STATE OF MICHIGAN
DEPARTMENT OF CONSERVATION
George E. Hogarth, Director

GEOLOGICAL SURVEY DIVISION
R. A. Smith, State Geologist

Publication 38. Geological Series 32
OIL AND GAS FIELDS OF MICHIGAN

A DISCUSSION OF DEPOSITIONAL AND STRUCTURAL FEATURES OF THE MICHIGAN BASIN

BY ROBERT B. NEWCOMBE

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN THE UNIVERSITY OF MICHIGAN

PUBLISHED AS A PART OF THE ANNUAL REPORT OF THE GEOLOGICAL SURVEY DIVISION FOR 1932

FRANKLIN DEKLEINE COMPANY
PRINTERS AND BINDERS, LANSING
1933

Contents

Illustrations

Figures

Tables

LETTER OF TRANSMITTAL

To the Honorable, the Director, and the Board of Commissioners of the Department of Conservation of the State of Michigan:

Hon. George E. Hogarth, Director
Hon. William H. Loutit, Chairman
Hon. Harold Titus
Hon. Philip Schumacher
Hon. Harry H. Whiteley
Hon. George C. Fowler
Hon. M. J. Fox
Hon. Philip K. Fletcher
Hon. Ray E. Cotton, Secretary Gentlemen:

I have the honor to present herewith a report of monographic proportions on the Oil and Gas Fields of Michigan by Dr. Robert B. Newcombe, Petroleum Geologist of the Geological Survey staff, with the recommendation that it be printed and bound as Publication 38, Geological Series 32, of the Geological Survey Division, Department of Conservation. This report was conceived with the discovery of the Muskegon field late in 1927 and has been in preparation since the beginning of 1931. It is largely a subsurface study of the stratigraphical and structural geology of the State from well records of all kinds, including logs, cuttings, and cores, and will supplement previous publications 14 and 37, now out of print.

Much time was spent in the Muskegon and Mount Pleasant districts, as well as in scattered sections of the State where "wildcat" drilling operations were in progress. Nearly all of the important tests were visited and the report includes much technical and statistical matter with respect to the oil and gas industry of the State. Since 1926 Michigan has risen as an oil producing. State until in 1932 it ranked above all the eastern states except Pennsylvania. This is largely due to increased knowledge of its structural geology, which led directly to the discovery and development of the Central Michigan pools.

This geological knowledge is the basis for directing the search for new oil and gas pools, and is embodied in the comprehensive report following. From known facts arise new theories, which if essentially correct and workable, are valuable guides in prospecting relatively unknown areas. The general distribution and major geological structure of the rocks in the State and certain conceptions of the origin and growth of the so-called Michigan Basin are presented in the first part of the report. In the second part a fuller description of the different proved structures and of the known oil and gas fields is given, together with the economic and technical aspects of their development. The report is concluded with a brief outline of the results of drilling operations outside the known fields in the less explored counties.

As an oil producing State, Michigan is relatively young, but up to the end of 1932 it had produced over 20 million barrels of oil. New pools are being discovered almost every year. Several known structures of considerable size are still untested and other structures doubtless will be discovered with further drilling. Some of these structures doubtless will prove to be commercially productive of oil and gas.

The value of this report to oil and gas operators and citizens of the State should be large and its effect far-reaching. It must be emphasized, however, that despite the large amount of study given, many of the conclusions and conceptions advanced are merely tentative. They are intended to guide prospecting for oil and gas in Michigan more intelligently, and, it is hoped, more effectively and profitably.

Much is still to be learned about the structure of the rocks in many areas of the southern peninsula. These areas are for the most part underlain with known oil and gas producing horizons. They are, however, mantled with such thick cover of glacial deposits of sand, gravel, and clay that preliminary exploration is expensive and costs of development may be locally almost prohibitive. Notwithstanding these unfavorable factors, exploration is extending successfully into several areas of thick drift, especially in the line of known "anticlinal structural trends."

On the whole, geophysical methods of prospecting have not been particularly successful in locating favorable structures, although they have been known to check some of the known structures. Test drilling by core and hollow rod methods has revealed several large anticlines and definitely outlined others. Most of this testing has been done by operating concerns with small tools and under our oil and gas laws the details of these discoveries are not freely accessible.

The successful use of geophysical methods in the past few years has made the uninitiated more susceptible than ever to the wiles of the "doodlebug" operator and his extravagant claims of success for instruments of every size and description, though these almost without exception are not based on any known scientific principle. Against such claims the unwary must be on continual guard or else be led into unsound speculation where hazards are usually greater than the average for the petroleum industry.

The role of the promoter in the oil and gas business is an important one, and "wildcatting" or drilling in undeveloped territory is his forte. It seems fitting here, however, to sound a warning against inequitable "deals" in which some promoters figure. The magic charm of the word "oil" has spelled and always will continue to spell riches to the man of comparatively small means. If he wishes to take a long chance in a well of highly uncertain possibilities he should at least take the precaution to investigate the share which his dollar will reap in the undertaking, as compared to that of the promoter.

The production of oil in Michigan hast thus far been largely from porous limestone "pay" horizons in rocks of Devonian age. This fact has led in the past year to the perfection of a method of acid treatment for increasing output from both new and old wells. This new method for increasing oil and gas recovery will probably do in limestone producing horizons what shooting did previously in sandstone horizons. This very promising advance in technical practice is being closely watched in all sections of the country where oil and gas are being produced.

The future of Michigan's oil and gas industry now seems bright and its possibilities are only beginning to be revealed, but our attitude should be one of conservative optimism. The costs of discovery and development apparently will be relatively large in comparison to many other districts, although there are doubtless many relatively shallow fields still to be discovered. The geologic background of the Michigan Basin is so nearly similar to that of the surrounding states of Ohio, Indiana, Illinois, and Kentucky, and the Province of Ontario, where oil and gas have long been produced, that it is logical to assume that similar fields and production will be developed in Michigan.

The accompanying report should greatly aid in this development.

Very respectfully,
R. A. SMITH,
State Geologist.

June 15, 1933.

OUTLINE OF REPORT

Michigan has joined the rank of states which produce important quantities of oil and gas. The petroleum industry has contributed a large amount of geological data relative to features of deposition and structure of the region, particularly in the southern peninsula of the State. The information gained from drilling operations has shown more exactly than heretofore the succession of sedimentary beds in many areas. Strata of relatively the same age can now be correlated from one part of the State to another with much greater ease and certainty than in the past. The stratigraphic section is well known in certain districts where a large number of wells have been put down. The differences in the geological column in these separate districts suggest new theories of the history of sedimentation in the Michigan Basin. The complete history of deposition is still vague, because of the lack of adequate paleontological studies of the well cuttings and cores. This report brings together and attempts to coordinate numerous facts concerning the depositional and structural history of the Michigan Basin province.

Structural features in the rocks of the Lower Peninsula of Michigan are determined chiefly by comparing samples and logs of wells and drawing subsurface contour maps. The scarcity of rock exposures in most of the State restricts the study of both the major and minor structures largely to this method of approach. Geophysical prospecting has not been particularly successful in southern Michigan for locating anticlinal structures, and deep wells and shallow test holes have been the chief source of our knowledge of structural conditions.

It is shown by areal geology maps, structural contour maps, thickness maps, and the general nature of sedimentation that the basin is a somewhat elongated sedimentary trough or possibly a geosyncline. The close relation of the smaller anticlines and synclines to this large regional structure is suggested. A theory is advanced to explain the origin of the Michigan synclinal basin. This Basin probably began at about the same time as the Lake Superior geosyncline and developed through successive periods into its present form and area. The development of the Basin is traced so far as the structural and stratigraphic data permit. The various known periods of folding that have affected the Basin are listed in an attempt to account for the possible origin and explain the characteristics of the better known structures which have caused the accumulation of commercial pools of oil and gas. Some of the forces and factors which may have controlled and modified these structures are also suggested.

The various local anticlinal folds in Michigan, best known from the results of recent drilling, differ somewhat in form but all seem to have certain, definite, common characteristics. These folds have unequal dip on each flank, and the steeper dip is usually on the side toward the center of the Basin. The general trend is northwest-southeast with the direction varying from N.40°W. to N.50°W. The trapping of pools of oil and gas seems to have been more or less localized by cross folding varying in direction from east-west to northeast-southwest. Most of the synclines or troughs are wide and flat in comparison to the anticlines. Strong lines of folding in the central portion of the State extend for long distances, but the individual anticlines are interrupted at intervals and offset in echelon or staggered fashion.

The outstanding depositional and structural features of the Michigan Basin region are compared and differentiated to show the general historic background of the structure of this isolated province. The objects sought are a fuller understanding of the origin and development of the great downwarped area, an explanation of its geosynclinal characteristics and a conception of the causes for its periodic isolation during geologic history. The solution of these problems depends on the completeness of the data in the different parts of the area and the correct interpretation of the facts,

The discussion follows under two main headings: General Geology and Economic Geology.

Part I—General Geology deals largely with the stratigraphy and structure of the Michigan Basin as a province. The chapters take up in order: Introduction, Geography, Descriptive Geology, Historical Geology, Structural Geology, and Theory of Origin and Growth of the Michigan Basin. In each chapter, the subjects are treated with the purpose of trying to solve the major structural problems of the Michigan Basin, the solution of which would largely explain the characteristics of the minor anticlines where commercial quantities of oil and gas might be expected.

The introduction deals largely with means and methods of developing this report, and sources of information are outlined. The Michigan synclinal basin is described along with a historical review of previous ideas concerning this large major structure. General conditions in the area are summarized.

In outlining the geography of the region, the various surface features are discussed, and the outstanding regional features of ground relief and drainage are described. The setting of the Michigan Basin with respect to other physiographic provinces together with the isolation brought about by the basins of the Great Lakes is shown.

The chapter on descriptive geology includes a description of Michigan rocks in the order of age. From oldest to youngest are the underlying Crystalline Rocks or Basement Complex, the overlying Paleozoic strata, and the Pleistocene or surface deposits of glacial origin. The Paleozoic formations of Michigan are listed and described. The formations of each period are tabulated and correlated with comparable strata in adjoining states or provinces. In some cases, they are also compared with the classical type section of New York State.

Historical geology is a reading of past events as shown by the rocks. The events in the history of deposition in the Basin are given in order from the Cambrian period to the present, and the climatic and physiographic factors influencing the sedimentary history are postulated. The various invasions and recessions of the sea with respect to the land and the tiltings of the Basin are also considered. The configuration of the Michigan Basin during successive periods is shown by means of equal thickness or isopach maps for the formations laid down after Salina time. The formations below the Salina have not been penetrated by the wells in the central part of the State. The known formational overlaps are described, and the possible events bringing about these overlaps are suggested. The history of the surface features of Lower Michigan is traced, and the remnant features of pre-Pleistocene (before the Ice Age) topography, so far as known, are shown by a contour map of the bedrock surface. Conclusions or inferences as to the nature and extent of pre-glacial drainage systems are drawn from this map. The possible origins of the topographic basin in central Michigan and the basins of Lakes Michigan and Huron are also discussed.

The structural geology of a region is partly reflected by the distribution of surface rocks. This is shown by a revised map of the areal geology of the southern peninsula, on which there are several new formation contacts. The conditions of overlap and the amount of formation thickening into the central area of the Basin is illustrated by stratigraphic cross sections. The results of folding in the rocks of Lower Michigan are shown graphically on a regional structural contour map. An analysis of the recognized periods of folding and the different disconformities completes the discussion.

The proposed theory of origin and growth of the Michigan Basin is simply a hypothesis which seems to fit the conditions as known. In advancing this theory, the Basin is shown in its larger structural features to have many characteristics of a geosyncline. It seems by analogy to be similar in many respects to the Appalachian geosyncline and probably originated at the time of the Keweenawan movement. The source of the pressure was apparently to the northeast. Through periods that followed, the major and minor directions of the somewhat elongated basin were greatly modified by crustal disturbances originating from other directions. These later disturbances restricted it at successive times and brought about salt forming conditions. The cause of the forked outline of the Cincinnati arch is correlated with the movements affecting the Michigan Basin area, and the west branch (Wabash arch) probably originated much prior to the east branch. Aside from the primary structural factors that control the direction and alinement of folds in Michigan, there are several secondary factors. Among these modifying secondary structural factors, which have locally altered the direct warping effects of deformation, are included deep seated faulting, vertical compaction, solution, expansion, and reefs. The persistent structural trend lines give opportunity for speculation on the possible prolongation of folds beyond areas where drilling has been carried on. The surface features, which show angular arrangement and direction conforming with the general structural pattern, are pointed out. Important among these are the angular shore features along the Great Lakes, the comparatively long narrow lakes fringing the Lake Michigan shore, the pattern of drainage lines, the topographic features formed by glacial action, and the configuration of the bedrock surface. The relation of rock structure in mining districts of northern Michigan and of hinge lines of post-glacial uplift to zones of weakness is also noted. The correspondence of zones of structural weakness to the "hinge lines" may result in a fuller knowledge of the causes of post-glacial tilting and uplift movements.

Part II—Economic Geology deals with the application of geology to oil and gas operations in Michigan and takes up the discussion of structures where oil and gas have been found. The chapter headings are Oil and Gas Structures, Muskegon Structure, Central Michigan Structure, Howell Structure, and Undeveloped Structures. The fields are discussed separately with reference to their physiography, history, stratigraphy, structure, production, conditions of operation, and individual peculiarities. "Wildcatting" undertaken in search of new fields is summarized by counties.

The fundamental principles of oil and gas accumulation and the role played by geological structure in localizing oil and gas pools are briefly given. There are many conditions under which oil and gas may be found, and the principal ones are outlined and tabulated. The

Michigan structures containing oil and gas are fairly typical anticlines and domes. The structures fully described in previous reports are briefly mentioned.

The Muskegon structure is peculiar in shape and in the nature of its oil and gas producing horizons. The anticline is elongated east and west, although the axis or top of the fold is an arc which bends southeast giving it a "pistol" outline. The Traverse, "Dundee," and Monroe producing horizons are at different intervals below the tops of the formations and carry larger quantities of natural gas than those in the central part of the State. The intensity of folding w about the same in the Devonian as in the Mississippian beds, but the structure is offset or largely gone at depth beneath the Salina rock salt strata. The water conditions at Muskegon are rather typical of limestone fields, and the brines are of high concentration. The development of the field is now in its last stages.

The Central Michigan structure includes two more or less parallel lines of folding, the Greendale and Broomfield "highs." Several oil and gas pools have been discovered along the Greendale high and one gas pool on the Broomfield high. The area illustrates well the echelon or staggered arrangement of individual anticlines and domes and the relatively great width of the synclines in comparison to the anticlines in the central part of the Basin. The producing structures are known as the Mount Pleasant structure and East Extension, Leaton structure, Vernon structure, Broomfield structure, Clare structure, and Porter structure. The nature of the Dundee oil production with the relatively small amount of associated gas in the "pay" horizons is typical of fields centrally located in a major depositional basin. There is some production in the Traverse and Monroe. Gas and a small amount of heavy oil is found in the Michigan "stray sand" a short distance above the Marshall. The properties of the crudes vary progressively in the different fields toward the center of the Basin, increasing in gravity from 40.4° to 44.5° Be. Water conditions are not uniform throughout the area. The brines show certain progressive changes in composition with depth which, although not always regular, indicate an increase in specific gravity, calcium chloride, potassium chloride, and bromine, and a decrease in sodium chloride. The disconformity at the top of the Dundee limestone is an important factor limiting the extent of the productive areas.

The Howell structure is the most pronounced individual structure known in southern Michigan. It seems to be a broad feature, but the highest dome mapped on the crest of the fold is comparatively narrow. The southwest flank of the anticline dips very sharply for Michigan structures, and there is good evidence that this side of the fold is steeply faulted, at least in the Devonian beds. In size and general characteristics, the structure compares very closely to the LaSalle anticline of Illinois. The highest part of the dome has not been tested for oil and gas, but a small producing gas well was found in the immediate vicinity of Howell. It is thought that much of the oil and gas that might have accumulated in the Berea, Traverse, Dundee, and Detroit River has escaped because of fracturing in the rocks. The deeper possibilities in the Salina, Niagaran, and Trenton have not been tested. Structurally, the area is an important feature in the explored portion of the Michigan Basin.

The undeveloped structures of Michigan have not been very thoroughly worked out and, except where core drilled, simply represent the projected trends of known anticlines. For this reason, their exact locations and intimate features are indefinite. These structures are discussed by counties, taking up first the scope of developments and the general nature of the folding, and then the findings in individual "wildcat" wells. The counties where no important showings of oil and gas have been found are taken up separately, under the heading of miscellaneous counties.

PART I—GENERAL GEOLOGY

Chapter I. INTRODUCTION

REASONS FOR THE REPORT

Until the beginning of extensive oil and gas development in 1926, the details of bedrock geology in the Lower Peninsula of Michigan were practically unknown except in a few small areas. No part of the United States is so deeply buried and completely covered by glacial deposits as this great peninsula. Searching for truths of correlation and sedimentary history in this expanse is like a navigator on an uncharted sea. The geology of its borders is slightly known, but the interior district contains county after county about which practically no stratigraphic information has heretofore been made available. As a result, this fascinating area with its unique conditions has never received from geologists the attention it rightly deserves.

Fortunately, developments in the last five years (1926-1931) have served to largely remove this difficulty. The discovery of oil at Saginaw, Muskegon, and Mount Pleasant resulted in the drilling of over 1,600 wells in various sections of Lower Michigan. The deep wells: have been sufficiently scattered to afford a large amount of reliable stratigraphic and structural data. These wells, together with test drilling and coring operations, have furnished many records and sets of samples which await further study.

NATURE OF THE REPORT

This report consists of a consolidation of all the known geological data into a regional study with particular emphasis on depositional and structural features. The limitations of subsurface determinations due to the regrettable lack of paleontologic verification are recognized. It is hoped, however, that the geological data herein compiled and analyzed will serve a useful purpose and many perplexing questions will be at least partly answered. Those conclusions which are debatable may possibly open some new thought and a more thorough investigation of the facts may thereby result.

Subsurface studies of the several productive oil field areas are included to give an idea of some of the more minute details of structure and its effect on sedimentation. The fields included in particular are those near Muskegon, Mount Pleasant, and Howell. The last named has not been developed to the extent of the other two, but it is discussed because detailed information is available, the structure is the most pronounced of any known structure in the State, and the sharply folded and apparently faulted character of its southwest flank presents unusual conditions.

SOURCES OF THE DATA

The sources of data for this report have been widespread. Reconnaissance observations have been made in nearly all the areas of outcropping rocks in the southern peninsula and in numerous localities of the northern peninsula. Several places where the rocks concealed in Michigan come to the surface in bordering states have likewise been visited for purposes of comparison. The available well data have been compiled, tabulated, and plotted in graphic form. A great many sets of samples have been examined, both on file in the Geological Survey office and in oil company files about the State. Frequent visits have been made to well operations for the purpose of securing "first hand" supplementary data and to the geological surveys of the neighboring states for making comparative studies of well cuttings.

LIMITATIONS OF THE GRAPHIC MATERIAL

The numerous computations of the thickness of strata and of the depths of the various formations with reference to sea level are not shown on the finished maps because of their small scale. Moreover, graphical representation of features of deposition and structure by means of contour maps is more clearly portrayed without a confusing mass of statistical detail.

Complete summaries of the thicknesses of the different formations in separate well sections and the plus and minus datum numbers showing elevation of the several key beds or horizons would consume more space than the present work will allow; hence, these figures together with hundreds of detailed well logs are omitted from this report. The factors of correct interpretation and proper ethical use of the information available have been taken into consideration. The tabulated summaries and original maps are in the files of the Michigan Geological Survey which in most cases may be consulted for purposes of comparison and verification.

As additional information accumulates from the results of new drilling, many of our present conceptions of depositional and structural features in the State will have to be changed. The results of this compilation are by no means final, and the purpose of the study is to bring together and coordinate the known facts that new facts as discovered may be better interpreted. Wells that are to be drilled in the Michigan Basin region in the years to follow will doubtless alter present ideas of stratigraphical and structural geology in a marked degree. Drilling operations are continually bringing forth rock material which forces reexamination of theories and working hypotheses which were once considered fixed or practically proved.

A publication of this type must be somewhat technical for obviously geological facts can be given best in terms of geological usage. Every effort, however, has been made to define words and explain phrases which would be unfamiliar to the average reader. Simplicity has been sought without destroying scientific exactness, and the end desired is a statement of conditions which will be within the grasp of everyone who may find occasion to read this report.

ACKNOWLEDGMENTS

complete acknowledgment of aid and cooperation which furthered the preparation of this report is difficult. The sources were varied and included not only the literature having direct relation to the problem at hand, but also articles gleaned from trade journals, and many personal communications in the field and office. The association of men concerned with development of oil and gas resources in Michigan continually stimulated the pursuit of this undertaking.

The reports and publications of the United States Geological Survey, the United States Bureau of Mines, the Geological Survey of Canada, the Ontario Bureau of Mines, the Michigan Geological Survey, and the Geological Surveys of surrounding states have frequently been consulted. Many pertinent articles in publications and bulletins of learned societies, such as the Geological Society of America, American Association of Petroleum Geologists, Michigan Academy of Science, American Institute of Mining and Metallurgical Engineers, and many others were reviewed. Periodicals like the American Journal of Science, Journal of Geology, and Economic Geology, were frequently consulted, and many articles from sources that cannot be fully enumerated were read.

The study of structural and depositional features in Michigan was prompted by connections with the Michigan Geological Survey and the great mass of important well data which in the past few years had rapidly accumulated in the State. The outline of the scope of the report was submitted to R. A. Smith, State Geologist, who aided in the writing, the mapping, and the final compilation by giving many suggestions from his wide experience with intimate features of Michigan geology. Several unpublished reports by W. I. Robinson, formerly with the Michigan Survey, were very helpful in writing the descriptive geology of the State.

The members of the Michigan Geological Survey staff gave much assistance by their whole-hearted cooperation. A large amount of field data for the Central Michigan Area were obtained by F. M. Anderson and F. H. Loveday, and the Muskegon Field was scouted by W. L. Daoust C. Harold Riggs. O. F. Poindexter examined many of the well cuttings and F. E. Frye, Petroleum Engineer, carried on a great deal of the compilation and made rough drafts of several cross-sections. Lyle Price prepared a large number of the graphic logs and George Granger and Robert Thompson did most of the drafting.

Geologists employed in Michigan by the several operating oil companies furnished a large amount of data and these men have been frequently consulted on problems of correlation and details of structural interpretation. Of this group, W. A. Thomas, George W. Pirtle, G. A. Foster, Virgil E. D. Kirkham, Kurt deCousser, Hugh D. Crider, V. G. Hill, and Ralph Melhorn offered helpful suggestions and constructive criticisms of the work while in progress. Several other geologists have also given assistance.

Much information has been gained from members of surveys and institutions of adjoining states. Particular thanks are due R. B. Harkness, Commissioner of Natural Gas in Ontario; Prof. J. E. Carman, Ohio State University; A. H. Bell and L. E. Workman of the Illinois Geological Survey; Ira Edwards and Gilbert O. Raasch of the Milwaukee Public Museum; and F. T. Thwaites of the Wisconsin Geological Survey for kind communications and personal references. Prof. G. M. Ehlers of the University of Michigan; Prof. E. R. Cumings of Indiana University, and Prof. W. A. Kelly of Michigan State College have greatly assisted in matters of correlation and stratigraphy.

Special acknowledgment is due Prof. W. H. Hobbs of the University of Michigan, under whose inspirational guidance this work was attempted. Prof. A. C. Lane of Tufts College and Prof. C. M. Nevin of Cornell University were consulted on a few of the stratigraphic and structural problems. Prof. C. W. Cook of the University of Michigan was constantly in touch with the progress of the work and assisted in the preparation of the manuscript. Prof. E. C. Case, A. J. Eardley, and D. C. Chapman also made helpful suggestions.

The writer is particularly grateful to the officials of numerous oil companies, the Michigan Well Drillers Association, and the field scouts who secured much statistical material. Members of several divisions of the Department of Conservation offered frequent courtesies which were very helpful in the completion of certain sections. Finally, much appreciation is due Miss Thelma T. McBeavy who aided in the details of preparation.

GENERAL DESCRIPTION OF THE MICHIGAN BASIN

The Michigan Basin designates an area of stratified rocks classified on the basis of the major geological structure which underlies it and largely governs its subsurface and surface features. The center of the territory embraced is the approximate center of the southern peninsula of the State of Michigan and because this point is structurally lowest, the rocks cropping out on the margins are to be found at greatest depths in the central area. This structural and depositional province is styled a "basin" because the dimensions in any direction across it are so nearly the same. The surface expression of the rocks comprising the province is less symmetrical around the borders than near the center where outside structural controlling factors are less effective. The outline of the outcropping rocks occupying the central part of the surface area is more or less elliptical with the major axis of the ellipse extending in a northwest-southeast direction. The major and minor diameters of this ellipse as indicated by the outer boundaries of the Pennsylvanian rocks are in the ratio of about 4 to 3 which is far from the early conception of an almost circular basin structure.

The term "synclinal basin" was used by Van Hise and Leith[1] and is accepted as being more truly descriptive of the exact structural relationships which exist throughout the region than any other caption. A "syncline" is a geological term indicating a down-fold in the rocks and is usually related specifically to a "canoe-shape" warping which pitches from both ends towards the center and whose longer dimension is noticeably greater than the transverse. It is evident from the structure of the province that it is a syncline in character, and details to further support this statement are exhibited in the thickness of the sediments and the directional relationships of the minor folding discussed in later paragraphs.

AREA COMPRISING THE MICHIGAN BASIN PROVINCE

The area comprising the Michigan Basin province includes about 106,700 square miles and stretches from Fort Wayne, Indiana, on the south, to Whitefish Point near Sault Ste. Marie, Michigan, on the north, and from west to east about 370 miles. The State of Michigan makes Canada, on the east. The distance from north to south is about 410 miles and from west to east about 370 miles. The State of Michigan makes up nearly half of the province and another third includes Lake Michigan and Lake Huron, which are entirely within the area. Small portions of the states of Wisconsin, Illinois, Indiana, Ohio, and the province of Ontario, Canada, account for the remainder of the Basin province as shown in Figure 1.

By far the largest continuous land area in the Michigan Basin province is the southern peninsula of Michigan. This area embodies 38.5 per cent of the "basin" or 40,789 square miles. The shape of this peninsula resembles a mitten, and the area northeast of a line from Bay City to Port Huron is commonly called the "Thumb" district because it corresponds to the thumb of the mitten. Frequent reference to the "Thumb" will be made in describing this part of the State. Since the discussion will be largely confined to geological conditions in the southern peninsula, the term "Michigan" will apply only to the Lower Peninsula unless otherwise designated.

PECULIARITIES OF THE AREA

Although small portions of the Michigan Basin occur in other states, the greater part of the area is entirely isolated by bodies of water. Generally, it is extremely difficult to follow rock formations from one state to another where the state boundaries are merely arbitrary lines and gaps in exposures are relatively small. In Michigan, it is even more difficult to correlate the beds with those in bordering states because the Great Lakes serve as a natural barrier in tracing formations from the nearest localities where they have been more thoroughly studied. Deductions about the continuity of beds must be drawn by methods other than direct comparison between outcrops.

