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thesis entitled

FAULT PATTERNS IN SOUTHEASTERN MICHIGAN

presented by

Jeanne Ann Fisher

has been accepted towards fulfillment
of the requirements for

Masters degree in Geology

Major professor

Date February 27, 1981

O-7639

FAULT PATTERNS IN SOUTHEASTERN
MICHIGAN

By

Jeanne Ann Fisher

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Geology

1981

ABSTRACT

FAULT PATTERNS IN SOUTHEASTERN MICHIGAN

By

Jeanne A. Fisher

Southeastern Michigan has three major structural features: 1) the Lucas-Monroe Monocline, 2) the Howell Anticline and, 3) the Sanilac County Monocline. All three of these features trend northwest-southeast, all are faulted on the southwest side with the faults downthrown to the southwest. The Sanilac County fault is a reverse fault.

These features are parallel to the southeastern limb of the Mid-Michigan anomaly which overlies a graben of Keweenawan age. It is suggested that pre-existing basement fabric has controlled the development of Paleozoic structure. The three major structural features were created by a combination of vertical movements of Precambrian basement blocks and a horizontal shearing force derived from tectonic events outside the basin.

Isopach map patterns confirm that these faulted structures were intermittently active during much of Paleozoic time. Major movements occurred at the end of Mississippian time when the present structural configuration was attained.

This thesis is dedicated to my father.

ACKNOWLEDGMENTS

The author wishes to thank Dr. F. W. Cambray, Chairman of the Guidance Committee, for his advice and help in the preparation of this study. Thanks are also extended to Dr. J. H. Fisher and Dr. J. T. Wilband, for their suggestions and review of the thesis.

Gratitude is expressed to Ms. Josie Rouse, for her expert typing of the manuscript.

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INTRODUCTION

General

Two fundamental questions concerning the geology of the Michigan Basin are -- why did the basin subside; and what is the origin of the folded and faulted Phanerozoic structures in the basin? Many theories have been offered to explain this phenomenon, but none have been proven conclusively. An important key to solving such problems lies in the structure of the basement rock. The model for evolution of the basin being tested in this thesis is that it subsided on faults, the orientation of which was determined by weaknesses in the Precambrian rocks below. Linear trends of thickness variation in the Paleozoic sediments are thought to represent the persistence of such Precambrian weaknesses during subsidence. If the structure of the Precambrian rock of Michigan could be analyzed, then the origin of the forces which deformed it, and the mechanism by which it subsided would become more clear.

Investigation of deep basement structure in the Michigan Basin is hampered by the mantle of glacial drift and Paleozoic sediment that covers virtually the entire basin area. Phanerozoic sediments reach a maximum of 15,000 feet in thickness. This has obliged researchers to rely on information gathered from wells to provide clues to structure. Most of these wells were drilled for the purpose of petroleum exploration, and they seldom extend to basement rock. To date, only 33 wells out of thirty-four thousand have reached the Precambrian, and 22 of these are concentrated in the southeast quarter of Michigan (Fig. 1). Southeastern Michigan was chosen for this study due to its better well control.

When the 33 known elevations for the Precambrian basement in Michigan are utilized to draw a structure contour map, the picture which invariably emerges is that of a smooth, slightly elongate bowl (Fig. 2). This results from data which is sparse, and inadvantageously located. It is proposed that the Precambrian surface of the Michigan Basin is far from being structurally featureless, and is in actuality quite complex.

Purpose of Study

A fault analysis of the basement rock in Michigan yields important information for reconstructing the history of the basin. It is unlikely that at the time the basin subsided, the basement existed as an unbroken, homogenous unit that sagged in a ductile manner. Thus, a model for the behavior of crystalline basement material should take into account its brittle nature, and susceptibility to breakage over time. Deformation and faulting early in its existence would create fractures, or lines of weakness. It is difficult to imagine a force which could impose upon these initial fractures a new pattern of breakage.

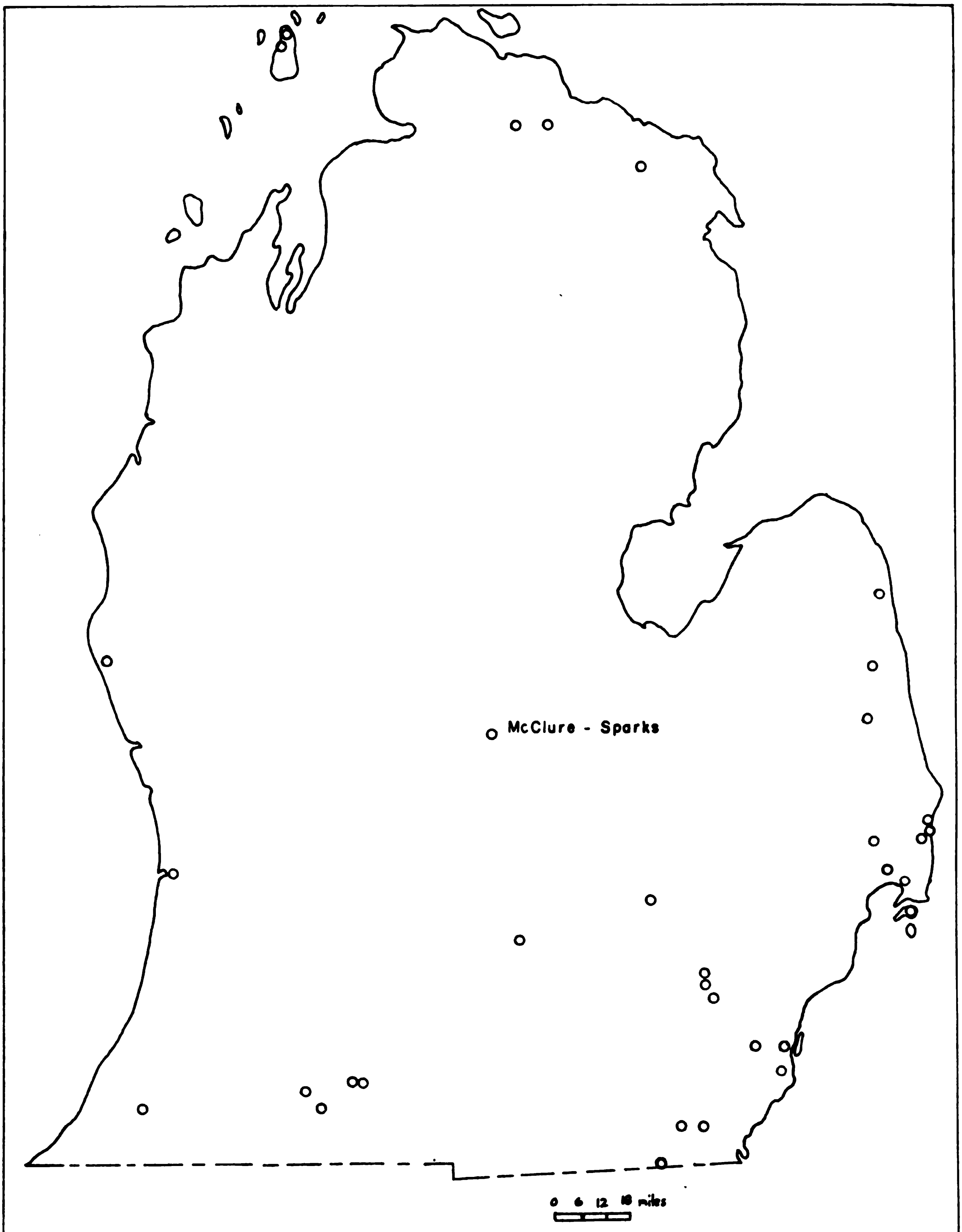


Fig. 1. Location of wells that reach the Precambrian.

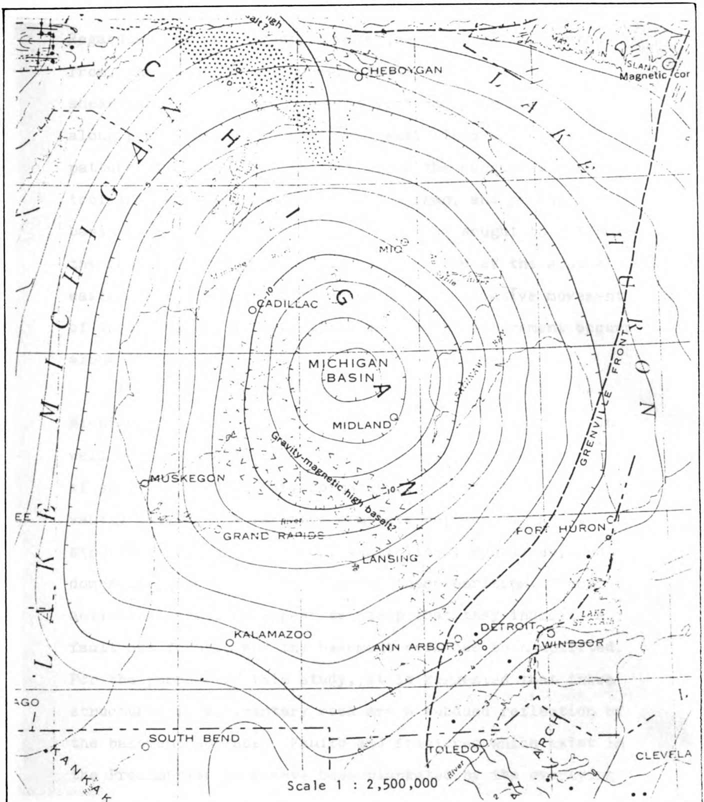


Fig. 2. Basement rock map of Michigan (from U.S.G.S. Basement rock map of the United States, 1968) (Contours are on the Precambrian; contour interval 1,000 feet).

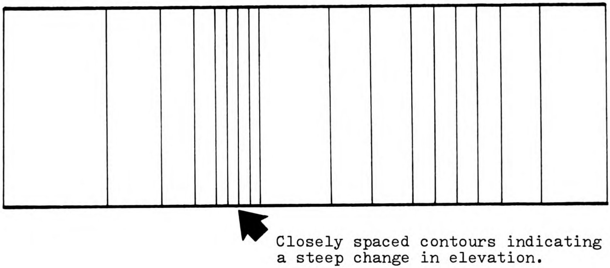
Regardless of the direction subsequent forces originated from, the tendency of basement fault blocks would be to shear past one another, or slip vertically up and down along pre-existing lines of weakness. This ancient pattern of breakage is thought to be the mechanism controlling structure in southeast Michigan, and probably the basin as a whole. In this study, it was sought to determine the fault pattern in the Phanerozoic rocks of the southeastern Michigan Basin, to ascertain the relative movement of these faults, and the times during which movement occurred along them.

A detailed structure map of the Precambrian of the Michigan Basin cannot be constructed from the sparse deep well control available to date. However, on structure maps of shallower sedimentary formations, for which control is vastly improved, a far more complete representation of structure can be determined. Anticlines, synclines, and domes of large magnitude occur in these horizons. Some anticlinal features appear so steep that they indicate a fault has formed, and the basement rock has been uplifted. For the purpose of this study, it is suggested that these structures in sedimentary rock are a subdued reflection of the basement surface. Faults and fractures which exist in the Precambrian rock have been blanketed by the overlying sediments, which increasingly subdue sharper, more contrasting elevation differences which exist across fault blocks. Fault locations are surmised indirectly from structure maps of shallower horizons, where the elevation of a rock unit changes significantly over a small distance (Fig. 3). Faults are also placed on isopach maps, where abrupt changes in unit thickness may indicate tectonic movement during deposition.

The structure of the basement in southeastern Michigan, as revealed by this study, may well be typical of the entire basin. Determination of a general structural trend would contribute toward fitting the Michigan Basin into a regional tectonic pattern. This trend would also provide a basis for explaining local structure and its relation to the Mid-Michigan anomaly. Knowledge of the Precambrian is of great economic value, as structural petroleum traps in Paleozoic sediments may be associated with deep basement relief.

Area of Study

The southeastern portion of Michigan was chosen for study because although there are few deep wells that reach basement rock in the Michigan Basin, they are for the most part concentrated in an area extending east from range 3 west, to the eastern edge of the state, and south from township 20 north, to the Michigan-Ohio boundary (Fig. 4). Extensive drilling of areas in and around the Albion-Scipio field, the Howell Anticline, the Lucas-Monroe Monocline, and the reefs on the St. Clair platform in Macomb and St. Clair Counties, has resulted in good well control (Plate 1). For the purpose of comparison and extrapolation of structural



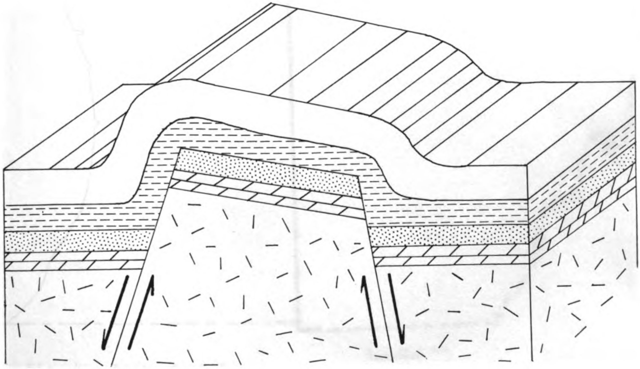


Fig. 3. Sedimentary layers blanketing basement structure.

