Therefore, the eastern half of the map was contoured with dashed lines to represent the uncertainty of the contours.

As mentioned before, two troughs trending east-west are evident in the western portion of Oceana County at both the Dundee and A-2 Carbonate levels. A-2 Carbonate well control for the trough in southern Benona Township is good and the contours generally mimic those of the Dundee map. Although A-2 Carbonate well control for the trough of southern Pentwater Township is not as good as the southern trough and therefore cannot be as well defined, the trough is undoubtedly present.

Associated with the trough of Benona Township is a sharply defined isolated low. This low is confirmed by two wells, both of which produce hydrocarbons. Hydrocarbon production is from Niagaran pinnacle reefs which underlie the A-2 Carbonate. Comparison of the nearby wells with the low producing wells reveals that the A-1 and A-2 Evaporite units overlying the reef wells are very thin (49 and 62 feet for the A-1 Evaporite, 123 and 235 feet for the A-2 Evaporite) compared to the nearby non-reef wells (for example 205 feet and 305 feet for the A-1 and A-2 Evaporites, respectively). Thus, the A-2 Carbonate top in the wells with thin evaporite units is very low.

Depositional thinning of evaporites over pinnacle reefs is typical in the Michigan Basin. Therefore, the troughs in Pentwater and Benona Townships may be the result of other reefs with thin overlying evaporite units and resultingly low A-2 Carbonate tops in these troughs. Other explanations for such troughs are faulting, salt solution, and of course, gentle folding of the strata resulting in a structural syncline. These possibilities are examined in the section on interpretation and conclusions.

## Cross-Section Analysis-General

Six stratigraphic cross-sections were constructed in order to determine the degree to which salt thicknesses vary near structure. The cross-sections were constructed using no horizontal scale and vertical scales of one inch equals 200 feet and one inch equals 40 feet. When a well in a cross-section did not penetrate the entire column of interest, correlations were projected across the imaginary well bore which is represented by dashed lines. The cross-sections reveal that the major variation in salt thickness is the general basinward thickening of the salt units. However, there are some interesting exceptions to this general trend which are examined in the following sections.

## East-West Falmouth Field Cross-Section: Dundee to Niagaran (Plate 9)

The East-West Falmouth field cross-section shows a constant thickness for the Detroit River Salts unit as a whole from the west across the crest of the field to well five where the unit then thickens eastward to well ten by 30 feet. The individual salts of the Detroit River Salts unit are examined in the detailed Falmouth Field cross-sections.

The F-Unit gradually thickens basinward across the field by 46 feet, while the D and B Units remain a constant thickness throughout the cross-section. The A-2 Evaporite thins 40 feet from well one to well eight (about 4 miles), and then begins to thicken toward well nine. The A-1 Evaporite also thins across the field, however the maximum thinning occurs between wells one and four (about 3 miles). The unit thins 46 feet from well one to well four, then thickens basinward.

North-South Falmouth Field Cross-Section: Dundee to Niagaran (Plate 10)

The F,D, and B Units and the A-2 Evaporite show essentially constant thickness across the Falmouth field from north to south. The Detroit River Salts unit varies slightly across the field, thinning 13 feet from well one to well five, then thickening towards well eight. The A-1 Evaporite thickens gradually by 45 feet across the section from well one to eight.

East-West Falmouth Field Cross-Section: Dundee to Base of Detroit River Salts (Plate 11)

Because of the complex stratigraphy of the Detroit River Salts unit, it was decided that detailed cross-sections of this unit were necessary in order to determine whether or not salt thicknesses vary significantly across structure. As seen in the previous cross-sections, the Detroit River Salts unit remains a nearly constant thickness across the Falmouth field. However, significant thickening or thinning could occur in the salt units and be unnoticed because the overlying anhydrites and carbonates were correspondingly thinning or thickening.

In the East-West Falmouth field cross-section, the entire Detroit River Salts unit varies by only 25 feet, about 3 percent of the unit thickness. Of the four wells used in this cross-section, well two at the crest of the structure, has the thinnest Detroit River Salts unit (651 feet), while the most basinward well, well four, has the thickest (676 feet). Well two shows 373 feet of salt and 278 feet of anhydrite and carbonate. Well four shows 419 feet of salt and only 257 feet of anhydrite and carbonate. Thus, the off-structure well four has 46 feet more salt and 21 feet less anhydrite and carbonate than well two at the crest of the Falmouth anticline.

Well one has 652 feet of the Detoit River Salts unit. This off-structure well shows the opposite trend of well four by having 352 feet of salt (21 feet less than the well at the crest of the structure) and 300 feet of anhydrite and carbonate (22 feet more than at the crest).

The trend across the field from west to east is apparently one of increasing salt thicknesses and decreasing anhydrite and carbonate thicknesses. For example, the first anhydrite at the top of the Detroit River Salts unit pinches out from west to east and the two salt beds it separates in well one, merge and become one large salt bed at well four. Similar stratigraphic changes occur in other parts of the column across the field. However, no drastic variation in the thickness of a particular bed occurs across the field.