The southern peninsula is bordered in every direction except to the south by a major body of water. Lake Michigan on the west, lakes Huron and Michigan on the north, and lakes Huron, St. Clair, and Erie on the east, entirely separate this part of the State from other areas where similar rocks are exposed at the surface. In working out the geology of the region, the question arises as to what has happened throughout geological time where these great expanses of water now exist.

The known rocks which underlie the southern portion of the State are entirely of sedimentary origin; that is, they were laid down as sand and clay, or lime muds in great bodies of water of shallow marine inland which somewhat resembled our present Great Lakes. In the formation of these rocks, the waves worked on the shores of the land masses which remained above water during the various geological periods. During a greater part of the time when the sediments were being deposited, this part of Michigan was occupied by a somewhat isolated sea in a relatively similar position to the Lower Peninsula now. As a result, the rocks which were formed are mostly peculiar to this area alone, and find no exact counterpart in adjoining regions.

In a similar fashion the southern peninsula was in general structurally isolated, and the great earth movements which caused folding of the rocks affected this area in a unique manner. The principal factor in both the depositional and structural history of the "basin" was its location with respect to the great masses of crystalline rocks. At certain times, the forces causing folding originated in these areas which were also the primary source of the sedimentary materials.

The crystalline rocks are those rocks composed of closely fitting mineral crystals as contrasted with those made up of cemented sedimentary materials. In a broad sense, the term is applied to all rocks of crystalline texture derived by crystallization from a magma (liquid molten rock or lava) and to highly folded rocks which have undergone recrystallization through the effects of heat and pressure. This class of rocks may be either old or young in age, but in the Michigan area they constitute some of the oldest rocks on the North American Continent.

To the west, northwest, and northeast of the Michigan Basin are great areas of crystalline rocks. One of these areas, situated in Wisconsin and the northern peninsula of Michigan, is known as the "Wisconsin island" because of its persistence as a land mass above water throughout the greater part of geologic time. The other, located in the province of Ontario, Canada, is known as "Laurentia" or sometimes simply the great "Canadian Shield." These great land masses have had a profound effect upon the Lower Peninsula of Michigan throughout geologic history.

The relative scarcity of outcrops in the southern peninsula of Michigan is a serious obstacle to geological study. Out of the sixty-eight counties in this area, forty are without any outcrops, and many counties contain only a single small rock exposure. Outcropping rock is most abundant in the counties bordering the Great Lakes and in the southeast and south central parts of the State. The best exposures are in the northeast corner bordering Lake Huron, where rock occurs at the surface in many places in several townships of Alpena and Presque Isle counties. A general idea of the localities in which bedrock is exposed may be obtained from Figure 2, which shows the approximate location of the principal outcrops and larger quarries. Many of the old quarries are now abandoned and partly or wholly filled with water.

HISTORICAL DISCUSSION

During their early explorations along the shores of the Great Lakes, the Jesuit Missionaries recognized some of the mineral possibilities of Michigan. Douglass Houghton[2] in his second annual report presented before the legislature in 1839 recognized the general geological structure of the State. He wrote "My examinations would lead me to infer that the coal of the central part of our state, and that upon the Illinois river, is embraced in a rock which belongs to the same portion of the great basin; . . . . .." From these remarks, we may infer that he had in mind somewhat the general "basin" structure of the southern peninsula. In a later report, Bela Hubbard[3], who was then Assistant Geologist under Houghton, outlined in greater detail the arrangement of rocks in the southern peninsula.

During the Foster and Whitney survey of the Lake Superior Land District, James Hall visited the principal localities of outcropping sedimentary rocks and made a number of fossil collections and observations. His summary[4] of the general structure of the region follows:

"The bearing and inclination of these successive groups indicate that they formed the outer margin of a great geological basin, whose greatest depression is in the Lower Peninsula of Michigan, where the surface is occupied by rocks of the Carboniferous epoch. It is only in a northern and northwestern direction, however, that we are enabled to trace the strata in a descending order quite to the lowest members of the series, and even to the non-fossiliferous series beneath them. In other directions, we find the most elevated portions of the border exposing only members of the upper, or at most of the middle, portion of the Silurian system."

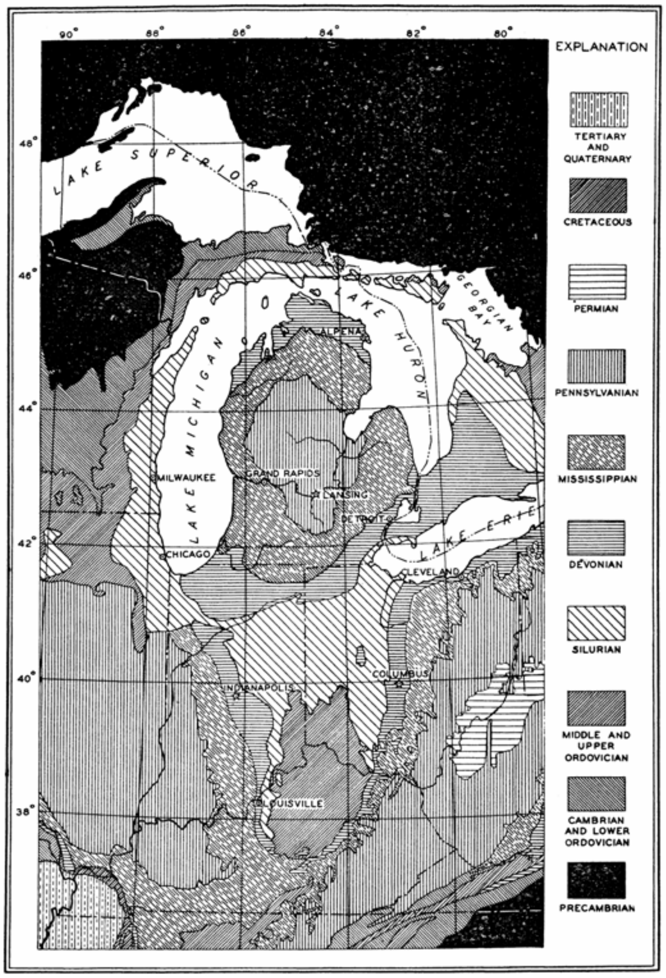


Figure 1. Geological map showing the area which comprises the Michigan Basin province. (After Bailey Willis with revisions for Michigan.

His was the first real conception of the major geological structure of the State, and the general picture as presented by him has not been greatly altered up to the present.

The common popular description of the Michigan Basin was initiated by Winchell[5] in 1860 when he wrote, "It appears, therefore, that the Lower Peninsula of Michigan is surrounded on all sides by ancient axes of elevation; and even if the surrounding regions do not in all cases actually occupy a higher level, we must expect to find the strata dipping from all sides toward the center. Each rocky stratum of the Lower Peninsula is, therefore, dish shaped. All together, they form a nest of dishes. The highest strata are near the center of the peninsula; and passing from this point in any direction, we travel successively over the outcropping edges of older and older strata. The irregularities in the shape of these dishes, will be pointed out in the sequel."

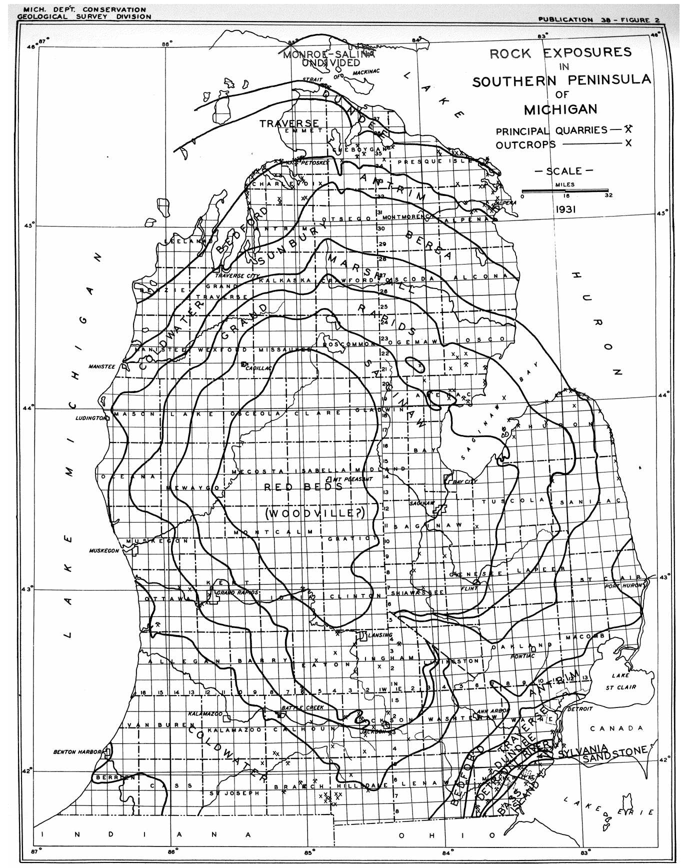


Figure 2. Rock exposures and quarries in the southern peninsula of Michigan.

This "pile of dishes or saucers" idea has prevailed up to the present day, and Michigan has been known as an almost perfect basin structure. In a broad way this notion of basin structure still maintains, but the perfection of shape and proportion is now greatly modified. Corrections to the areal geology of the southern peninsula (see pl. II) show a slight elongation of the "basin," and the subsurface contour map (see pl. Ill) illustrating the structural configuration of the rocks shows the important parallelism of folding to this axis of elongation. Additional features of deposition and structure which are to be described will illustrate that this area is an elongated basin of geosynclinal origin with characteristics which are common to great geosynclines or basins of deposition.

Early observations were limited by scattered exposures within the State and the remoteness of outcrops in adjoining states. The small amount of drilling done through a long period of years added a very limited amount of new information and preexisting views were not extensively altered. Rominger[6], Lane[7], and Smith[8], although recognizing the irregularities did not depart greatly from the idea of simplicity and regularity in the general outline and structure of the Michigan Basin.

The discovery and the development of oil and gas have helped to solve a variety of important geologic problems in Michigan which are important in commercial enterprise, as well as the assembling of basic scientific facts. Detailed records and samples from wells, accurate locations and elevations, and close examination of conditions found and materials obtained are rounding out a more complete and exact history of the rocks of the region. Deep wells have been put down during the past five years in nearly every county in the State and in almost every case accurate records have been secured. The study of these well records has given rise to a number of new conceptions of stratigraphy and structure.

[1]Van Hise, C. R., and Leith, C. K., The Geology of the Lake Superior Region: U. S. Geol. Survey, Mon. 52, p. 109 (1911).

[2]Publication of Michigan Historical Commission: Geological Reports of Douglass Houghton, Lansing, p. 175 (House Documents, 1839, No. 23) (1928).

[3]Hubbard, Bela, Fourth Report of the State Geologist: Sen. Document, No. 16, p. 137 (1841); also Publication of Michigan Historical Commission: Geol. Reports of Douglass Houghton, pp. 612-613 (1928).

[4]Foster, J. W., and Whitney, J. D., Geology of the Lake Superior Land District, Part 2: U. S. Senate Document, Exec. No. 4, Spec, sess. March 1851, p. 113 (1851).

[5]Winchell, Alexander, First Biennial Report of Progress of the Geological Survey of Michigan: p. 44 (1861); also Proc. A. A. Adv. Sci., Pt. 2, p. 27 (1876).

[6]Rominger, Carl, Geology of the Lower Peninsula: Geol. Survey of Michigan, Vol. Ill, Pt 1, pp. 2.1, 22 (1876).

[7]Lane, A. C., The Geology of Lower Michigan with reference to Deep Borings: Geol. Survey of Michigan, Vol. V, Pt. II, p. 1 (1881-1893).

[8]Smith, R. A., The Occurrence of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub, 14, Geol. Ser. 11, p. 19 (1912).

Chapter II. GEOGRAPHY

PHYSIOGRAPHY

GENERAL FEATURES

The area of the Michigan Basin falls within the broad physiographic classification of the Glaciated Plains province, which extends from the Appalachian province westward to the Great Plains and from the Ozarks northward to the Lake Superior upland and Canada. In the classification of Fenneman[1], it is one of the several divisions of the Central Lowland. All of the district is characterized by comparatively low relief, and the surface configuration is largely the result of glaciation.

The various subdivisions of the Glaciated Plains province have been differently named in various states located within the borders of the Basin. The southern peninsula of Michigan occupies the central position in the included territory and its physiographic divisions as shown in Figure 3, are the Erie lowland, the Thumb upland, the Saginaw lowland, the Northern upland, and the Michigan lowland. The Erie lowland is sometimes termed the Huron-Erie plain and the Michigan lowland may be taken as a part of the larger Mississippi lowland. The arrangement shows the uplands of the Lower Peninsula surrounded by plains partly covered by the lake waters.

The part of the Basin lying within the province of Ontario, Canada, is included in the ground relief classification of the Huron-Erie plain. The Huron and Erie plains can be separated only with difficulty because the rock escarpment which usually divides the two plains is almost imperceptible at the surface. The ridge is low and obscured by drift and this makes the two plains appear as one.

Northwestern Ohio also embodies a part of the Erie plain and the Thumb upland. Hubbard[2] divides the district into "lake plains" and "till plains." Northwestern Indiana and northeastern Illinois come within the Michigan lowland. Malott[3] calls the northwest corner of Indiana the Northern Moraine and Lake region. The part of eastern Wisconsin included by the Michigan Basin belongs in the Michigan lowland. Martin[4] names this district the Eastern ridges and lowlands. The area is essentially a belted plain and is made up of relatively parallel ridges with their steep slopes facing outward from the center of the Basin.

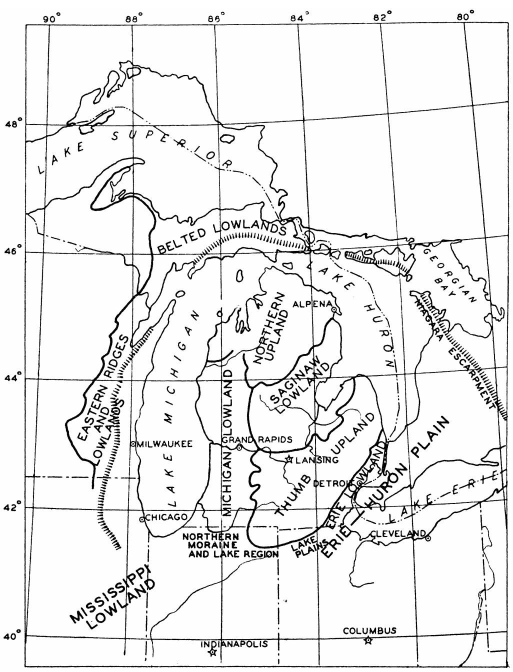


Figure 3. Physiographic divisions and subdivisions of the region included by the Michigan Basin.

The eastern part of the northern peninsula of Michigan constitutes a belted plains area and Scott[5] calls the district the Lowland province. The province is within both the Michigan and Lake Superior lowlands. The physiography is governed by resistant rock ledges and glacial deposition. Two pronounced rock ridges extend across the peninsula from east to west in a wide arc conforming to the shape of the northern rim of the Michigan Basin structure. These ridges have a steep slope on the north, and a gentle slope on the south which conforms approximately with the dip of the rocks. Such topographic forms are known as "cuestas."

An almost continuous chain of cuesta ridges partly surrounds the Basin area in a semicircular curving trend from the vicinity of Hamilton, Ontario, northwestward to the northern peninsula of Michigan and thence south through Wisconsin to a little southwest of Chicago. This feature known as the Niagara escarpment is caused by the resistant beds of Niagaran limestone. The escarpment practically outlines the Michigan Basin and only lacks typical development on the south, where it is largely hidden by glacial deposits and modified by the structural influence of the great upwarping of the Cincinnati arch. Cumings and Schrock[6] aptly describe the Michigan Basin as, "an oval area of cuesta, lake, and glacial plain, rimmed around by an almost complete circle of Niagaran limestones and dolomites, which rise into bold scarps and cliffs in Ontario, upper Michigan, and northeastern Wisconsin, but are far more subdued to the southward. To this upstanding formation lakes Michigan and Huron owe their familiar outlines, and Bruce and Dorr peninsulas and Manitoulin Island their existence."

TOPOGRAPHY

The elevations of the southern peninsula of Michigan range from a minimum of 571 feet at the level of Lake Erie to a maximum of 1,710 feet in northern Osceola County a few miles southeast of Cadillac. The greatest lake depth is in the north central part of Lake Michigan. It is about 300 feet below sea level and, therefore, the total relief of the region is approximately 2,000 feet. The average altitude of the peninsula, as calculated by Leverett, is 835 feet[7] above sea level.

The region of highest average elevation is the Northern upland, the altitude generally ranging from 1,100 to 1,800 feet. The area rising above 1,200 feet amounts to 1,500 square miles and is very largely in Osceola, Wexford, Missaukee, Crawford, and Otsego counties. Two other elevated districts are situated within the Thumb upland. These are in northern Oakland and Hillsdale counties and reach an altitude of over 1,300 feet. The Thumb upland generally ranges between 800 and 1,000 feet in elevation.

The Saginaw lowland which extends; from Saginaw Bay southwesterly into the peninsula has a general elevation between 600 and 800 feet, but it is crossed by glacial ridges which in places rise up to 1,000 feet. The Michigan lowland is generally from 700 to 900 feet in elevation and is influenced by gently rolling glacial topography. Sharp, scalloped sand dune ridges border Lake Michigan and rise abruptly to over 200 feet above the Lake, which has a level of about 580 feet.

Leverett[8] concludes that about 96 per cent of the peninsula stands at elevations between 580 feet, the approximate level of Lakes) Michigan and Huron and 1,200 feet. Of this percentage about one-half falls below 800 feet, one-third between 800 and 1,000 feet, and the remaining one-sixth, which is very largely in the northern half of the peninsula, above 1,000 feet.

The diagonal pattern of the uplands and lowlands should be emphasized, as on the east side of the peninsula each province trends in a northeast-southwest direction. The regional topography conforms somewhat to the surface configuration of the rock which underlies the glacial drift sheet mantle. This is more particularly true in the Thumb upland area than in the Northern upland, where the unusual thickness of drift material adds greatly to the total elevation. The descent on the border of the Northern upland from 1,100 feet or more to about 800 feet is rather abrupt and gives this area the appearance of a table-land. The Northern upland then slopes off gradually and is indented with river valleys which merge into the Saginaw and Michigan lowlands.

DRAINAGE

The drainage of the southern peninsula is partly to the St. Lawrence and partly to the Mississippi through the Chicago drainage canal. The divide between east and west flowing streams of the southern peninsula takes a general north-south but somewhat zig-zag course through the central part of the peninsula. The direction is locally northwest-southeast and northeast-southwest, making a rough diagonal drainage pattern which Winchell[9] recognized years ago. The Lake Michigan and the Huron-Erie drainage areas are about equal.

The principal streams head in the upland districts, and the St. Joseph is the only river system having any great amount of drainage area outside the State. The drainage is very haphazard and entirely post-glacial with youthful streams whose courses are often obstructed and result in many small lakes and swampy undrained areas.

The Saginaw river system contains the largest drainage area, amounting to about 6,246 square miles, but the Saginaw River proper is only 20 miles long. The sources of its tributaries rise in both the Northern and Thumb upland areas and its waters empty into Saginaw Bay. The stream is very unusual in having the mouth near the geographic center of its drainage area because of the great indentation of the bay.

Grand River is second in size and rises in the Thumb upland near the line of Jackson and Hillsdale counties. The drainage area of the Grand River is 5,572 square miles and its length is 300 miles, the longest river in Michigan. It empties into Lake Michigan at Grand Haven.

The third largest system is the St. Joseph in the southwestern corner of the State. This river has a total drainage area of 4,586 square miles, of which 2,916 square miles are in Michigan and 1,670 square miles in Indiana.

Other large drainage systems are the Muskegon and its tributaries draining 2,663 square miles; Kalamazoo, 2,064 square miles; Manistee, 2,018 square miles; Au Sable, 1,932 square miles; Cheboygan, 1,594 square miles; Thunder Bay, 1,275 square miles; Raisin, 1,129 square miles, and the Huron, 1,043 square miles. All the remaining streams have drainage areas of less than 1,000 square miles.

The rivers which originate in the Northern upland province, important among which are the Thunder Bay, Au Sable, Manistee, and Muskegon, have the largest amount of fall. The Rifle River, although only 45 miles In length, has a fall amounting to 725 feet, which is greater than the fall of any other river in the State. On this account the stream has cut a deep valley through the glacial drift and exposed several unusual rock ledges.

The Flint River, a tributary of the Saginaw system, has more fall than any other river rising in the Thumb upland. The Kalamazoo River of Lake Michigan drainage and the main streams which drain into lakes St. Clair and Erie also rise in this upland province.

LAKE BASINS

The lake basins of the Michigan region represent a distinct physiographic province. Hydrographic charts published by the War Department, U. S. Lake Survey show the results of soundings and give an excellent idea of the relief and configuration of their floors.

Lake Superior is the deepest of the Great Lakes, having a maximum depth of 1,290 feet and a mean depth of 800 feet. The bottom is very irregular and shows many steep slopes. The depression forming the basin of the lake is of structural origin and conforms with some regularity to the general structure of the area that it encloses. Van Hise and Leith[10] presented a map which shows by means of contours the relief of the Lake Superior Basin, together with the basin of the northern half of Lake Michigan.

The basin of Lake Michigan is usually considered to be a depression resulting from erosion. The most of its bed is between 300 feet above and 300 feet below sea level. The maximum depth is 923 feet and the mean average depth is 600 feet, with the deepest portion extending north and south from about latitude 44°20' to 44°40'. This deep part of Lake Michigan is divided into two basins[11] by a plateau 300 to 342 feet beneath water level, the northerly one being deeper than the one to the south. Soundings show the greatest depth of the northern basin to be 923 feet and the southern to be 576 feet. Grand Traverse Bay occupies a deeply cut basin which has a maximum depth of 612 feet in its east branch. An escarpment with a drop of 456 feet in a little over a mile is present along the east side of the Lake Michigan basin and numerous channels occur in the north end. Leverett[12] has drawn several profiles illustrating the relief of the bottom of Lake Michigan.

A deep portion of Lake Huron extends northwest-southeast from Presque Isle to Kincardine, Ontario. The maximum depth is 750 feet and the mean depth approximates 470 feet. Grabau[13] has traced a profile section across Lake Huron from Point Au Sable to Cape Hurd, showing the continuance of a cuesta ridge on the lake floor. Saginaw Bay is a long shallow arm of Lake Huron, extending transverse to the direction of the deepest depression of the latter. The bed of the bay is relatively flat and is usually more than 500 feet above sea level.

Lake Erie is the shallowest of the Great Lakes and in but few places exceeds 150 feet in depth. Spencer[14] states that the deepest sounding is 210 feet and the mean depth between 72 and 78 feet. The topography of the floor of the western end of Lake Erie is relatively level.

The inland lakes of Michigan constitute an important phase of the State's physiography. These lakes are of various types, but for the most part they are the result of ground water filling in the depressions left by the irregular deposition of the materials during the retreat of the ice sheet. Many of the lakes of this origin have been modified later by inundations of the glacial Great Lakes in their various stages and the action of shore processes.

The larger lakes within the peninsula are confined to the northern and north central portions. Inland bodies of water are concentrated within those parts of the state where interlobate areas were formed through glacial action. An interlobate area is the locality where two great ice tongues of the glacier front actually converge and increase the quantity of material deposited. The irregularities in relief and the nature of the deposits resulting are usually favorable for the formation of inland lake basins. The inland lakes have been classified by Scott[15] into lakes of the Cheboygan River region, lakes of the Grand Traverse region, lakes of the various interlobate areas, and miscellaneous lakes of the different morainic and outwash systems. It has been estimated[16] that Michigan has more than 5,000 lakes with a total area of 712,864 acres. The largest of these is Houghton Lake in Roscommon County which is 30.8 square miles in area and 9.3 miles long by 5.2 miles wide.

---

[1]Fenneman, N. M., Physiographic Divisions of the United States: Annals of Assoc. of Am. Geog., Vol. VI, PI. I, pp. 19-98 (1917).

[2]Hubbard, George D., (Peattie, Roderick, author), Geography of Ohio: Geol. Survey of Ohio, Bull. 27, 4th Ser., p. 3 (1923).

[3]Malott, Clyde A., Handbook of Indiana Geology: Publication No. 21, Dept. of Conservation, Div. of Geology, p. 83 (1922).

[4]Martin, Lawrence, The Physical Geography of Wisconsin: Wisconsin Geol. & Nat. History Survey, Bull. 36, p. 29 (1916).

[5]Scott, I. D., Inland Lakes of Michigan: Michigan Geol. & Biol. Survey, Pub, 30, p. 16 (1921).

[6]Cumings, E. R., and Schrock, R. R., Niagaran Coral Reefs of Indiana and Adjacent States and their Stratigraphic Relations: Bull., Geol. Soc. Am., Vol. 39, pp. 579-620 (1928)

[7]Leverett, Frank, Surface Geology of Michigan: Michigan Geol. & Biol. Survey Pub 25 p. 108 (1917).

[8]Leverett, Frank, Op. cit, p. 108.

[9]Winchell, Alexander, The Diagonal System in the Physical Features of Michigan: Am. Jour. Sci. & Arts, Vol. VI, 3D Ser., pp. 36-40 (July, 1873).

[10]Van Hise, C. R., and Leith, C. K., The Geology of the Lake Superior Region: U. S. Geol. Survey, Mon. 52, p. 86 (1911).

[11]Spencer, J. W., Origin of the Basins of the Great Lakes of America: Am. Geologist, Vol. VII, p. 90, 91 (1891).

[12]Leverett, Frank, The Illinois Glacial Lobe: U. S. Geol. Survey, Mon. 38, pp. 13, 14 (1899)

[13]Grabau A. W., Guide to the Geology and Paleontology of Niagara Falls and Vicinity: Bull., New York State Museum, No. 45, p. 54 (1901).

[14]Spencer, J. W., Discovery of the Pre-Glacial outlet of the basin of Lake Erie into that of Lake Ontario—with notes on the origin of our Lower Great Lakes: Proc. Am. Philos. Soc., Vol. 19, p. 307 (1880-1881).

[15]Scott, I. D., Inland Lakes of Michigan: Michigan Geol. and Biol. Survey, Pub. 30, Geol. Ser. 25, pp. 68-267 (1921).

[16]Wood, L. H., Geography of Michigan: Horton-Beimer Press, Kalamazoo. Michigan, p. 44 (1914).

Chapter III. DESCRIPTIVE GEOLOGY

CRYSTALLINE ROCKS

The crystalline rocks which underlie the Michigan synclinal basin are divided into two types, the igneous and metamorphic. Igneous rocks crystallize out from a magma (molten rock) and become solidified either by rapid or gradual cooling. Metamorphic rocks are a type which obtain a close crystalline texture through the transforming effects of heat and pressure incurred through great earth movements. The original source before metamorphism may be either a sedimentary or an igneous rock.