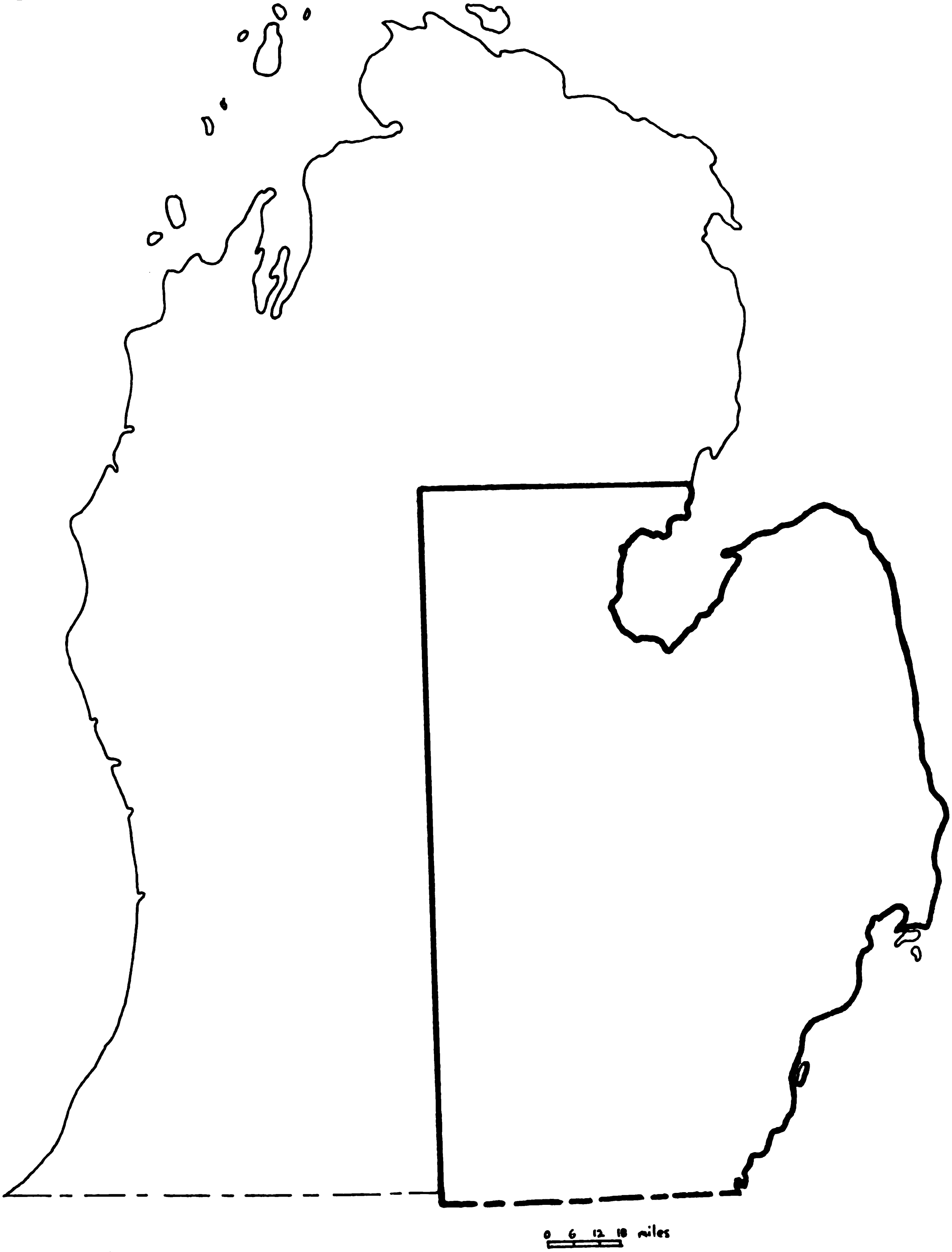


Fig. 4. Area of study.

trends in basement rock from surrounding areas, the southeastern portion of the basin is ideal due to its proximity to the extensive deep well coverage in Ontario and Ohio. The drilling in these regions has revealed the structure and lithology of the Precambrian in much greater detail than can be discerned for the Michigan Basin. This information, integrated with the deep well control in southeastern Michigan, allows the projection of well-defined trends north from Ohio, and west from Ontario, into the basin (Fig. 5). For example, the Michigan Lucas-Monroe Monocline begins in Ohio as the Bowling Green Fault.

In addition to having the best deep well control in the state, the study area includes a portion of the Mid-Michigan gravity and magnetic highs. These anomalies, thought to be associated with basement structure and lithology (Hinze, 1969), transect the Lower Peninsula roughly diagonally from northwest to southeast, and terminate a short distance into Ontario (Fig. 6). Structural complexities in the Michigan Basin that are suggested by gravity and magnetic maps (Fig. 7) may be confirmed when more deep tests are completed in the future. It may be deduced from these geophysical surveys, and from extrapolation of structural trends found in the study area, that the remainder of the basin is in all probability similar in structural character to southeastern Michigan.

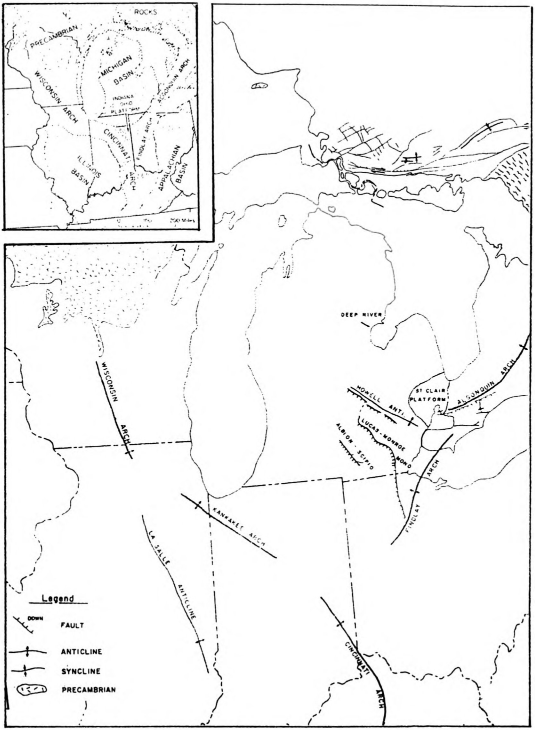


Fig. 5. Major structural features in southeastern Michigan and surrounding areas (after Fisher, J. H., 1972, inset after Rudman, 1965).

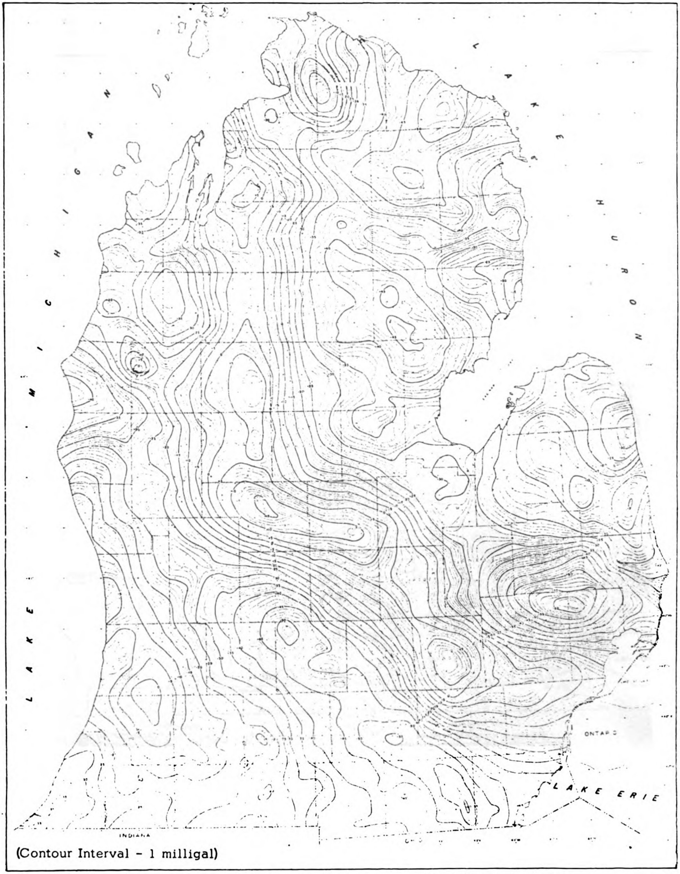


Fig. 6. Bouguer gravity anomaly map of Michigan (Hinze and Merritt, 1969).

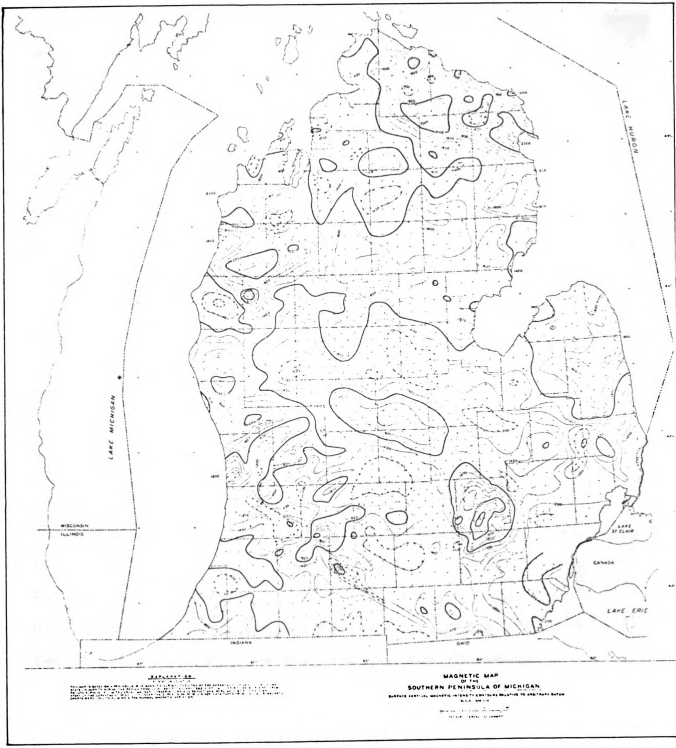


Fig. 7. Magnetic map of the Southern Peninsula of Michigan (Hinze and Merritt, 1969).

Method of Study

Data for subsurface maps prepared for this project were obtained by the correlation of 1,000 gamma-ray neutron geophysical well logs from the Michigan State University collection, and the McClure Oil Company. Written well descriptions, or driller's logs, on file at the Michigan State Geological Survey were used for tops in wells where no geophysical logs were available. Where information found in these logs was vague or contrasted significantly with coverage nearby from geophysical well logs, the data were omitted; where tops fitted in with the general pattern, they were utilized. Formation tops were picked and used to prepare a series of structure contour maps and isopach maps.

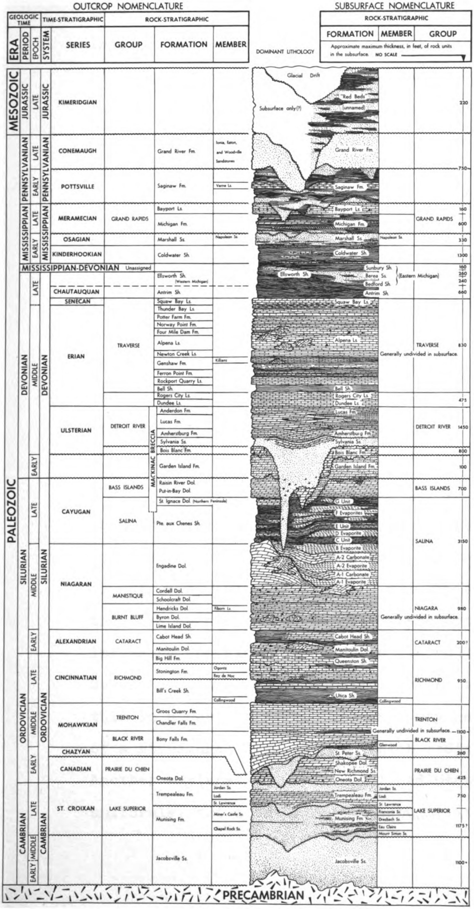
Three structure maps were designed to delineate the structural configuration at shallow, intermediate, and deep levels within the stratigraphic column (Fig. 8). The shallow formation chosen was the Dundee (Plate 1), (elevation +500 to -3,100 feet); the intermediate formation, the A-2 carbonate (Plate 2), (+200 to -6,000 feet); and the deep formation, the Trenton (Plate 3), (-1,000 to -8,000 feet). Deeper formations than the Trenton (Glenwood, Prairie du Chien) were not picked as control for these horizons is restricted to very few wells in the study area. The Dundee, A-2 carbonate, and Trenton are all widespread in extent and can be traced with confidence across most of the Michigan Basin. All three formations produce a

STRATIGRAPHIC SUCCESSION IN MICHIGAN

PALEOZOIC THROUGH RECENT

PLEISTOCENE NOMENCLATURE

ERA	SYSTEM	SERIES	STAGE	
CENOZOIC	QUATERNARY	RECENT		
		PLEISTOCENE	Wisconsin Glaciation	Valders Stade
				Two Creeks Interstade
				Mankato Stade (Pt Huron?)
				Cary Stade
				Tazewell Stade
			Sangamon Interglaciation	
			Illinoian Glaciation	



MICHIGAN DEPARTMENT OF NATURAL RESOURCES

Howard A. Tanner, Director

GEOLOGICAL SURVEY DIVISION

Arthur E. Slaughter, State Geologist and Chief

ACKNOWLEDGEMENT. Compiled with the counsel of colleagues in this department, the U. S. Geological Survey, Michigan's universities, other state Geological Surveys, and geologists within Michigan's oil and gas industry. Dr. Aureal T. Cross, Department of Geology, Michigan State University, identified rocks of Mesozoic age and suggested provisional age assignments.

GEOLOGIC NAMES COMMITTEE

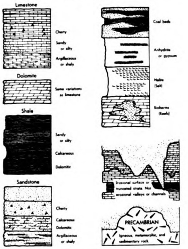
Garland D. Ells, Chairman, Robert W. Kelley, Secretary, Harry J. Hardenberg, L. David Johnson, Harry O. Sorensen

INFORMAL TERMS

Principal oil and gas pays, and informal terms used in petroleum exploration and applied to parts of formations or groups in the subsurface.

STRATIGRAPHIC POSITION	INFORMAL TERMS	PAYS
Basal sandstones of Saginaw Fm.	Parma sandstone	
In lower part of Michigan	triple gyp.	
	brown lime	
	stray-stray ss.	Gas
	stray dol.	
	stray ss.	Gas & Oil
Marshall Ss.		Gas & Oil
Coldwater Sh.	Coldwater lime	
	Weir sand	Gas
	Coldwater red-rock	
In upper part of Ellsworth Sh.	"Berea" (Western Michigan)	Oil & Gas
Berea Ss.	Berea sand (Eastern Michigan)	Oil & Gas
Squaw Bay Ls.	Squaw Bay	Oil & Gas
Upper part of Traverse Group in Western Michigan	Traverse formation	
	Traverse lime	Oil & Gas
	Stoney Lake zone	Oil & Gas
Rogers City Ls.		Oil & Gas
Dundee Ls.		Oil & Gas
Dundee Ls. (?), Upper part of Lucas Fm. (?)	Reed City zone	Oil & Gas
In Lucas Fm.	massive salt	
	big salt	
	sour zone	Oil & Gas
	massive anhydrite	
	big anhydrite	
	Richfield zone	Oil & Gas
Amherstburg Fm.	black lime	
Part of Salina Group E Unit	E zone (or Kintigh zone)	Oil
Divisions of A-2 Carbonate in Western Michigan	A-2 dolomite	Gas
	A-2 lime	
A-1 Carbonate	A-1 dolomite	Oil & Gas
Upper part of Niagaran Series	brown Niagaran	Oil & Gas
	gray Niagaran	
	white Niagaran	
Part of Niagaran Series	Clinton shale (Eastern Michigan)	
Trenton Group		Oil & Gas
Black River Group	Black River formation	Oil & Gas
	Black River shale	
	Van Wert zone	
Oneota Dol.		Oil

EXPLANATION



GEOLOGIC NAMES COMPILATIONS: Harry O. Sorensen, Cambrian and Ordovician; Robert W. Kelley, Early and Middle Silurian; Garland D. Ells, Late Silurian through Detroit River Group of Devonian age; Harry J. Hardenberg, Dundee Limestone through Traverse Group of Devonian age; L. David Johnson, Antrim Shale through the Pennsylvanian System; F. Wells Terwilliger, glacial geology of the Cenozoic.