North-South Falmouth Field Cross-Section: Dundee to Base of Detroit River Salts (Plate 12)

The North-South Falmouth field cross-section shows little variation in the Detroit River Salts unit thickness. Well one has a total unit thickness of 650 feet, while wells two and three have unit thicknesses of 651 feet and 645 feet respectively. Total salt thicknesses for wells one, two and three are, 369 feet, 373 feet and 359 feet respectively; anhydrite and carbonate thicknesses are, 281 feet, 278 feet, and 286 feet respectively. As in the east-west cross-section, the north-south cross-section shows that no significant thickening or thinning of a salt bed is offset by a corresponding thinning or thickening of an overlying anhydrite or carbonate bed.

<u>East-West Enterprise Field Cross-Section: Dundee to Base of Detroit River Salts (Plate 13)</u>

The Detroit River Salts unit thins 11 feet from well one to well three in the east-west Enterprise field cross-section. The total salt thickness in wells one, two and three is 461 feet, 458 feet and 449 feet, respectively. Anhydrite and dolomite thicknesses are 299 feet, 294 feet and 300 feet for wells one, two, and three respectively.

It is interesting to note that the trend across the field from west to east is a marginward thinning of the Detroit River Salts unit. Although the unit is nearly 100 feet thicker than at Falmouth field, the maximum unit thickness is apparently located between the two fields and begins to thin at the Enterprise location. This is best illustrated by the first salt at the bottom of the Enterprise wells. This salt is 52 feet thick in well one, but only 23 feet thick in well three. This thin salt is nearly compensated for by a gradual thickening of some of the overlying units in well three compared to wells one and two. Elsewhere in the stratigraphic columns of the wells in the cross-section, no significant variation in bed thickness occurs.

North-South Enterprise Field Cross-Section: Dundee to Base Detroit River Salts (Plate 14)

The Detroit River Salts unit thickness varies only 6 feet across the north-south cross-section. Similarly, the total salt thickness in these wells varies little across the field. Examination of the cross-section reveals that no significant change in individual bed thicknesses occurs along the line of the north-south cross-section.

## CONCLUSIONS AND PETROLEUM POTENTIAL

Based on the analysis of the nine structure contour maps, and six cross-sections prepared for this study, several broad conclusions can be made concerning the structure and alteration of structure in the study area. Additionally, several important aspects of the petroleum potential of the study area and the basin as a whole can be addressed.

Structure in the study area is dominated by a northwest-southeast trend, with a less prominent northeast-southwest trend also detectable. The nosing features described earlier exhibit a strong northwest-southeast trend. Other anticlinal features show a north-south trend such as the Woodville, Cannon Creek and Reed City fields. Many workers have noted similar trends throughout the basin. Mescher (1980) and Fisher, J.A. (1981) related such trends in southeastern Michigan to the Mid-Michigan Gravity Anomaly. This gravity anomaly also transects the study area trending just west of north.

No direct evidence of faulting is present in the study area. However, faults may control many of the observed structural features. For example, placement of northwest-southeast trending faults with the northeast side upthrown along the noses would allow the contours to approach the nosing areas without strongly deviating from their gentle arc. Faults proposed by Mescher and Fisher such as the Sanilac, Howell Anticline, Lucas-Monroe, and Albion-Scipio in southeastern Michigan also trend northwest-southeast with the northeast side upthrown.

Faulting is also suggested in the study area because of the tendency of the anticlinal structures to show increased closure with depth and locally increased porosity. Such increased relief with depth in anticlines is indicative of basement faulting or basement topographic relief. Many workers have related porosity development in Michigan anticlinal fields to migration of dolomitizing fluids along faults.

Faulting might also be suggested in Benona Township of Oceana County, where the A-2 Carbonate is anomalously low and the A-1 and A-2 Evaporites are thin. The salts of this area may have been removed by fluids migrating along a fault. It is interesting to note that the Amoco Production Company Isley Unit #1-22 drilled to the Ordovician St. Peter Sandstone, 1100 feet below the top of the producing Niagaran reef. Amoco may have been looking for a fault trap at depth and noticed reef indicators in the Niagaran.

Alteration of structure by salt solution and flowage appears to be minimal in the study area, except for the documented Mackinac Breccia area (Landes, et al., 1945) and the relationship between reef growth and salt deposition. The most striking variation in salt thickness occurs in Benona Township of Oceana County where regional thicknesses of 200 feet and 300 feet for the A-1 and A-2 Evaporites respectively, thin to 62 feet and 123 feet in the Amoco Isley #1-22 well. However, this thinning may be related to a lack of salt deposition on the reef crest rather than solution or flowage associated with structure or faulting.

The A-1 and A-2 Evaporites thin over the Falmouth field and have altered the structure of the overlying sediments slightly. The axis of maximum salt thinning changes from well one at the A-1 level to well eight at the A-2 level. This change in the axis of maximum thinning may be related to a change in the structural axis of the field. Such a change in structural axis is further suggested by comparison of the Dundee and Trenton Falmouth field structure contour maps.