The crystalline rocks are the great basement upon which the sometimes less indurated sedimentary series are later deposited. There are two great systems of crystalline rocks which have been called Archean and Algonkian. The Archean rocks are divided into two large groups, the Keewatin and the Laurentian series. The Algonkian is divided into the Huronian and Keweenawan series.

The description of the crystalline rocks is largely the same as used by Van Hise and Leith[1], whose major conceptions have not been greatly modified up to the present day. The lowest rocks of Archean age found in the Lake Superior region are sometimes termed the basement complex, of which the Keewatin constitutes the oldest series. The Keewatin comprises two great formations, the one being igneous and predominant, the other sedimentary and subordinate. The igneous rocks make up a great volcanic series which consists mostly of basalts and intermediate rocks. Greenstones and volcanic fragmental rocks are often associated with the lavas. The sediments of the series include quartzites, slates, iron-bearing formation, and subordinate dolomite. The metamorphosed slates and graywackes are often similar to the schistose phases of the greenstone. Folding is usually close and the beds stand at steep angles. Topograpically, the Keewatin, though rough in detail, has on the whole less bold relief than the Algonkian.

The rock types of the Laurentian series contrast sharply with the Keewatin, the intermediate and basic rocks being subordinate and granite, granitoid, gneiss, and syenite predominant. The Laurentian intrudes the Keewatin in various shapes and forms, thus profoundly altering the Keewatin rocks to more complex types. In some places the two are so intimately mixed that separation is difficult.

The Archean rocks are distinctly similar throughout the Lake Superior region and probably have the same characteristics beneath the Michigan synclinal basin.

The Algonkian system on the whole contrasts with the Archean in being dominantly sedimentary rather than igneous, less metamorphosed, and in having an easily recognizable stratigraphic sequence, and a characteristic topography. The sediments were probably subaerial in part but largely assorted and deposited by water. The iron bearing formations found within this system are regarded as having an exceptional character[2], being derived partly from submarine volcanic rocks either in magmatic solutions or by the reaction of hot volcanic material with sea water, or both.

The Huronian and Keweenawan divisions of the Algonkian are subdivided into lower, middle, and upper. Some of the representatives of these groups are locally missing.

The term Huronian was first used by the Canadian geologists, Logan and Murray[3], for rocks occurring along the north shore of Lake Huron. Although later controversies concerning the limitations of the series have resulted, common characteristics are so widespread that the name still holds throughout the vast area of the northern Great Lakes district. The lower Huronian includes a great clastic formation which is superimposed by a cherty limestone or dolomite. In most places the clastic formation includes in ascending order a conglomerate, a quartzite, and a slate. Contemporaneous igneous rocks are not important in the lower Huronian, but small dikes of intrusive rock locally cut out the lower Huronian rocks. This is in striking contrast with the Archean and evinces the existing unconformity between the two.

The middle Huronian is the important iron-bearing series in several northern Michigan ranges. Although not always totally present, the sequence of a clastic series usually consists of a conglomerate, a quartzite, and an iron-bearing slate followed by a cherty iron formation. Igneous rocks are locally present in association and both extrusive and intrusive types are represented.

The upper Huronian (Animikie group) consists mainly of a thick slate formation carrying two or more iron-bearing beds or lenses near its base and possibly others higher in the group. The slates which are interbedded with the iron-bearing formations and quartzites are closely folded, often schistose, and display strongly developed cleavage. The rocks of this group are often penetrated by or associated with basic extrusive lavas or intrusive granites. The Animikie is the only group that is practically continuous throughout the separate individual Huronian areas and constitutes the principal iron-bearing group of the entire region. Its extent may be realized in the possibility that it may correlate with the slates in the Black Hills of South Dakota and the Belt series of Montana. Seaman and Lane[4] have suggested that the section may approximate 4,000 feet thickness in the Lake Superior region.

The Keweenawan series covers a wide expanse along the Lake Superior border and is separable into three divisions, the lower, middle, and upper. The sediments are predominantly red in color, feldspathic, and poorly sorted. The lower Keweenawan consists of conglomerates, sandstones, shales, and limestones, and the division is widespread in occurrence. The classification of the lower Keweenawan has been eliminated by some students of the region[5].

The middle Keweenawan was a time of combined sedimentary and igneous action and the rocks contain many types resulting from the two classes of deposition, together with alteration products. The igneous rocks are both deep seated and extrusive and include basic, acidic, and intermediate varieties, the basic rocks being dominant. Much of the detrital material is derived from rocks of the formation itself and gives rise to an extremely complex mass.

The upper Keweenawan was a period of normal sedimentation. At the base of this series are thick conglomerates which are overlain by shales and a very thick sandstone formation.

The Keweenawan consists mostly of land deposits and igneous flows. The flows probably welled out under water many times. Felsitic types of conglomerate are the principal sedimentary rocks in the Keweenawan series and are usually underlain with amygdaloidal conglomerate consisting largely of basaltic materials. Ash and tuff, various types of extrusive lavas, and amygdaloids or traps constitute the characteristic igneous rocks. The maximum thickness of the series has been estimated[6] to be over 37,000 feet.

SEDIMENTARY ROCKS

The sedimentary rocks were deposited in shallow bodies of water which occupied the Michigan region at successive periods. These inland seas came in and withdrew as warping of the land brought about basins which connected with adjacent basins of deposition or the more permanent oceanic areas. The sediments were laid down in shallow shore waters through physical agencies (wind, current, and wave action) and sometimes in deeper waters through precipitation by chemical agencies or animals living in the sea. The total thickness of sedimentary rocks in the central part of the Michigan Basin probably aggregates over 12,000 feet and consists of sandstones, shales, and limestones with various other gradational types. The generalized section, including a brief description of the Paleozoic rocks of Michigan, is shown in Table I. Some of the units which appear in this table have not been substantiated by fossil evidence, but they are so similar in position and character to named units that it seems practical to include them.

In the additional correlation tables which follow for the different periods, many units are not directly comparable between States and the exact correspondence is in doubt. However, these tables probably show the equivalency of formations with sufficient accuracy to materially aid those who are unfamiliar with Michigan rocks in obtaining a better idea of the geological section in the State.

CAMBRIAN

The lowest known sedimentary rocks above the Keweenawan were named by Houghton[7] the Lake Superior sandstone. This formation includes the thick massive and cross bedded sandstones outcropping in places along the south shore of Lake Superior from Keweenaw Bay to Neebish Rapids in the St. Mary's River. These sandstone beds are nearly equivalent to the Potsdam of New York and probably underlie most of the southern peninsula, although they have never been penetrated in the central part of the Basin.

Lane[8] suggested a twofold division into a redder lower portion and a white upper portion and proposed the name "Jacobsville" for the sandstone skirting the coast at intervals from east of the Copper Range to Grand Island. The upper 250 feet, which is lighter in color and forms the bluffs back of Munising, was called the Munising sandstone. The separation between the two probably marked a period of submergence in which the iron-bearing rocks were not subject to erosion.

The lower beds of the Lake Superior sandstone are red to brown color with streaks and mottlings of white or gray and a conglomerate at the base. The thickness of the formation near Grand Marais is about 1,500 feet, but at the east end of the Upper Peninsula this dwindles to between 100 and 300 feet. The amount of Lake Superior sandstone in the deepest part of the synclinal basin in the southern peninsula is not known.

A further division of the rocks comprising the Lake Superior sandstone in Michigan has been made by Thwaites[9] of the Wisconsin Survey. The most recent correlation of the Cambrian rocks of the Upper Mississippi Valley region made by Ulrich and Kesser[10] is shown in Table II. Thwaites[11] believes that several other changes should be made in the present interpretation of Cambrian rocks, particularly that the Mendota is a local facies of the basal Trempealeau; the Devil's Lake is upper Mazomanie; and the Mazomanie is simply a lithologic phase of the Franconia as first defined. The approximate correlation of the Michigan Cambrian rocks with the formational units proposed for Wisconsin and Northern Illinois is indicated in Table II. The divisions by

Logan[12] from subsurface studies in Indiana are also incorporated in this table. Thwaites[13] has recognized Trempealeau, Mazomanie, and Dresbach in well cuttings from near Escanaba and it is possible that the Wisconsin nomenclature would be more fitting for the Cambrian rocks which underlie southern Michigan than the terms now in current use. A brief description of these rocks as outlined by Thwaites[14] for Wisconsin and northern Illinois will give some idea of the lithology of the sandstone beds.

TABLE I.—*Paleozoic Formations in Michigan (Generalized)*

System	Series		Formation or Group			Description	Thickness
Permo-Carboniferous (?)			"Red Beds"			Shale, sandy shale, gypsum red, pink, gray	"0-180"
				Woodville (Ionia)		Sandstone, red, pink, russet	
Pennsylvanian	Pottsville		Saginaw			Sandstone, shale, limestone, coal, white, gray, red, black	"0-500"
			Parma			Sandstone, conglomerate, white, gray	"0-220"
Mississippian	"Late" (Tennesseean)	Chesterian	Grand Rapids	Bayport		Limestone, sandy limestone, blue, gray, buff, cherty	"0-100"
		Meramecian		Michigan		Shale, anhydrite, gypsum, dolomite, sandstone, gray, black, green	"0-550"
	"Early" (Waverlian)	Osagian	Marshall	Napoleon (Upper)		Sandstone, gray, white, brown, green; thin conglomerates	"150-560"
				Lower Marshall		Shale, sandstone, sandy, shale, gray, green, pink, red; thin conglomerates	
		Kinderhookian and Chattanoogan	Coldwater			Shale, limestone, gray, blue, black, red, sandy, calcareous	"600-1,100"
			Sunbury			Shale, black, brown, pyrite	"0-100"
			Berea			Sandstone, white, gray, pyrite	"0-270"
			Bedford			Shale, gray, red, sandy	"0-160"
				Ellsworth		Shale, gray, greenish gray, sandy	"400-600"
			Antrim (Upper part)			Shale, black, brown, dark gray	"140-460"
Devonian	Upper	Senecan	Antrim (Lower part)			Shale, black, brown, dark gray, concretionary	"140-460" (Total)
	Middle	Erian	Traverse	Thunder Bay	Petoskey	Limestone, shale, gray, blue, buff, black	"60-800+"
				Alpena	Charlevoix		
				Long Lake	Gravel Point		
				Rockport			
				Bell		Shale, shaly limestone, blue, gray	"0-80"
		Ulsterian	Dundee			Limestone, buff, gray, dolomitic, cherty	"0-300"
			Mackinac				
	Lower	Oriskanian	Oriskany (?)			Sandstone, sandy limestone, buff	"0-5"
		Helderbergian	Detroit River	Lucas		Dolomite, buff, blue, gray, brown; salt, anhydrite	"0-1060"
				Amherstburg			
				Anderdon			
				Flat Rock			
			Sylvania			Sandstone, sandy dolomite, chert; white, buff	"0-300"
Silurian	Upper	Cayugan	Bass Island	Raisin River		Dolomite, limestone, anhydrite, buff, blue, gray	"400-520"
				Put-in-Bay			
				Tymochtee			
				Greenfield			
			Salina			Dolomite, anhydrite, gypsum, rock salt, shale, buff, gray, red	"0-1570"
	Middle	Niagaran	Engadine			Dolomite, bluish white, hard	
			Manistique	Cordell		Limestone, dolomite, white, blue, gray, buff, cherty, shaly	"270-800"
				Schoolcraft			
			Rochester (?)				
			Burnt Bluff	Hendricks			
				Byron			
			Mayville				
	Lower	Medinan or Alexandrian	Cataract		Cabot Head	Shale, red, blue, greenish blue	"0-205"
					Manitoulin	Dolomite, limestone, cream, gray	"0-150"

TABLE I.—*Paleozoic Formations in Michigan (Generalized)*—Continued

System	Series		Formation or Group		Description	Thickness
Ordovician	Upper	Cincinnatian	Richmond	Big Hill	Shale, calcareous shale, blue, gray, red	"215-600"
				Stonington		
				Bill's Creek		
			Eden			
			Utica	Collingwood	Shale, black to gray	"50-300"
	Middle	Mohawkian	Trenton	Galena (?)	Limestone and dolomite, brown, buff, gray, shaly	"100-870"
				Prosser		
			Black River	Decorah		
				Platteville		
		Chazyan	Stones River (?)		Limestone, shaly	"0-30"
	Lower	Big Buffalo	St. Peter		Sandstone, white, yellow, brown	"0-500 (?)"
		Canadian	Prairie du Chien "Calciferous"		Dolomite, dolomitic sandstone, sandy dolomite, buff, gray, red, blue, oolitic, chert	
		Ozarkian	Hermansville			"0-250"
Cambrian		St. Croixan	Lake Superior	Munising	Sandstone, red, pink, white, variegated, cross bedded	"0-1500"
				Jacobsville		

Table I. Palaeozoic formations in Michigan (Generalized).

The Mount Simon formation is gradational into the Eau Claire above. The formation in central Wisconsin is mainly coarse to medium grained, gray or yellow sandstone with a few layers of green, blue, and red shale. Farther south less of the sandstone is coarse grained and locally there are pink layers, the color of which is deepest in the finer grained sands.

The Eau Claire formation is made up of both sandstone and shale in varying proportions. The upper and lower parts are filled with thin seams and small lenses of greenish or bluish gray shale, and most of the sandstone is very fine grained. The Eau Claire is marked by extreme variability in lithologic character, and scarcely any two well records in Wisconsin or Illinois display the same succession in detail. Dolomite beds are most common near the bottom and the top of the formation. Many red erratic "marl" layers are found in the Eau Claire near Milwaukee where it represents the uppermost formation of Cambrian age.

TABLE II.—*Cambrian**

Michigan Lane—1908			Wisconsin Thwaites—1923.	Indiana Logan—1926.	Northern Illinois Thwaites—1927.	Upper Mississippi Valley Ulrich and Resser 1930.
St. Croixan	Lake Superior	Munising	Madison	Jordan	Jordan	Jordan
			Mendota, Devil's Lake			
			Jordan			
		Jacobsville	Trempealeau	Lodi St. Lawrence	Trempealeau	Trempealeau Norwalk Lodi St. Lawrence
			Mazomanie	Franconia Upper Greensands Middle Limy Shales Lower Greensands	Mazomanie	Mazomanie
			Franconia		Franconia	Franconia Ironton
			Dresbach	Dresbach	Dresbach	Dresbach
			Eau Claire	Eau Claire	Eau Claire	Eau Claire
			Mount Simon	Mount Simon	Mount Simon	Mount Simon

*In a recent discussion on the Sub-Trenton Formations in Ohio (Jour. Geol, Vol. XL, No. 8, pp. 673-687; 1932), Isabel B. Wasson includes from a deep well study, in descending order: the Jordan, Trempealeau, Mazomanie, Dresbach, and a series of red shales and sandstones tentatively correlated with the Red Clastic series of Minnesota. The Eau Claire and Mount Simon formations thin eastward and are seemingly absent in most of Ohio.

Table II. Cambrian correlations in the Michigan Basin region.

The Dresbach formation consists of medium grained pure white sandstone with some yellow layers. The cement is mainly silica and locally the formation is quartzitic. The upper and lower contacts are gradational, but Thwaites has eliminated from the Dresbach, all fine grained, calcareous, or glauconitic sandstones.

The Mazomanie is fine to medium grained gray to dark red sandstone, irregularly cemented by dolomite and locally there are beds of red, green, and gray calcareous shale. The formation overlaps the fine grained, gray to green, somewhat calcareous Franconia sandstone to the west and, therefore, replaces the Franconia in eastern Wisconsin.

The Trempealeau formation consists of sandy dolomitic shales, the St. Lawrence or "Black Earth" dolomite, Lodi yellow and purple thin bedded dolomite, locally called "shale", and the Norwalk fine grained sandy dolomite. The yellow color of the Lodi member does not persist with depth but is replaced by gray. The purple tints maintain and the base of the formation is marked by a greensand conglomerate.

The Jordan sandstone is noted for its pure white color and fine to medium grain. Ulrich[15] would confine the name Jordan to the coarser grained sandstone near the top and exclude the fine grained sandstone below. Yellowish color and calcite or dolomite concretions are abundant where the formation occurs at the surface. The formation has not been distinguished in northeastern Illinois but it has been recognized[16] in Michigan.

The Madison, Mendota, and Devil's Lake formations which Thwaites[17] placed in the Cambrian are named from very local occurrences and are now considered Ozarkian in age by some students[18] of the Wisconsin Cambrian. Many well sections show these formations poorly developed and they can only be separated from the underlying Jordan sandstone with great difficulty. The Madison is a fine grained, buff, calcareous sandstone grading into a pure white, medium grained sandstone at the bottom; the Mendota is a gray dolomite with purple and greenish gray blotches; and the Devil's Lake is a gray and yellow more or less glauconitic sandstone and quartzite pebble conglomerate.

Figure 4. Wells which have penetrated Trenton limestone in Michigan. (Numbers indicate the thickness of the Trenton).

ORDOVICIAN

The Ordovician rocks are not exposed in the southern peninsula of Michigan, and the existing section in that part of the State can only be correlated from deep borings. The wells which have penetrated Trenton limestone of Ordovician age are shown in Figure 4, and the thickness of the "Trenton" is indicated where they have gone completely through that formation. Very little drilling has been carried on below the base of the Trenton and only one well, located in St. Clair County, has been drilled into pre-Cambrian rocks.

The beds of Ordovician age are divided into lower, middle, and upper. The various divisions possess predominant lithologic characteristics, which are sandstone and sandy dolomite in the Lower Ordovician, comparatively pure limestone in the Middle Ordovician, and fossiliferous shaly limestone and shale in the Upper Ordovician. The divisions, with their respective correlations for the several states surrounding Michigan, are indicated in Table III. The formations equivalent to the new Ozarkian and Canadian systems proposed by E. O. Ulrich are shown.

In Michigan the early name for rocks of the Prairie du Chien group which outcrop in the northern peninsula on Calciferous creek, a branch of the Au Train River, and on the St. Mary's River near west Neebish rapids, was the Calciferous[19] formation. The lower part of this formation was called the Hermansville[20] limestone, and this term is still used.

The Prairie du Chien group consists of white to buff dolomitic sandstone and sandy dolomite, usually with red ferruginous beds and often oolitic. In describing Wisconsin and Illinois occurrences, Thwaites[21] emphasizes that "the presence of oolitic chert is a certain marker of the Lower Magnesian group, since it has not been discovered in any of the adjacent dolomite formations. In places where the underlying or overlying sandstones are absent this criterion is almost indispensable." Wells which have penetrated the group in the southern peninsula of Michigan have not revealed with certainty the three-fold division of Shakopee, New Richmond, and Oneota, but the general lithologic characteristics are very typical of these members. The New Richmond member is now considered by many stratigraphers to be merely a lenticular sandstone bed in the Shakopee dolomite. Greenish shale; red, pink, and purple fine grained, sandy magnesian limestone and dolomite; and white, buff, and pink oolitic and dense chert are the prevalent rocks of the Prairie du Chien. A very great thickening of the formation is noted in the deeper parts of the synclinal basin.

The St. Peter sandstone occurs rather irregularly because of the pronounced disconformity at the base. Wells drilled in the Upper Peninsula show a rapid change in thickness of the formation from place to place, and none of the holes which have been drilled through the Trenton in southeastern Michigan have found typical St. Peter beds. The formation is present in Calhoun and Berrien counties, and also in Ottawa County where an abnormal thickness was found. The sandstone is "clear white" to buff and some beds are very pure. Special studies[22] of the St. Peter sandstone, which correlate its beds over wide areas and outline the physical and chemical properties of the rock, show the extent of pre-St. Peter erosion with a relief ranging from 40 to 200 feet, and conclude that the formation is primarily of marine derivation from the north and northwest.

The Middle Ordovician, or Mohawkian Series, is commonly shown in well records as "Trenton," a name familiar to all drillers in the Middle Western states. The exposures of Trenton limestone in Michigan are confined to localities in the Upper Peninsula, which are mostly in the vicinity of the Escanaba, Whitefish, Menominee, and Rapid rivers. A few scattered outcrops are in the eastern part of the peninsula near the St. Mary's river and north of Drummond Island.

Table III.—*Ordovician*

		Michigan	Ontario	Ohio	Indiana	N. Illinois	Wisconsin
(Upper)	Cincinnatian	Richmond Big Hill Stonington Bill's Creek	Richmond-Queenston	Richmond-Queenston	Richmond	Richmond Maquoketa	Richmond Maquoketa
			Dundas	Maysville	Maysville		
		Eden		Eden	Eden		
		Utica Collingwood	Utica Collingwood		Utica		
(Middle)	Mohawkian	Trenton Galena (?) Prosser	Trenton	Trenton	Trenton	Galena	Galena
		Black River Decorah Platteville	Black River		Black River	Black River Decorah Platteville	Black River Decorah Platteville
		Lowville (?)					
	Chazyan	Stones River (?)	"Chazy"				
(Lower)	Big Buffalo	St. Peter		St. Peter	St. Peter	St. Peter	St. Peter
	(Canadian of E. O. Ulrich)	Prairie du Chien "Calciferous"	"Beekmantown"	Sandy Dolomite (Unnamed)	Prairie du Chien Shakopee	Prairie du Chien Group Shakopee	"Lower Magnesian Group" Shakopee
					New Richmond	"New Richmond"	
	(Ozarkian of E. O. Ulrich)	Hermansville			Oneota	Oneota	Oneota
							Madison Mendota, Devil's Lake

Table III. Ordovician correlations in the Michigan Basin region.

The "Trenton" is best developed in the southeastern part of the State where the rocks are under cover. The thickness of the formation in the southern peninsula (see fig. 4) ranges from about 400 feet on the west side to over 860 feet on the east side near the St. Clair and Detroit rivers. In well samples the brown shade of the limestones is characteristic and easily distinguishable. The shade changes from buff to variegated browns with occasional gray. The beds are usually rather pure calcium carbonate, but in Ottawa County the lower part of the formation is slightly dolomitic and there is a sandy phase which probably correlates with the sandstone in Wisconsin described by Thwaites[23]. He states: "The base of the Black River is sandy in many localities, and along a belt which runs south from Milwaukee parallel with the Lake Michigan shore, there is a distinct bed of sandstone near the bottom of the group; this is known to well drillers as the 'Trenton Stray Sand.' It has a maximum known thickness of about 30 feet and consists of rather coarse-grained gray calcareous sandstone. This rock differs from the St. Peter in greater size of grain, lack of chert fragments, and in its dolomite cement which is locally sufficient to cause the rock to break in thin chips under the drill." Occasionally shales are penetrated in the Trenton from wells in southern Michigan but their occurrence is comparatively rare.

According to Smith[24], in the northern peninsula the Trenton has three phases, (1) an upper granular, crystalline, dolomitic limestone of alternating blue and brown layers terminating at the base in a dark or black bituminous limestone, (2) a middle portion of cherty layers or lenses alternating with thick beds of limestone, and (3) a basal member of blue shales and limestone, a part of the latter being black or dark. The sandy middle division and the lower blue shaly one appear to have a widespread distribution. A partial correlation of the Trenton rocks has been made by Robinson[25] and Ulrich[26]. The Trenton probably comprises several formations which correspond to the Lower Blue, Upper Buff, Upper Blue, and Galena of the Wisconsin section, and to beds between and including the Lowville and Trenton of the New York section. Black River and possibly Stone's River have been recognized from well cuttings, and Hussey[27] makes reference to Black River affinities of fossils found in the Richmond beds. The "Trenton" of Michigan probably includes, therefore, the Galena, Black River, Lowville, and possibly Stone's River formations.

The Upper Ordovician, sometimes termed the Cincinnatian series or group, consists largely of gray to black shales and gray fossiliferous limestones. In the southeastern part of the State, the upper beds of the group may contain red, purple, or green shales which disappear almost entirely on the west side of the southern peninsula. The Cincinnatian series is commonly from 570 to 610 feet thick in southeastern Michigan, 360 to 390 feet in western Michigan, and 170 to 250 feet in northwestern Michigan. The lack of red and green color seems, therefore, to be due to absence of beds.

The Utica-Collingwood formation is gray to black bituminous shale and its thickness is generally 50 feet in the Upper Peninsula and from 100 to over 200 feet in the Lower Peninsula. The formation is not exposed but Collingwood[28] fossils have been found near Newberry in drift material, and from these fragments the approximate boundaries can be somewhat accurately traced in this part of the northern peninsula.

The presence of the Lorraine formation in Michigan is questionable, and, although Eden was recognized from well cuttings and Eden fossils were described by Rominger[29], there is evidence from later work by Hussey[30] that the Bill's Creek locality represents a stage of the Richmond. The rocks considered to be Lorraine age consist of blue fossiliferous shale near the top, black and gray shale near the base, and are very dark colored when wet. They are from 200 to 300 feet thick in southeastern Michigan.

The Richmond beds have been divided by Hussey[31] in ascending order into the Bill's Creek, Stonington, and Big Hill members. The rock is thin bedded, often very fossiliferous soft shale which contains occasional hard layers. Numerous thin strata of argillaceous limestone are inter-bedded with shale. The color is dark gray to dark chocolate brown on fresh surfaces but invariably bluish after weathering. Locally the bedding is even but more generally it is irregular.

The upper part of the Bill's Creek formation is correlated with the Maquoketa shale, but the lower part, together with the Stonington and Big Hill beds is more definitely Richmond age. The Richmond rocks of Michigan contain faunal elements resembling forms from southwestern Ohio beds and the Elkhorn (Upper Richmond Group) of Indiana and Illinois. Some of the Michigan fossils also bear strong resemblance to those from equivalent strata in Wisconsin.

The Richmond-Queenston rocks are different in southeastern Michigan, where the beds are red, purple, and greenish. The beds when separated on the basis of color, amount to 275 feet at Chesterfield (Macomb County); 190 feet at Dearborn (Wayne County); 60 feet at Dundee (Monroe County); 10 feet at South Rock wood (Monroe County); and 40 feet at Strasburg (Monroe County). These figures indicate a pronounced thinning of the red horizon from Macomb county southward through Wayne and Monroe counties. The Cincinnatian series as a whole thins to the west and northwest.

SILURIAN

The Silurian rocks of Michigan consist largely of limestones, dolomites, and products of evaporation such as salt, gypsum, and anhydrite. A few shale beds were laid down during the early stages of the period. Apparently Silurian time marked the beginning of conditions which were duplicated throughout the area several times during the remainder of geologic history. Isolation of the Basin occurred periodically to such an extent that conditions of evaporation recurred in the three successive Devonian, Mississippian, and Permo-Carboniferous (?) periods at times when no exactly comparable beds were deposited in the adjacent basins of deposition. The tentative correlation of the Silurian formations in the states of the Michigan Basin province and New York is shown in Table IV.

The Cataract formation at the base of the Silurian is not exposed in Michigan so far as known, but rocks of this age have been identified from well cuttings at various places in the southern peninsula and were first recognized in 1914 by R. A. Smith. The formation outcrops on Manitoulin Island, Ontario, and the exposures and fauna were described by Williams[32], who differentiated the basal Manitoulin limestone and the Cabot Head shale members and referred to their original descriptions[33].