Fig. 8

CHART 1

THIRD PRINTING 1977

distinct easily recognizable pattern on geophysical well logs. It is suggested that the sedimentary layers increasingly subdue basement relief upward. Therefore, the deepest formation should exhibit the largest elevation contrasts, the intermediate formation more gradual elevation changes, and the shallowest formation still lesser changes. These three formations are of interest economically, as they all produce oil and gas. The Dundee has been the most prolific producer of petroleum in the state. The A-2 carbonate is one of the units forming the Niagaran reef trend (which includes pinnacle reefs) (Fig. 9), which has proven to be a substantial reservoir of oil and gas. The Trenton is notable for dolomitized zones along faults that create traps for petroleum. The Albion-Scipio field produces from just such a zone in the Trenton limestone.

Isopach maps are useful for revealing the pattern of a rock unit at the time of deposition. Isopachs can be used to determine the location of faults where large thickness contrasts within a unit may indicate the existence of a growth fault. They may similarly be used to indicate the periods during which faults were active, by establishing where anomalous thicknesses lie adjacent to fault lines. Several factors can be involved which cause a formation to thin in a certain area. The area may have been the site of a structural high, across which sediments thinned. Another explanation may be that sediment was deposited uniformly, but a later uplift brought about erosion of the

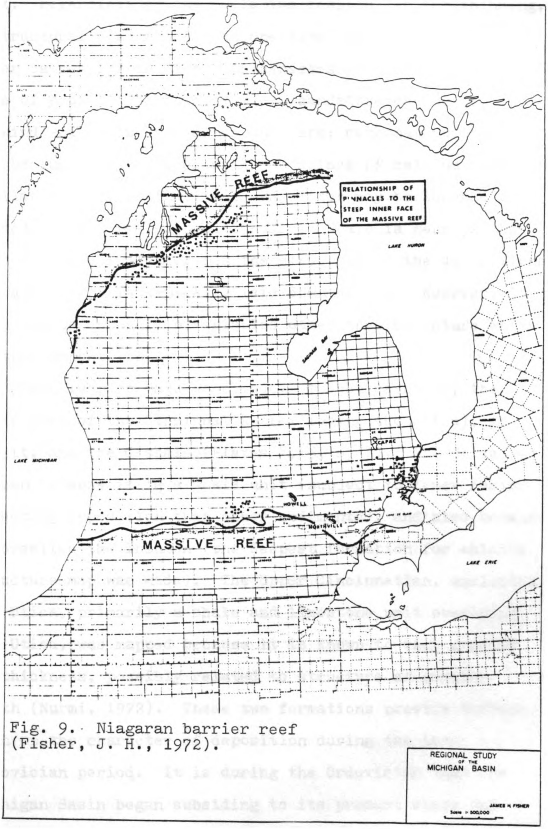


Fig. 9. Niagaran barrier reef (Fisher, J. H., 1972).

unit. Regardless of the mechanism responsible for thinning, a structural high existed at one time over that area. Other causes for anomalous thicknesses are peculiar to the type of sediment deposited; i.e., sandstone can be mounded by wind and waves into dunes and bars; carbonate deposition can be inhibited by deep water or a lack of calcium carbonate availability (starving); and evaporites may be leached or caused to flow post-depositionally. Shale is perhaps the most reliable indicator for the structure of the depositional surface, as it is typically laid down evenly. However, it also may be subject to variables other than structure which control deposition.

Four isopach maps were made: the Utica shale, the upper part of the Cincinnatian (excluding the Utica), the B-unit, and the C-shale (Plates 4, 5, 6, 7). The Utica was chosen because it is a shale unit (subject to fewer factors affecting deposition than other sediments), and also because it overlies the Trenton (the deepest formation for which a structure map was made). The Upper Cincinnatian, excluding the Utica, primarily a shale and limestone unit overlying the Utica, was mapped because it is known to vary greatly in thickness, possibly related to structure at greater depth (Nurmi, 1972). These two formations provide information on the character of deposition during the Late Ordovician period. It is during the Ordovician that the Michigan Basin began subsiding to its present shape and size (Fisher, 1969). These units may reveal the nature of the movement which occurred along faults as the basin began to sink. The B-unit is one of the thickest of the Salina salt units. It was mapped because it is the first evaporite unit of the Salina sequence to be deposited across the Niagaran barrier reef in southern Michigan, which trends through the study area. Examination of an evaporite is also of interest as the thickness of a salt may respond to structure and tectonic movement. Salt can be deposited thinly over a pre-existing positive structure, or thinned post-depositionally by solution or flowage. Salt may be thin due to depositional patterns, or it can be caused to flow away from the crests of anticlines, or be leached along fault zones. As it is not possible to determine which of these mechanisms may have been responsible for controlling the thickness of a salt as it is seen in an isopach map, pinpointing the time of movement or uplift becomes difficult. It is known that the thickness of the B-unit responds remarkedly to Niagaran reefs (Mesolella, 1974), and it may likewise respond to structure. The C-shale, directly overlying the B-unit varies considerably in thickness, a feature possibly related to structural movement. This unit was selected for mapping to see if the variations in thickness bore any relation to structure. All of the formations chosen for isopach mapping are easily recognizable on geophysical well logs.

Isopach maps are an aid to understanding trends in deposition relative to relief when compared with structure maps. They provide evidence for the location of faults and indicate the time and nature of movement along them. To further depict abrupt changes in dip along possible faults, a series of cross-sections were drawn along lines normal to the major structural trends (Appendix A).

The lack of direct geologic information on the basement rock of the Southern Peninsula of Michigan has led to the use of geophysical surveys to determine the nature of the Precambrian basement. Gravity and magnetic surveys have reinforced the theory that the basement rocks are structurally and lithologically complex. The Mid-Michigan anomaly, the major feature dominating the gravity map, and to a lesser extent the magnetic map, has been interpreted as an effect of mafic rocks of Keweenawan age (Late Precambrian, 1.1 to 0.8 billion years before present) (Hinze, 1969). This mafic material is thought to represent a relict rift zone associated with Keweenawan igneous activity (Fig. 10). "Continuous gravity and magnetic anomalies indicate that it is an extension of the structures of the Lake Superior Basin and its associated igneous activity. The Lake Superior structures, in turn, have been correlated with the Mid-Continent gravity high." (Thiel, 1956). The Mid-Continent gravity high, and the Mid-Michigan gravity high (Fig. 11), along with a gravity anomaly of comparatively less length, known to extend north of the Keweenaw Peninsula to Lake Nipigon in Canada (Halls, 1978), appear to form the three arms of a failed triple junction. It is possible

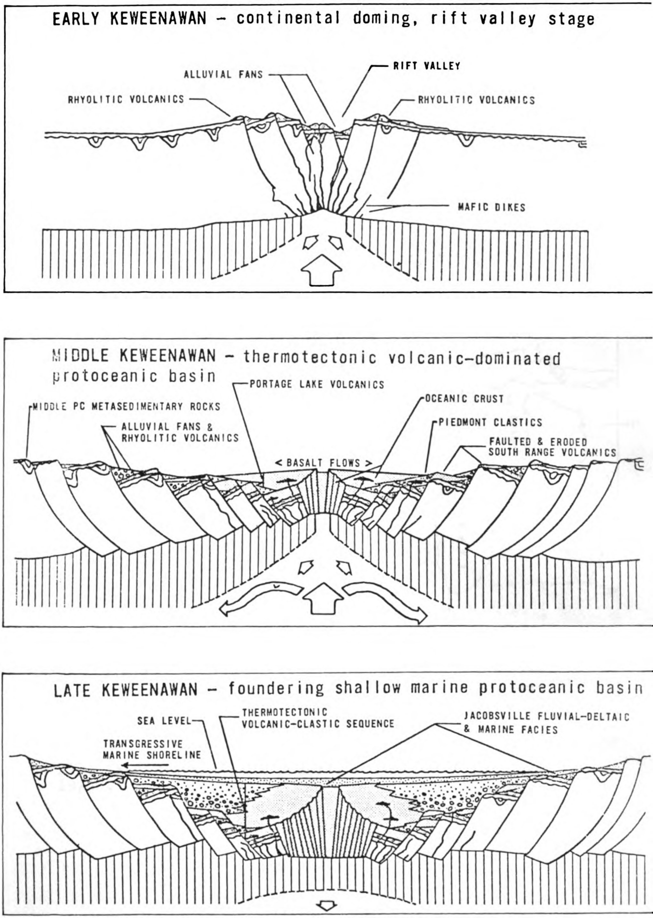


Fig. 10. Keweenawan rifting and associated igneous activity (Fowler and Kuenzi, 1978).

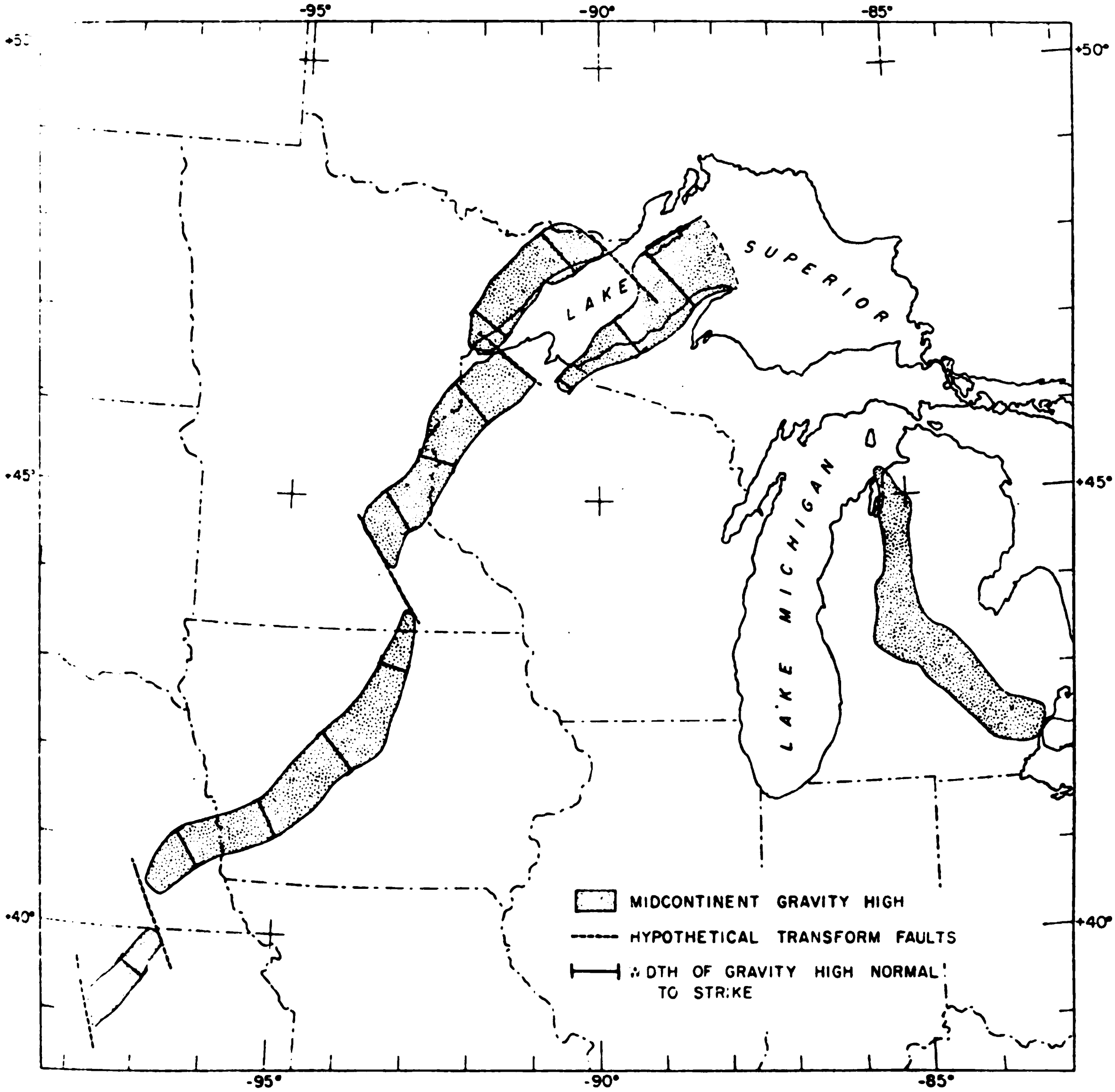


Fig. 11. Midcontinent gravity high (Chase and Gilmer, 1973).

that the trend of the Michigan arm of this triple junction was controlled by pre-existing lines of weakness in the Precambrian basement. The integration of gravity and magnetic maps with structure and isopach maps can be used to establish the character of deep basement structure in Michigan.

Earthquake epicenters were plotted to show where deep basement seismic activity may correspond with known fault locations, or indicate the locations of faults not yet mapped (Fig. 12). These epicenters may yield clues concerning the location of unmapped faults, or they may reinforce the location of known faults. This evidence of present day earthquake activity emphasizes the periodic reactivation of movement along these old fault trends.

In summary, it is proposed that the basement rock of Michigan exhibits a faulting pattern which had its genesis early during the Precambrian. This pattern is a product of ancient deformation. Once these lines of weakness were developed, they remained unchanged throughout the geologic history of the region. Subsequent deformation, regardless of the direction from which it originated, resulted in shearing and slipping of fault blocks, and vertical movements along these pre-existing lines of weakness. This pattern of ancient breakage is what controls structure in southeastern Michigan, and probably the basin as a whole. The nature of this pattern should be expressed in the trends of faults, folds, and possibly the orientation of