The minor variation of the thickness of the Detroit River Salts unit as a whole, and the individual salts within the unit, is not a significant modifier of structure at the Falmouth and Enterprise fields. The only detectable trend in the Detroit River Salt thicknesses seems to be a general basinward thickening of the salts at the expense of the carbonate and anhydrite thicknesses. The possibility of more intense salt solution and flowage in the study area is not precluded by the findings of this study, however. Salt thicknesses tend to vary more significantly near their depositional limits, as in Allegan County and southwestern Ontario. In the study area, however, limited well control required that the affects of salt thickness variation be examined in Missaukee County, where the salt thicknesses are high. As well control improves, significant variation in salt thickness might be found near the depositional limits of the various salt units, especially near the basin margin where the units are closer to the surface and more susceptible to leaching by meteroic water and ground water.

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Figure 12 shows the areal extent of some of the various salt units in the Michigan Basin.

Exploration efforts to locate salt collapse porosity features and associated faulting and dolomitization should be concentrated near where the underlying salt units pinch out. In the study area, for most salt units, this occurs in the western and northern counties, such as Oceana, Mason, Manistee, Benzie, and Grand Traverse.

Based on these findings, it is concluded that structure in the northwestern portion of the Michigan Basin is controlled by basement faults and is not widely altered by salt solution or flowage. Most of these faults trend northwest-southeast and are probably associated with the failed rift arm which transects the area and is visible as the Mid-Michigan Gravity Anomaly. Even basement structure away from the actual rift zone probably was affected by the stresses associated with rifting and these areas would also develop structural trends parallel to the rift trend. A secondary system of fracturing might also develop perpendicular to the rift trend. Such a trend would be analogous to transform faults at divergent margins. In the Michigan Basin, such a trend would be oriented northeast-southwest. The structural trend in southwestern Michigan is northeast-southwest, as are the offset trends in the Albion-Scipio field. Mescher (1980)

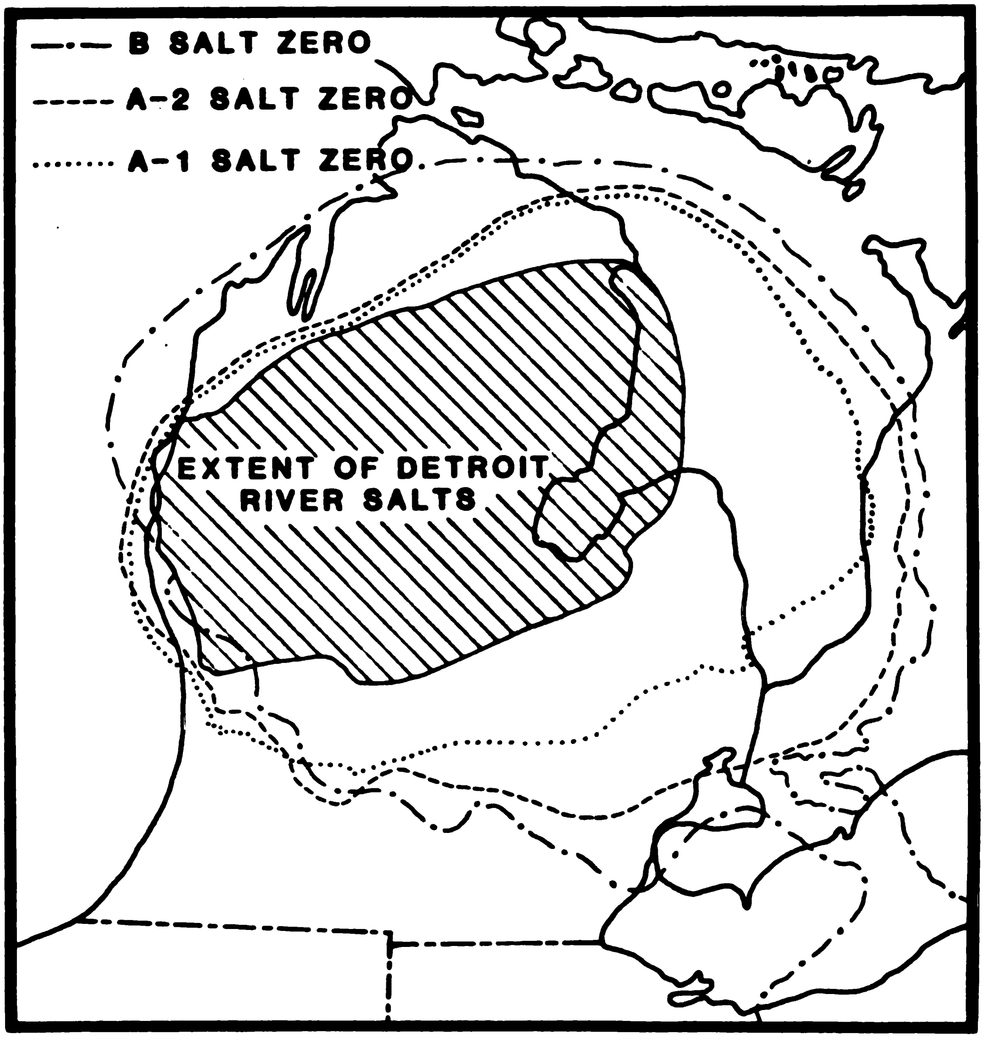


Figure 12. Extent of Lower Salina and Detroit River Salt Units. (After Nurmi and Friedman, 1977 and Landes, 1951)