The Manitoulin member is gray to cream colored magnesian limestone or dolomite and the color is so very characteristic that the formation is readily identified by the examination of well cuttings. The exposed section is described as "a resistant, thin to thick bedded, gray or buff weathering dolomite, which when fresh, is hard and of light, blue-gray color. . . . . The contact with the underlying green Richmond shale is sharp but the basal Manitoulin dolomite is somewhat argillaceous. The two faunas have practically nothing in common."

The Manitoulin varies from 40 to 50 feet thick in the southeastern part of the State, 90 to 100 feet in the south central part, and 130 to 150 feet in the northwest part. Minor variations in thickness are possibly due to the coral and bryozoan reefs described by Williams[34], but in general there is a progressive thickening to the northwest toward the Upper Peninsula. At Seul Choix Point near Manistique, Schoolcraft County, 50 feet of strata are correlated as Manitoulin, indicating that the beds are thinning again. The formation has been found in every deep well drilled and probably underlies the entire Silurian area of the southern peninsula of Michigan, and southwestern Ontario. The Manitoulin beds are correlated[35] with the Kankakee of Illinois and the Brassfield of Ohio.

The Cabot Head shale is more variable in lithology than the Manitoulin member. The beds usually consist of red, purple, and greenish gray limy shales, and isolated dolomite lenses or lentilles are described from the type locality. The thickness ranges from 25 to over 100 feet in wells. The average is about 70 feet and the thickest series was found in the south and southeast part of the state. This contrasts sharply with the Manitoulin which thickens in the opposite direction. The shades of color are also less pronounced in the western part of the synclinal basin.

A definite correlation has been made between the Cataract in Ontario and Michigan by identification of faunal species from well cuttings. Ehlers[36] examined samples from St. Clair and Dearborn in 1923, and on the discovery of *Sceptropora fustiformis* (Ulrich) and *Dalmanella aff. eugeniensis* (Williams) pronounced them "Cataract."

TABLE IV.—*Silurian*

Michigan		Ontario	Ohio	Indiana	Illinois	Wisconsin		New York
Cayugan (Upper)	Bass Island Raisin River Put-in-Bay Tymochtee Greenfield	Akron Bertie	Bass Island Raisin River Put-in-Bay Tymochtee Greenfield	Kokomo		Waubakee		Upper Cayugan Akron Bertie Series
	Salina	Salina (Camillus)	Salina					Lower Cayugan Camillus Syracuse Vernon (Pittsford)
Niagaran (Middle)		Guelph		Huntington (Including New Corydon)	Port Byron	Guelph		Guelph (?)
	Engadine	Lockport	Cedarville Springfield		Racine	Racine		Lockport
	Manistique Cordell Schoolcraft		Niagara	Liston Creek	Waukesha	Waukesha	Upper coral beds Lower coral beds	
	Rochester (?)	Rochester		Mississinewa	Joliet			Rochester
	Burnt Bluff (Clinton) Hendricks Byron Mayville	Clinton	Dayton (?)			Byron Mayville		Clinton
Medinan (Lower) or Alexandrian	Cataract (Medina) Cabot Head Manitoulin	Medina-Cataract Cabot Head Manitoulin	Brassfield		Kankakee Edgewood			Medina-Cataract

Table IV. Silurian correlations in the Michigan Basin region.

The Niagaran rocks of the northern peninsula have been divided by Ehlers into the Clinton and the Lockport groups. The Clinton includes the Mayville dolomite at the base, and the Burnt Bluff and Manistique limestones and dolomites. The Engadine dolomite is about equivalent to the Racine of Wisconsin and Illinois, a portion of the Huntington of Indiana, and probably parts of the Guelph of Ontario and New York. There is a difference of opinion about the Burnt Bluff and Mayville being equivalent to the Clinton of New York State. Cumings[37] believes that these strata should be correlated with the beds lower in the scale, possibly the Cataract of Ontario. In 1930, he stated[38], "the Mayville and the Byron are believed to be western calcareous equivalents of the entire Cataract formation of Ontario and Manitoulin Island, and may rise even into Clinton and Rochester horizons."

The rocks of Niagaran age outcrop in two widely separated areas in the northern peninsula. The larger of these forms a broad arcuate belt extending from St. Martin, Poverty, Big and Little Summer Islands at the entrance of Green Bay to the eastern side of Drummond Island. The smaller area is located in southeastern Houghton County about 117 miles from the nearest Niagaran rocks which are to the south and probably represents a Paleozoic outlier protected from erosion by down folding or a series of faulting movements.

The Mayville formation was first described by T. C. Chamberlin[39] and can be traced from northeastern Wisconsin into Michigan. The rocks are mostly thick bedded dolomites with uneven structure and rough pitted surfaces on the weathered ledges. The beds are gray, light buff, yellowish, and cherty. Scattered outcrops extend from the head of Big Bay de Noc, northeastward and then easterly to Drummond Island. The thickness is from 50 to 100 feet and increases westward toward the Wisconsin line.

In 1921, Ehlers[40] correlated the rocks of the Burnt Bluff formation as follows: "The overlying Burnt Bluff formation seems to be limited above by a disconformity, and without doubt is a northeastward extension of the Byron, Transition, and lower part of the Lower Coral Beds of Wisconsin. Certain beds of the formation, that is, the Piborn limestone and the upper part of the Hendrick's Series of R. A. Smith's tentative classification, are regarded by Savage and Crooks as being of Alexandrian age. The Burnt Bluff formation, which includes these beds is thought by the writer to be of Niagaran age." Recently Ehlers[41], has included the Hendricks and Byron as individual members of the Burnt Bluff formation. Excepting several limestone beds of the Hendricks member, the lithologic character of the Burnt Bluff formation is persistent for long distances. The strata consist of variable limestones and dolomites with some shale, and dolomite in many places grades into limestone along the bedding. The type section of the formation is at Burnt Bluff on Big Bay de Noc, and the top is clearly marked by a massive, coarsely crystalline light brown dolomite of the Manistique formation containing molds of *Pentamerus*. This section is 248 feet thick, which includes the Byron member with 117 feet of thin-bedded and laminated light gray dolomitic limestones, and the Hendricks member with 121 feet of strata, containing a greater number of dolomite beds. Thick beds of brown dolomite are prominent in the upper part but in the lower part there is more lithological similarity to the Byron member.

Between southeastern Schoolcraft County and southern Chippewa County most of the Hendricks strata are comparatively pure limestones. Smith[42] named these pure limestone beds in the upper part of the Hendricks the Fiborn limestone. These beds are buff to grayish buff dense grained to lithographic limestone containing small disseminated crystals of calcite. Smith observed the possible lenticular nature of the Fiborn and stated that, "further field work and faunistic studies . . . . may show that the Fiborn limestone should be included in the Hendricks Series." Savage and Crooks[43] also favored this explanation of conditions and the detailed work of Ehlers[44] has added further supporting evidence.

The Rochester, formation has not been found exposed in Michigan, but both Lane and Smith[45] correlate cuttings from wells with the Rochester of New York. Williams[46] believes that the formation thins westward, but recently Curnings[47] points out evidence that the Mississinewa shale which probably extends into southern Michigan, has Rochester affinities. On the basis of lithology and stratigraphic position, beds ranging from 10 to 50 feet thick which have been observed in wells in western Michigan (Muskegon, Newaygo, Ottawa, and Oceana counties) are correlated as Rochester.

At the type locality[48] the Rochester shale is 85 feet thick and consists of fissile, dark gray shale with some calcareous beds. In the entire State of Michigan, the beds correlated as Rochester are from 30 to 80 feet thick and contain blue shale or shaly limestone. Occasionally the horizon is absent.

The Manistique formation is exposed over a wide area and forms regular and pronounced escarpments or cuestas across the northern peninsula. The best outcrops give rise to bluffs on the west side of Garden Peninsula, near Manistique and Gould City, north of Engadine, east of Trout Lake, at Rockview, and on Drummond Island. The formation was defined by Smith[49] as a thick succession of dolomite and high magnesian limestones extending from the base of the Engadine dolomite downward to the top of the Fiborn limestone. Ehlers[50] later divided the Manistique into the Cordell and Schoolcraft members.

The thickness of the formation is about 150 feet and includes dolomites and dolomitic limestones varying in color from pure white, light gray, and buff to blue, dark gray, and brown. The texture is earthy or finely crystalline to coarsely crystalline, and some massive beds are present. Many of the beds are very fossiliferous, especially in reef areas like those which occur two or three miles north of Engadine in Mackinac County and about seven miles north of Cedarville in Chippewa County. A large number of the beds are dense with conchoidal fracture and banded or laminated; others are granular, extremely cherty, nodular, and contain silicified fossils.

The Manistique correlates with the Coral Beds (Waukesha) of Wisconsin and the Liston Creek of Indiana, which according to Cumings and Schrock[51] occur "inter-related to the pronounced unusual reef coral structures." Cumings[52] believes that "the coral beds (Louisville, Listen Creek, Waukesha, Manistique as restricted, etc.) constitute the most reliable and easily traceable horizon in the entire Niagaran. In the Michigan Basin region, they constantly occur immediately beneath a very massive, saccharoidal, light gray, pure dolomite, variously known as Racine, Engadine, Lockport, and Huntington (lower)."

The Engadine dolomite is the uppermost formation of the Niagaran, equivalent to the Racine of Wisconsin, a portion of the Huntington of Indiana, and possibly the lower part of the Guelph of Ontario. The formation crops out across the Upper Peninsula in a broken escarpment from Seul Choix Point, Schoolcraft County, to Drummond Island, Chippewa County. It is extensively exposed at or near Engadine, Rexton, and Garnet; north of Hessel, Cedarville, Nunns Creek, and Detour; and along the southern shore of Drummond Island.

The Engadine strata consist of very thick and massive beds of hard, crystalline, saccharoidal dolomite which is predominantly bluish white in color. Some beds are mottled bluish white and very light gray, and the mottling resembles marble. Weathering changes the bluish white beds to light buff or brown, but the white color is preserved on some of the weathered surfaces of the dolomite, and the huge detached blocks of the rock can thus be recognized for long distances. Some of the beds contain many cavities, which are generally lined with dolomite crystals. The Engadine is normally pure dolomite, and the beds display very poorly developed irregular jointing. The massive character of the fresh dolomite is usually changed to a very thin and even-bedded rock after extensive weathering. Occasionally sand grains are disseminated through the beds, and the rounded and frosted surfaces of the grains suggest wind action.

The dark argillaceous dolomites of Salina age overlie the Engadine, but the contact of the two formations has never been seen in Michigan. Well cuttings show a marked change in lithology at this point in the stratigraphic sequence and a rather exact separation of the Engadine and Salina can ordinarily be made on this basis. The individual members of the Niagaran are not easily distinguished in well cuttings. The blue-gray color and fineness of drill samples characterize the Engadine (Guelph) and variable gray colors characterize the Manistique, Rochester, and Burnt Bluff formations (Lockport-Rochester-Clinton). The thickness of the entire Niagaran series ranges from 100 to 130 feet in the southern part of the Lower peninsula, 140 to 300 feet in the central part, and up to 420 feet in the northwestern part. These figures indicate a progressive thickening of the Niagaran to the northwest in a similar manner to the Manitoulin dolomite. The Niagaran of the northern peninsula is composed of about 600 feet of strata.

The Salina formation is more extensively developed in the Michigan Basin than any other region. Although its maximum thickness, has probably never been penetrated by wells, over 1,200 feet of Salina has been found in the western part of the state. The presence of an additional 500 feet of Salina strata in the central part of the "basin" is suggested by convergence studies.

The formation first named by Dana in New York in 1864 was described in Ohio by J. S. dewberry[53], and the series was later recognized in Michigan rocks by A. C. Lane[54]. The rocks of this age may possibly be included in exposures in the St. Ignace peninsula region of upper Michigan, but the type locality is in northern Ohio on the peninsula north of Sandusky Bay and at South Point on Put-in-Bay Island. Williams[55] has described the Salina rocks in Ontario and the distribution and correlation of the Salina beds in the surrounding states have been discussed at length by Alling[56].

The character of the Salina rocks is variable. The formation usually contains buff to brown dolomite, anhydrite, gypsum, and salt beds with minor amounts of red, green, and rarely blue to black shales, and dolomitic marls or oozes. In the western part of lower Michigan, pink and red dolomites associated with light greenish buff dolomites are invariably present near the bottom of the Salina. These red strata may possibly be Clinton in age. The salt beds are absent near the margin of the "basin," and several writers[57] have outlined the area supposed to be underlain by salt. (See fig. 9). Cook[58] described the Salina rocks in the deepest part of the Michigan synclinal basin which had been explored up to 1913. These individual salt beds may differ slightly in stratigraphic position because of their formation in separate basins of evaporation. Minor salt beds also occur which cannot be traced over wide areas. The thickness of the larger beds is usually over 200 feet and this increases locally up to 300 feet. Cross sections show how the thicker salt beds persist and diverge into the center of the basin area. (See figs. 10 and 11).

The Upper Silurian rocks of Michigan were first named the "Monroe beds" by Lane[59] who included under this division all of the section from the top of the Niagaran to the base of the Dundee (Onondaga). Grabau and Sherzer[60] more definitely limited the "Monroe" to its present status and Carman[61] suggested the term Monroe "division" for the equivalent rocks in Ohio. The original term "Lower Monroe" has been superseded by the Bass Island dolomite or Bass Island series proposed by Grabau[62]. The base of the Bass Island formation, as defined[63], is rather indefinite and can only be determined by using the top of the first salt bed as the uppermost Salina. This is a very uncertain method of separating the two formations because the existence[64] of persistent salt in the Detroit River is liable to cause erroneous correlation. According to wells already drilled, the thickness of the Bass Island (i.e. top of salt to base of Sylvania above) is generally about 400 feet. Unless other reliable criteria are found, it will be necessary to define the formation on the same basis suggested by Lane.

The Bass Island dolomite is separated[65] into four subdivisions:

Rasin River dolomite	200 feet
Put-in-Bay dolomite	100 feet
Tymochtee shale	90 feet
Greenfield dolomite	100 feet

The Raisin River dolomite is the only member exposed in Michigan, but an incomplete section[66] of the entire formation was studied at the Detroit salt shaft. The other members of the formation outcrop in western and northwestern Ohio, as well as on the islands in the western end of Lake Erie. The formation as a whole is composed of gray to drab argillaceous dolomite, gypsum, anhydrite, and some shale. Fluorite has been observed. The beds are usually thin, compact, and often oolitic or brecciated. The brecciation is very characteristic and is conspicuous in Monroe, Cheboygan, and Emmet counties, Mackinac Island, and on the St. Ignace Peninsula. This same type of breccia is also encountered in wells. The Monroe formation is noted for its hard compact texture which makes drilling very difficult. The oolitic beds are characteristically underlain by fine grained dolomites which show gnarled, mottled, and streaked patterns of blue and gray buff color.

The Greenfield dolomite is a drab, fine grained dolomite with carbonaceous partings and commonly occurs in beds from 2 to 6 inches thick, but locally there are more massive beds which form prominent ledges. Intraformational brecciated beds and stromatoporoid reef-life areas have been found, and a green shale is at the base in its type locality near Greenfield, Highland County, Ohio. This member seemed to be absent in the Detroit Salt Shaft and this condition, together with the occurrence of other thin sections of the Bass Island rocks found in wells, suggests that the Greenfield and perhaps higher beds rest by overlap on the Salina.

The Tymochtee shaly dolomite seems to have been identified from well cuttings, but the formation does not outcrop in Michigan. The Tymochtee beds have never been observed in contact with the Greenfield or Put-in-Bay members and its stratigraphic relation is somewhat uncertain. Possibly the Tymochtee represents a shaly phase of the Greenfield but Carman[67] would prefer to continue its classification as a separate member. The rock is described as a drab shale with bituminous films, weathering blue and chocolate. The shale is very dark colored in places and resembles the Ohio shale.

The Put-in-Bay dolomite consists largely of fossiliferous waterlime which is well exposed on Put-in-Bay Island, one of the Bass Islands in western Lake Erie. The rock is typically a gray-drab, brecciated, rough textured, massive dolomite that weathers with a knobby surface. Some of the beds are thin and apparently all of them were laid down in this form. The beds are rich in celestite (mineral strontium sulfate) as well as fluorspar, and two horizons of breccia have been observed at several exposures. The contacts with the Greenfield and the Tymochtee have not been found, but the thickness probably varies from 50 to over 100 feet.

TABLE V.—*Devonian*

		Michigan	Ontario	Ohio	Indiana	Illinois	Wisconsin	New York
(Upper)	Chautauquan and Senecan	Antrim (Lower part)	Port Lambton Huron	Ohio (Lower) Cleveland Chagrin* Huron Olentangy	New Albany (Lower part)	Cedar Valley Wapsipinicon		Catskill Chemung Portage Genesee Tully
(Middle)	Erian	Traverse— Thunder Bay Alpena Long Lake Upper Middle Rockport	Hamilton Ipperwash Petrolia Widder "Olentangy"	Silica	Sellersburg Beechwood	Hamilton Lingle	Milwaukee	Hamilton Moscow Ludlowville Skaneateles Cardiff
		Bell	Delaware	Delaware	Silver Creek	Misenheimer		Marcellus
		Dundee	Onondaga Springvale	Columbus	Jeffersonville (Corniferous)	Onondaga Grand Tower		Onondaga
		Mackinac			Geneva Pendleton	Dutch Creek		Scoharie
(Lower)	Oriskanian	Oriskany?	Oriskany	Oriskany				Oriskany
	Helderbergian	Detroit River Lucas Amherstburg Anderdon Flat Rock	Detroit River Lucas Amherstburg Anderdon Flat Rock	Detroit River Lucas Amherstburg				Helderberg Group
		Sylvania	Sylvania	Sylvania				
					Kenneth			

*Ulrich places Chagrin below Huron

Table V. Devonian correlations in the Michigan Basin region.

The Raisin River dolomite is extensively exposed in the vicinity of Monroe and along the Raisin River in eastern Monroe County, Michigan. The member usually has a thickness of about 200 feet, and there are several oolitic zones. The rock is commonly blue gray to drab, banded and argillaceous dolomite with numerous carbonaceous partings along the bedding planes. The Raisin River member contains layers or zones of variegated dolomite which are dense, compact, break with conchoidal fracture, and resemble castile soap in color. The intimate character of the oolites has been studied by Sherzer[68] who concluded that their origin was similar to the oolitic sands of the Great Salt Lake, Utah. He believed that these beds were very possibly laid down in bodies of water temporarily separated from the open sea and resulted from a secretionary growth of calcium carbonate caused by colonies of algae. The alteration of this calcium carbonate to dolomite ((Ca, Mg) CO_3) has somewhat modified the original physical structure and conceals its identity.

DEVONIAN

The Devonian period opened with a basal deposit of sandstone and ended in a widespread series of black and gray shales. Early in Devonian times the Salina was apparently reworked and conditions favoring evaporation were again in force. The Middle Devonian was essentially a time of limestone deposition, and the great thickness of Traverse and Dundee limestones is typically developed in the Michigan Basin area. The correlation of Devonian rocks in Michigan with the adjoining states, and the typical New York section is shown in Table V.

The Sylvania sandstone was laid down on a relatively uneven surface and rests on different members of the Bass Island formation. Carman[69], who found Detroit River fossils within a foot of the base of the formation, determined the age of the Sylvania as Devonian. He also believed that the sandstone was only locally of wind blown origin and that as the sea transgressed over older beds in the northwestern Ohio region, a thin layer of wind-worked sand was redeposited under water.

A detailed study of the Sylvania by Grabau and Sherzer[70] produced evidence in support of its aeolian origin. The rock consists of remarkably pure white quartz sand which is usually but slightly coherent. Binding material when present consists of dolomitic cement. The grains are frosted and well rounded, giving evidence of wind action. The sandstone may grade into dolomitic sandstone, arenaceous dolomite, and white cherty dolomite. Often the Sylvania is separated into two or more thick massive sandstone beds by layers of siliceous dolomite. Sometimes stratification is obscure and the beds range from a few inches to a few feet in thickness. Cross bedding at unusually high angles is characteristic. The grains are somewhat uniform in size, and secondary growth of quartz around the original grain is common. The color is generally very white and sparkling, and the sand is often compared to snow, flour, salt, or granulated sugar.

The thickness is usually 100 feet or less but locally over 250 feet. The sandstone may be replaced entirely by white cherty and siliceous dolomite and is not easily recognized in wells. The formation is widely distributed throughout the Michigan Basin and practically all borings that go deep enough encounter beds which in some way resemble the Sylvania. Even in southwestern Michigan where much of the formation seems to be replaced by a bright green shale, occasionally well rounded sand grains are imbedded in the shale. The absence of water in the formation in some wells nearby those having a large flow is additional evidence that it was deposited irregularly and on an uneven surface. The Sylvania brines are strongly sulfurous, and masses and veins of celestite ($SrSO_4$) and native sulfur are common in the rock. Weathered exposures are streaked and stained a brown color from iron compounds derived by the reduction of disseminated pyrite and leaching of iron from overburden.

A belt of Sylvania which is mostly drift covered, extends northeasterly through Monroe County. Outcrops are not abundant but on account of its unusual purity, the sandstone where it is at or near the surface is worked for glass sand.

The Detroit River formation rests unconformably upon the Sylvania sandstone and is typically the Michigan representative of the Monroe series. The four recognized members in ascending order consist of the Flat Rock dolomite, Anderdon limestone, Amherstburg dolomite, and Lucas dolomite. The entire formation is not always present as described because some of the lower members are eliminated by overlap. The Detroit River beds are made up of gray to buff, granular dolomite, magnesian sandy limestone, pure coralline fossiliferous limestone, shaly limestone, anhydrite, gypsum, and rock salt. The occurrence of salt is confined to the north central part of the Michigan Basin.

The Detroit River series shows a rapid thickening toward the center of the Basin, where its thickness is over 1,000 feet. The normal thickness for the Detroit River district is between 200 and 300 feet, and type exposures, therefore, represent a relatively small part of the formation. The outcropping areas and important quarry localities are shown in Figure 2. The individual members of the Detroit River have not been separated in the northern part of the State.

The Flat Rock dolomite member is named from Flat Rock, Wayne County, Michigan. The rock is dark gray, very compact, porous, magnesian sandy limestone, or locally a shaly limestone. At Flat Rock the formation is described as a brown dolomite, thin bedded, hard and practically devoid of fossils. Nodular concretions of gypsum were observed in some of the beds uncovered by ditching operations along the Huron River. In the Detroit salt shaft, the lowest beds are Flat Rock dolomite with a thickness of 47 feet, and the thickness for southeastern Michigan ranges from 40 to 100 feet. The separate members of the Detroit River formation cannot usually be identified from well samples.

The Anderdon limestone is extensively quarried about a mile northeast of Amherstburg on the Ontario side of the Detroit River. This is the typical exposure of the formation. It is made up of stromatopora reefs passing laterally and downward into evenly bedded shaly limestone. The limestone has conchoidal fracture, and some of the lowest beds show mottling. Others are laminated. There are thin beds of sandy limestone, and one of these containing a few crinoid discs is oolitic. The limestone is very pure and analyses showed as high as 99% $CaCO_3$. The exposed section is 24 feet thick and the upper surface is an important disconformable contact, with characteristics suggesting aeolian erosion. The Dundee limestone of Middle Devonian age rests directly on the Anderdon at this place.

Test holes at Sibley quarry, Wayne County, and the Detroit salt shaft enabled Sherzer[71] to determine the approximate limits of thickness of the Anderdon to be from 35 to 60 feet, but this range is probably only applicable over a very restricted area. The formation is not usually recognized in deep wells, but fossiliferous limestone[72] has been found in well cuttings of probable Detroit River age. It is very possible that much of the oil derived from the Muskegon oil field, Muskegon County, was produced from porous Anderdon beds.

The Amherstburg member or "transition" bed was the name applied by Grabau and Sherzer[73] to the rocks exposed in the bed of the Detroit River by the Livingstone channel cut opposite Amherstburg, Ontario. The range of thickness in Wayne County is probably about 20 to 50 feet. The rock is brown or drab, porous, fossiliferous dolomite, and the layers are generally thick and cavernous. The Amherstburg fauna[74] is the largest and most robust of the Monroe and contains an abundance of corals. Grabau[75] emphasizes the affinities of this fauna with the Akron dolomite and Bertie waterlime of western New York.

The Lucas dolomite is typically exposed in Lucas County, northwestern Ohio. In Michigan, 189 feet of the formation was found in the Detroit salt shaft. Southwestward from Oakwood, the suburb of south Detroit where the shaft is located, it is entirely cut out in several localities by post-Monroe erosion. Carman[76] has found a stylolitic disconformable plane of contact with a few feet of relief at the top of the formation. The thickness of. the Lucas is probably 200 feet or more in some places in southeastern Michigan.

The rock is a drab dolomite with some banding and lamination. Certain layers are streaked and mottled with blue, and occasional beds of almost pure calcium carbonate are present. The Lucas strata are thinner bedded and more even grained than the Amherstburg below. Grains of sand have been found near the contact at the top of the Detroit River series, both on the outcrop and in wells. This occurrence strongly suggests that remnants of sand deposited in Oriskany time are present in Michigan.

The fauna of the Lucas member has Silurian affinities, and it is on this basis that some stratigraphers are hesitant about calling the Detroit River beds Devonian. Grabau[77] believes that Lucas time was represented by a hiatus in western New York, but that the beds are equivalent to the Manlius and Rondout of eastern New York.

The Mackinac limestone described from the Mackinac region in northern Michigan contains a fauna[78] fixing it somewhat lower in the column than the Dundee of the southeastern part of the State. The rock is gray to buff limestone which has been greatly broken up and shattered and later recemented by a limestone sand or flour. The fragments are occasionally found almost in place, but more often they are scattered into a jumbled mass. These brecciated rocks grade laterally into steeply dipping layers and apparently were developed along a shore line. Their origin is not well understood, and this problem offers unusual opportunity for critical study. Some of the best exposures of the Mackinac limestone are on Mackinac Island and near St. Ignace in the Upper Peninsula. These beds are also exposed in the Lower Peninsula two to four miles south and southeast of Mackinaw City. This region includes the "Mill Creek section" in the northwest corner of Cheboygan County.

The Dundee limestone which is about equivalent to the Onondaga of New York is widespread in the Michigan Basin. The thickness varies from less than 50 feet in western Michigan to over 300 feet in the Saginaw Bay region, where the formation has been penetrated in many wells. In the western and central parts of the State, the correlation of well cuttings shows it very thin or locally absent. The irregularities of the land surface upon which the Dundee was deposited and the pronounced denudation at the close of Dundee time contributed to the variable thickness of the formation.