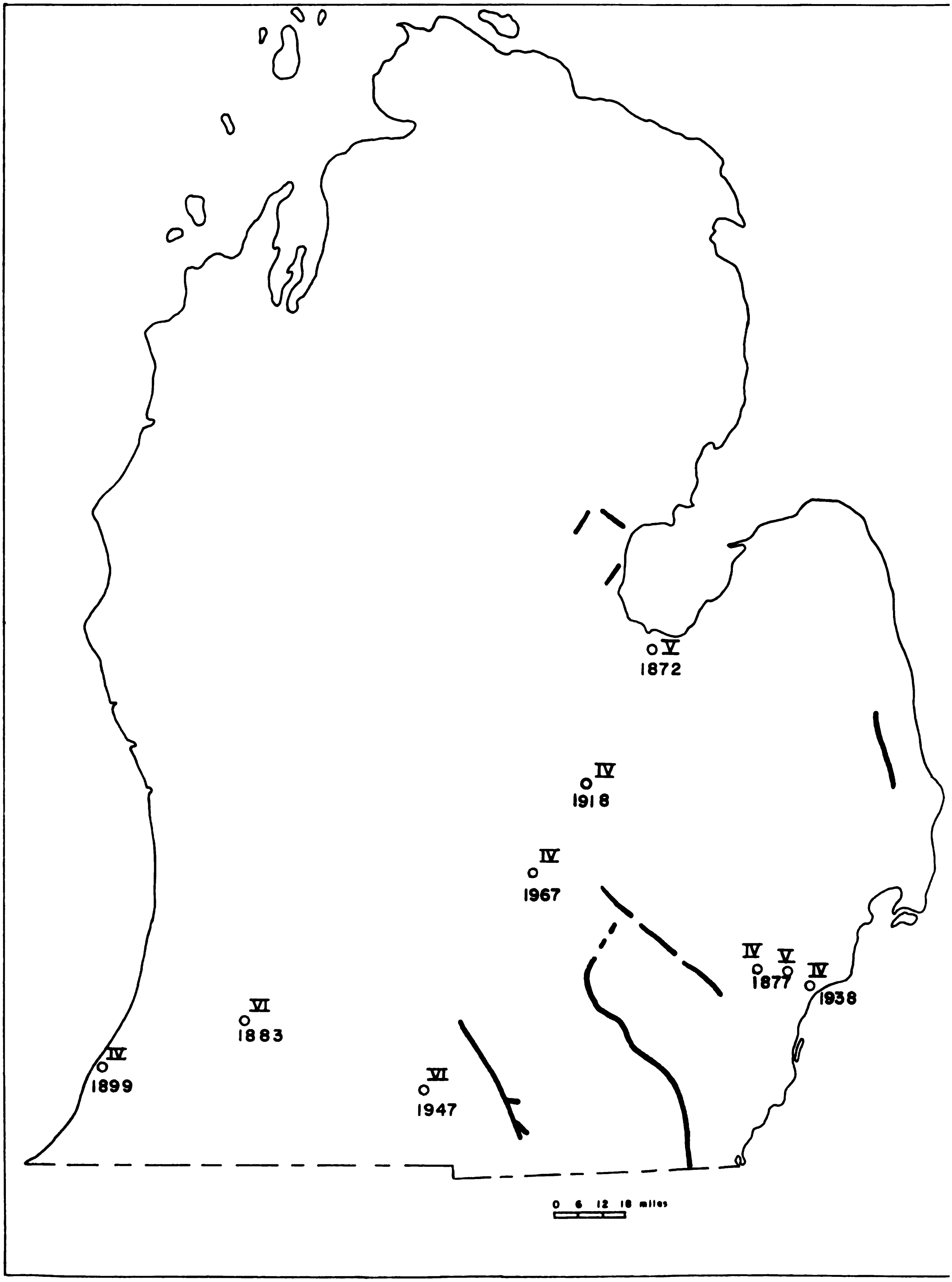


Fig. 12. Earthquake epicenters and faults in southeastern Michigan. Modified Mercalli scale intensities greater than III are shown (Consumers Power, 1978).

the Mid-Michigan gravity high, transecting Michigan's Lower Peninsula. Structure maps are used to delineate structural trends, and isopach maps are used to determine times when movement has occurred along faults.

Three cross-sections were made and included in Appendix A that illustrate the change in elevation across the Bowling Green Fault, the Lucas-Monroe Monocline, the Howell Anticline, and the Sanilac fault. Elevations were taken from the Dundee structure map, which is the structure map with the greatest control. Ultimately this information may contribute toward a more complete understanding of the genesis of the Michigan Basin, and the structures in Phanerozoic sediments within it.

Error Analysis

There are basically two procedures in the preparation of data for this study which allow for the introduction of error. First, the correlation of formation tops may vary between investigators. The pinpointing of a top is usually accurate within two to five feet. Poorly recorded or printed logs, on which the graph is obscured, may introduce larger errors. Formation tops may be inaccurate where boreholes have been deviated somewhat, or whip-stocked. In most cases, slanted boreholes (which would exaggerate thicknesses and the depth of formations) are compensated for after deviation surveys are run. Some minor error is introduced regardless, as few wells are perfectly vertical. Secondly, contouring is an individual interpretation of a rock surface or thickness. In areas where control is sparse, interpretations by two different researchers can be very different. These are the factors which can introduce variability into the data, and its interpretation.

The maps have the densest control, and therefore, the greatest accuracy in St. Clair and Macomb Counties where extensive drilling has been done in the area of the Niagaran reef trend. Good control exists in Hillsdale and Jackson Counties where the southeastern portion of the Albion-Scipio field is located, and along the axes of the Lucas-Monroe Monocline and Howell Anticline. Control is sparse in and around the Detroit Metropolitan area, and in Genesee, Lapeer, and Oakland Counties. Control is absent on the Dundee and A-2 carbonate maps, where these formations subcrop in Monroe and Wayne Counties.

Previous Work

The prominent structural trends in Michigan have long been recognized, and many theories offered for their origin. Early studies based on maps drawn with significantly less data than is available today have become somewhat dated; yet have provided a broad foundation for subsequent work.

Robinson (1923) proposed that the structural elements observed in the Michigan Basin were folds resulting from vertically acting forces rather than compressional ones. He described five fold-types that could be formed in this manner: domes (genetically related to batholiths and laccoliths), radial linear folds, concentric terrace folds, linear terrace folds, and monoclinal folds related to deep-seated faulting. Of these types, radial linear folds (Fig. 13) as well as concentric and linear terrace folds, may account for smaller features seen in structure maps of sedimentary formations. These fold types, which according to Robinson, are the result of intermittent subsidence and downwarping, are probably not responsible for the major, well-defined structural trends that dominate the southeastern Michigan Basin. This is also the opinion of Pirtle (1932) who says these trends were not formed as a result of settling.

Pirtle (1932) sought to explain structure in the basin in relation to the positive areas surrounding it. He believed the Wisconsin, Kankakee, and Cincinnatian arches to have played a role in the depositional and structural history of the Michigan Basin. He states that the basin had a Precambrian origin and that the structures within are "controlled by trends of folding or lines of structural weakness which originated in the basement rock". Citing the oblong trend of the basin, more evident in the older formations, he suggests the basin formed as a geosyncline paralleling a mountain range, the remnant of which is seen today as the Wisconsin Arch. These Precambrian mountains eroded to their igneous and metamorphosed core, shedding sediment into the Michigan Basin. Pirtle recognized the dominant northwest-southeast trends in the basin, as well as weaker subordinate trends running southwest-northeast.

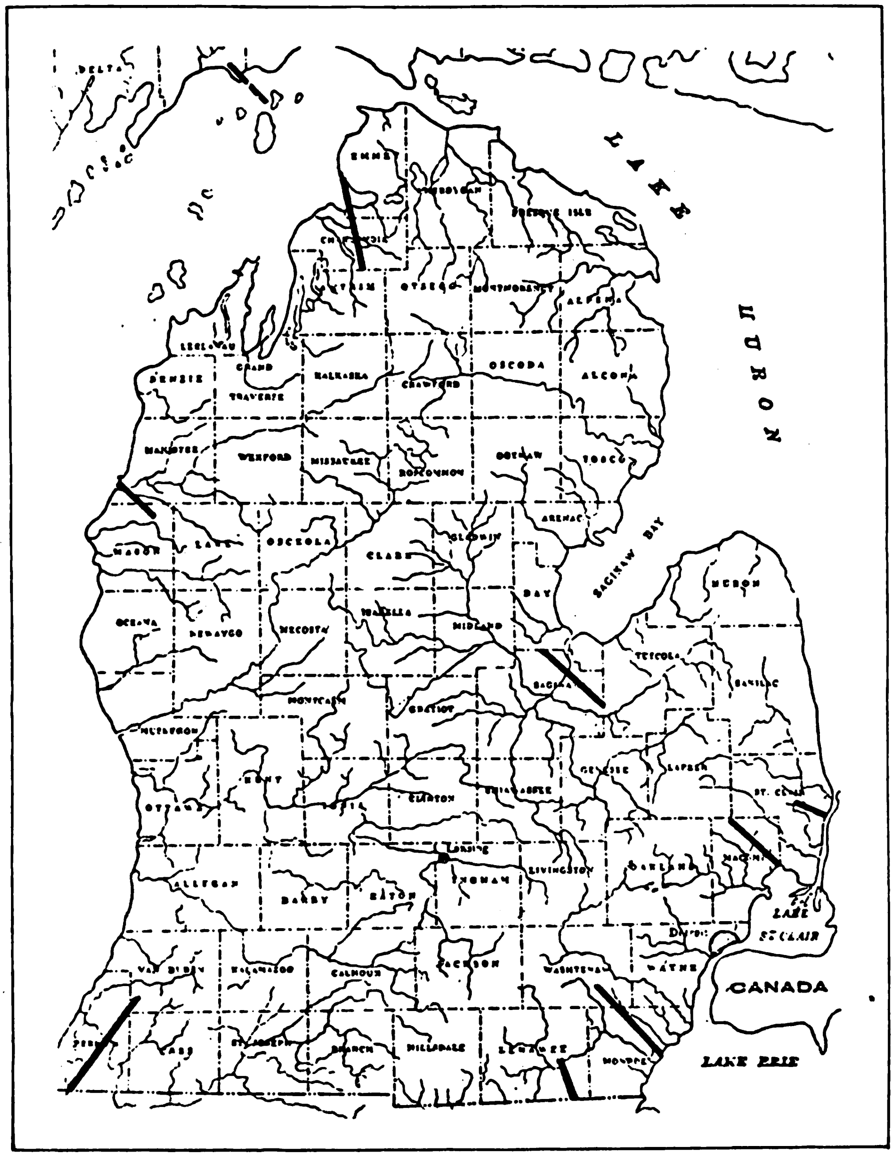


Fig. 13. Radial fold pattern (after Robinson, 1923).

These lesser trends are evident in southwest corner and in the center of the basin. He concluded that folds were formed where horizontal forces caused movement along fractures in the basement which had been formed by vertical forces early in the history of the basin. One of the most intense periods of horizontal stress occurred near the end of Middle Mississippian time.

Newcombe (1933) was the first to endeavor to synthesize all available information into a superb series of maps and a comprehensive report of the geology of the Michigan Basin in his Michigan Geological Survey publication, "Oil and Gas Fields of Michigan". This study, for its time, was an excellent account which is still sought for its clear presentation, predictions, and hypotheses, many of which have been proven accurate by new data from the thousands of wells drilled since it was written. For example, Newcombe's structure map of the Traverse formation is still valid. Among his hypotheses is the suggestion that the Lake Superior Basin is a rift valley that connects with the Michigan Basin--an idea long before its time and later supported by geophysical surveys conducted by Hinze in 1963. Newcombe considered the basin to have originated during the Precambrian, and that structure was related to zones of weakness that developed in basement rock in Keweenawan time. Downwarping of blocks in the basement came about due to a change in direction of tangential forces transmitted horizontally through "deep-seated rocks", i.e., forces originating from events as distant as the Appalachian orogeny. He believed the major stresses which created the synclinal basin to have been exerted primarily from the northeast prior to Keweenawan time, but that the basin's present character and shape were not developed until later.

Lockett (1947), like Pirtle, favored a relationship with surrounding positive areas as a cause for the formation of the basin and the structures within it. He suggests that where the Wisconsin and Kankakee Arches lie today was once a mountain range comparable to the Alps or the Rockies. As this range eroded, a substantial sediment load collected in the surrounding low areas, and caused them to sink. The mountains were eroded to their core prior to the Paleozoic, but the deep roots of the mountains kept the areas positive. This was possibly an effect of isostatic rebound as well. Lockett argues that the northwest-southeast trends in the southeast corner of the basin formed during subsidence as fractures paralleling positive areas to the northeast and southwest. The sediment load then caused differential downwarping and step-faulting to occur toward the center of the oblong basin. Neither Pirtle nor Lockett take into account the lack of geosynclinal-type sediments in the Michigan Basin. There is a conspicuous lack of coarse conglomerate that should exist if the erosion of the Wisconsin range was to have initiated the subsidence of the basin.

Cohee (1944-1948) prepared an excellent series of maps on the Michigan Basin, including structure maps, isopach maps, and numerous cross-sections based on outcrops and the well data available at the time. This work is summarized in a 1958 publication by Cohee and Landes. In this article they acknowledge the dominant northwest-southeast trend, noting that no dominant trend exists specifically in the southwest area of the basin. They stress that comparison of various structural horizons over the Howell Anticline reveal a lateral movement of its axis. The contour axis on the Dundee is 1 ½ miles west of the axis as it appears on the Niagaran. Cohee and Landes consider the basin to have begun subsidence in the Late Silurian, with intermittent folding occurring throughout the Paleozoic, and the major folding to have taken place in Late Mississippian time.

Hinze (1963) examined the regional structure of the Michigan Basin from gravity and magnetic maps made from observation points covering the entire Southern Peninsula of Michigan. Observation stations were established at the corners of townships and at areas of special interest throughout the basin. The resulting gravity and magnetic maps are representative of geological conditions primarily in the Precambrian basement rock. An anomalous gravity and magnetic high transects the basin from the northwest to the southeast, which at least in southeastern Michigan can be seen to parallel structure. The causative mass for this anomaly is suggested to be basic rock in the basement complex of the late Precambrian, possibly of Keweenawan age. This suggests a relationship between the Lake Superior basin, and the Michigan Basin. As the form and magnitude of this major gravity and magnetic anomaly is similar to the anomalous Mid-Continent gravity high, the Michigan anomaly may be an extension of this feature. In later papers, Hinze and Merritt (1969) and Hinze, et al. (1975), it is suggested that the anomalous area delineates a rift arm. This arm was part of a triple junction, according to Halls (1978), the other two arms of which are represented by the Mid-Continent gravity high, and an area with a weakly developed positive gravity anomaly, trending northeast from the eastern end of Lake Superior. If rifting was initiated, mafic material may have welled up along the faults of the rift valley, filling the graben. When rifting aborted, the denser rock remained to produce an unusually high gravity and magnetic anomaly.

Ells (1969) summarized all previous work done in the Michigan Basin. Basing his structural analysis on his own maps, and those of Cohee (1944-1948), he discusses the basin's origin and framework, focusing on the Howell Anticline. He declines to place a major fault along this dominant feature, but instead suggests it is formed by a series of minor faults. In an area he designates as the Washtenaw Anticlinorium, he postulates the existence of three major fault blocks which have moved relative to one another in a vertical manner (Fig. 14). This he says is the cause of structure in the southeast; and may be the key to structure in the basin as a whole.