and Fisher, J. A. (1981) also noticed a secondary northeast-southwest trend in southeastern Michigan.

As noted earlier, the dominant stream orientation in Missaukee and Oceana Counties appears to parallel the mapped subsurface structure. The statements made concerning stream orientation are from general observation only; no statistical analysis has been made. Whether the geomorphology of the extensively glaciated Michigan Basin reflects bedrock structure is unknown and is simply reported here as an interesting observation.

The force or forces which initiated regional basin subsidence are still unclear, but locally subsidence was probably controlled by downdropping of basement fault blocks. Differential movement of these blocks through time could account for the variation in the basin's rate of subsidence and migration of the depositional center that is seen in Michigan.

If these conclusions are correct, they suggest that the Michigan Basin contains large, unexplored or poorly explored areas with petroleum potential. For example, increased structural closure with depth suggests that many shallow fields may overlie undiscovered fields with more closure. Yet, few of the central basin Devonian fields have been tested deeper than the Devonian Detroit River Group, and few of the tested fields have more than one deep test well.

Exploring for deeper pay horizons below known producing horizons is made difficult because in basement controlled structures, the deeper horizons have less areal extent than the shallower horizons. This situation is diagrammed in Figure 13 and is illustrated in the Dundee and Trenton structure contour maps of Falmouth field (Plate 6 and Figure 11, respectively). As can be seen in Falmouth field, a single deep test might not have found gas in the Praire du Chien Formation. Several wells drilled on closure at the Dundee level did not find hydrocarbons at depth. Similarly, a well drilled at a structurally prime location on a shallow horizon may not be at a structurally prime location at depth in the case of an asymmetrical anticline such as the one in Figure 13. A dipmeter log run in such a deep test could prove invaluable in determining where the crest of the structure is located.

With these ideas in mind, numerous fields in Michigan may have deep potential in such reservoir rocks as the A-2 and A-1 Carbonate, Niagaran, Clinton, Trenton-Black River, and Praire du Chien Formations. One such field is in Claybanks Township of Oceana County. Although the single deep test well in the field is necessarily

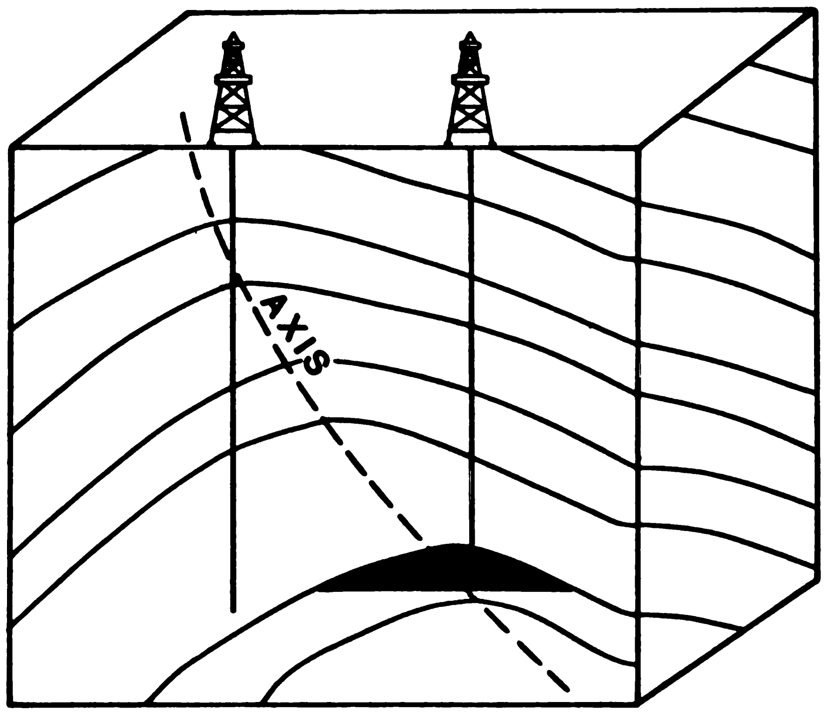


Figure 13. Asymmetrical Anticline.

contoured to be directly in the center of the closure, it may only be on the flank or low on closure of the anticline at the A-2 Carbonate level if the structure is asymmetrical. A single well cannot adequately test such a structure without seismic control and a dipmeter log.