The exposures of Dundee are confined to the southeastern and northern sections of the State and have been extensively described[79]. The two largest quarries are the Sibley quarry of south Detroit and the Calcite Quarry in Presque Isle County near Rogers City where over three miles of quarry face is open. Many beds recognized in the formation in the Sibley quarry do not correlate with those to the north, and similarly the fauna at Calcite differs materially from that in the southeastern part of the State. The Dundee of Michigan apparently consists of a number of fauna! elements due to the presence of local basins and barriers in the region.

Generally speaking, the lithologic features of the beds are fairly continuous over the State. The rock is gray to buff, cherty, crystalline, fossiliferous limestone usually of high purity. Dolomitic beds appear near the bottom of the formation, and there are occasionally sandy strata at the base. If the shale which is usually present above the Dundee is thin or absent, the Dundee beds penetrated in wells can be distinguished from the Traverse only with greatest difficulty.

The chert in the formation occurs as nodules, seams, or beds up to several feet in thickness. Bituminous matter is frequently encountered, and porous layers of the limestone are important oil and gas reservoirs in the State. Some of the coralline, crinoidal and other fossiliferous beds are very porous and stylolitic structures frequently exist through the rock. Numerous seams of crystalline calcite show that extensive solution has taken place.

Although the Bell shale is regionally a wedge shape deposit and thins to the southwest, it occurs at the base of the Traverse formation with great uniformity over relatively large areas. The shale is generally blue gray to dark gray calcareous rock, often very fossiliferous, and usually nearly black at the base. The beds are correlated with the Marcellus of New York.

Exposures of the Bell shale are not abundant because the formation weathers readily and is rapidly removed by erosion. In fact, the strata are apt to cave when drilled and the beds are frequently termed "soap rock" by drillers. The shale was named from an outcrop north of Bell, Presque Isle County, but it is best exposed now in the quarry of the Kelley Island Lime and Transport Company at Rockport, northeastern Alpena County.

The thickness of the Bell shale usually varies from 60 to 80 feet in the northern part of the State, but the upper and lower limits of the member are frequently difficult to determine in wells. The shale at the base of the Traverse is over 200 feet thick in central Michigan, and possibly the beds correlated with the Bell shale in well records may include other parts of the Traverse formation. The basal shales of the Traverse thin very rapidly to the south and southwest and show considerable irregularity in thickness in this part of the State. Recognizable beds of Bell shale cannot be found in many wells in southwestern Michigan. The formation seems to have been deposited in a sea which transgressed to the west, and the basal shale member of the Traverse in western Michigan probably corresponds stratigraphically to higher beds of the Traverse farther toward the center of the State.

The Traverse formation is widely exposed in the northern part of the Lower Peninsula. Its boundaries and the location of many important exposures are indicated in Figure 2. The principal areas of Traverse rocks are in Alpena and Presque Isle counties, and the Little Traverse Bay region. The beds are partially equivalent to the Hamilton of New York, but Pohl[80] has recently shown that the Traverse group should be placed in the column between the Onondaga and Hamilton. The members of the group have been variously subdivided[81], but the threefold division into the Long Lake series, Alpena limestone, and Thunder Bay series seems to be the more appropriate. Ver Wiebe[82] suggests that the Long Lake series be divided into the upper, lower, and Rockport limestone. Pohl[83] has separated the Traverse group on the west side of the State in descending order into the Petoskey formation, Charlevoix stage, and Gravel Point stage. The committee[84] of the U. S. Geological Survey on geologic names has accepted only the term "Traverse formation" for the entire group and does not recognize by name any subdivisions.

The Traverse is composed of an alternating series of beds of limestone, shale, dolomitic limestone, and anhydrite. The beds of anhydrite have been observed only in well cuttings and may be incorrectly correlated. The limestones vary greatly in color, texture, and composition. The color is commonly neutral gray weathering to buff or brown, but occasionally it may be lighter gray, buff, or even white. The numerous shaly beds give the Traverse a characteristic blue-gray color in contrast to the consistent light buff of the Dundee. The texture of the limestone varies from fine grained or lithographic to coarsely crystalline. Reworked coral reef material is present in the form of consolidated lime sands and lime mud. The shales are usually calcareous and in many places very fossiliferous. Generally, shale predominates in the southern and southeastern parts of the State and limestone beds are less common. Limestone is more abundant than shale in the Alpena district, and in the Little Traverse Bay region the shale members are greatly reduced in number and thickness. Dolomite and anhydrite are found in the Traverse in wells in the western part of the State.

The Traverse formation was first separated into individual members by Grabau[85] in 1902. The nomenclature of Grabau is still used, but some of the formation boundaries and stratigraphic limits of the various members have been changed by recent field work. The maximum thickness of the Traverse which exceeds 800 feet is in the north central part of the State in an area trending northwest-southeast from the mouth of Saginaw Bay to the head of Grand Traverse Bay. In the Alpena region and the central part of the State, the usual thickness is about 600 feet; in the Port Huron-Detroit region, 200 to 400 feet; and in southwestern Michigan, less than 150 feet.

The Traverse formation is typically developed in Michigan and contains a large variety of fauna. A wide diversity of forms, many of which show a northern derivation, have been classified by several students[86] of the region and this point has been emphasized by Pohl[87] in his recent discussion.

The Long Lake series (Lower Traverse) in the Alpena-Presque Isle district has a 40 foot bed of limestone at the base, which Smith[88] named the Rockport limestone. This member is essentially a stromatoporoid, corraline, fossiliferous limestone with a dark or black bituminous crystalline matrix. Locally it is shaly and very siliceous. The middle member of the series is about 70 feet thick, largely shaly, and cannot usually be found outcropping because it weathers away. The upper member contains about 80 feet of thin bedded, shaly, and fossiliferous gray limestone. Most of the limestone beds of the middle and upper members of the Long Lake are largely a mass of crinoid stems and fragments. The total thickness of the Long Lake series ranges from 190 to 200 feet.

The Alpena limestone is the comparatively pure middle limestone member of the Traverse characterized by an extensive system of coral reefs. This member is a distinct lithologic unit of gray to buff, cherty, bituminous limestone strata joining the reefs which locally possess dolomitized "chimneys." There are a number of thin lenses of shale, generally very calcareous and fossiliferous. The Alpena beds are more resistant than the rest of the Traverse and form a pronounced topographic feature. On this elevated area are superimposed the network of low ridges caused by the coral reefs, Grabau[89] stated in his latest work that there was 155 feet of Alpena limestone in the Thunder Bay region, but Ver Wiebe[90] determined this member to be 126 feet thick.

The Thunder Bay series (Upper Traverse) crops out in several localities in Alpena County, on Thunder Bay, and along the Thunder Bay River. Ver Wiebe[91] limited this series from 110 to 140 feet thick, consisting of thin limestones, shaly limestones, and calcareous shales. The limestone layers are bluish gray to pale buff in color and weather to a rusty yellow or brown. The beds are usually very fossiliferous, containing crinoids and abundant corals. The blue gray to black shales weather readily into blue clay. None of the beds are particularly distinctive, and the series is an alternating sequence of shales and limestones which possess no outstanding characteristics.

The Antrim shale is essentially brown to black and dark gray bituminous shale with many concretions, particularly concentrated in a zone near the base. The concretions are of two types, the one made up largely of bituminous slightly magnesian limestone and iron carbonate (siderite) and the other of iron sulfide (pyrite). The type of concretionary structure made up of carbonates has been extensively discussed by Daly[92] and Ver Wiebe[93], and occurs widespread throughout the State at about the same horizon in the Antrim shale. When encountered in wells it is usually termed "lime" or "hard shell" and is brown to greenish colored and coarse textured. The average diameter of the concretions is about 2 feet and the usual maximum about 3 feet, with reported sizes up to 6 feet. The bituminous calcite (anthraconite) has a concentric crystallization with the long directions of the crystals normal to the central core. The beds are usually bent or domed about the concretions and planes of jointing do not split them, thus indicating that they attained their present form at a comparatively recent time.

The pyrite type of concretion is distributed through the formation, or arranged in definite rows more or less parallel to the bedding. The concretions are spherical or somewhat flattened spheres (spheroids) and their size ranges from an inch to approximately 3 inches in diameter. These pyrite concretions seem most abundant near the base of the formation.

There are exposures of the Antrim shale in the Alpena region (Paxton quarry in particular), southern Cheboygan County, and south and southwest of Little Traverse Bay. The beds crop out under the drift in an arcuate belt circling the northern part of the Lower Peninsula and the southeast and southwest corners of the State, as shown in Figure 2.

The Antrim beds usually contrast rather sharply with the Traverse below, but in central Michigan they may alternate upward with gray and green shales which grade into either the Bedford or Ellsworth formations. The brown color is largely caused by macerated organic fragments and spore cases (*Sporangites huronensis*) disseminated through the rock. The similarity of the brown well cuttings to coffee grounds has given rise to the term "coffee" shale which is extensively used by drillers. The bedding is thin or fissile, and tarry, brittle, coal-black seams occur in the ledges where the rock is exposed. The formation is comparable to the Ohio shale, with which it is generally correlated.

The thickness varies from less than 100 feet to over 450 feet in various parts of Michigan, with the beds thickest in the central area of the Basin and the north Saginaw Bay region. The maximum thickness may be exaggerated by incorrect correlation, as the physical appearance of the overlying Bedford may be very much like the Antrim. The problem of correlating the black shales in Michigan seems to be as perplexing as that which caused the famous Ohio controversy of overlap versus lateral gradation, which Prosser[94] very thoroughly summarized. The possibilities are essentially the same. There is meager subsurface evidence to shows that the Antrim is overlapped[95] by the Bedford in the western part of the State, grades laterally[96] into the Bedford in the north central part of the State, and that the Berea-Bedford pinches out[97] between the Antrim and Sunbury in the south central part of the State Ulrich[98] found faunal evidence to show that the upper part of the Antrim black shale is rather definitely of Mississippian age. The final solution of this problem will probably be complex and require detailed study of micro-fauna from well cuttings and a much larger number of accurate sections than are now available from present well records.

MISSISSIPPIAN

The opening of the Mississippian period marked the return of conditions in Michigan favoring the accumulation of clastic deposits. On the eastern side of the State, these conditions continued with brief interruptions throughout the entire period. A thick and almost continuous shale series was deposited in the central and western parts of the State near the middle of the period.

Although continuous salt beds have not been found, the Michigan synclinal basin again became an area in which drying up of the seas was going on near the close of the Mississippian. Possibly, evaporation was frequently interrupted or else the rock salt formed was entirely removed by subsequent solution. The latter explanation seems plausible when one considers the amount of weathering and extensive erosion which must have followed at the end of Mississippian times.

The period ended in a general invasion of the sea giving rise to a thin but rather continuous deposit of limestone. Excepting when impure limestone was laid down during Coldwater time on the west side of the State, this was the first return of seas rich in lime (calcium carbonate) since Devonian. At the close of Mississippian, the area was uplifted and deeply eroded, removing many of the upper members and bringing about the uneven surface of disconformity. This disconformity is the most pronounced since the close of Silurian. The correlation of the Mississippian rocks of Michigan with those of neighboring states in the Michigan Basin region is shown in Table VI.

The exact time at which the Mississippian began is still somewhat uncertain. The Bedford formation was tentatively placed in the Devonian by Lane[99], and his correlations have been followed in subsequent publications of the Michigan Geological Survey. The discovery of Mississippian fossils in the upper beds of the Antrim would seem to show the Mississippian age of the Bedford formation. In Michigan it is simply a lithologic unit as no distinctive fauna has been found locally in the strata of apparent Bedford age.

The beds exposed south of Ellsworth, Antrim County, have not been correlated definitely with the Bedford shale of Ohio. Similar strata to those near Ellsworth were described by Winchell[100] in 1861, when he stated "On the east shore of Grand Traverse Bay, nearly opposite the north end of Torch Light Lake, is a bed of green shale occupying a position above the black shale. It is rather a soft, semi-indurated clay, traversed by bands of lighter color, apparently calcareous.

"No rocks have anywhere been seen reposing upon the black or green shales."

TABLE VI.—*Mississippian*

Michigan			Ohio	Indiana	Illinois	Wisconsin
Tennesseean (Late)	Chesterian	Grand Rapids "Series" Bayport	Maxville	Upper Chester: Buffalo Wallow Siberia Tar Springs	Kincaid-Clore Palestine Menard-Vienna Tar Springs	
				Middle Chester: Glen Dean Hardinsburg Golconda Indian Springs Cypress	Glen Dean Hardinsburg Golconda Cypress-Bethel	
				Lower Chester: Beech Creek Elwren Reelsville Sample Beaver Bend Mooretown Paoli	Undivided	
				St. Genevieve	St. Genevieve	
	Meramecian			Mitchell	St. Louis	
		Michigan		Salem	Spergen	
				Harrodsburg Upper Lower	Warsaw	
Waverlian (Early)	Osagian			Borden "Knobstone"		
		Marshall Upper (Napoleon) Lower	Logan Black Hand	Edwardsville Floyds Knob Carwood Locust Point	Keokuk	
		Coldwater	Cuyahoga	New Providence (Kenwood Beds at the top)	Burlington Fern Glen	
	Kinderhookian and Chattanoogan			Rockford	Chouteau Hannibal Louisiana Sweetland Creek	
		Sunbury	Sunbury			
		Berea Bedford Ellsworth	Berea Bedford			
		Antrim (Upper part)	Ohio (Upper part)	New Albany (Upper part)		Black shale (unnamed)

Table VI. Mississippian correlations in the Michigan Basin region.

The best exposure of these strata is about 1½ miles south of Ellsworth, in the Petoskey Portland Cement Company quarry, where a ledge of 30 to 40 feet of greenish gray shale is being worked. The location of this quarry is in the NE.¼ NE.¼ sec. 26, T.32N., R.8W., Banks township, Antrim County, Michigan. The total thickness of the strata between the top of the brown Antrim shale and the base of a red shaly limestone, probably of Coldwater age, in the western part of the State is between 500 and 600 feet. It is proposed that these beds be called the Ellsworth shale and that the type section be referred to the above locality. A complete section of the formation is found in the Charles

Reeths No. 1 well, NW.¼ NW.¼ sec. 9, T.10N., R.16W., Muskegon township, Muskegon County, where the shale series is 530 feet thick. This section includes blue shale, light and dark gray shale, and greenish gray shale, and follows below. The green color and smooth fracture along the bedding planes are the principal lithologic characteristics. Locally, thin layers may be sandy or calcareous.

Ellsworth Section from log of Muskegon Oil Corporation's—Charles Reeths No. 1 Well.

Location: On the Charles Reeths farm, NW.¼ NW.¼ Sec. 9, T.10N., R.16W. ¼ mile from north property line and 300 feet from west property line. Elevation: 628.5 feet above sea level. Drilled for Muskegon Oil Corporation by Gray Drilling Co., Milwaukee, Wisconsin. Completed in December, 1927. Initial production—330 bbl. oil and 494,000 cu. ft. gas. Record compiled from driller's log and set of samples by R. B. Newcombe.

Formation.	Thickness, *Feet*	Depth, *Feet*
Ellsworth Formation:		
Shale, blue and red (calcareous)	10	880
Shale, light gray	40	920
Shale, blue gray (hard)	20	940
Shale, soft, light gray	30	970
Shale, blue	100	1,070
Shale, gray to greenish gray	30	1,100
Shale, greenish gray	80	1,180
Limestone, sandy (with show of oil)	1	1,181
Shale, gray to greenish gray	29	1,210
Shale, light gray	10	1,220
Shale, greenish gray	70	1,290
Shale, light gray	20	1,310
Shale, greenish gray	40	1,350
Shale, gray	10	1,360
Shale, greenish gray	30	1,390
Shale, gray	10	1,400

This section formerly was correlated in wells as Berea-Bedford, but convergence studies indicate that the beds are not exactly equivalent to these formations (see fig. 21), and some of these strata are older than the Berea and Bedford of eastern Michigan. A plausible explanation for this relationship is that the "basin" was tilted downward to the northwest during early Mississippian time, and the thick shale series (Ellsworth) was probably deposited by a sea which came in from the south and southwest. At the beginning of Bedford time, a southeastward tilting took place along the same general axis, and the Bedford sea of Ohio entered the Michigan Basin from the southeast. Perhaps, the waters from this direction mingled with the sea previously existing in the western part of the Basin. Following the Bedford sea, the Berea incursion occupied about the same area.

The Bedford section is thin in the central part of the State and sandstone members of the Berea appear above it. The Bedford which occurs beneath the Berea in this area and farther east is gray in color and varies in thickness from a few feet up to 300 feet. The area underlain by the Bedford has not been separated on the map from the Antrim. (See pl. II).

A red shale occurring locally in the upper part of this gray shale section is very similar to the red Bedford of Ohio. On these grounds, Bobinson[101] suggested that this bed be correlated with the Bedford. Lane[102] had previously believed that the red horizon represented land waste from the Berea. The correlation with the Ohio red Bedford seems essentially correct in Jackson, Eaton, and other southern counties of the Lower Peninsula, but apparently it does not hold for a persistent red limestone at about the same stratigraphic position in the western counties. There is substantial proof to show that this red limestone should be placed in the lower part of the Coldwater shale. It can be correlated in wells across the Lower Peninsula with a red shale member which is from 0 to 30 feet above the Sunbury shale in the eastern part of the State.

The Berea formation has never been observed at the surface in Michigan, but its outcrop can be traced in wells in an interrupted arc around the east side of the southern peninsula. In wells the rock cuttings from the beds are fine grained, somewhat micaceous; sand with disseminated pyrite staining the characteristic gray color to a yellow or brown. The quartz grains are angular, usually transparent, uniform in size, and sometimes poorly cemented. The sand is much coarser grained on the east side of the State in the "Thumb" region northwest of Port Huron. Gray shale generally separates the individual beds of sandstone and calcareous layers have been found in certain localities.

The Berea thins rapidly westward in central Michigan and has always been found absent west of the line indicated on the map. (See fig. 5). Apparently during Berea deposition, there was a land area extending from northern Gladwin County in the central part of the Lower Peninsula to southern Calhoun County in the southwestern part. The area of greatest sinking in the synclinal basin during this period was in the "Thumb." As shown in Figure 5, the formation extends in this direction over a large part of the adjoining States to the southeast. The beds are well developed in Ohio and West Virginia and have been traced into Pennsylvania[103]. In these States, the Berea has been an important producer of oil and gas. The unusual deposition[104] in deeply eroded channels, so common in northern Ohio, will probably be found to extend into the Michigan Basin. The thickness of beds varies from a mere parting to over 300 feet, and abrupt changes evidently take place over very short distances. In wells, the Berea has frequently been mistaken for sandstone beds in the lower part of the Coldwater shale. These layers resemble one another strikingly and may have been derived from similar sources. Possibly, the lower Coldwater sandstones came from the reworking of Berea beds exposed elsewhere.

The Sunbury formation usually rests directly upon the Berea and consists of brown to black, unctuous, pyritous shale. In some places, the shale is dark gray and has several lithologic phases. The Sunbury is not exposed and has not been mapped as a separate formation in Michigan. It is included with the Coldwater, a much thicker shale series above.

The maximum thickness of the formation is over 100 feet, but it usually has from 10 to 30 feet of strata. A red shale member is often present at from 0 to about 30 feet above the Sunbury. This shale changes to a red shaly limestone in the western part of the State and is one of the most persistent "marker" beds in that region. Where this red limestone is found, the Sunbury does not usually amount to more than a carbonaceous parting. Locally the black shale becomes abnormally thick, as in northeastern Ottawa and southern Newaygo counties.

Figure 5. Known extent of sandstones which have been correlated with the Berea. (diagonal pattern). Other symbols show the Devonian and earlier formations (vertical pattern), Mississippian areas where the Berea is lacking or undescribed, (blank), and probable extent of the Berea (dashed line). Stars indicate places where the Berea is known to thin rapidly. (After W. I. Robinson with revision).

The type locality for the Sunbury shale is on Rattlesnake Creek about two miles east of Sunbury, Delaware County, Ohio. The beds have not been classified as a definite formational unit in Michigan but they are correlated with the Giro section because of lithologic similarity and the typical Bedford-Berea-Sunbury order found in well cuttings. This seems to be a plausible supposition and is fairly well established. Diagnostic fossil species have never been found in the comminuted material from wells.

The Coldwater formation is the thickest series of shale beds in Michigan and although predominantly shale, its lithologic character changes progressively across the State. In the "Thumb" and Saginaw Bay regions the Coldwater formation is almost entirely shale. In the western part of the State, local limestones and calcareous beds are characteristic. Some of these limestones are oolitic, and beds have been traced by means of wells across several townships. Nodules and concretions of clay ironstone and siderite are present in well confined zones. Red shale beds are occasionally found in the Coldwater formation in the eastern counties of the State.

The typical color of the shales is blue gray to greenish, and there are occasionally dark gray beds which may appear black when wet. The shale layers vary in hardness from slate-like to almost like gumbo. Drill cuttings often contain large chips.

The area underlain by the Coldwater formation forms a wide arcuate belt around the southern peninsula. Exposures and rock near the surface have been described from Branch, Calhoun, Huron, Hillsdale, Sanilac, and St. Joseph counties. The type locality is in the valley of the Cold-water River, Branch County, where shale from several quarries has been used for the manufacture of cement. The exact age of the formation is rather uncertain, but the lower beds are probably equivalent to the Cuyahoga of Ohio and the New Providence of Indiana. The upper strata of the Coldwater may be equivalent in part to the Black Hand of Ohio.

The base of the Coldwater as originally defined is delimited by the top of the Berea sandstone, but in the present classification it is marked by the top of the black Sunbury shale. The top of the formation grades upward without sharp demarcation into the basal beds of the Marshall sandstone. The change is frequently inconspicuous and very indefinite. Three criteria have been used for fixing the top of the Coldwater: the appearance of highly micaceous sandstone, red color, and locally a calcareous, fossiliferous bed. None of these characteristics are continuous throughout the entire State and the top of the formation as now used is, therefore, often very hypothetical.

The total thickness of the Coldwater beds varies from about 500 to over 1,000 feet, with an average of about 800 feet. The fastest sinking part of the "basin" extended in a northeast-southwest direction during Coldwater time, but a deep trough also intersected this in northern Midland County in a general northwest-southeast direction. The areas of thickest sedimentation were confined to central Michigan, where over 1,000 feet of Coldwater was laid down. These areas include the greater part of ten counties.

The Marshall formation comes to the surface in an almost continuous belt surrounding the central part of the southern peninsula. (See fig. 2). Close scrutiny shows the belt to be roughly a distorted square. The corners of this square are in northeastern Huron County, southeast central Hillsdale County, southwestern Oceana County, and southwestern Otsego County. Exposed sections are abundant in Huron, Calhoun, and Jackson counties, and there is a large abandoned quarry in southwestern Ottawa County.

The formation is divided into the Upper Marshall or Napoleon sandstone and the Lower Marshall and is probably Burlington and Keokuk in age, correlating in part with the Black Hand and Logan of Ohio. In a recent paper Thomas[105] proposes a three fold division of the Marshall, utilizing the term "Upper Marshall" in a different sense than is now prevalent, and retaining the term "Napoleon" for the continuous sandstone beds near the top of the formation. He describes a persistent upper sandstone similar in lithologic properties to the Napoleon and separated from the Napoleon by a greenish gray shale, a limestone, or a coal. Other evidence is also given to show that there is an important hiatus within the Upper Marshall as originally defined.

That a significant time break took place is fairly certain, as the green material within the described shale has been found to be glauconite, which is a common associate at surfaces of disconformity. Furthermore, the appearance of the limestone indicates different conditions of deposition than in the preceding period. Evidence of this break has been found in several parts of the State, and it seems to have taken place more or less uniformly.

Despite these facts the new division of the Marshall formation suggested by Thomas[106] is not favored, because the features of Marshall deposition can explain the conditions fully as well without requiring such a pronounced break within a named unit. The local absence of a part of the Napoleon and also beds of the Lower Marshall is significant proof of the intensity of erosion which took place at the close of Marshall time. It is logical to assume that there were numerous islands in the seas of the succeeding age and much of the Napoleon sandstone was, therefore, reworked and redeposited. The resulting beds; thus contain sand grains which are remarkably similar to the Napoleon. These sandstones would occupy a position above the old land surface, and would not be of Marshall age but would correspond to the Michigan formation above. This explanation seems to harmonize with existing conditions.

The Lower Marshall is difficult to distinguish from the Coldwater beds below, but the gradational change can usually be determined by the appearance of several varieties of mica disseminated through the layers. The strata consist largely of thin conglomerates, light greenish gray gritstones, and green and red shales. A fine grained grit of light greenish gray color is characteristic of the formation. This grit becomes shaly by vertical and horizontal gradations, sometimes maintaining its characteristic tint and sometimes changing to a deep reddish brown color. The green and red colors are bright and distinct when the rock is wet and contrast strikingly in drill cuttings. The conglomerate near the base of the formation described by Lane[107] as the "peanut conglomerate" occurs regularly in wells in the "Thumb" district. The red color so common in the Lower Marshall of eastern Michigan disappears locally in the western part of the State, particularly in southern Kent and adjoining counties. In some places the absence of red Lower Marshall agrees rather closely with the structural position of the locality, the synclines containing a preponderance of red strata and the anticlines practically none. In northwestern Michigan where the Marshall thins, the red micaceous beds are absent and instead there is a pink tinted sandstone member in the upper part of the formation. This may be explained by lateral change in the color and texture of the Lower Marshall and the small amount of Napoleon in western Michigan; removal of Lower Marshall red micaceous sandstones by the Napoleon sea gradually invading the land along its western shore line, thus adding red color to the beds; or coloration of the Napoleon sandstone beds from the western source of sediments in the iron-bearing regions, as suggested by Thomas[108].

The Napoleon sandstone has been extensively described in early reports and papers by Winchell[109], Rominger[110], and Lane[111], and the examination of well cuttings has added much new data in the past few years. The rock is mostly white sandstone with impurities of pyrite which form brown stains. The light greenish tint of many of the sand grains is characteristic and some of the grains consisting of undecomposed feldspar are pink in color. Often the matrix[112] binding the sandstone grains consists of kaolinitic material which has been determined as gibbsite (Al_2O_3) ($3H_2O$). The grains are angular and in local beds they are relatively uniform in size, although where cross bedding has been found the grain size is not so regular.

The sandstone is open textured and an important water bearing formation wherever it occurs. Under sufficient cover the beds contain a brine strong with salts of bromine, iodine, and chlorides of calcium and magnesium. Small quantities of heavy oil and some gas have been found in the reworked beds for a long time thought to be in the upper part of the Napoleon. The formation is usually superimposed by dolomitic limestones of the Michigan series, and the greenish color of the associated shale is significant in correlation.

Commonly in the north central area of the "Thumb" district, the interval[113] between the green glauconitic layer and the eroded top of the Napoleon sandstone is about 15 feet. The glauconite bed either rests between two layers of hard limestone or is associated with a single layer which is sometimes present alone. A thin series of shales separates the limestones from the top of the Napoleon. This interval represents the "break" described by Thomas[114].