Fisher (1969), in an examination of the early Paleozoic history of the basin, demonstrated with isopach maps that the Michigan Basin began as an embryonic basin during Cambrian time, evolving into a true basin of its present shape and size in the Ordovician, with significant subsidence in the Mohawkian and the Cincinnatian. The Algonquin Arch was intermittently positive during the Early and Middle Ordovician (Sanford, 1961), but by Cincinnatian time (Late Ordovician), it was no longer a positive feature capable of influencing patterns of sedimentation. The basin at this time was relatively shallow, with a center of deposition in the Saginaw Bay Area. In the Early Silurian, the shallow basin accumulated a thin blanket of shales and carbonates, and by the Middle Silurian had developed a massive barrier reef around its margin. Isopachs of the Niagaran have been interpreted to indicate that these marginal reefs starved the interior of the basin, as a marked thinning is seen toward the center of the basin. The major sinking of the basin was during Salina time, when a thick accumulation of carbonates, evaporites, and shales appear in the column. Following deposition of the C-shale, there was a regression of the sea from the southeast platform in Michigan, which is accentuated by

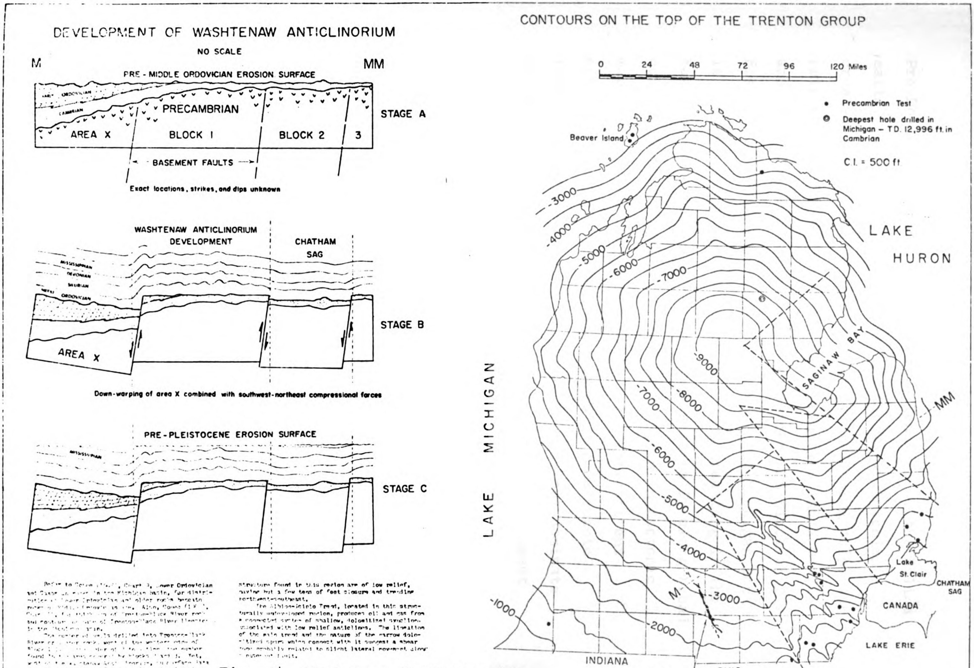


Fig. 14. Washtenaw Anticlinorium (Ells, 1969).

Pre-Devonian erosion, and extensive leaching of the Salina salts. Intermittent uplift during the Early Devonian created several major unconformities. Following this, the rate of sinking increased and is marked by a thick Middle and Upper Devonian sequence of carbonates and black shales. Fisher (1969) believes the structure of the Michigan Basin is controlled by a rectilinear pattern of faulting in the basement rock that changes direction regionally along broad curving trends. Such a pattern can be seen in tectonic maps of the Canadian Shield (Fig. 15). Intermittent movement along these faults throughout the Paleozoic formed both the northwest-southeast trends that dominate the basin structure, and the weaker northeast-southwest trends.

Brigham (1971) used computer contoured maps of various units and structural horizons in a study of southwest Ontario and southeast Michigan. This work includes a general review of the history, structure, and stratigraphy of that area.

Nurmi (1972), in a regional study of the Ordovician in Michigan, subdivided the Cincinnatian formation into six units. The oldest of these, the Utica shale has long been accepted as a distinct unit. Nurmi found that the Upper Cincinnatian could be divided into five additional units that are recognizable throughout the state. Although they do not have a common thickening pattern individually, isopached together as a unit, a center of deposition appears

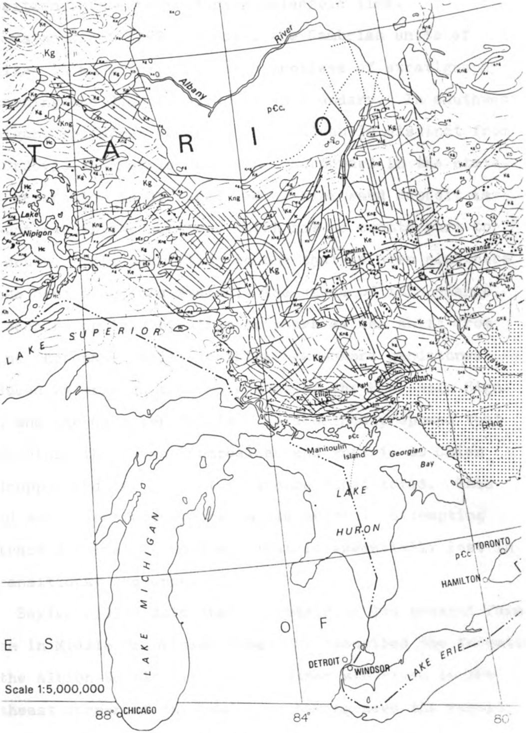


Fig. 15. Rectilinear pattern of faulting in the Canadian Shield (Tectonic map of Canada, 1969).

north of Saginaw Bay. This was the typical center for deposition in the basin during Paleozoic time.

Catacosinos (1973) studied the Cambrian units of Michigan in an attempt to solve problems of stratigraphy concerning the Cambrian-Ordovician boundary. In southwest Michigan, the Upper Cambrian Trempealeau is distinct from the Ordovician Prairie du Chien. Northward in the state, this separation is obscured and a thick sand deposit is encountered in the section, which has no counterpart to the south. This transition is one that is seen elsewhere in the central United States. The cause of this change has been recognized by stratigraphers as the shift from marine carbonate facies to thick near-shore sandstones produced by erosion from mountains of the Wisconsin Highland and the Canadian Shield. Catacosinos proposed that in Michigan the terms Trempealeau and Prairie du Chien be dropped and the term St. Lawrence substituted. This would avoid controversy that would arise in attempting to trace a formation boundary that is essentially lost in a transitional sequence.

Seyler (1974) said that the basin in its present form began in Middle Ordovician time. He described the formation of the Albion-Scipio field and another structure in the northeast corner of the basin, as having been the result of wrench faulting during Trenton time.

Mesolella (1974) published a regional study of the Niagaran and the pinnacle reefs associated with it, in which he discusses the Lower Salina sequence as well. He presents an excellent set of maps of the carbonate and evaporite units deposited during Middle to Late Silurian time.

Autra (1977), studying the same units as Mesolella, showed they were deposited during a period of rapid non-uniform subsidence of the basin, and suggested that the north half of the basin subsided 1,000 feet more than the south half during the same period of time.

Lilienthal (1978) constructed a series of cross-sections in the basin, radiating from the Sparks deep test in Gratiot County. These cross-sections are the first to be based on geophysical well logs, and were used extensively for the correlation of formation tops in this study.

STRATIGRAPHY

Radiometric dating of crystalline material from three deep tests shows that the Precambrian basement rock which underlies the southeastern part of the Michigan Basin to be on the order of 0.9-1.0 billion years old. This correlates with metamorphic events associated with the Grenville Orogeny and also with Keweenawan rifting. The majority of the drill tests have encountered granite or granite gneiss, but the basement lithology is considered more varied (Hinze and Merritt, 1969). Geophysical surveys have yielded highly irregular gravity and magnetic responses possibly caused by the presence of mafic material. This is suggested to be the source of the Mid-Michigan gravity anomaly (Hinze and Merritt, 1969). The Phanerozoic sediments overlying the basement reach an estimated thickness of 15,000 feet. They range from Cambrian sandstones to Jurassic red beds. All periods, Cambrian through Pennsylvanian, are represented, as well as Jurassic. The sediments are largely a sequence of carbonates and shales, with lesser amounts of evaporites and sandstone (Brigham, 1971).

The Trenton formation of Middle Ordovician age is composed of light-brown to brown and gray biolastic limestone of fine to medium crystallinity (Cohee, 1945), (Fisher, et al., 1969). It also contains thin beds of black carbonaceous shale with associated nodules of black chert. In the Southern Peninsula it ranges in thickness from 200 - 475 feet. The Trenton becomes more argillaceous in the northern portion of the Southern Peninsula, but in general throughout the basin the shales are more abundant near the base (Lilienthal, 1978). Dolomitization may occur in the section, but it is usually confined to the axes of major anticlines and to faults such as the Albion-Scipio. This illustrates the importance of the Trenton group as a major source of oil and gas in Michigan. The contact of the Trenton with the overlying Utica shale is perhaps the most easily recognizable and reliable marker on log curves, due to the sharp break from the highly radioactive Utica shale.

The Utica shale is a uniformly gray to dark gray shale with minor amounts of greenish-gray and black shale in its upper portions (Lilienthal, 1978; Fisher, et al., 1969). In southeast Michigan, some limestone stringers occur in the middle of the unit. The top of the Utica is not well defined. In many places it appears gradational into lighter gray shales, with a weaker radioactive response. It is quite variable in thickness, ranging from 200 - 400 feet in southeastern Michigan. It can be seen to thin anomalously in small localized areas of southeastern Wayne County.

The Upper Cincinnatian Series is the uppermost sequence of Ordovician sediments. It is composed of red, green, and gray shales, argillaceous and fossiliferous limestone, and dolomite. It ranges in thickness from 250 to nearly 600 feet in the Michigan Basin. Individual beds undergo facies changes in various portions of the depositional area. However, Nurmi (1972) and Lilienthal (1978) prove that with the use of gamma-ray logs, the series could be divided into six units, including the Utica shale, which are traceable over a large part of the basin. A red shale in the uppermost zone of the Cincinnatian is sometimes identified as the Queenston shale, and gives a reliable top to the sequence. Where dolomite stringers occur instead, the top is more difficult to distinguish on logs and in samples.

The A-2 carbonate of Salina age consists of gray to brown limestones and dolomites. Where it overlies the reef complex on the margin of the basin it is usually dolomite (Lilienthal, 1978). Within the A-2 carbonate, shale and anhydrite beds occur in the center of the basin, but these are poorly developed. The thickness of the A-2 carbonate averages 150 feet in the central basin area, but thins to 50-75 feet over the reef areas at the basin's margin. Where the A-2 carbonate has added to pinnacle reefs, it may thicken to as much as 275 feet. These anomalous values are highly restricted in area, the largest pinnacle reef in Michigan being approximately 10 miles long, and three to four miles wide.

The B-unit is predominantly a thick salt layer with interbedded shales, anhydrite, and dolomite toward the top. It is over 475 feet thick at the center of the basin, but thins to 50 feet toward the southern reef complex as the lower salt pinches out (Lilienthal, 1978). Along the southeastern margin, the distribution of the B-unit becomes irregular, probably as a result of solution. Its generally low radioactive response makes it easily recognizable on log curves.

The C-shale is a greenish-gray and partially dolomitic shale (Brigham, 1971) often containing anhydrite nodules (Fisher, et al., 1969). The C-shale is notable for its comparatively irregular thickness, ranging from 50-200 feet, its widespread occurrence, and its constant radioactive character. Some variations in thickness are found in a small area of southern Michigan where it thickens to approximately 200 feet, and in extreme northern Michigan where it thins markedly (Lilienthal, 1978). Irregularities in its thickness are probably controlled by solution and or collapse of the underlying B-unit.

The Dundee is a buff to brownish gray, fine to coarsely crystalline limestone. In much of the central basin, it is composed of limestone and dolomite with some anhydrite beds. In the extreme west and southwest areas, however, it is entirely dolomite (Lilienthal, 1978). Dolomite, when present, is generally found at the base of the formation. The Dundee in this study combines the Rogers City limestone with the Dundee limestone. The differentiation between these two formations are based on faunal succession and minor lithologic differences

(Lilienthal, 1978). The Dundee is found throughout the Southern Peninsula. It varies tremendously in thickness, from less than 40 feet in western Michigan, to as much as 475 feet in the area of Saginaw Bay. In southeastern Michigan it lies directly under the glacial drift, and can be seen in outcrops along Mason Creek in Monroe County. According to Gardner (1974) the Dundee appears to be a shelf carbonate with dark fine-grained offshore facies deposited in a sea transgressing east to west. The Dundee has been the most prolific producer of oil and gas in Michigan.

STRUCTURE

Two major considerations in basin analysis are the nature of the force that caused the basin to subside, and the mechanism of deformation within the basin with attendant faulting and folding. Basin subsidence is a problem for which many theories have been advanced. For the Michigan Basin, no adequate explanation has been made that fits the known periods of subsidence as recorded by the sedimentary column. There are aspects of some subsidence models which may apply in part to what has occurred in the basin. Perhaps several of these events occurring in a concerted manner are responsible for phases of movement or deformation. Deep well tests and geophysical surveys have yielded information on the character of the Precambrian basement. The structural trends in the southeastern corner of Michigan must be explained indirectly from the consideration of the well data available.

Models of Basin Subsidence

The factors to be considered in basin subsidence are: the location of the basin within the continental plate; the time of sinking; the depth, size and shape of the basin as well as structure within it and surrounding it. The continental interior of the United States can be divided into the stable interior and the foreland. In the stable interior, the Michigan, Illinois, and Williston basins began subsiding in their present size and shape during

Ordovician time (J. H. Fisher, personal communication). All three basins cease to subside in Pennsylvanian time. In contrast to this, the foreland basins have their strongest period of subsidence during the Pennsylvanian (e.g., Anadarko Basin, Denver Basin). The Anadarko Basin stabilizes by the middle of the Permian. The Denver Basin undergoes an additional subsiding phase during the Cretaceous. Thus, the pattern of subsidence for the basins is episodic, becoming younger from the shield margin outward. Some major influence must affect these regions or basins in a concerted sequence of subsidence and deformation (Sloss and Sleep, 1978).

Pirtle (1932) and Lockett (1947) are proponents of the theory that the weight of sediments eroded from a high region and accumulating in a low region create sufficient force to initiate the downwarping that is the beginning of a basin structure. They favor this model for the origin of the Michigan Basin, stating that a tremendous sediment load was deposited in Michigan when the Precambrian mountains to the west in Wisconsin were eroded. The sediment load which accumulated in the Michigan Basin may have contributed to its sinking, but it is unlikely that these sediments have a provenance in Wisconsin.

If material from a nearby mountain range was being deposited in the basin, it would be expected that a thick sequence of conglomerates would occur. There is no evidence for such an accumulation. Taking into consideration the thin (1-2 feet) pebble layers in the McClure Beaver Island wells, these beds or layers are not of a magnitude to represent the erosion of a giant mountain range. It is probable that the major erosion of these ranges took place during the Precambrian and prior to the formation of the Michigan Basin.

Pirtle and Lockett both suggest the possibility that the Michigan Basin is a geosyncline bordering the Wisconsin Mountains and that the basin folds are orogenic. Orogenic folds are asymmetric away from the major deforming force. Michigan Basin folds show no such pattern of eastward asymmetry. An additional problem in applying this mechanism to the formation of the Michigan Basin is that structural trends are best developed in the center of the basin, appearing muted or even non-existent on the margins. It is difficult to conceive of an orogenic force which would deform the basin interior, but not the margins. Tectonic basins of the western foreland area such as the Powder River Basin and the Bighorn Basin exhibit intense deformation around the margins, and basin centers that are virtually undeformed. The Michigan Basin shows the converse of this. Finally, there is no known orogenic force from the northeast or the southwest that could produce the observed dominant northwest-southeast trend of folding during Paleozoic time.

Haxby, et al. (1976) proposed a heating event, that originated in the mantle, and could have altered metastable gabbroic rocks in the lower crust to eclogite. The eclogite being more dense, upon cooling, caused the basin to sink. This heavy material creates subsidence from beneath as opposed to sedimentary loads pushing down from above. A problem with this theory is that a heating-cooling event should create a regular uninterrupted pattern of subsidence. Instead, the pattern of subsidence in the Michigan Basin is irregular. It sinks intermittently and at variable rates throughout the Paleozoic. No evidence of a high heat flow in the basin area has yet been found.