Seismic control should be inexpensive to obtain and process over known producing structures. The area of interest is well defined as the area in and directly around a particular field. Well control in the field would allow exact determination of the thickness of the glacial till and the depth to particular stratigraphic intervals. Such stratigraphic knowledge would allow precise processing of the seismic data in order to accurately predict the shape and orientation of the structure of interest.

Salt collapse structures are probably best explored for with seismic data selectively collected along the depositional edges of the various salt units with lines shot perpendicular to the northwest-southeast structural trend of basin.

Northwestern Michigan is also perspective for Niagaran pinnacle reefs, both in the well established reef trend of Kalkaska, Grand Traverse and Manistee Counties, and in the newly established areas of Mason and Oceana Counties. The possibility of pinnacles in

Oceana County has been firmly established by Amoco's two discoveries in Benana Township and more discoveries are sure to follow as more is learned about this area (see Hartsell, 1982).

The prominent nosing areas, where deep faulting may control these features, have not been adequately explored. Development of oil and gas trapping structures at depth is possible along such features. Most of the noses described in this paper make attractive exploration areas because they lie along the basin margin and require shallower wells than the basin interior. Similarly, offset exploration to the Dart-Edwards 7-36 well along the trend of the Mid-Michigan Gravity Anomaly would be most economical north of Missaukee County towards the basin margin.

Undoubtedly, new oil fields will be discovered in Michigan as features such as the ones discussed in this paper are explored in the future. It is hoped that the ideas presented here might encourage the discovery of some of these new fields.

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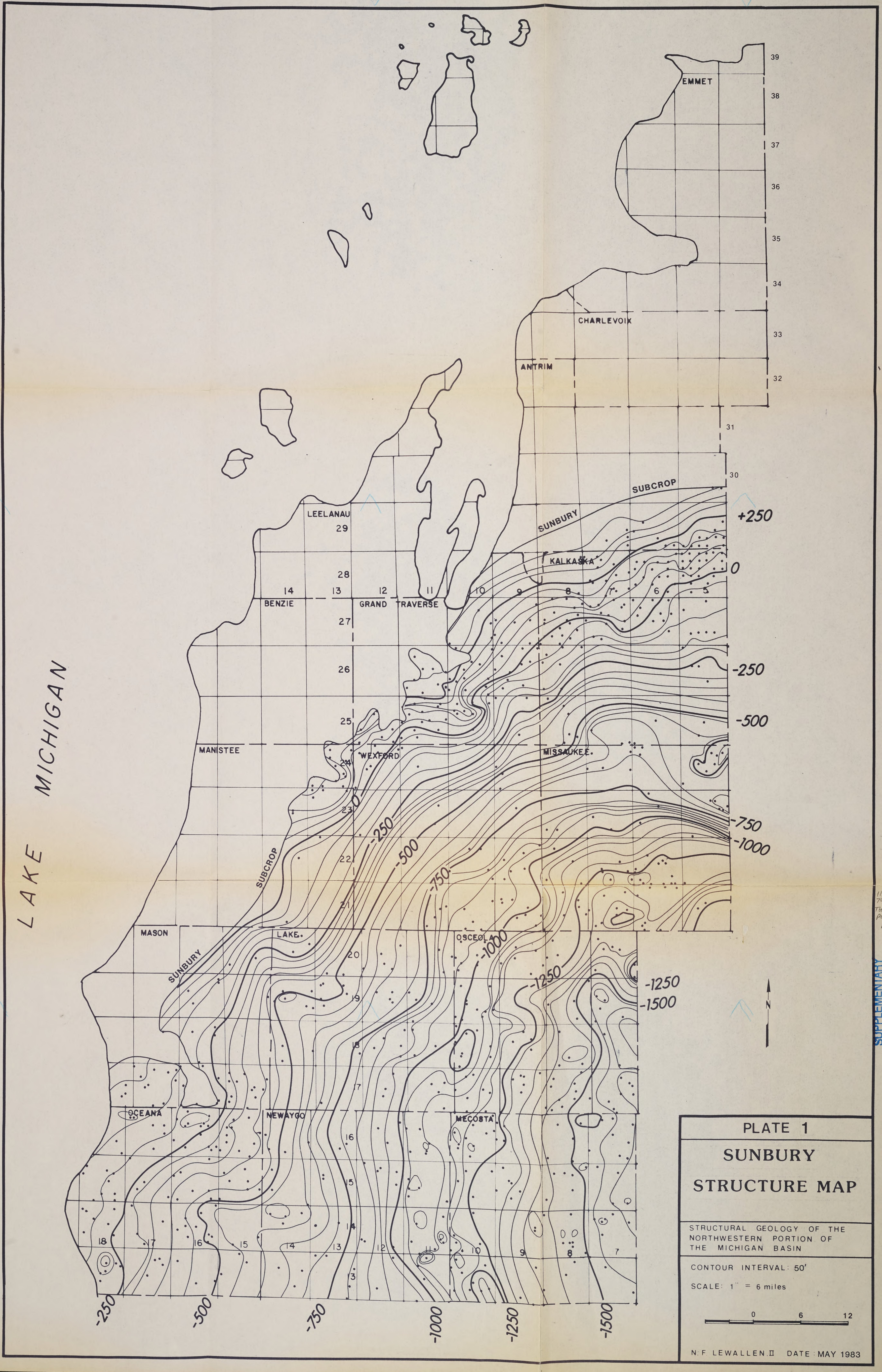