The Marshall formation ranges from less than 150 feet to over 560 feet thick, the thickest section being found in eastern Clinton and Gratiot counties and the Saginaw Bay region. The exact amount of Lower Marshall is not easily determined but the Napoleon sandstone generally contains from 80 to 100 feet of strata, although over 200 feet of Napoleon has been correlated in wells. The Marshall formation thins rapidly toward the central part of the State and is generally less than 250 feet thick west of Isabella County.

The Grand Rapids series has two members, the Lower Grand Rapids or Michigan formation, and the Upper Grand Rapids or Bayport limestone. During the deposition of the series, there was an emergence in the early stages and a general transgression of the sea at the close. The Michigan formation is typical of the Michigan synclinal basin area. The beds were deposited on an uneven surface resulting from extensive denudation at the close of Marshall time, and at the end of the Mississippian period intensive erosion again took place, cutting deeply and removing large quantities of the materials laid down. A series resulted which is extremely irregular and contains a wide variety of deposits. The concentration of sediments and chemical precipitates in local basins shows a close relation to structure. The thickest Michigan formation beds are found in the synclinal areas.

The Michigan formation marks the return of conditions favorable to evaporation and apparently isolated seas were predominant. The Basin seems to have been cut off from outside connections for considerable periods of time, and numerous thick deposits of anhydrite and gypsum were the result. Bedded salt has not been reported from the formation, although veinlets of salt have been observed.

A bed of hard, brown to buff, impure, dolomitic limestone usually occurs at the base of the Michigan formation and separates it rather sharply from the underlying Napoleon sandstone. The formation consists largely of gray, greenish gray, and dark gray shales which are frequently bituminous in the lower members. Sandstones occur locally in some areas and those near the base of the series which consist largely of reworked Marshall sands serve as an important reservoir of natural gas in the central part of the State. Red sandstones and shales are also found locally, especially in thick sections of the formation and in structural "lows." Several types of gypsum and anhydrite occur in bedded deposits and disseminated nodules of varying sizes. Gypsum and anhydrite are generally most abundant in the lower part of the formation and occurrences of these minerals have been discussed in detail by Grimsley[115].

Exposures of Michigan formation rocks are not usually well preserved because of the readiness with which they slack and weather. The beds come nearest the surface in Kent, Arenac, Iosco, and Ogemaw counties. Gypsum is extensively quarried and mined in the vicinity of Alabaster, Iosco County, and Grand Rapids, Kent County, and the color of the raw mineral product varies from cream white to pink and red and the texture from needle-like to granular. In the south part of the State in Jackson County, Michigan series beds are thin or entirely absent, and the Bayport limestone locally rests directly upon the Marshall sandstones. Where the entire Grand Rapids, series is absent, the Parma sandstone of Pennsylvanian age has been found locally to be in direct contact with the Marshall with scarcely I perceptible break.

The area where Michigan formation rocks come to the surface (see fig. 2) has an arcuate rectangular outline with the long direction trending northwest-southeast in the central part of the State. The belt narrows and widens and is locally interrupted to the southeast by the overlap and removal of beds caused by the pronounced arch in the vicinity of Howell. This area includes about half of the southern peninsula and the outcropping belt of soft non-resistant rocks exercised important control upon the localities of intensified pre-glacial erosion.

Drill cuttings from the Michigan formation are easily distinguished by the greenish gray color and the presence of sulfates. Cores often show fractures cemented with selenite (a mineral form of gypsum) and evidently a large amount of adjustment in the beds has taken place as the result of solution. The solubility of the gypsum is illustrated by the fluted appearance of the weathered surface where it is exposed. Breccias or recemented fractured beds are common throughout the formation.

The thickness of the Michigan formation varies widely over small areas and is closely related to structure. The formation may be locally absent but generally it is from 50 to over 550 feet thick and the thickest sections are largely in the central part of the State. The stratigraphic position of the series is not well determined, but Lane[116] considers the rocks of this age to include Keokuk, a part of the Kinderhook, and possibly the lower St. Louis of the Illinois section. Beds which are directly equivalent have not been found in Ohio and the time of emergence is considered to be about the close of Osage. Much further paleontologic study of the faunas in the Michigan formation rocks must be carried on before the problems of correlation can be definitely settled.

The Bayport limestone is; mapped with the Michigan formation as a member of the Grand Rapids series, but it constitutes a distinctly separable formation although often variable in color, texture, and composition. It contains white to light gray, dark gray, and bluish limestone, magnesian limestone, and dolomite. Lenses of sandstone and sandy, nodular cherty beds are locally present and in places show greenish colors near the contact with the underlying Michigan formation. The sand content increases toward the base and the rock passes into a white, firm to poorly cemented, coarse grained sandstone. Intraformational breccias and conglomerates with limestone pebbles have been observed in cores. There is abundant evidence that the Bayport was extensively reworked by the Pennsylvanian sea and numerous isolated remnants and layers of material from other beds resulted. Limestone beds are frequently interspersed with sandstone resembling the typical Parma sandstone above.

The maximum thickness of the Bayport is about 100 feet but it usually contains from 40 to 60 feet of strata. Exposures occur in Jackson, Eaton, Huron, Tuscola, Arenac, and Kent counties, and large quarries are in operation at Bayport, Huron County, and Bellevue, Eaton County. The beds are highly fossiliferous in the upper part of the section, and there are some thin strata high in calcium carbonate. The contact of the limestone with the white Parma sandstone above is not always sharp, but usually there is sufficient contrast to separate the formations.

The Bayport limestone is probably equivalent in age to the upper part of the St. Louis, and the St. Genevieve limestone of the Mississippi Valley section. The beds can also be compared approximately with the lower part of the Maxville of Ohio. Recent determinations[117] of bryozoa and brachiopod species suggest Warsaw affinities, but this may possibly be explained by the long range of many species occurring in typical Warsaw beds. For the time being, the Bayport is provisionally correlated with upper St. Louis and St. Genevieve and may be as old as Warsaw.

PENNSYLVANIAN

The Pennsylvanian rocks of Michigan have been studied only in very limited areas. They have been isolated by erosion from the large basins of coal deposition in other states and except in a few small areas are also deeply buried by glacial material. Because of these conditions, the beds cannot be definitely traced from adjoining states and faunal evidence by which they may be correlated is meager. The approximate correlations of the Michigan rocks with the Pennsylvanian and Permian of Ohio and Indiana are shown in Table VII.

The system has three members called the Parma, Saginaw, and Woodville in ascending order. The Parma sandstone which is the basal member was deposited upon an irregular land surface. It is sometimes absent or poorly developed. The Saginaw formation is the thickest series in the Pennsylvanian and in numerous places contains beds of coal which are locally workable. The Woodville sandstone is usually present at the top of the coal measures and is probably an emergent type of deposit, forerunner to conditions of evaporation under which gypsum was formed. The Parma sandstone is typically exposed in Jackson County and is named from Parma, a small town west of Jackson. The rock is white, quartzose, glistening sandstone, locally coarse to conglomeratic. The small milky white pebbles have been compared to "split peas," the white color is characteristic although coaly terrestrial material has been found, and the rock is here and there stained with iron. Its stratigraphic position to the Bayport limestone below is an important aid in identifying the Parma. Reworked Bayport material may be found within the formation, and this locally contributes a greenish color.

The Parma has been recognized in numerous wells throughout the State, and this shows that it was deposited widely. The thickness is variable and seldom attains over 100 feet except where the sand has filled deep valleys in the pre-Pennsylvanian land surface. About 50 feet of Parma sandstone is usually present.

Fauna has not been found to aid correlation, but the relation of the Parma to the overlying Saginaw formation would place the age as Pottsville. The position of the beds in the stratigraphic column may be equivalent to the Mansfield of Indiana and the Connoquenessing (Massilon)[118] sandstone of Ohio, but this is entirely inferential. The exact correlation of the Parma will be in doubt until some fauna! occurrences are found within the formation or closely associated beds to more closely fix its age.

TABLE VII.—*Pennsylvanian and "Permo-Carboniferous?"*

	PERMIAN.			
Michigan	Ohio		Indiana	Illinois
Red Beds (?) (These strata of unknown age may range anywhere from Conemaugh to Permian or possibly higher in the column. The basal sandstone member is probably exposed at Ionia)	Dunkard	Washington		
		Greene		
	PENNSYLVANIAN			
	Monongahela			
	Conemaugh			
Woodville (Ionia)	Allegheny			
Saginaw (Grand Ledge Fauna=Lower Mercer of Ohio)	Pottsville			
Parma		Connoquenessing (?)	Mansfield (?)	

Table VII. Pennsylvanian and "Permo-Carboniferous" (?) correlations in the Michigan Basin region.

The Saginaw formation contains the coal bearing measures of the Michigan Basin and is composed of many beds of shale and sandstone. These beds are usually lenticular and so limited in extent that they cannot be traced from one locality to another. The shales are light to dark gray and black and some of the beds have been termed "fire clay." The sandstones are generally white to light gray and somewhat micaceous, the mineral being the light colored muscovite. Seams of siderite (black band ore) and nodules of siderite, pyrite, and sphalerite are present. There are a few thin limestone members in the Grand Ledge area where the most extensive Pennsylvanian fauna in the State has been found.

The widespread occurrence of the "Red Beds" and the basal sandstone (Woodville or Ionia?) has limited the territory underlain by the Saginaw formation to an arcuate belt around the center of the State, and thereby restricted its area! extent. Where exposed beneath the drift, the total amount of strata is exceedingly variable due to wearing away by ice action and erosion. The greatest reported thickness is about 500 feet. The best exposures are in Jackson, Genesee, Saginaw, Bay, Shiawassee, Ingham, Eaton, and Arenac counties, and various mine openings in these areas and in Huron and Midland counties have added to the information concerning these rocks. (See fig. 2).

The age of the formation has recently been discussed in detail by Kelly[119], who added several new species to the sparse assortment of fossils which occur in black shales and thin limestone beds of the Grand Ledge region, Eaton County. He confirms the findings of White[120] and the writings of Lane[121] by maintaining that the general correlation should be with the upper part of the Ohio Pottsville. Faunal evidence is reviewed which indicates that the Michigan forms were not derived from the Ohio forms and that "the Michigan Basin may have been connected with that of Indiana and Illinois." A quotation from J. Marvin Weller states that one species (*Spirifer boonensis*) characterizes horizons in Indiana and Illinois which are probably nearly equivalent to the Lower Mercer limestone of Ohio.

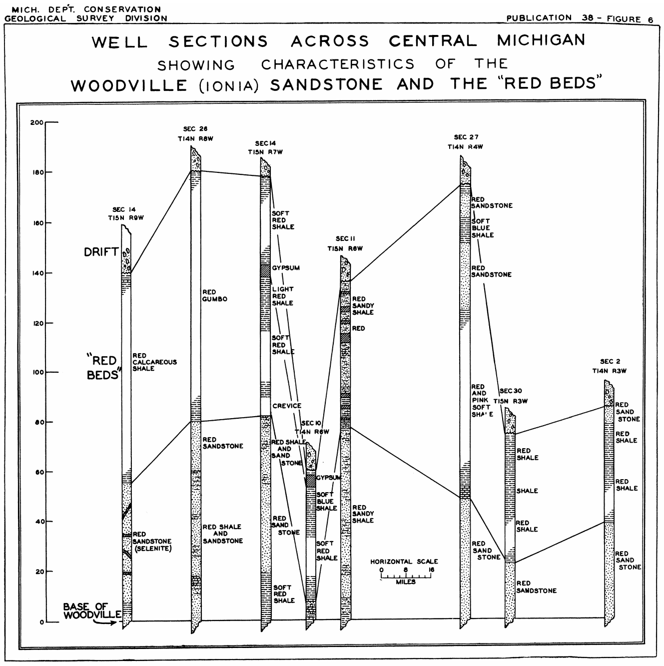


Figure 6. Well sections across Central Michigan showing characteristics of the Woodville (Ionia) sandstone and the "Red Beds."

The Woodville[122] sandstone in its originally described locality at the Woodville mine in sec. 36, T.2S., R.2W., Jackson County, has not proved to be the highest member of the coal measures, as defined. A more typical section is found between Lyons and Ionia, Ionia County, where a heavy sandstone high up in the series is exposed. This member is a red or brown, fairly coarse grained, cross-bedded sandstone with white or greenish gray spots and streaks. An upper red sandstone similar to that which occurs near Ionia has been traced by well records across the central counties of the State. The name of Woodville applying to a sandstone, which at its type locality is only a lenticular, restricted bed, probably should be dropped. A better name for the apparently persistent basal pink or russet colored sandstone of the "Red Beds" section would be the Ionia sandstone, suggested by Lane[123] in 1909.

A maximum thickness of 95 feet is recorded at Ionia but this much sandstone is not common. Some of the variations in the formation are indicated in Figure 6, which shows the probable correlation of a number of wells across the central part of the State. The area underlain by the Ionia sandstone is not mapped, but it probably includes a narrow belt which parallels the inner boundary of the Saginaw formation.

Fossils have not been found in these sandstone beds, but Lane[124] suspected the possibility of their being "Permo-Carboniferous" (?) in age, or lower Conemaugh, at the earliest. He believed that the local absence of the sandstone was due to the fact that it rests disconformably on the Saginaw formation below.

"PERMO-CARBONIFEROUS" (?)

The return of aridity and other conditions favorable to evaporation is indicated by a series including red shale, red to greenish sandy shale, sandstone, and gypsum. These beds occur above a thick basal sandstone and are widespread in the central part of the State. The basal sandstone member is probably equivalent to the Ionia sandstone or Woodville as first defined. The beds are found directly beneath the glacial drift throughout an area of about seven counties and attain a maximum reported thickness of 180 feet. Exposures have not been found and the beds remain unnamed because of their comparatively recent discovery and the difficulty of correlation due to the apparent absence of faunal material. Many of the layers are soft and the samples secured from drilling operations are usually poor.

The series is provisionally given the very generalized name "Red Beds" for identification purposes, with full appreciation that the term will probably be inadequate. The physical characteristics of the beds seem to compare rather closely with the Permian "Red Beds" of the southwestern sections of the United States, but this does not in any way imply a proposed correlation with any particular section. In fact, these strata could include beds from Pennsylvanian to Triassic in age and still possess practically the same lithological properties as described. The conditions which characterize "Permo-Carboniferous" deposition were apparently present in the restricted Michigan "basin." However, these conditions may have existed prior to the time that they prevailed in the typical southwestern "Red Beds" region. This conception was proposed for other sections of the eastern United States by Case[125] upon discovery of "Permo-Carboniferous" vertebrates in Conemaugh beds of Ohio.

There is no definite evidence at the present time to indicate that these beds should be separated in age from the previously described Woodville (Ionia) sandstone. The red color of the sandstone suggests aridity and possibly other climatic conditions favorable to dessication. Perhaps deposition was almost continuous so that no pronounced breaks occur in the entire red series. Well samples from new drillings and cores may bring about a better solution of this problem in the future.

The Woodville and "Red Beds" have been mapped as one complete unit in the region penetrated by the drill in central Michigan. The shape of the area underlain by these beds is roughly elliptical with the major axis almost due north and south. (See fig. 2) This area is apparently asymmetrical to the depositional "basin" and confined to the northwest side. However, it is probable that because of their soft, plastic character and the resemblance to certain types of red lake clay and boulder clay these beds have not been recorded in many wells. The exact limits of the area underlain by "Red Beds" is, therefore, not very accurately defined.

PLEISTOCENE

The Pleistocene deposits of Michigan which make up the surface material of a large part of the State have been extensively described[126]. The work of ice in sculpturing the hard rocks and molding surface features, acting as an agent for transporting incoherent rock debris, and serving as a barrier for impounding great inland fresh water lakes, is the determining factor in the origin of the surficial deposits of Michigan. The resulting material is known as *drift* and may be either stratified or unstratified. Boulder clay, lake clay, sand, and gravel are very widely scattered and irregularly distributed. These weathered materials dumped by the receding glacier during the various interrupted stages of its existence form a mantle or cover of variable thickness over most of the southern peninsula. The greatest known thickness is about 884 feet in southeastern Wexford County, but the thickness generally is from 100 to 300 feet. The areas of thick drift conform closely to the regions of high pre-glacial relief, but in some cases old drainage channels have been filled with glacial deposits. Here the drift is abnormally thick.

The ice advanced over the region because of several successive cold stages and retreated during relatively warm periods. The recognizable deposits in Michigan from two of these stages are the Illinoian and Wisconsin drift sheets. The Illinoian drift was subject to a considerable amount of weathering prior to the Wisconsin stage, and the lime removed by solution was reprecipitated in the spaces between the grains. The resulting boulder clay, or till, as it is sometimes called, is consequently somewhat hardened and is usually termed "hardpan" by water well drillers because it is difficult to penetrate. The color is generally blue gray thus contrasts distinctly with red to brown boulder clay which is more common in the younger drift. In addition to the leached clay which resulted from weathering processes during the interglacial period, dark black humous soils formed in swampy places. These interglacial soils contain remains of leaves, plants, and animals revealing the climatic conditions of the time. Evidence of erosion of the Illinoian drift prior to the Wisconsin stage is available from the topographic relief shown in wells penetrating the entire thickness of the Wisconsin drift sheet. The deposits of Wisconsin drift are less consolidated and do not show the same extensive effects of weathering as the earlier deposits. Locally, they are somewhat hardened by the action of solutions which filter through the and gravel and by the precipitation of lime, iron oxide, etc., cement the pebbles together. This cemented gravel, sometimes termed "crag," is similar in appearance to concrete. It has been found along hillsides, in gravel pits, and in wells.

The origin of the Wisconsin drift sheet has a complex history. The great mass of ice which covered the region was adjusted and controlled in movement by the depressions which existed prior to its formation. Be of this conformity to the larger valleys, the ice moved over the country in lobes or tongues which in this particular area occupied the basins of Lake Michigan, Lake Huron, Lake Erie, and Saginaw Bay. These lobes have been called the Michigan, the Saginaw, and the Huron-Erie lobes. The deposits from melting at the ice margin or front of the ice lobes were laid down when the ice fronts stood for some time at certain positions. At the junction of two lobes the quantity of material resulting from melting of the ice was much larger, and the deposits were, therefore, much thicker in these localities. Usually the interlobate areas, as they are called, correspond with the pre-existing pre-glacial topographic ridges and account for the rough correspondence of thick glacial deposits to the preexisting topography.

The principal surface features produced by the glacial deposits are called terminal moraines, kames, eskers, drumlins, ground moraine, and outwash. The terminal moraines are knolls or ridges consisting of boulder clay and more or less of sand and gravel. They are formed at the margin of the ice by the accumulation of debris from melting. Kames are modified types of terminal moraine and are usually sharp knolls or steep conical hills within the moraine. The material is sand and gravel rather than boulder clay. Eskers or "hogbacks" are steep, winding, snake-like ridges, consisting of the sand and gravel deposited by streams flowing within or at the base of the ice mass. Drumlins are inverted canoe-shaped hills of boulder clay, extending parallel to the ice movement, and were probably molded beneath the ice. Their exact origin is still in doubt. Ground moraine consists of the low hills and plains of till formed beneath the ice, when the retreat was sufficiently rapid to prevent the building of terminal moraine. Outwash is usually represented in the landscape by a comparatively level plain and is made up of sand and gravel deposited by the sheet-like bodies of running water or braided streams which flowed from the front of the ice. Sometimes the deposits of out wash have a "pitted" surface because of the subsequent melting of buried blocks of ice. The continuity of these glacial features is determined by the position of the several ice lobes when they were formed. The various morainic systems have been traced out in detail and given local names. They are fully described and shown by means of maps in the comprehensive reports on the glacial geology of Michigan[127].

Surface deposits indirectly caused by the continental glacier were laid down in the glacial lakes formed when retreats and advances of the ice diverted and choked drainage so as to impound the water. These lakes attained different forms and sizes near the close of Wisconsin glaciation as the ice lobes retreated into their respective basins. The elevations at which their waters stood were closely related to the numerous changes in outlet. At different times the lakes were drained by the Fort Wayne outlet and the Wabash River; the Chicago outlet and the Illinois River; the Imlay outlet westward across Michigan and thence to the Chicago outlet; the

Grand River outlet across Michigan to Lake Chicago which then occupied the southern end of the present Lake Michigan; the Ubley outlet across the "Thumb" to Lake Saginaw, and the Grand River outlet to Lake Chicago; the Trent outlet across Ontario and the Mohawk outlet across New York to the Hudson River; and the North Bay, Ottawa River outlet to the St. Lawrence. As the lakes stood at different levels, individual beaches, bars, barriers, and offshore features were formed and remain now as evidence of their former presence.

The Lakes were known in the order of their formation as Lake Maumee, Lake Arkona, Lake Whittlesey, Lake Wayne, Lake Warren, Lake Lundy, Lake Algonquin, and the Nipissing Great Lakes. The elevations at which they stood were not in direct relation to the order of existence, but a general oscillation took place in the direction of lower levels. This complication arose from the distribution of the topographic features of the region, the deepening of the outlets, a differential uplift of the land, and the shifting back and forth of the ice fronts.

The deposits of the glacial lakes were governed by the position of the shores. The basins of the lakes are left as comparativly level expanses underlain by different types of lake clays and silts. Near the former beaches, parallel ridges exist which represent the shore features generally common to all lakes. These features may be traced for miles as ridges of assorted sand and gravel with distinctive slopes which give further evidence of their origin.

[1]Van Hise, C. R., and Leith, C. K., Geology of the Lake Superior Region: U. S, Geol. Survey, Mon. 52, pp. 597-615 (1911).

[2]Van Hise, C. R, and Leith, C. K., Op. cit., p. 602.

[3]Logan, W. E., and Murray, Alexander, Geology of Canada: Geological Survey of Canada, p. 50 (1863).

[4]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: Jour. Geology, Vol. 15, p. 686 (1907).

[5]The Copper Deposits of Michigan: U. S. Geol. Survey, Prof. Paper No. 144, p. 18 (1929).

[6]Copper Deposits of Michigan: Op. cit., p. 18.

[7]Houghton, Douglass, Michigan Senate Document No. 7, pp. 74-75 (1840).

[8]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept. of the State Geologist, pp. 38, 39 (1908).

[9]Thwaites, F. T., Stratigraphy and Geologic Structure of Northern Illinois; Illinois Geol. Survey—Report of Investigations No. 13, p. 10 (1927).

[10]Ulrich, E. O., and Resser, C. E., The Cambrian of the Upper Mississippi Valley: Bull. Pub. Mus. City of Milwaukee, Vol. 12, Pt. 1, p. 11, (1930).

[11]Thwaites, F. T., Written communication (March 6, 1931).

[12]Logan, W. N., The Geology of the Deep Wells of Indiana: Dept. Conservation, Div. Geology, Pub. 55, p. 8 (1926).

[13]Thwaites, F. T., Personal communication.

[14]Thwaites, F. T., The Paleozoic Rocks found in Deep Wells in Wisconsin and northern Illinois: Jour. Geol., Vol. XXXI, No. 7, pp. 546-553 (1923).

[15]Ulrich, E. O., Notes on New Names in Table of Formations and on Physical Evidence of Breaks between Paleozoic Systems in Wisconsin: Wisconsin Acad. Sci., Trans., Vol. 21, pp. 72-90 (1924).

[16]Hussey, R. C., Personal communication.

[17]Thwaites, F. T., Op. cit., pp. 544-546 (1923).

[18]Edwards, Ira, Personal communication (March, 1931).

[19]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept. 1908, p. 40 (1909): also Jour. Geol., Vol. XV, p. 694 (1907).

[20]Bayley, W. S., The Menominee Iron Bearing District of Michigan: U. S. Geol Survey. Mon. 46, p. 494 (1904).

[21]Thwaites, F. T., The Paleozoic Rocks found in deep wells in Wisconsin and Northern Illinois: Jour. Geol., Vol. XXXI, No. 7, p. 542 (1923).

[22]Dake, Chas. L., The Problem of the St. Peter Sandstone: School of Mines & Metallurgy, Univ. of Missouri, Bull. Tech. Ser., Vol. 6, No. 1 (1921).

Berkey, C. P., Paleogeography of St. Peter Time: Bull. Geol. Soc. Am., Vol. 17, pp. 229-250 (1906).

Sardeson, F. W., The St. Peter Sandstone: Bull. Minnesota Acad. Sci., Vol. IV, pp. 64-88 (1910).

Lamar, J. E., Geology and Economic Resources of the St. Peter Sandstone of Illinois: Illinois Geol. Survey, Bull., 53, pp. 14-31 (1928).

[23]Thwaites, F. T., Paleozoic Rocks found in Deep Wells in Wisconsin and Northern Illinois: Jour. Geo., Vol. XXXI, No. 7, p. 540 (1923).

[24]Smith, R. A., The Occurrence of Oil and Gas in Michigan: Mich. Geol. & Biol. Survey, Pub. 14, p. 23 (1912).

[25]Robinson, W. I., Unpublished manuscript.

Case, E. C., and Robinson, W. I., The Geology of Limestone Mountain and Sherman Hill in Houghton County, Michigan: Michigan Geol. & Biol. Survey, Pub. 18, Geol. Ser. 15. pp. 174-176 (1915).

[26]Ulrich, E. O., Communication on Ford well, (1917); also tentative correlation of named Geologic Units of Michigan, compiled by M. Grace Wilmarth (June 1, 1929).

[27]Hussey, R. C., The Richmond Formation of Michigan: Cont. from Mus. of Geol., Univ. of Michigan, Vol. II, No. 8, p. 150 (July 15, 1926).

[28]Ruedemann, R., and Ehlers, G. M., Occurrence of the Collingwood Formation in Michigan: Cont. Michigan Mus. of Geol. Vol. II, No. 2, pp. 13-18 (July, 1924).

Hussey, R. C., Personal communication.

[29]Rominger, Carl, Geological Survey of Michigan: Vol. I, Part III, pp. 51-52 (1873).

[30]Hussey, R. C., The Richmond Formation of Michigan: Cont. from Mus. of Geol., Univ. of Michigan, Vol. II, No. 8, p. 131 (July 15, 1926).

[31]Hussey, R. C., Op. cit, p. 120.

[32]Williams, M. Y., The Silurian Geology and the Faunas of Ontario Peninsula, and Manitoulin and Adjacent Islands: Canada Dept. of Mines, Geological Survey, Memoir 111, No. 91, Geol. Ser., pp. 28-39 (1919).

[33]Williams, M. Y., Manitoulin: Ottawa Nat., Vol. XXVII, p. 37 (1913).

Grabau, A. W., Cabot Head: Bull., Geol. Soc. Am., Vol. 24, No. 3, p. 460 (1913).

[34]Williams, M. Y., Op. cit., p. 28 (1913).

[35]Savage, T. C., Silurian Rocks of Illinois: Bull., Geol. Soc. Am., Vol. 37, pp. 513-533 (1926).

[36]Ehlers, G. M., The Presence of Cataract Strata in Michigan Supported by Faunal Evidence: Michigan Acad. Sci., Arts & Letters, Papers, Vol. 3, pp. 281-283 (1924).

[37]Cumings, E. R., Written communication (1931).

[38]Cumings, E. R., Two Fort Wayne Wells in the Silurian and Their Bearing on the Niagaran of the Michigan Basin: Proc. Ind. Acad. Sci., Vol. 39, p. 198 (1930).