Geophysical Surveys

The lack of deep test data in the Michigan has made the use of geophysical methods an important tool in determining the lithology and structure for the Precambrian of Michigan. Rudman (1965) discussed the trend and significance of the Mid-Continent gravity high. This anomalous gravity high extends from Kansas through Nebraska, Iowa, and Minnesota, and terminates in the Keweenaw Peninsula in upper Michigan. These linear gravity highs are thought to be the result of dense mafic material rising along faults in the basement complex. Hinze (1963) shows an anomalous gravity and magnetic trend extending from the region of Traverse Bay into the southeastern corner of Michigan, transecting the Lower Peninsula. This trend dies out in southeastern Michigan or just across the boundary into Ontario. He suggests that the Mid-Continent and Mid-Michigan gravity highs are related. If forces in the mantle began the development of a rift valley then Keweenawan basalts may have welled up along fractures and filled the graben with dense mafic rock. Supporting evidence for the existence of these faults comes from seismic lines made north-south and east-west through the Gratiot County, McClure-Sparks deep test (COCORP, Cornell University, 1978).

The McClure-Sparks #1 deep test, Sec. 8, TION-R2W, cut a fairly typical section of the Paleozoic sedimentary column of Michigan, with the exception of a slight thickening of the lower Paleozoic formations. Below this, the well encountered 5,000 feet plus, of red beds of presumably Freda (Keweenawan) age (Van der Voo and Watts, 1978). The Mt. Simon sandstone (basal Upper Cambrian) thickens markedly in the well. This suggests that subsidence was continuing at a lesser rate during Mt. Simon time.

<u>Precambrian Tests of the Lower Peninsula of Michigan</u>

Of the 33 wells drilled to the Precambrian in the Lower Peninsula to date, only two encounter sedimentary units below the Mt. Simon (the McClure-Beaver Island #1, and McClure-Sparks #1). The 800+ feet of sediments encountered in the Beaver Island well are primarily coarse sandstone of an arkosic nature interbedded with thin beds of conglomerate. Fowler and Kuenzi (1978) believe these sediments were eroded from a granitic terrain, and deposited by turbidity flows. They cite coarse red beds in the Sparks well as further proof of turbidite material and cite evidence for a Bouma sequence in the Sparks well.

The remainder of the wells in Michigan encounter, below the Mt. Simon, a relatively sharp Precambrian contact with, at best a few feet of granite wash overlying granite, granite gneiss, quartzite and occasionally schist. None of these wells encounters a red bed sequence like that found in the Sparks well. This may indicate that the Sparks well was in a structurally low area, possibly a rift in the Precambrian surface, which collected a red bed sequence. However, the Mobil-Messmore #1 well to the southeast, which was structurally high on the Precambrian, accumulated no such sequence. The Mobil-Messmore has a thin (abnormal for the area) section of Mt. Simon sandstone. Either this well is on a basement topographic high or a horst block, but either way this indicates that the graben dies out to the south as no red beds are present.

The structural trends in the southeastern Michigan Basin are most likely controlled by many fault blocks which lie in a rectilinear pattern similar to that found in Canada to the north (Pirtle, 1932; Ells, 1969; and Fisher, 1969). This idea has been suggested by several researchers (see above) who agree on the mechanism, but disagree on the time the fault blocks formed, the orientation of the stresses that deformed the basement initially and those which caused movement of these blocks in subsequent periods. When the igneous rock that forms the basement cooled, it formed a joint pattern. Deformation or major forces can also create a joint pattern. Subsequent forces exerted on these blocks from any direction could cause vertical or horizontal movement along these planes of weakness. As these fault blocks were subjected to stresses from different directions, they could have moved up and down vertically or sheared by one another much as ice flows on a lake responding to wind action (Fig. 16).

Some of the structure within a basin may be related to its subsidence. Robinson (1923), for example, explains radial folds as being due to subsidence. These are for the most part, very minor structural noses or crinkles in the sedimentary layers around the periphery of the basin in response to subsidence. The premise of this thesis is that none of the major trends in the Michigan Basin are of this origin; instead, structures seen in the Paleozoic sediments reflect movement on lines of pre-existing weakness during basin subsidence. Therefore, movement along faults during basin subsidence was responsible for the structures developed in Paleozoic sediments, but the fault pattern itself pre-dates basin subsidence, and was created by a different mechanism altogether. Many of the major structures present in interior basins have external origins. For example, the faulted Nemaha Arch which extends from Oklahoma City to Omaha, Nebraska, transects the old Salina Basin, but obviously was not created by Salina Basin tectonics. The LaSalle Anticline, which extends into the Illinois Basin, is a similar feature, in having originated in northern Illinois, outside the basin. This argues that some major

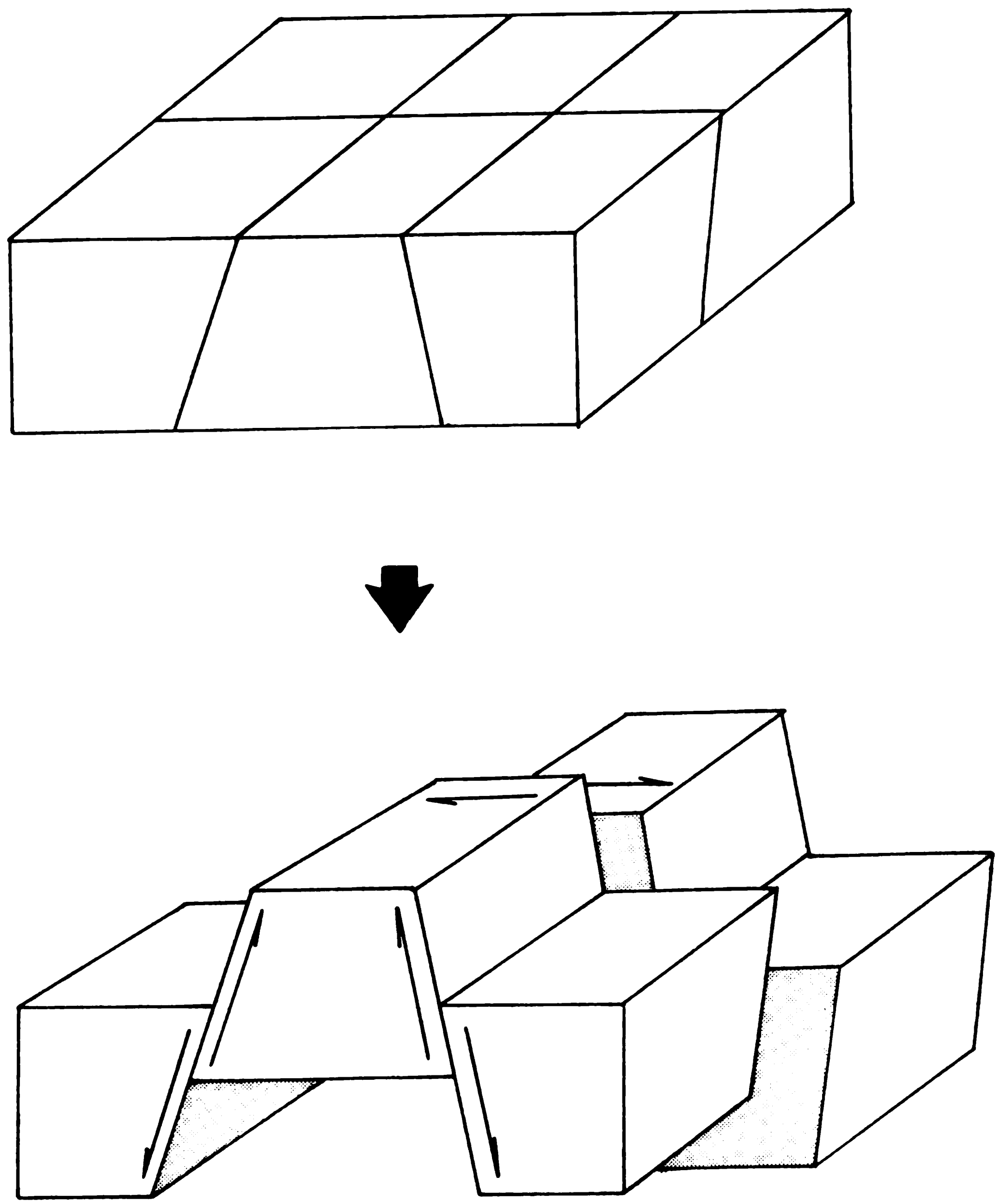


Fig. 16. Vertical movement and horizontal shearing of basement blocks in response to regional stresses.

structures in interior basins would still be present regardless of whether or not these basins were present. Therefore, the mechanism for the formation of some major structures in basins is not necessarily related to basin subsidence.

DATA ANALYSIS

The location of faults in southeastern Michigan has been determined indirectly by examination of the structure and thickness of sedimentary units, as insufficient deep well coverage of the Precambrian makes mapping of the basement rock impracticable. It is proposed that the convergence and abrupt change of direction of contour lines over a short distance indicates that a fault exists through such an area. Similar abrupt changes in the thickness of a rock unit may indicate the presence of a fault that was active at the time the unit was deposited. To reinforce trends surmised from structure and isopach maps, geophysical surveys, seismic information, and earthquake epicenters have been utilized.

It can be seen from the Dundee, A-2 carbonate, and Trenton structure maps that the region of southeastern Michigan forms a portion of a basin which centers on the Saginaw Bay area.

Of the three structure maps, the Dundee (Plate 1) has the best well control, and so is used for the analysis of structural trends within the study area. Three major trends are seen in the Dundee. These are the Lucas-Monroe Monocline, the Howell Anticline, and a monocline in Sanilac and St. Clair Counties. The southeast end of the West Branch Anticline, a major feature north of Arenac County, is not discussed here as the greater part of the anticline lies outside the study area. The Albion-Scipio trend is not evident in the Dundee. Three minor features are seen in the Dundee. These are an anticlinal nose in Lapeer County, an anticlinal nose in Sanilac County, and a wide syncline, south of Saginaw Bay.

The placement of faults on a structure map is a subjective process, and may differ between workers. The structure maps are drawn entirely without faults so that the readers may make their own interpretations. The fault trend map (Plate 8) indicates the placement of faults in areas in which, in the opinion of the writer, the degree of merging of contours indicates faulting. Additional faults have been added to this map in areas where faults are surmised to exist based on borehole data and seismic surveys. Faults, determined in this manner, and not by this study, are indicated by dashed lines.

The Lucas-Monroe Monocline (Fig. 17) trends approximately 20 to 40° west of north from Monroe County, nearly 70 miles. The west flank of the monocline appears steeper than the east. In the area of T1N, R2E, there is an elevation change in the Dundee of 700 feet over a distance of two miles. Directly opposite on the east flank in T1N, R4E, the same elevation change occurs over a distance of 7 to 8 miles. The Lucas-Monroe feature has a well-defined axis, and exhibits a very strong nosing trend which more closely resembles anticlinal structure rather than that of a monocline. However, all of the literature to date describes

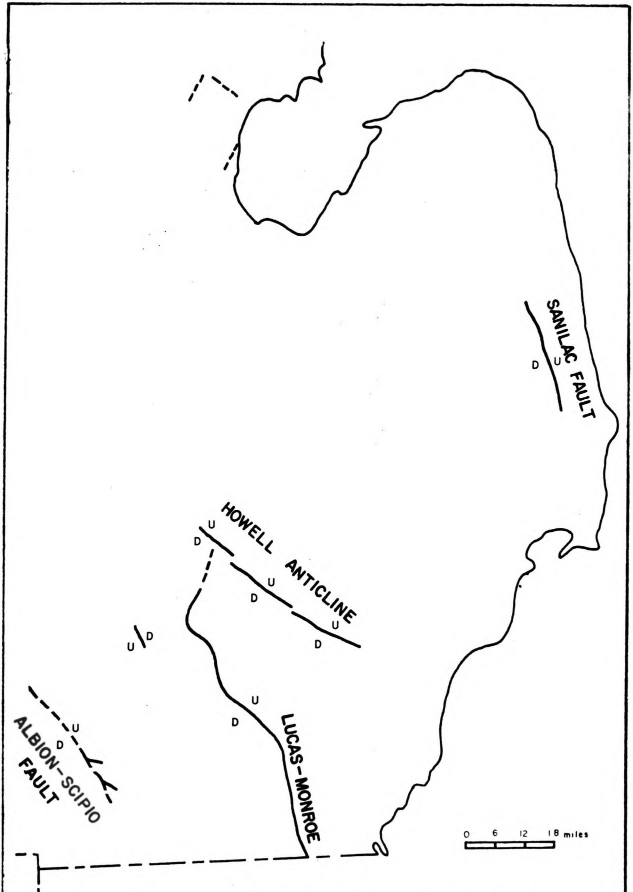


Fig. 17. Fault trends in southeastern Michigan. Dashed lines indicate faults based on oil field studies (Merritt, 1968; Landes, 1948; Lundy, 1968b).

the Lucas-Monroe as a monocline, and the writer is following this convention. The northern part of the axis curves into a north-south pattern, almost intersecting the Howell Anticline. A narrow syncline separates the two positive features.

The Howell Anticline is by far the most dominant linear feature in the Michigan Basin. It trends between 40 to 60° west of north and extends from Wayne to Clinton County, a distance of approximately 50 miles. The west flank of the Howell is very steep. In Livingston County elevation changes up to 1,000 feet occur with a distance of three miles.

A monoclinal feature in Sanilac and St. Clair Counties trends slightly northwest for approximately 30 miles. This feature exhibits elevation changes of 500-600 feet across a distance of three miles--a dip half as steep as that along the west flank of the Howell Anticline.

These three large scale features are considered by the author to have been faulted where the placement of contour lines indicate the steepest dip (Plate 8). All faults trend generally northwest-southeast, consistent with the regional trend of folds and domes in the study area.

In northwestern Lapeer County, a smaller scale anticlinal nose juts basinward along the -1,500 foot contour line. The feature is less linear than those previously described, but is slightly elongate in an east-west direction.

An anticlinal flexure in northern Sanilac County trends very slightly north of east, and noses into a small dome structure in Tuscola County.

South of Saginaw Bay a large wedge-shaped syncline occurs which extends from western Sanilac County to Midland County. The syncline broadens westward, as far north as Bay County, and as far south as Shiawassee County. The axis of this syncline trends slightly north of east.

On the whole, structure in the A-2 carbonate (Plate 2) reflects that of the Dundee. The dip along the flanks of the major trends, the Lucas-Monroe Monocline, the Howell Anticline, and the Sanilac County Monocline, steepens somewhat in the A-2 carbonate. This is to be expected as relief should become less subdued downward in the column. North of the -3,500 foot contour line, control for this horizon is very sparse. The elevations for wells that are known are honored, but where data is lacking, contours have been shaped to those on the Dundee.