PLATE 1

SUNBURY STRUCTURE MAP

STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

CONTOUR INTERVAL: 50′

SCALE: 1″ = 6 miles

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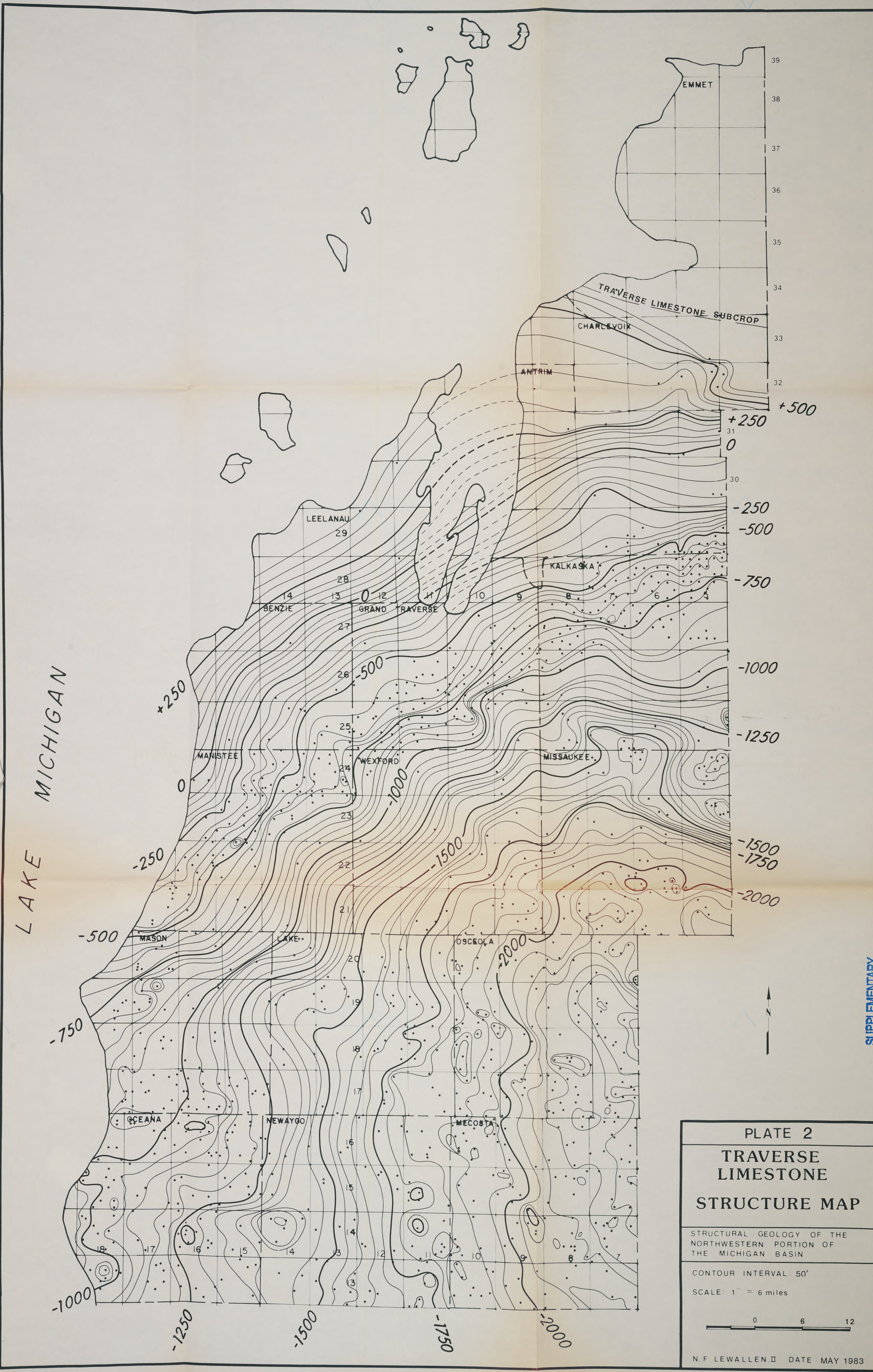
N.F. LEWALLEN II DATE: MAY 1983




## PLATE 2

# TRAVERSE LIMESTONE STRUCTURE MAP

STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

CONTOUR INTERVAL: 50'