[39]Chamberlin, T. C., Geology of Eastern Wisconsin: Wisconsin Geol. Survey, Vol. II, pp. 336-345 (1877).

[40]Ehlers, G. M., Niagaran Rocks of the Northern Peninsula of Michigan: Abstract Bull., Geol. Soc. Am., Vol. 32, pp. 129-130 (1921).

[41]Ehlers, G. M., Unpublished manuscript.

[42]Smith, R. A., A Report on Michigan Limestones: Michigan Geol. & Biol. Survey, Pub. 21, Geol. Ser. 17, Part 11, pp. 153-156 (1915).

[43]Savage, T. E., and Crooks, H. F., Early Silurian Rocks of the Northern Peninsula of Michigan: Am. Jour. Sci., Vol. XLV (195), p. 62 (1918).

[44]Ehlers, G. M., Op. cit.

[45]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan; 10th Ann. Rept. of State Geologist, p., 56 (1908).

Smith, R. A., The Occurrence of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 14, Geol. Ser. 11, p. 24 (1912).

[46]Williams, M. Y., The Silurian Geology and Faunas of Ontario Peninsula, and Manitoulin and adjacent Islands: Canada Dept. Mines, Canada Geol. Survey, Memoir 111, Geol. Ser. 91, p. 52 (1919).

[47]Cumings, E. R., Silurian Studies. Two Fort Wayne Wells in the Silurian and their bearing on the Silurian of the Michigan Basin: Proc. Ind. Acad. Sci., Vol. 39, p. 196 (1930).

Cumings, E. R., and Schrock, R. R., Geology of the Silurian Rocks of Northern Indiana: Dept. Conservation, Div. Geology, Indianapolis, Pub. 75, pp. 62-63 (1928).

[48]U. S. Geological Survey, Niagara Folio No. 190, p. 7 (1913).

[49]Smith. R. A., A Report on Michigan Limestones: Michigan Geol. & Biol. Survey, Geol Ser. 17, Pub. 21, Pt. II, p. 152 (1915).

[50]Ehlers, G. M., Unpublished manuscript.

[51]Cumings, E. R., and Schrock, R. R., Geology of the Silurian Rocks of Northern Indiana: Dept. Conservation, Div. Geology, Indianapolis, Pub. 75, pp. 138-164 (1928).

[52]Cumings, E. R., Silurian Studies. Two Fort Wayne Wells in the Silurian and their bearing on the Silurian of the Michigan Basin: Proc. Ind. Acad. Sci., Vol. 39, p. 193 (1930).

[53]Newberry, J. S., Ohio Geol. Survey, Vol. I, Pt. 1, pp. 63, 132 (1873).

[54]Lane, A. C., Report of State Geologist of Michigan: Michigan Geol. Survey, Rept. for 1891-1892, pp. 66, 67 (1893).

[55]Williams, M. Y., Op. cit.

[56]Alling, H. L., Geology and Origin of the Silurian Salt of New York State: Bull. New York State Mus., Pub. 275, pp. 7-22 (1928).

[57]Smith, R. A., Mineral Resources of Michigan: Michigan Geol. & Biol. Survey, Pub. 35, p. 36 (1924). (Discussion written by W. I. Robinson).

Cole, L. H., The Salt Deposits of Canada and the Salt Industry: Canada Dept. Mines, Mines Branch, No, 325, p. 20 (1915).

Alling, H. L., Op. cit., p. 9.

Newcombe, R. B., Mineral Resources of Michigan with a report on Oil and Gas Development: Michigan Geol. & Biol. Survey, Pub. 37, p. 91 (1928).

_____, Interpretation of Recent Discoveries in the Salt-Bearing Rocks of Michigan: Michigan Acad. Sci., Arts and Letters, Vol. XII, p. 249 (1930).

[58]Cook, C. W., The Brine and Salt Deposits of Michigan: Michigan Geol. & Biol. Survey, Pub. 15 (1913).

[59]Lane, A. C., Report of State Geologist of Michigan: Michigan Geol. Survey, p. 66 (1891-92).

_____ Geological Survey of Michigan: Vol. V. Pt. II, pp. 26-28 (1895).

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

[61]Carman, J. Ernest, The Monroe Division of Rocks in Ohio: Jour. Geol., Vol. 35, No. 6, pp. 481-506 (1927).

[62]Lower Monroe—A Revised Classification of the North American Siluric System: Abst. Sci. N. S., Vol. 27, p. 622 (1908).

Bass Island Series—New Upper Siluric Fauna from Southern Michigan: Bull. Geol. Soc. Am., Vol. 19, p. 553 (1909).

[63]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept. of State Geologist, pp. 62-67 (1909).

[64]Newcombe, R. B., Interpretation of Recent Discoveries in the Salt-Bearing Rocks of Michigan: Michigan Acad. Sci., Arts and Letters, Vol. 12, pp. 239-250 (1930).

[65]Grabau, A. W., Sherzer, W. H., Op. cit., pp. 27-41.

[66]Sherzer, W. H., Geology of Wayne County: Michigan Geol. & Biol. Survey, Pub. 12, Geol. Ser. 9, Fig. 21 (1911).

Fay, Albert H., Shaft of the Detroit Salt Company: Eng. & Min. Jour., 91, p. 565 (1911).

[67]Carman, J. Ernest, Op. cit., p. 489.

[68]Sherzer, W. H., Geological Report on Monroe County: Michigan Geol. Survey, Vol. VII, Pt. 1, p. 62 (1900).

[69]Carman, J. Ernest, Op. cit, p. 497.

[70]Grabau, A. W., and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, pp. 81-86 (1910).

[71]Sherzer, W. H., Geology of Wayne County: Michigan Geol. & Biol Survey, Pub. 12, Geol. Ser. 9, p. 210 (1912).

[72]Newcombe, R. B., Middle Devonian unconformity in Michigan: Bull. Geol. Soc Am Vol. 41, p. 733 (1930).

[73]Grabau, A. W., and Sherzer, W. H., Op. cit., p. 48.

[74]Carman, J. Ernest, Op. cit., p. 499.

[75]Grabau, A. W., and Sherzer, W. H., Op. cit., p. 234.

[76]Carman, J. Ernest, Op. cit., p. 500.

[77]Grabau, A. W., and Sherzer, W. H., Op. cit., p. 234.

[78]Grabau, A. W., Discovery of the Scoharie Fauna in Michigan: Bull. Geol. Soc. Am., Vol. 17, pp. 718, 719 (1907).

[79]Sherzer, W. H., Geology of Wayne County: Michigan Geol. & Biol. Survey, Pub. 12, Geol. Ser. 9, pp. 199-208 (1911).

_____, Detroit Folio: U. S. Geol. Survey, Geol. Atlas No. 205, p. 7 (1917).

_____, Geology of Monroe County: Michigan Geol. & Biol. Survey, Vol. VII, Pt. 1, pp. 18-100 (1900).

Smith, R. A., A Report on Michigan Limestones: Michigan Geol. & Biol. Survey, Pub. 21, Geol. Ser. 17, p. 159; pp. 248-249; 250-258; 265-267 (1915).

Lane, A. C., Report of State Geologist for 1891-1892: Michigan Geol. Survey, p. 66 (1893).

Lane, A. C., and Seaman, A, E., Geological Section of Michigan: Michigan Geol, & Biol. Survey, Ann. Rept. for 1908, pp. 69-71 (1909).

Grabau, A. W., Geology and Paleontology of the Devonic Formations of Northern Michigan: Unpublished manuscript.

[80]Pohl, E. R., The Middle Devonian Traverse Group of Michigan: A Summary of Existing Knowledge: Proc. U. S. Nat. Mus., Vol. 76, Art. 14, p. 33 (1929).

[81]Newcombe, R. B., Op. cit, pp. 728-730.

[82]Ver Wiebe, W. A., Stratigraphy of Alpena County, Michigan: Michigan Acad. Sci., Arts and Letters, Vol. 7, pp. 181-192 (1926).

[83]Pohl, E. R., Op. cit, p. 34, pl. 2.

[84]Wilmarth, M. Grace, Tentative correlation of the named units of Michigan (June 1, 1929).

[85]Grabau, A. W., Stratigraphy of the Traverse Group of Michigan: Geol. Survey of Michigan, Ann. Rept., pp. 163-210 (1902).

_____, A Preliminary Geologic Section in Alpena and Presque Isle Counties, Michigan: Am. Geologist, Vol. 28, pp. 177-189 (1901).

[86]Ehlers, G. M., Cooley, Mary, Hussey, R. C., Oral communication.

[87]Pohl, E. R., Op. cit., pp. 33-34.

[88]Smith, R. A., Report on Michigan Limestones: Michigan Geol. & Biol. Survey, Bull. 21, Geol. Ser. 17, p. 175 (1915).

[89]Grabau, A. W., Geology and Paleontology of the Devonic Formations of Northern Michigan: Unpublished manuscript, p. 84.

[90]Ver Wiebe, W. A., Op. cit., pp. 186, 187; also unpublished manuscript.

[91]Idem, pp. 187-190; also unpublished manuscript.

[92]Daly, R, A., The Calcareous Concretions of Kettle Point, Lambton County, Ontario; Jour. Geol., Vol. 8, pp. 135-150 (1900).

[93]Ver Wiebe, W. A., Unpublished manuscript: Michigan Geological Survey files.

[94]Prosser, Chas. S., The Devonian and Mississippian formations of Northeastern Ohio; Ohio Geol. Survey, Bull. 15, 4th Ser., pp. 509-529 (1912).

[95]Ulrich, E. O., The Chattanoogan Series with special reference to the Black Shale Problem: Am. Jour. Sci., 4th Ser., Vol. 34 (184), pp. 157-183 (1912).

[96]Kindle, E. M., Stratigraphic Relations of the Devonian Shales of Northern Ohio: Am. Jour. Sci., 4th Ser., Vol. 34 (184), pp. 187-213 (1912).

[97]Morse, W. C., and Foerste, A. F., The Waverly Formations of East Central Kentucky: Jour. Geol., Vol. 17, pp. 164-177 (1909).

[98]Ulrich, E. O., Black Shale Problem in Michigan: Bull. Geol. Soc. Am., Vol. 38, p. 231 (1927). Printed by title only—substance of discussion by verbal communication with G. M. Ehlers.

[99]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: Ann. Rept. of State Geologist, Michigan Geol. Survey, pp. 73, 75 (1909).

[100]Winchell, Alexander, Geology, Zoology and Botany of the Lower Peninsula: First Bien. Rept. Geol. Survey of Michigan, Pt. 1, Geology, p. 72 (1861).

[101]Robinsom, W. I., Unpublished manuscript.

[102]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept, of State Geologist p. 73 (1909).

[103]Ver Wiebe, W. A., The Berea Formation of Ohio and Pennsylvania : Am. Jour. Sci.. Vol. XLII, pp. 46, 47 (1916).

[104]Burroughs, W. G., The Unconformity between the Bedford and Berea Formations of Northern Ohio: Jour. Geol. Vol. 19, pp. 655-660 (1911).

_____, Berea Sandstone in Eroded Cleveland Shale: Jour. Geol., Vol. 22, pp. 766-771 (1914).

_____, Economic Geology of the Berea Sandstone Formation of Northern Ohio: Ec. Geol., Vol. 8, pp. 469-488 (1913).

[105]Thomas, W. A., A Study of the Marshall Formation in Michigan: Michigan Acad. Sci., Arts and Letters, Papers, Vol. XIV, p. 493 (1931).

[106]Thomas, W. A., Op. cit.

[107]Lane, A. C., Geological Reports on Huron County: Geol. Survey of Michigan, Vol. VII, p. 19 (1900).

[108]Thomas, W. A., Op. cit., p. 494.

[109]Winchell, Alexander, First Biennial Report of Progress of the Geological Survey: Michigan Geol. Survey, pp. 88-91 (1861).

_____, Proc. Am. Philos. Soc., Vol. 11, pp. 57-83 (1869).

_____, Proc. Am. Philos. Soc., Vol. 12, pp. 385-418 (1870).

[110]Rominger, C., Geology of the Lower Peninsula: Michigan Geol. Survey, Vol. III. Pt. 1, pp. 69-101 (1876).

[111]Lane, A. C., Geological Report on Huron County: Geol. Survey of Michigan, Vol. VII, Pt. II, pp. 16-18; 86-98 (1900).

_____, and Seaman, A. E., Notes on the Geological Section of Michigan: Michigan Geol. Survey, Ann. Rept. of State Geologist for 1908, pp. 79-83 (1909).

[112]Thomas, W. A., Op. cit.

[113]Kirkham, Virgil R. D., Personal communication.

[114]Thomas, W. A., Op. cit.

[115]Grimsley, G. P., The Gypsum of Michigan and the Plaster Industry: Geol. Survey of Michigan, Vol. IX, Pt. 2 (1904).

_____, Origin of Gypsum with special reference to the Origin of Michigan Deposits: Kansas Acad. Sci., Trans., Vol. 19, pp. 110-117 (1903).

[116]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept. of State Geologist, p. 84 (1909).

Lane, A. C., Geological Report on Huron County: Geol. Survey of Michigan, Vol. VII, p. 16 (1900).

[117]Kelly, W. A., Personal communication.

[118]Stout, Wilber, Personal communication.

[119]Kelly, W. A., Lower Pennsylvanian Faunas from Michigan: Jour. Paleont., Vol. IV, No. 2, pp. 129-151 (June 1930).

[120]White, David, Letter quoted in Coal of Michigan: Geol. Survey of Michigan, Vol. VIII, Pt. 2, p. 45 (1902).

[121]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: Ann. Rept. of State Geologist, pp. 87-89 (3900).

[122]Winchell, Alexander, Geology, Zoology, and Botany of the Lower Peninsula: Geol. Survey of Michigan, First Bien. Rept., pp. 114, 115; 126, 127 (1861).

[123]Lane, A. C., and Seaman, A. E., Op. cit, p. 89 (1909).

[124]Lane, A. C., and Seaman, A. E., Idem, p. 89 (1909).

[125]Case, E. C., Permo-Carboniferous Conditions versus Permo-Carboniferous Time: Jour. Geol., Vol. 26, pp. 500-506 (1918).

_____, Carnegie Inst. Washington, Pub. 283, pp. 187-193 (1919).

_____, Michigan Acad. Sci., 20th Ann. Rept., p. 82 (1918).

[126]Leverett, Frank, and Taylor, Frank B., The Pleistocene of Indiana and Michigan and the History of the Great Lakes: U. S. Geol. Survey, Mon. 53 (1915).

_____, Surface Geology and Agricultural Conditions of Michigan: Michigan Geol. & Biol. Survey, Pub. 25 (1917).

_____, Moraines and Shore Lines of the Lake Superior Region: U. S. Geol. Survey, Prof. Paper, 154-A (1929).

Russell, I. C., and Leverett, Frank, Ann Arbor Folio: U. S. Geol. Survey Folio 155 (1915).

Sherzer, W. H., Detroit Folio: U. S. Geol. Survey Folio 205 (1916).

[127]Op. cit.

Chapter IV. HISTORICAL GEOLOGY

DIFFICULTIES IN TRACING THE EVOLUTION OF THE SYNCLINAL BASIN

The geologic history of the Michigan synclinal basin from its beginning to the present is difficult to trace with any degree of continuity. The deep burial beneath glacial drift and the isolation from other depositional provinces allow only very broad generalizations from the usually accepted methods of tracing faunal evolution and strand line displacement. Surface outcrops are few and far between. The proper solution seems to rest with careful examination of well records, accurate determination of the sections thus disclosed, and correct interpretation of their relation to the regional setting. The early correlations will require frequent revision until regional aspects are more fully understood, and the methods of correlation must necessarily become more exact by the rigid application of micro-paleontology, micro-lithology, heavy mineral studies, and the close examination of chert residues. Until these detailed studies have been pursued, it will be necessary to rely on a more cursory examination of well record data in outlining the geologic history of the region.

PALEOZOIC ERA

CAMBRIAN PERIOD

LAKE SUPERIOR TIME

The earliest time of the Paleozoic era recorded in the rocks of Michigan is revealed by the clastic series of the Cambrian period. The origin of the structural downwarp giving rise to a basin of sedimentation occurred a long time prior to this era, but the continued sinking by the addition of sandy sediments was apparently accelerated. The land areas which were probably present to the west and also to the northeast must have had considerable relief, and weathering processes were relatively active. This is shown by the coarse texture of the material deposited and the content of undecomposed minerals. The conglomerate which in many places occurs at the base of the Lake Superior sandstone indicates that there was a rugged shoreline which was gradually worn down as the sea advanced. When the iron-bearing rocks became more thoroughly submerged, less ferruginous material was introduced into the sea, and the upper part of the Cambrian rocks indicates this condition by the absence of red color. A lapse of the processes of deposition and erosion in the Cambrian is suggested by the local absence of Trempealeau beds in eastern Wisconsin and northeastern Illinois. During the closing stages of Lake Superior time, (the Jordan of Wisconsin in part) a considerable portion of the sea probably withdrew and the land was elevated. The terrestrial conditions which resulted were possibly associated with arid climate, as three-sided faceted pebbles (dreikanter) which are considered by many as characteristic of desert erosion have been found.[1] According to Ulrich[2], marine connections existed repeatedly and perhaps continuously throughout the Cambrian between the seas of the upper Mississippi Valley and those of certain western and southwestern states.

ORDOVICIAN PERIOD

OZARKIAN TIME

A period of warping and extensive erosion took place during the interval between Cambrian and Ozarkian (Lower Ordovician) times. In northern Michigan, the Ozarkian sea contained a large quantity of lime and magnesia which was precipitated on the sands then present along low tidal flats. A quantity of oolitic dolomite resulted, and in the central part of Michigan a close adjustment between downwarping and deposition probably resulted in the laying down of an abnormal thickness of these sediments.

CANADIAN TIME

Depositional and faunal evidence from without the Michigan Basin province indicates that at the close of the Ozarkian, the land was again uplifted and subjected to subaerial erosion. Widespread seas inundated the region in Canadian time and the relief of the land areas was unstable as indicated by the irregular deposition of sandstones and cherty dolomites. The oolitic character of many of the cherts shows that the land area at infrequent intervals had a low relief, thus causing the formation of oolites by accretion of lime. The periodic sinking of the "basin" resulted in the deposition of an unusual thickness of these rocks in central Michigan. Only the very border deposits of this sea are revealed in the northern part of the State.

ST. PETER TIME

At the close of Canadian time and prior to the deposition of the St. Peter sandstone, the land was again deeply eroded. The irregular surface upon which the sandstone was deposited is well shown throughout the Mississippi Valley region, and particularly near Milwaukee, Wisconsin, where the St. Peter rests directly upon the Eau Claire formation of Cambrian age. The occurrence of residual soil and a basal St. Peter cherty conglomerate in other contiguous states is further evidence of this erosion surface. The presence of this conglomerate suggests the long continued work of large sized streams. The clean white sandstone indicates emergence and rather complete assorting by both wind and wave action. The sea probably transgressed over a shore area largely covered with dunes of windblown sand which were piled up by winds similar in type to those causing the present dune region along the eastern shore of Lake Michigan. Recent drilling in the interior of the Michigan "basin" has shown the St. Peter sandstone to have great thickness and unusual physical characteristics, comparable to subsurface occurrences in north central Illinois. This discovery gives evidence that the St. Peter sea not only advanced on the Wisconsin land mass from the south, but also occupied the Michigan Basin for a longer time than surrounding areas. The adjustment of downwarping to deposition load also took place as in previous periods. The low relief of the land and the completeness of dust removal by the wind is shown by the absence of coarse conglomerates and the purity of the fine grained sandstones. The thick deposits left in the deeper basins farther from shore are fine textured sandstones with only thin partings of shaly material. Climatic factors which favored rapid disintegration probably explain the scarcity of shales in these rocks.

TRENTON——BLACK RIVER TIME

Trenton-Black River time marked the return of climatic conditions favorable to lime deposition, and the seas transgressed far beyond the present limits of the low-lying Archean land mass to the northwest. Animal life thrived in these seas and relatively uniform conditions are indicated by the physical characteristics of the rocks. The maximum extent of the Trenton sea is not known, but the Limestone Mountain outlier in Keweenaw County suggests that it probably covered the entire Lake Superior region. The general direction and location of the northern shore line is suggested by the rate of thinning to the northwest. (See fig. 4).

DECORAH TIME

During Decorah time, a structural disturbance or slight uplift must have occurred to the northwest, but apparently the coarse sandstone beds to the north were not exposed to erosion because the material brought in was entirely calcareous shale. The Decorah beds thicken to the northwest and thus furnish evidence that their source was possibly from that direction.

Soon after Decorah time, the submergence probably was more widespread, and waters covered a vast expanse in north central Canada. The Wisconsin area then emerged, but the subsequent seas, including the upper Mohawkian of which there are no existing deposits farther west in Wisconsin, occupied the greater part of the Michigan synclinal basin.

CINCINNATIAN TIME

Preceding early Cincinnatian time, a slight elevation of the area made the sea shallower, and the waters of the Appalachian trough probably entered by a northeast connection. Climate in the east, assisted by abundant vegetation, favored complete land decay, and the widespread deltas which resulted were composed largely of bituminous muds. These beds are represented in Michigan by the Collingwood shale which covered a large part of the "basin" and spread westward beyond Newberry in the northern peninsula. As the dark colored mud was brought in, the basin gradually subsided. The toxic conditions caused in part by shallow waters changed as the water gradually deepened. With this deepening and clearing of the water, abundant life forms thrived. The sea came in again from the north and south, and many of the gray shale beds were probably derived from the weathering of limestone rocks which made up the shores of the neighboring land masses. The fossiliferous beds and thin limestones evince the tempering of climate. At the time of the Richmond invasion, the basin of deposition was not entirely isolated because floating faunal forms indicate currents and a connection to the eastward. The area was somewhat restricted to the south and any connections with adjoining basins in that general direction were only temporary. Near the close of Richmond time, residual red clays were forming in southeastern Michigan on the adjacent land mass, probably by the weathering of limestone. A gradual continental uplift took place and caused these transition beds to be deposited locally. Because of the ample supply of iron in the residual soils, these red and green shales were laid down well into the next period and are widespread throughout the northeastern United States.

SILURIAN PERIOD

CATARACT TIME

The Lower Silurian or Medinan began with an extensive transgression of the sea which deposited the Manitoulin beds. The Manitoulin sea encroached from the north, and the shores consisted largely of limestone. The composition of the waters must have been fairly uniform because the physical characteristics of the Manitoulin rocks are comparatively uniform throughout the area of the Michigan Basin.

Toward the end of Cataract time, the quantity of finely divided detrital material forming on the land increased. The Cabot Head shale was formed from the deposition of muds which consisted of highly oxidized red and green sediments. The colors resulted from the influences of climate and the nearby pre-Cambrian rocks which contained large quantities of iron. The red color alternates with green and gray, and the lighter color suggests that the ferruginous sediments originating in the north were reduced by the deoxidizing influence of marine conditions originating in the south.

NIAGARAN TIME

In middle Silurian or Niagaran time, the sea transgressed widely, a general deepening of basins took place, and the deposition of limestone and dolomite indicates that the climate was warm. Shallows must have existed temporarily during the formation of the Byron beds, which are locally argillaceous and contain "sun cracks" and ripple marks. The transgression took place from the north and probably originated in the Arctic[3] and Hudson Bay regions. Local connections may have been made with the St. Lawrence trough but the relations are not definite. The Burnt Bluff formation was laid down in a period when the deepest part of the Michigan synclinal basin was far north of its present location. The members of the formation thin rapidly into the central part of the southern peninsula, and this convergence supports the faunal evidence of northern origin. Local conditions of deposition and possibly later chemical changes brought about the lateral gradation of limestone into dolomite that is so common.

Shaly beds found in the Niagaran in wells in lower Michigan are lacking in the northern region where it is exposed. Possibly the Rochester formation, considered to have been removed[4] by erosion in many regions beyond the confines of the Michigan "basin," is preserved in the southern peninsula under the cover of younger rocks. The Mississinewa shale in northern Indiana, which possesses Rochester affinities, may have some bearing on this interpretation, but faunal evidence is lacking to substantiate the exact age of these shale beds. A change in the type of land waste and shallowing of the Niagaran sea certainly occurred in the region of southern Michigan.

The seas of Manistique time originated[5] in the Gulf of St. Lawrence and spread southwest as far as Iowa. The waters were relatively warm and undisturbed for coral beds are abundant in the lower strata of the formation, and conditions were generally favorable to the preservation of marine fauna. The Manistique seas transgressed from the north and formed an overlapping series of rocks similar to the Burnt Bluff formation. The deposition of the Engadine dolomite evidently marked a shallowing of comparatively restricted seas because the formation is locally arenaceous, and the life forms indicate approaching high salinity. An extensive system of coral and stromatoporoid reefs was built during this period and according to Cumings,[6] "after the time of the cherty coral beds (Manistique of Michigan), the teeming life of the Niagaran sea assumes complete mastery of the sedimentation and builds a formation, the Racine-Guelph, entirely derived from its own exuviae." The steepness of dip off many of these reef "mounds" is partial evidence for the intensity of wave action during the period. Dolomitization of the reefs was probably favored by the change in climatic conditions toward greater aridity. The increased salinity brought on by these climatic changes must have had a certain controlling effect upon the formation of the dolomites.

MONROE—SALINA TIME

Niagaran deposition culminated with a gradual emergence of continental areas resulting in the isolation[7] of the greater part of the interior Silurian sea into a vast, partially or entirely enclosed basin. In this manner, a period of dessication began and a favorable warm, dry climate probably assisted the evaporation. The brines were concentrated in great inland lakes or temporarily restricted embayments where thick deposits of anhydrite, gypsum, and salt precipitated as the solutions became super-saturated with respect to one or more of these substances. The Salina relict seas initiated the first important evaporite period which affected the rocks of the Michigan synclinal basin, and the resulting deposits of salt, anhydrite, and gypsum exercised a controlling influence on much of the ensuing geologic history of the region. Beds of gypsum and anhydrite were formed frequently in the periods that followed, and the products of weathering from shores composed of Salina rocks contributed high salinity to many of the subsequent seas. The shape and confines of the "basin" formed at this time were relatively permanent throughout the greater part of the Silurian and Devonian periods.

The approximate shape of the "basin" of deposition throughout Monroe and Salina times is shown in Figure 7 by means of an isopachous contour map. This type of map is designed to illustrate the thickening of beds into the center of the deepest part of the "basin," and each contour line represents an equal thickness of Monroe-Salina rocks. The area of maximum thickness is indicated to emphasize the extent of the region of greatest sinking and probably in most instances, the largest amount of deposition. This relation of the amount of deposition to the present thickness of the rocks is obviously an important one. However, it does not take into consideration the quantity of beds subsequently removed by weathering and erosion, or the character of the rocks laid down. These factors must be further evaluated when the maps are interpreted. The relation does indicate, however, the approximate size and dimensions of the synclinal or sinking area, the location of the major depression, the relative amount of down warping which has taken place, the factors influencing sedimentation and migration of the sea, and the possible causes of the warping movement.