Control for the Trenton (Plate 3) is even more highly restricted than for the A-2 carbonate. Contours north of the -5,500 foot line honor the elevations from the few wells in this area, but these are primarily shaped to the structure of the Dundee. In most respects, the Trenton reflects trends seen in the Dundee and A-2 carbonate structure maps. A steepening of dip beyond that seen in the A-2 carbonate is not in evidence. Possibly this is an effect of there being less control available for this unit.

Location of Faults

The Lucas-Monroe axis exhibits a great deal of curvature. It begins in Michigan trending only about 10° west of north between Monroe and Lenawee Counties, then turns westward to 50° west of north for approximately 15 miles. In the northwest corner of Washtenaw County, it trends further westward, only to curve back in a northeast direction, almost intersecting the Howell fault. This unusual pattern of curvature is confirmed by seismic information (J. H. Fisher, personal communication). This trend extends for approximately 70 miles in Michigan, but continues into Ohio as the Bowling Green fault. The offset is on the order of 500-700 feet over a distance of two miles--a relatively steep angle.

The Howell fault begins in northwestern Wayne County and trends roughly 50 to 70° west of north to northwestern Livingston County, a distance of approximately 40 miles. Contours on this structure suggested that it was comprised of at least three separate fault lines, the axes of which were slightly en echelon and offset by at the most, a mile or two. The Howell is an extremely high angle fault. An offset of 1,000 feet is seen within a distance of a half-mile.

A monoclinal feature in north-central St. Clair and southcentral Sanilac Counties, trends 10 to 20° west of north, from T8N, R15E, to T11N, R14E, for a distance of about 20 miles. This is a thrust fault, as indicated in the Humble-Hoppinthal borehole (Fig. 18).

A fault, only four miles long, trending 30 to 40° west of north, straddles the boundary between Ingham and Jackson Counties near T1S, R1W, but this is placed on the basis of changes in rock unit thickness, and is discussed later.

Three faults are placed in Arenac County based on oil and gas field reports. These faults are based on oil and gas producing features, Fig. 19. The location of the Albion-Scipio trend is based on geophysical data (Merritt, 1968).

The upthrown and downthrown sides of the faults, as they are today, is determined by comparing the elevations on each side of the fault line (see Plate 8). All the faults with the exception of the smallest one on the Jackson-Ingham County boundary, are downthrown on the southwest side, and upthrown on the northeast side.

In summary, the Dundee, A-2 carbonate, and Trenton structure maps indicate these formations dip regionally toward the center of the Michigan Basin. The dominant structural trends within this southeastern portion of the basin, as represented by faults, anticlines, synclines, monoclines, and domes is northwest-southeast. These trends are plotted and compared with the trend of the Mid-Michigan Anomaly in Figure 20. A high degree of parallelism can be seen to exist relative to this feature.

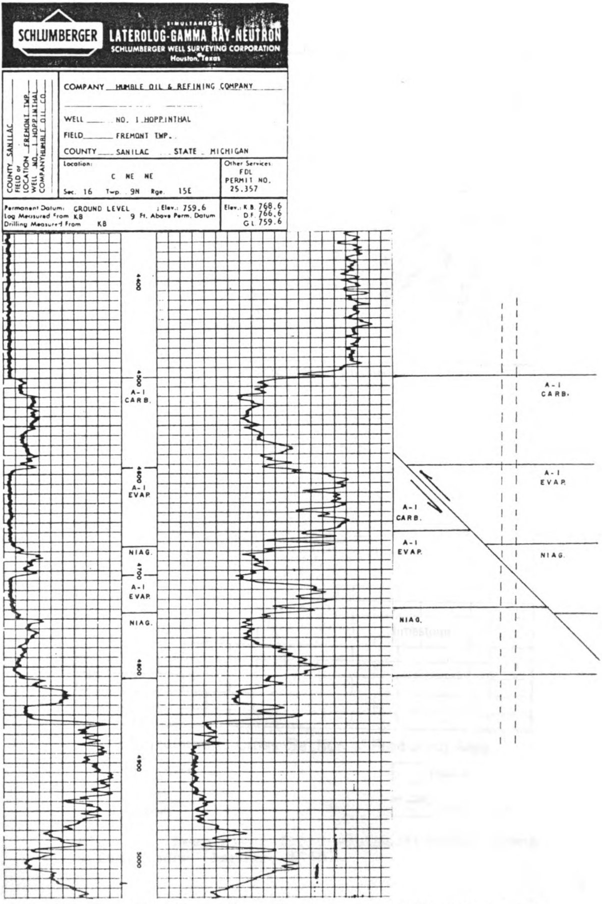


Fig. 18. Humble-Hoppinthal #1 showing repetition of the A-1 evaporite indicating a reverse fault.

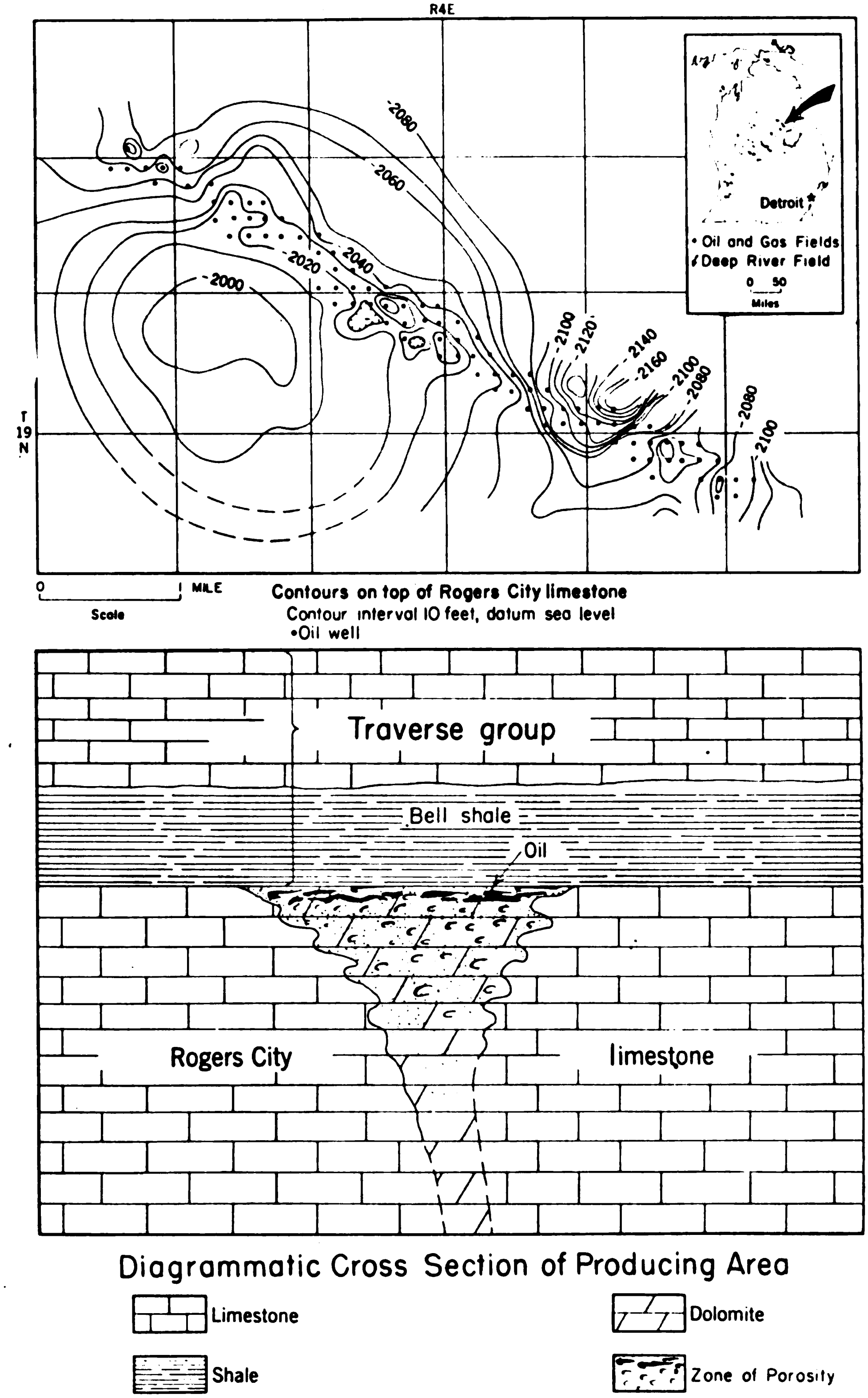


Fig. 19. Deep River field--dolomitization along a fault zone (Landes, 1958).

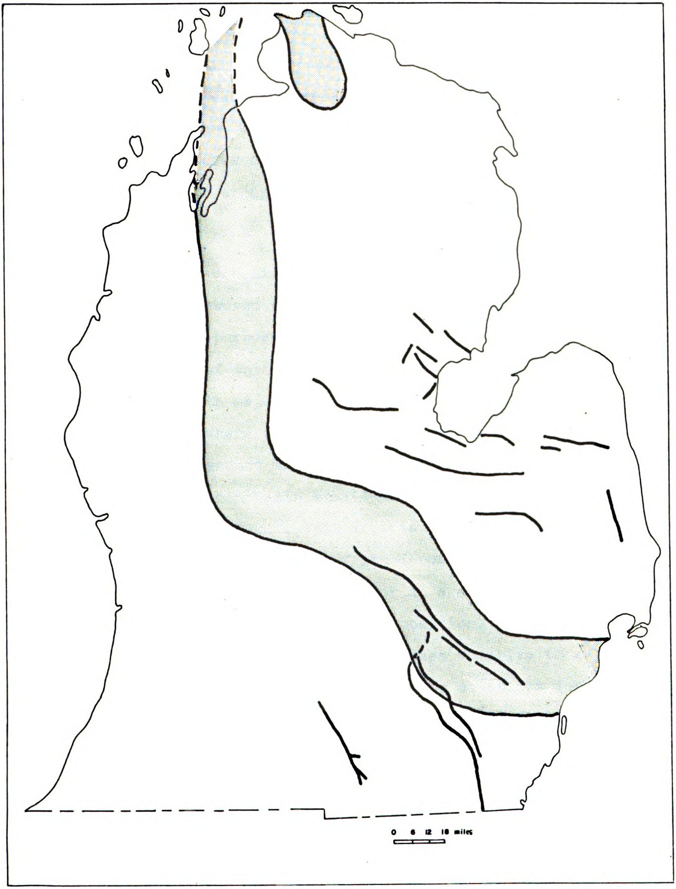


Fig. 20. Structural trends in southeastern Michigan relative to the Mid-Michigan gravity anomaly.

A weaker subordinate trend, northeast-southwest, is demonstrated by some structures in the study area. These are fewer in number, and of lesser magnitude and areal extent than the six features described here. The fault trends as determined by this study are summarized in Plate 8.

Isopach Analysis

Isopach maps can aid in determining the times during which movement occurred along faults. Isopach trends have been combined for purposes of comparison in Plate 9. The salient features of this map are that anomalous thicknesses are associated with major structural trends, and with Niagaran reefs. Where anomalous thicknesses are not in evidence, it is assumed that no uplift or downwarping was occurring (other than basin subsidence). Where a unit thins adjacent to a fault, that area is considered to have been upthrown during the time of its deposition. Anomalous thickening is considered evidence for an area being downthrown during the time of sediment deposition. In some places these trends of anomalous thickness relative to a fault oppose each other in different units deposited during different periods. This is considered to be proof that an inversion of structure has occurred (Fig. 21).

Movement of fault blocks along the Lucas-Monroe fault has not been consistent over time. The Utica shale (Plate 4) can be seen to thin anomalously along the northeast side of the fault. This indicates this side was upthrown in Utica time, similar to the position the fault is seen

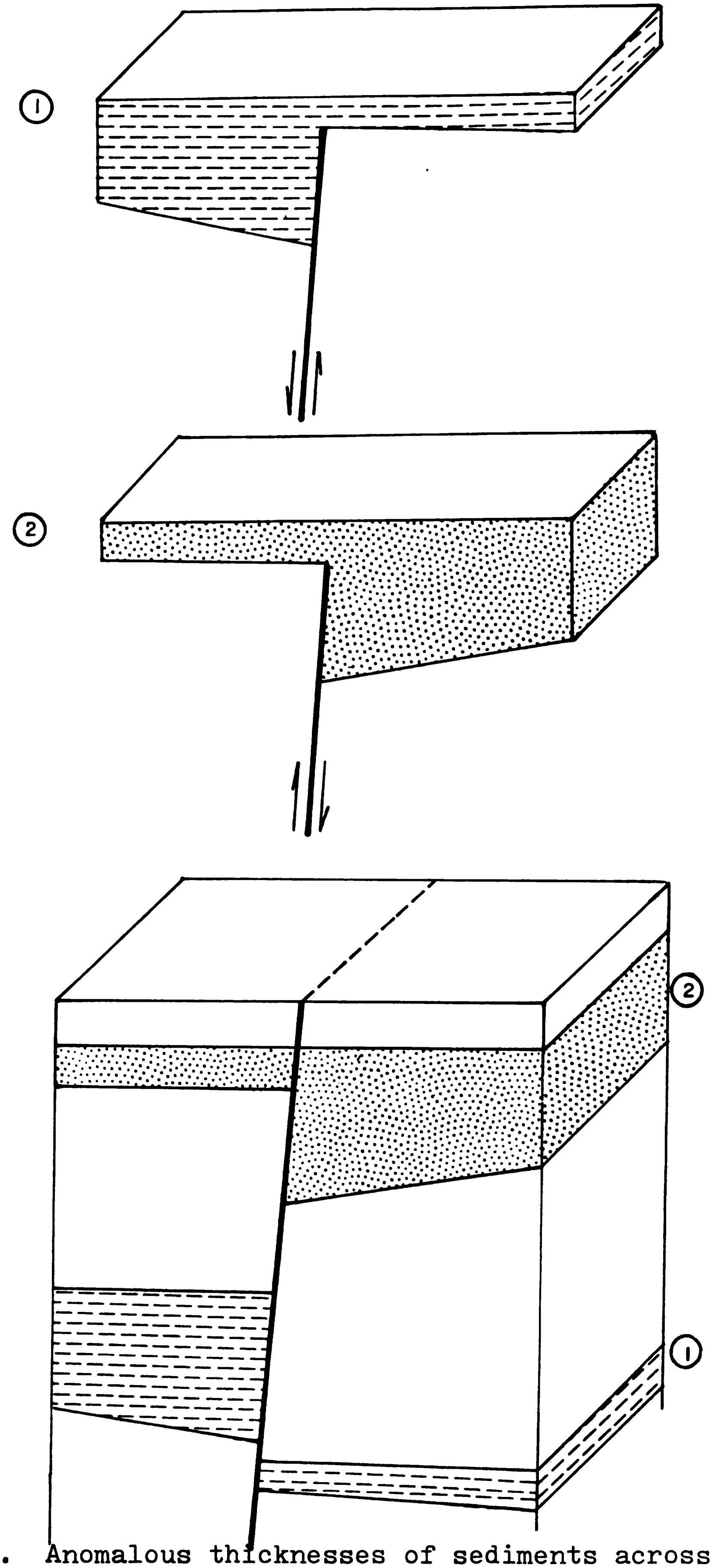


Fig. 21. Anomalous thicknesses of sediments across fault zones--evidence of structural inversion.

in today. The Upper Cincinnatian, however, (Plate 5) thickens on the northeast side to a tremendous degree in the west half of Monroe County. This is evidence for an inversion of structure in this region, indicating that in Cincinnatian time the downthrown side was to the northeast. Farther north in Washtenaw County, the Cincinnatian thins on the same northeast side. This can be interpreted to indicate that the Lucas-Monroe is probably a series of faults, rather than one single continuous fault. Fault blocks may at different times move independent of one another.