SCALE: 1" = 6 miles

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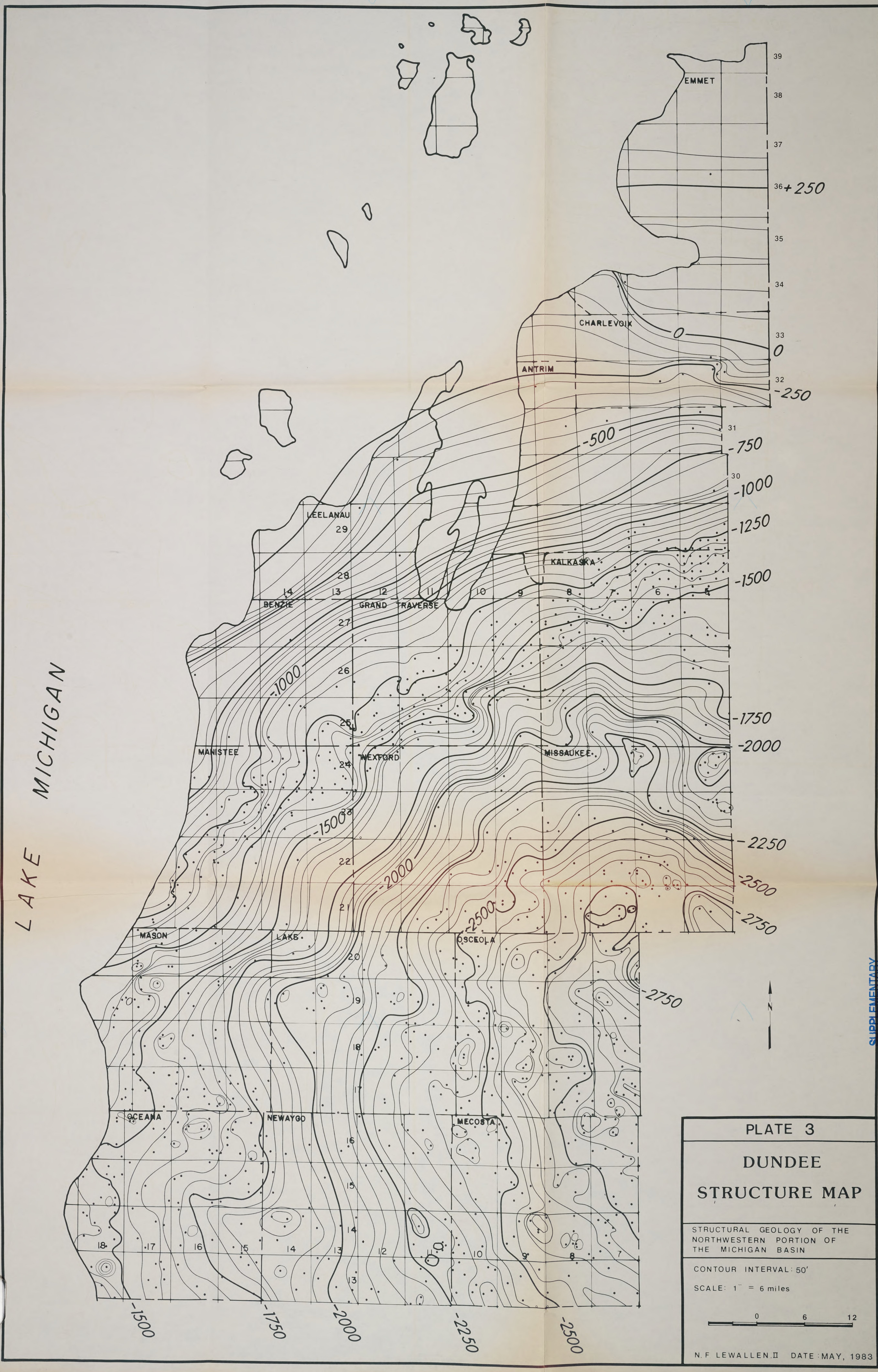
N. F. LEWALLEN II DATE: MAY 1983




## PLATE 3

## DUNDEE STRUCTURE MAP

STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

CONTOUR INTERVAL: 50'

SCALE: 1" = 6 miles

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N. F LEWALLEN. II DATE: MAY, 1983


## PLATE 4

## A-2 CARBONATE STRUCTURE

STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN

CONTOUR INTERVAL: 100'

SCALE: 1" = 6 miles

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N. F. LEWALLEN II DATE MAY 1983

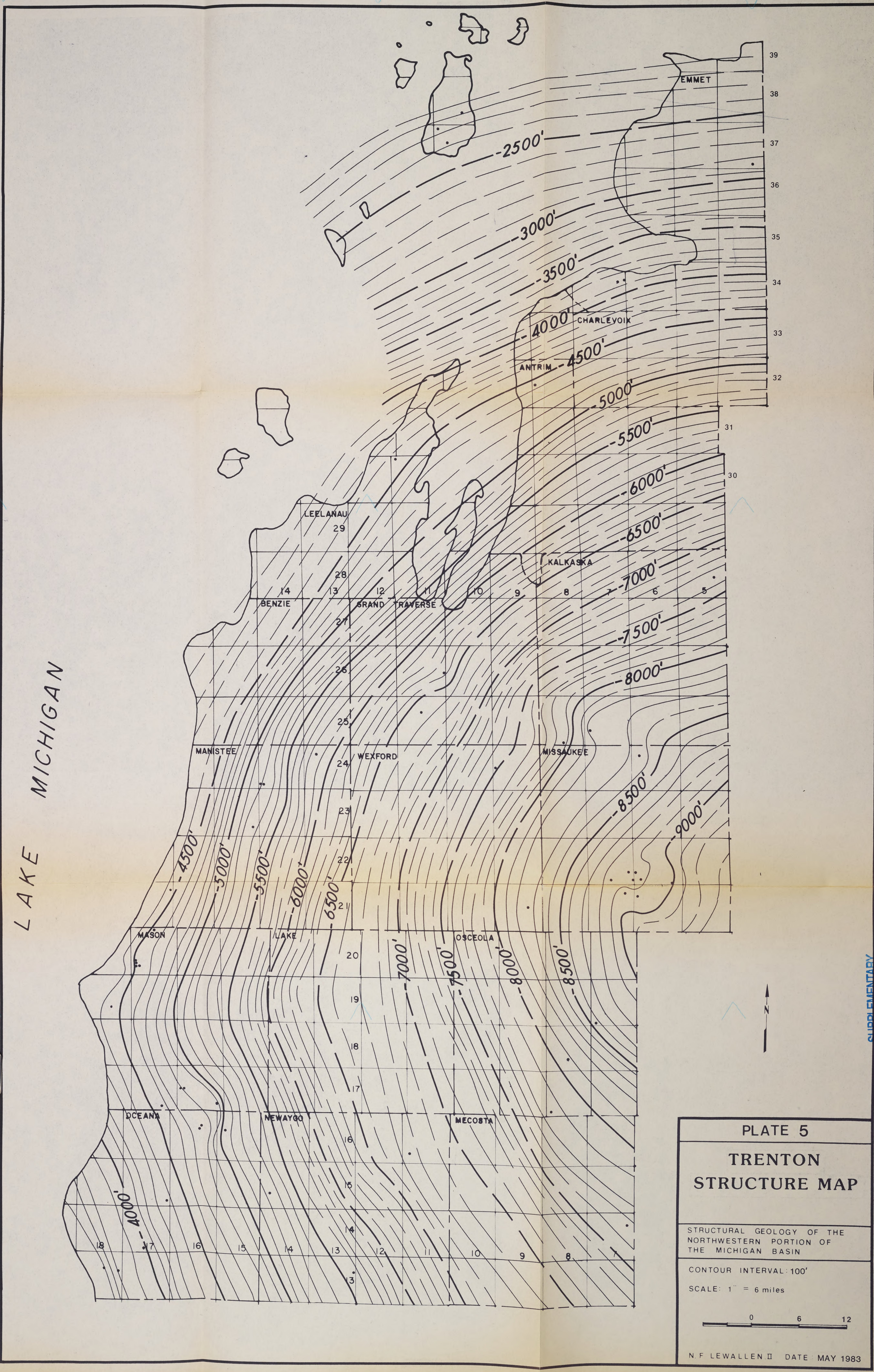
PLATE 5
TRENTON STRUCTURE MAP
STRUCTURAL GEOLOGY OF THE NORTHWESTERN PORTION OF THE MICHIGAN BASIN
CONTOUR INTERVAL: 100'
SCALE: 1" = 6 miles
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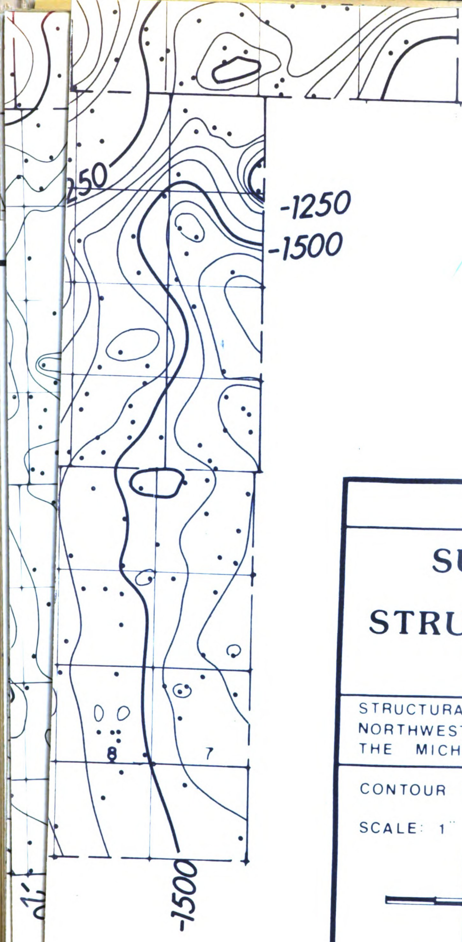


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