The B-unit thins along the southwestern side of the Lucas-Monroe fault. This could be a result of flowage caused by tectonic movement, an effect of deposition, or leaching of the salt across a positive area. The anomalous thin could possibly be reef controlled. If positive structure is the cause of thinning, then a structural inversion is indicated to have occurred between Cincinnatian and B-unit time, reversing the up and downthrown sides of the fault in that area. The C-shale (Plate 7) thins along the northeast side of the Lucas-Monroe in Washtenaw County, but an area of anomalously thick C-shale traverses the fault line, making an evaluation of the positioning of fault blocks vague.

Along the Howell fault, the thinning of the Utica northeast of the fault line indicates that the up and downthrown sides of the fault were positioned as they are today with the upthrown side to the northeast. An exception to this trend exists in central Livingston County where the orientation seems to have been the opposite. During Cincinnatian time, the general thickening of sediment on the northeast side indicates that structural inversion occurred. The fault blocks in central Livingston County also experienced inversion, as a reversal of the thickness trends prove. Anomalous thicknesses of the B-unit (Plate 6) are related to the Howell fault, as they are to the Lucas-Monroe, but the structural significance is similarly unclear. During the deposition of the C-shale in the Late Silurian, it appears that separate parts of the Howell fault were moving or had moved in opposing directions relative to one another. The southeastern "third" of the fault was downthrown on the northeast where the shale thickens, while the northwestern "third" of the fault was upthrown on that side where the shale thins. This provides support for separating the Howell into at least three shorter faults, along which movement was not identical or synchronous.

The Utica and the Cincinnatian thin over the Lapeer anticlinal nose. This indicates that either this area was positive during the Late Ordovician when these units were deposited, or that after the Utica was deposited, uplift began causing erosion of this shale, and prevented the even deposition of Cincinnatian sediment. By the time of the B-unit deposition, this area was no longer positive, or had ceased to experience uplift.

A marked contrast of thickness is seen in north central Jackson County during the deposition of the Utica shale, in Late Ordovician time. An anomalous thin area lies directly adjacent to an extremely anomalous thick area. This is evidently a growth fault, along which movement began as the Utica was being deposited. To the northeast downwarping created a low area into which the shale thickened. To the southwest, uplift caused the Utica to thin. Based on these changes in thickness, a northwest-southeast trending fault is indicated.

The epicenters of earthquakes occurring in Michigan since 1872 bear no direct relationship to the faulting pattern as revealed in this study. Epicenters are plotted relative to faults in Fig. 12. The roman numerals indicate intensity on the Modified Mercalli Scale. None of the epicenters fall along a fault line. The only pattern to be discerned is that epicenters are concentrated in south and southeastern Michigan. The 1967 quake of intensity IV near Lansing could possibly be related to the Howell fault, as it lies just northwest along its trend. The only conclusion that can be made is that since 1872 no movement detectable by seismic instruments has occurred along the faults in southeastern Michigan.

CONCLUSIONS

Southeastern Michigan is dominated by three major structural features -- the Lucas-Monroe Monocline, the Howell Anticline, and the Sanilac County Monocline. All three of these structures are faulted on the southwest side, with the faults downthrown to the southwest. The axes of these and other folds, parallel the trend of the southeastern limb of the Mid-Michigan gravity and magnetic anomalies, which probably overlie a graben of Keweenawan age. These three major structures and the minor features associated with them are controlled by a combination of vertical movements of basement fault blocks, and a horizontal shearing force derived from tectonic events outside the basin and culminating at the end of Mississippian time. Structure in the Michigan Basin as a whole is controlled by a rectilinear pattern of faults and fractures in the Precambrian basement. This fracture pattern originated early in the Precambrian history of the region.

Isopach map trends confirm that faulted structures were intermittently active during much of Paleozoic time. Alternating thick and thin trends occurring in different periods over the same area indicate that structural inversion of fault blocks has occurred. Since all of the four isopached units chosen for this study show anomalous patterns of thickness in the faulted areas, it is a reasonable assumption that movements were occurring along these faults throughout the Paleozoic. Variations in thickness of a stratigraphic unit along the same side of a fault indicate that movement was not uniform along the strike of these longer faults.

The epicenters of recent earthquakes in Michigan are not located along known faults in southeastern Michigan. These are minor earthquakes (maximum VI on the modified Mercalli scale) and may be associated with lesser faults.

The lack of conglomerate and arkose in the geologic column does not support the theory of basin origin which requires sinking under sedimentary loads derived from mountain ranges in either Wisconsin or the Cincinnati Arch area. The irregular pattern of subsidence in the Michigan Basin is not compatible with a single upper mantle-lower crust heating event. None of the present explanations of basin subsidence fits the observed pattern of formation thickening and fault movement observed in southeastern Michigan.

Albion-Scipio, the only giant oil field in Michigan, produces from a dolomitized zone in the Ordovician, Trenton and Black River Formations. The linear nature of the field indicates a fault origin. The trend and spacing of faults described in this study may be an aid in exploring for fields of this type.

APPENDIX A

APPENDIX A

Cross-Sections

These three cross-sections (Fig. A-1) illustrate the structure and comparative magnitude of the major folds in southeastern Michigan, as seen on the Dundee. These folds exhibit limbs with dips of sufficient steepness to suggest they reflect faulting in basement rock. The displacement across these large features is probably the result of slippage along several roughly parallel faults rather than along only one. Multiple faults are shown diagrammatically in the cross-sections, their exact locations are unknown. It is known that the Sanilac Fault is probably a reverse fault. A geophysical well log from Sanilac County (Fig. 18) records a repetition of section that may be the result of reverse faulting. The direction of the fault angle is not known, but is arbitrarily drawn for the purpose of illustrating the type of faulting present. The geographical positions of the cross-sections are illustrated in Figures A-2, A-3 and A-4.

Cross-section A-A' of the Bowling Green Fault illustrates this features monoclinal character. The displacement along the fault at this location is 850 feet. It can be seen from cross-section B-B' of the Lucas-Monroe Monocline, and the Howell Anticline, that these are the two most prominent features in southeastern Michigan. The displacement along

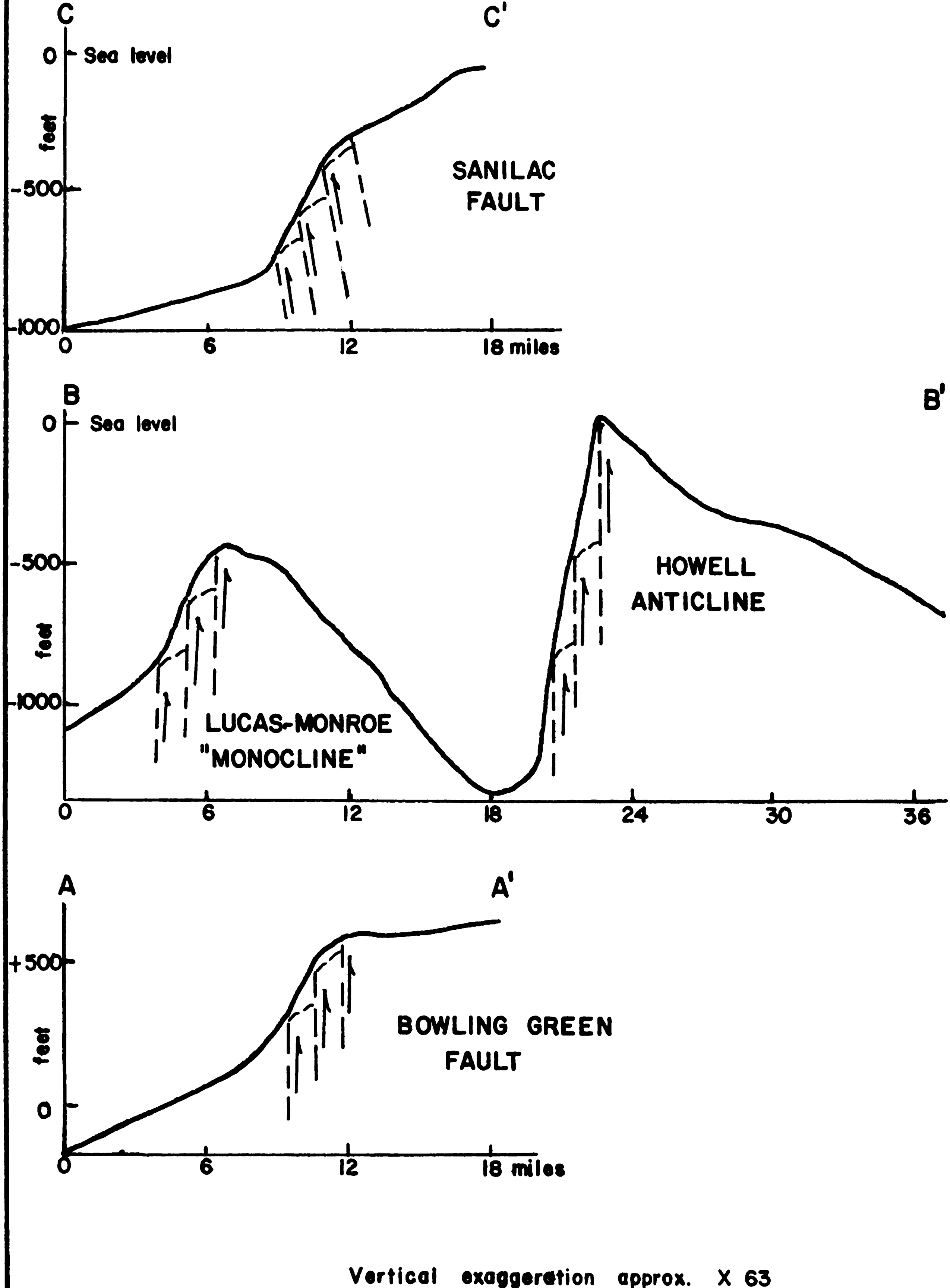


Fig. A-1. Cross-sections.

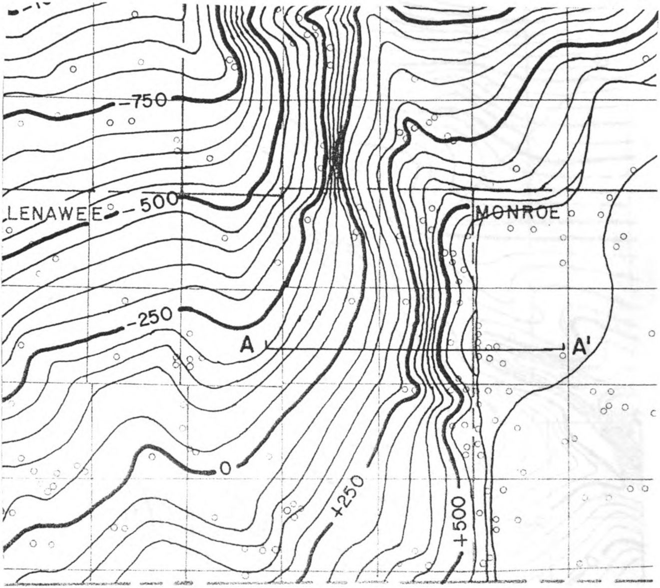


Fig. A-2. Location map, cross-section A-A'.

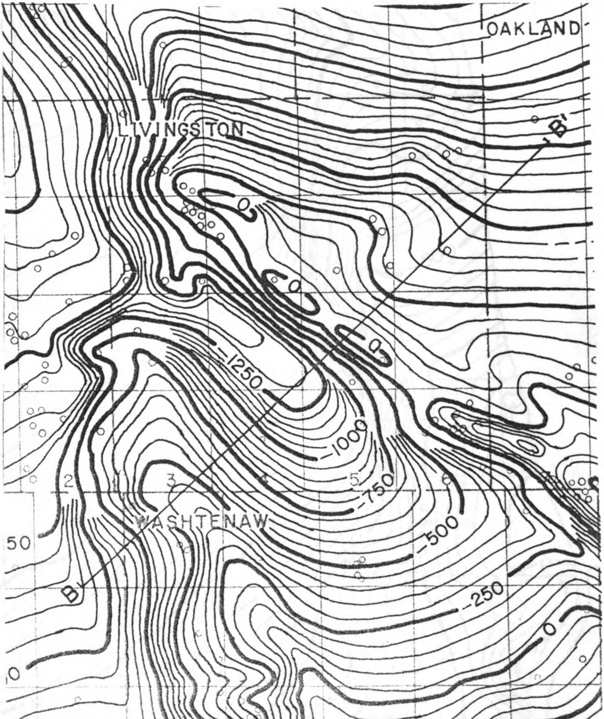


Fig. A-3. Location map, cross-section B-B'.

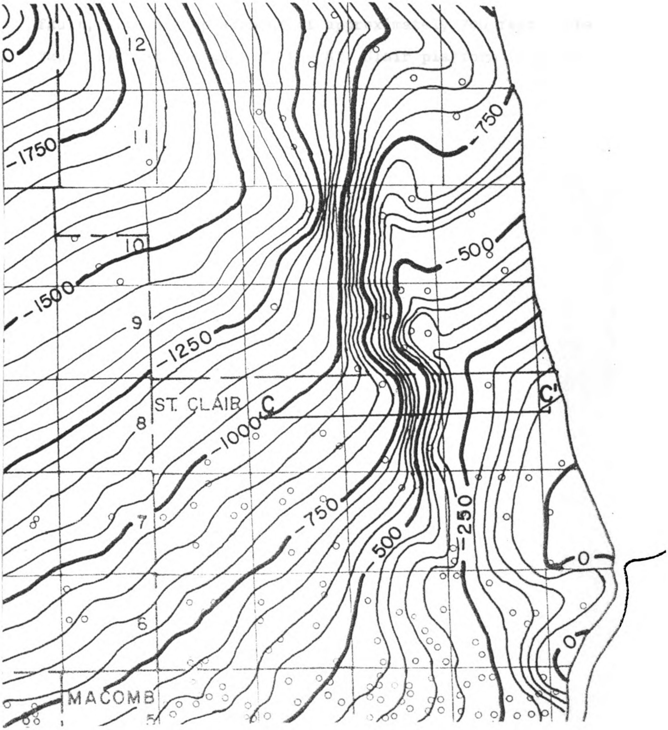


Fig. A-4. Location map, cross-section C-C'.

them is 650 feet and 1,300 feet, respectively.

The Sanilac Fault in cross-section C-C' is a reverse fault, with a displacement of approximately 700 feet. The fault lies at the edge of the St. Clair platform (Fig. 5).

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