The data used in constructing this map and other maps designed to show the results of subsequent periods of deposition were derived from the records of wells throughout the State. These data are subject, therefore, to errors of interpretation and correlation common to such determinations. Many anomalous figures have been disregarded, and in the dominant major features, the figures used should be essentially correct.

The rocks beneath the Salina have not been penetrated in the central part of the basin. This lack of information explains why thickness maps were not inserted earlier in the discussion of geological history. The Salina has not been reached by the drill in the deepest part of the synclinal area so that the map merely explains the rate of thickening of the beds and only gives a very general outline of the basin proper. Other maps which follow are compiled from a larger quantity of data and show more accurately the structural and depositional conditions.

The axis of the depositional area during Monroe-Salina time is shown to have a major northwest-southeast elongation, and the presence of a barrier in the southeastern part of the State is strongly evident. That there was a shore line with gentle offshore slope in proximity of southwestern Michigan is suggested by the decrease in the convergence rate in that direction. These features seem to point out the low nature of existing shores and the restriction of the basin from seaward connections to the south. The fine granular dolomites of the Salina and Monroe represent lime muds derived from the limestones and dolomites laid down in previous periods. Argillaceous elastics are not abundant in the Monroe-Salina rocks and this indicates that the "basin" was largely surrounded by limestone areas, and that climatic conditions were not favorable for complete disintegration into clay soils. The salinity of the sea prevented the existence of many forms of life, and the beds of the Salina are almost entirely non-fossiliferous. The marginal sediments were probably frequently reworked, and their salt content was added to the salt present in the marine water which might have been separated from the main part of the sea at the time of prior uplift.

Subsidence of the basin must have been gradual to permit additions of water without inundation, and sinking probably kept close pace with evaporation during the three successive periods when thick beds of salt were laid down so uniformly in the central area. The flooding of local basins and salt flats very likely added to the slowly increasing salinity of the larger bodies of water. Desert cloudbursts may have been effective in causing these additions, as aridity probably existed at intervals throughout the period. Seasonal dry winds might have also caused concentration of salt in lagoonal flats.

The local occurrence of red shales has been advanced as evidence for arid conditions, but these are not prevalent in all parts of the Michigan Basin. In the western section of the State, red dolomites occur near the base of the Salina beds, indicating the possibility of thorough decay of a limestone land area or deltaic enrichment of iron from streams traversing an exposed portion of the iron bearing regions to the northwest.

<u>BASS ISLAND TIME</u>

At the opening of Bass Island time, conditions were about the same as in the preceding Salina period. Lime muds were being deposited and evaporation was still in progress, but the "basin" became connected with outside sources of water which freshened the sea sufficiently to permit the existence of more abundant life. Climatic changes toward high humidity were possibly effective in preventing precipitation of salt and the more soluble chlorides. Frequent incursions of the sea took place from the Atlantic, but the basin showed a gradual shrinkage. Local restriction furnished conditions of evaporation which caused calcium sulfate to precipitate and form thick beds of anhydrite. Apparently, the Michigan "basin" was not so extensively downwarped as in the preceding Salina time because the thickness of the Bass Island rocks shows considerable uniformity throughout the explored area of the State. The sea transgressed westward across the region, and a mixture of dolomite slime with some clay mud was washed into the "basin." The water was relatively shallow because beds with carbonaceous films indicate that vegetation was then present. Oolites of possible algal origin suggest deposition on tidal flats. Shallow water is also indicated by the ripple marks and sun cracks which are preserved on the surface of certain beds. Some of the dolomite represents secondary replacement after limestone, but the most of it is probably the reworked product of original magnesian rock. The waters of Bass Island time reached as far as Milwaukee, and there was an intermittent connection with the Indiana basin through the structural depression known as the Logansport "sag." The Kokomo limestone in Indiana was most likely formed at the times of this connection.

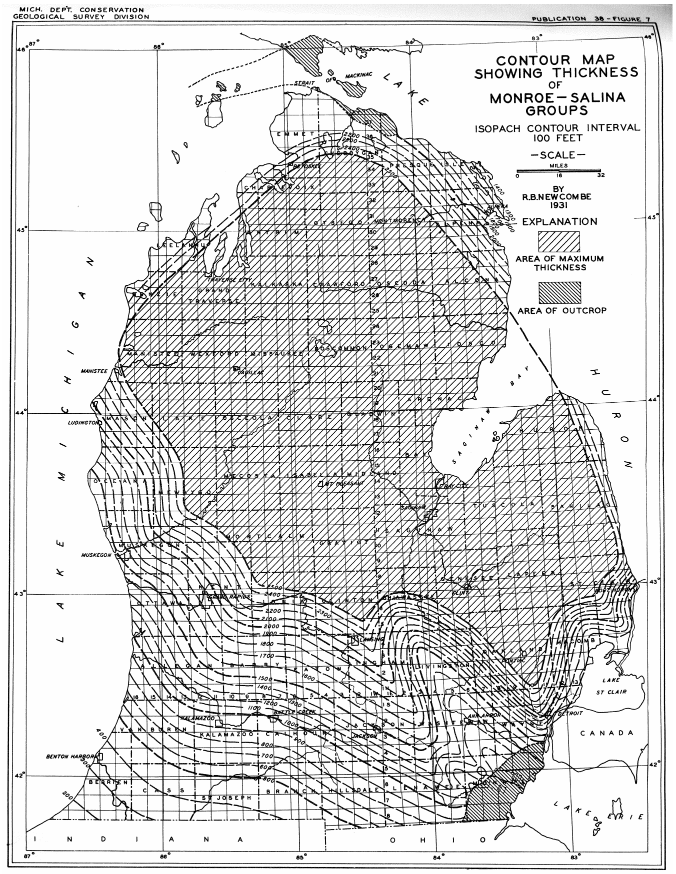


Figure 7. Contour map showing the thickness of the Monroe-Salina groups in the southern peninsula of Michigan.

DEVONIAN PERIOD

<u>SYLVANIA TIME</u>

The emergence or retreat of the sea preceding Sylvania time took place in the Michigan Basin prior to the withdrawal of waters in the east. The St. Peter sandstone and various Cambrian sandstones were laid bare, resulting in disintegration and assorting by the winds. These drifting sands were piled into dunes and reworked by the advancing Sylvania sea. Deposition of colloidal silica took place locally, and the finer products from breaking down of clastic rocks were carried into deeper water and formed the white cherty to sandy dolomites of central Michigan. As at the present time, prevailing winds were probably from the west, and an uplift had advanced the shore line well into the southeastern part of the State. Local climatic conditions, and the probable presence of abundant vegetation covering the lime rocks in the southwestern part of the State caused weathering of the land mass to a clay which gave rise to deposits of green shale. This shale contains scattered typically rounded Sylvania sand grains. The green color was probably due to reduction of ferric iron to the ferrous condition. The shale may possibly represent a seaward deposit, but the presence of imbedded sand grains suggests that the water was shallow.

Local readvances of the sea near the end of Sylvania time caused offshore or littoral conditions which gave rise to a purer dolomite that contains marine fossils. Additional sand was furnished at the time of the final retreat, and this sand was reworked by the oncoming waves at the close of the period. As a result of the reworking process, siliceous dolomite beds were deposited.

The formation was probably laid down on an uneven land area of some relief and possibly overlaps a number of older formations in adjoining regions. The summation of its history, according to Sherzer and Grabau[8], includes the basal layers as sedimentary, the body eolian, the upper eolian deposits reworked by a transgressing sea, and the materials in the main derived from the St. Peter. Basally, it rests upon successively younger strata southeastward from Wisconsin and is younger than the youngest bed upon which it rests. The final cementing of incoherent sand grains was effected by percolating water introducing secondary silica with magnesium and calcium carbonates. The sulfates carried in the water were reduced to sulfides, and calcium was locally replaced by strontium to form cavity fillings of the mineral celestite ($Sr SO_4$). Further reduction, possibly aided by bacterial action, formed small amounts of free sulfur. Later oxidation of iron sulfides on exposure to the air resulted in abundant staining of the beds with the oxides of iron.

<u>DETROIT RIVER TIME</u>

During Detroit River time, the sea probably invaded from the north and occupied a shallow trough. At this time, much of the continent was out of water, and evolution of Devonian forms was going on in more remote areas. The character of the fauna found in the rocks of the series fixes its age as Devonian. The waters transgressed from the northwest, and the deposits overlap successively younger rocks to the southeast. This condition of overlap is also present in the case of the individual members of the Detroit River series.

The configuration of the "basin" at the time the Detroit River was deposited is shown in Figure 8. The shape of the synclinal area was in general asymmetrical with the gentle slope to the northeast. The major elongation was slightly north-northwest of directly north-south, and the restricted deep part of the "basin" was approximately circular in outline. The position of the shores to the southwest and northeast is indicated by the gradual thinning of the beds in these directions. Local gentle warping is indicated by the basinward bends of the contour lines.

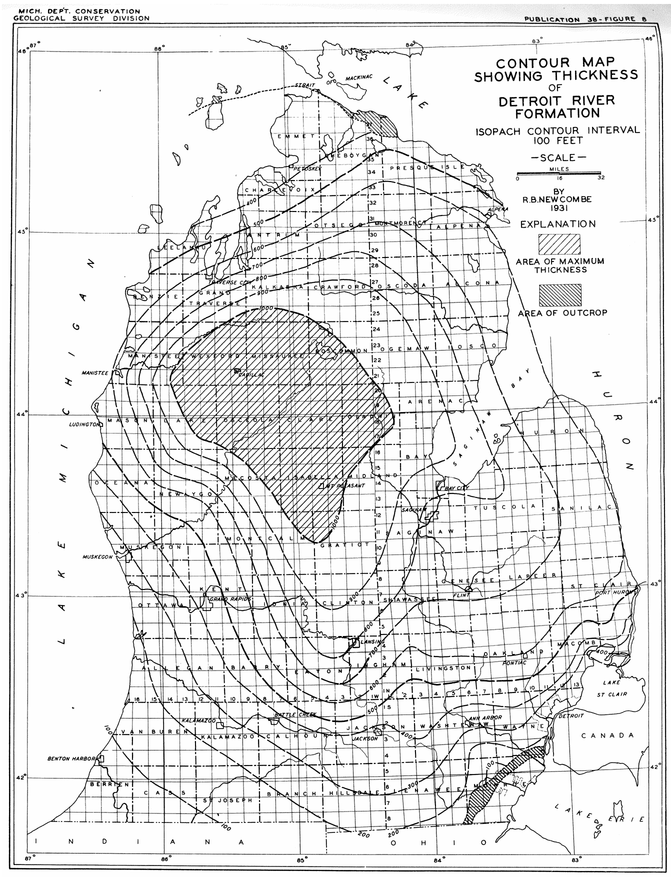


Figure 8. Contour map showing the thickness of the Detroit River formation in the southern peninsula of Michigan.

Near the close of the period, a warm climate brought on the formation and growth of corals, giving rise to the Anderdon reefs. These conditions of warmth and dryness and temporary restriction of the more interior portions of the "basin" caused the concentration of salt, and the deposition of saline residues. Restricted seas of evaporation did not remain so long as in Salina time, but several beds of rock salt were deposited in the central part of the "basin" during this period. There were possibly intermittent arid conditions with evaporation in excess of water additions. The Detroit River salt basin compares closely with the deepest downwarped part of central Michigan during Detroit River time. (See fig. 9). This relation supports the idea of salt forming from restricted or relict seas. The great salinity of the seas of this period possibly came about in part from stream erosion of earlier rocks containing salt beds. An explanation[9] for the Silurian aspects of the upper Detroit River fauna might be that "Devonian life probably did not migrate far into the center of the State; when the outlet to the trough was temporarily closed the remnants of the Silurian facies were brought back from the salt producing basin."

The distribution of the salt beds within the Michigan Basin is best illustrated by cross sections which demonstrate graphically the extent of the occurrence of salt. (See figs. 10 and 11). Other beds are disregarded in these sections and no stratigraphic sequence is given except the base of the Dundee formation, which may be used for comparing intervals within the Monroe-Salina groups. The general continuity of the thicker beds of rock salt in the deeper portion of the "basin" is shown. This feature is contrary to the generally accepted idea that salt beds in Michigan are irregular in their occurrence. The truth of this early conception probably maintains for the marginal deposits of thin beds where lagoonal districts and small individual basins were the controlling physiographic features in their formation. It seems conclusive, however, that over wide basins of sedimentation, salt concentration acts very much like any other chemical deposit in that the beds thicken more or less uniformly toward the region of major sinking.

DUNDEE TIME

A period of emergence and gentle folding followed the retreat of the last Detroit River sea, exposing the various Monroe beds to erosive agents. The general trend of the axes of this folding in southeastern Michigan is[10] N60°E. Erosion followed, and the absence of shales would indicate that the nearby land areas consisted of limestone. Solution and chemical wearing away were the dominant weathering processes, and plant life must have been almost absent.

As the sea advanced on the Michigan area from the east, the western part of the "basin" had been uplifted, and the eastern part depressed. The pre-Dundee folding was so slight that discordance in dip was not evident at the exposed contact of the Detroit River and Dundee beds. The first waters entering the basin carried some sand from the east where deposition of the Oriskany was going on in the Appalachian trough, but the invasion did not progress uniformly across the State. In the northern part of Michigan, the magnesian beds of the previous formation were reworked and breccias of doubtful and complex origin were formed near the base of the Dundee. Like the closing part of the Niagaran, the warm, dry climate, and clear water permitted corals and other life forms to flourish in abundance. Some forms were derived from the Atlantic and some probably came from southern connections, and the soft parts of certain organisms must have contributed to the bituminous products found in the rocks of this period. Various animals of the Dundee seas possessed siliceous hard parts and contributed silica. It also might have been deposited by direct precipitation (either from true solutions or colloidal solutions), or by replacement, thus forming beds and nodules of chert which are common to the strata.

The "basin" of deposition was greatly changed from Detroit River time, both in general uniformity and the position of the deepest trough. The thickest Dundee in the Michigan Basin is in a long narrow depression trending a little west of a north-south direction across the eastern side of the State. (See fig. 12). A ridge or upwarping apparently more or less parallel to the trough crosses Livingston County. This ridge widens out to a broad emergent region in the south central part of the State and joins with an east-west shallow area stretching across central Oceana, Newaygo, and Mecosta counties. The local basins almost parallel these shallow places. The greatest amount of sinking on the east side of the depositional basin is analogous to the Appalachian geosyncline where the sinking was also greatest on the east and seems to suggest a source of pressure from the eastward acting toward the west. This large basin is apparently asymmetrical in the central portion of the State and comparatively symmetrical to the northward. The presence of separate basins of deposition in the Michigan region during Dundee time is also indicated by the dissimilarity of faunas in the northern and southern districts of the State. The life forms from invasions of the sea originating in different quarters were prevented from completely intermingling because of this separation.

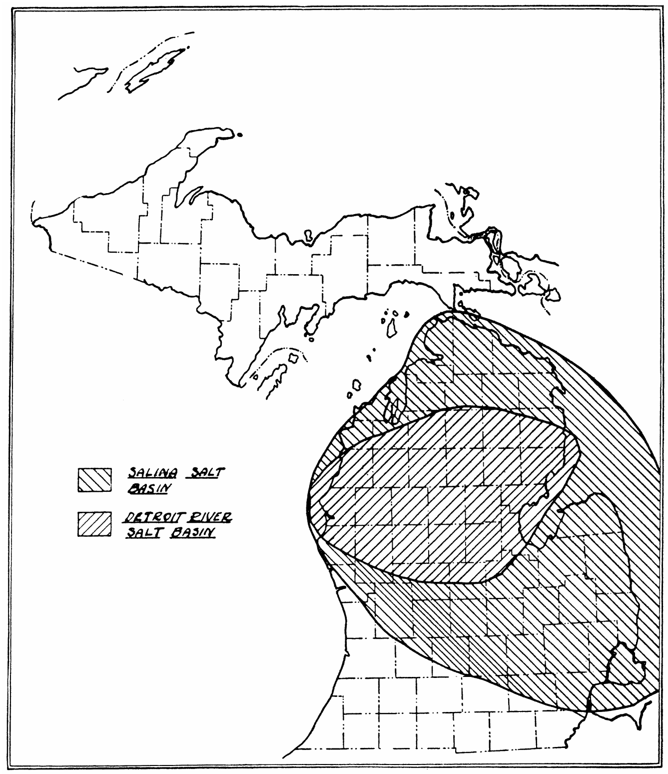


Figure 9. Map showing the approximate areas of the Detroit River and Salina salt basins.

TRAVERSE TIME

The period between the laying down of the Traverse and Dundee sediments was featured by a marked change in climatic conditions. The fine argillaceous weathering product making up the Bell shale is evidence of increasing precipitation and plant growth, and the honeycombed, irregular Dundee land surface is evidence of organic, humous acids in the surface material. The sea invaded from the north and deposits progressively overlapped older strata in the southern part of the State. Traverse beds probably rest on those of the Detroit River series in parts of southwestern Michigan, but exact identification is difficult. The basal black shale and the fossiliferous gray shale of the Traverse group indicate that the shores were low with abundant vegetal growth, and the climate was favorable to the preservation of life forms. This carbonaceous Bell shale also overlaps older beds consecutively to the southwest and thins to a mere parting in that direction. The thinning of beds to the southwest has been attributed to[11] both extensive erosion of the Dundee limestone and non-deposition of the Bell shale. Limestones were deposited as the sea deepened to the north. Upward and downward oscillations of the sea bottom or periodic withdrawal of waters from other causes formed alternating beds of shale, calcareous shale, and thin limestone. The source of much of the shale must have been to the east, and the derivation was likely from limestone shores as indicated by the calcareous character of the mud.

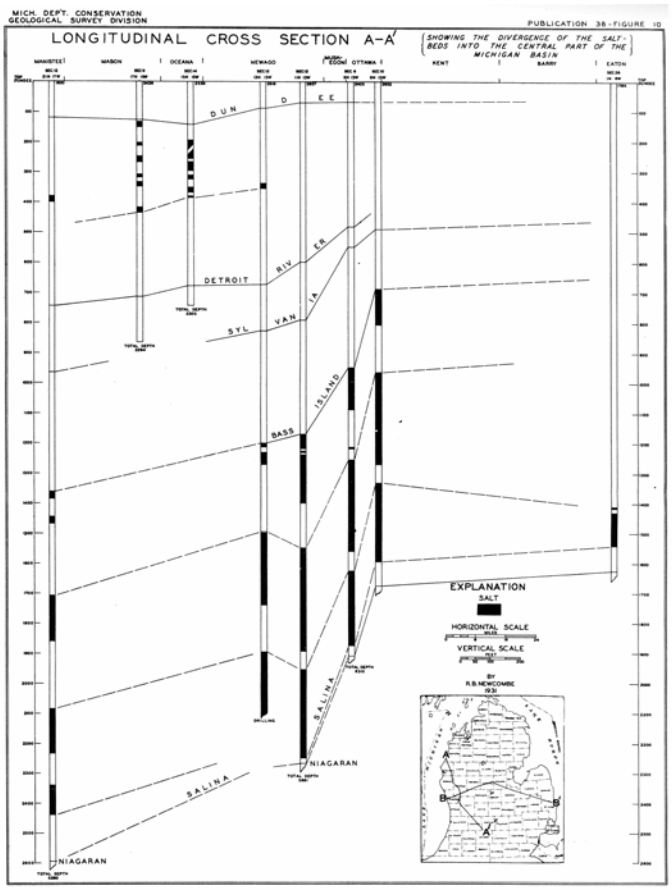


Figure 10. Longitudinal cross section (A-A') showing the thickening of the salt beds into the central part of the Michigan Basin.

Near the close of Traverse sedimentation, there was warm quiet water and the sea bottom subsided gradually. As a result, an extensive system of low coral and stromatoporoid reefs was built up over considerable areas. In northwestern Michigan, the reef formation was probably followed by somewhat violent wave action as shown[12] by broken up coral sands strewn in foreset beds which make up a "cross-bedded" limestone. The introduction of colloidal silica in the upper portion of the section brought about the formation of segregated and banded chert. This occurrence of chert seems to indicate strongly a return of conditions affected by shore influences, and waters from the land carrying silica in suspension mingled with the saline waters of the shallow inland sea.

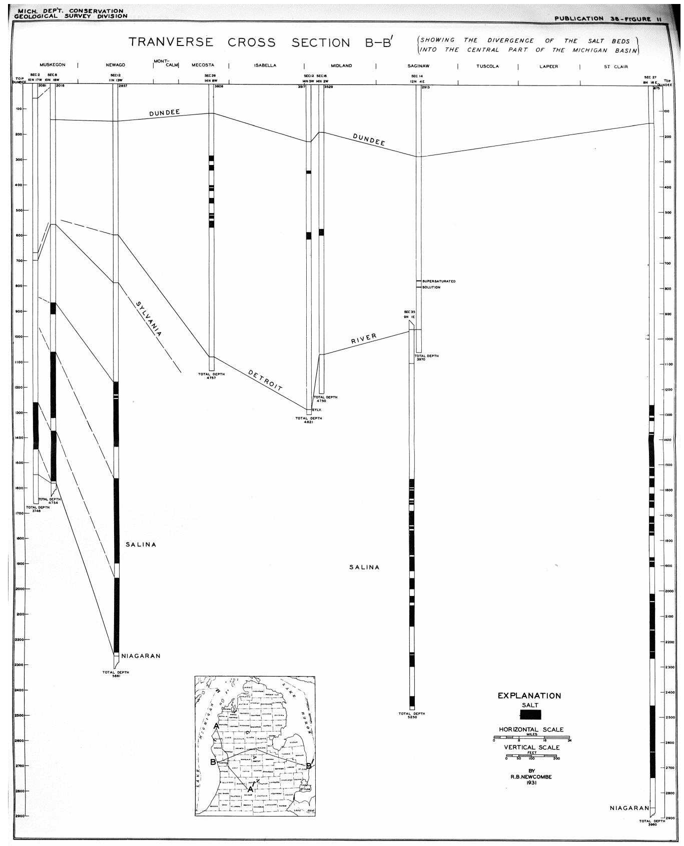


Figure 11. Transverse cross section (B-B') showing the thickening of the salt beds into the central part of the Michigan Basin.

The presence of anhydrite in the lower Traverse of western Michigan suggests that locally the sea was restricted, thus permitting drying up and evaporation. Slight emergence and erosion over most of the Traverse basin region probably took place near the close of the period. That the Traverse sea had northern connections[13] is proved by the fauna contained in the rocks.

During much of Traverse time the Michigan synclinal basin was divided in the northern part by an intermittent land barrier[14]. This fact is indicated by the difference in faunal life which occupied the separate regions and the evidence from the thickness map (see fig. 13), drawn to show the thinning and variation of the Traverse beds. An upwarping amounting to a thinning of over 200 feet of strata is shown to extend southeast from central Antrim County to central Ogemaw County. The two separate east and west basins trend parallel to this upwarped district, and the west basin seems to be asymmetrical with the steep dip into it from the west. The parallel warping in the central and southern parts of Michigan appears to have one pronounced direction in alinement with the deeper basins of sedimentation. The Livingston County ridge and the folds in the central part of the State evidently existed during Traverse time. The local basins associated with these structural highs are also shown. A prominent northeast-southwest structural element occurs in the southwestern section of the State and the flattening of slope in this region is present, as in previous periods of deposition. An important north-south structural element and an upwarping trending a few degrees east of north-south is characteristic of eastern Muskegon and Newaygo counties. This same shallow region of deposition seems to continue with somewhat less expression into Mecosta, Osceola, Wexford, and Missaukee counties. The importance of structural land barriers affecting deposition is well illustrated by the results of Traverse sedimentation.

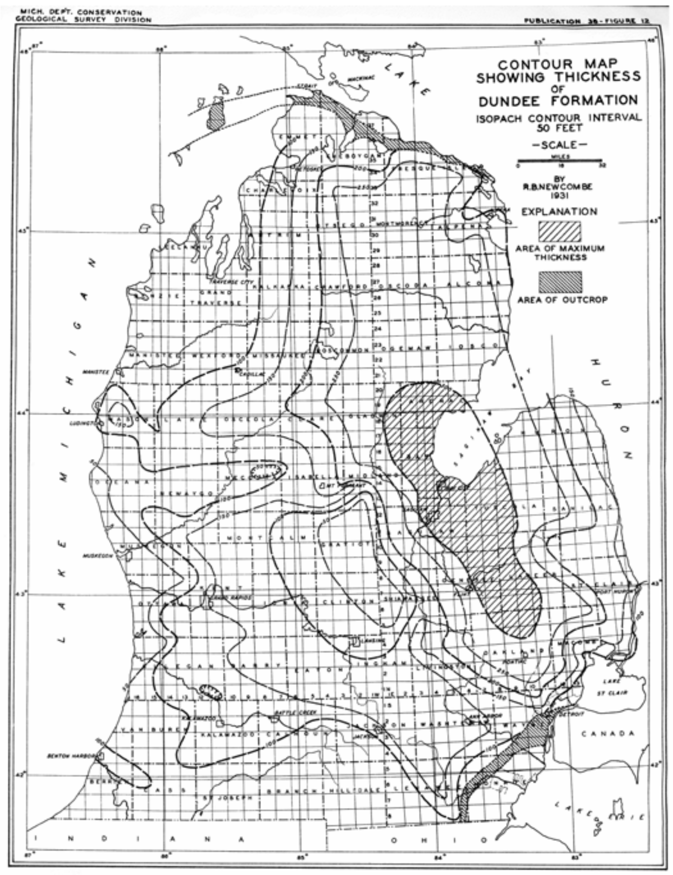


Figure 12. Contour map showing the thickness of the Dundee formation in the southern peninsula of Michigan.

Near the close of Traverse time, the land surface was worn down nearly to base level, and sluggish streams brought calcareous slime and argillaceous detritus into the sea. The upper Traverse beds are almost invariably shaly, but the color and general appearance does not suggest marked change in the other conditions that influence sedimentation. In some parts of the State, there may have been slight reelevation at the end of the deposition of the Traverse. Subsidence followed closely afterward and with this deepening of the sea came a changed climate, more moist and favorable to the growth of vegetation.

ANTRIM TIME

Antrim time was the beginning of a complete sedimentary cycle. This cycle due to periodic uplift of the land areas furnishing sediments resulted in a succession of black shales, gray shales, and sandstones. A similar cycle beginning with the Sunbury black shale was repeated later in the Mississippian epoch. During the Antrim, the relief of the land areas was still low, affording complete rock disintegration, and the streams carried large amounts of macerated swamp waste and other vegetal matter out on tidal flats where the black mud was deposited. The muddy seas brought about toxic conditions and only the most hardy floating forms of life were able to live in this environment. The carbonaceous material from the biochemical breaking down of these entombed animals, the spore cases, and the other remains of vegetation probably are the source of the oil and gas which originated in this formation. Much of the calcareous material in the Antrim sea is in the large concretions which are thought to have been formed about the same time that the deposits were laid down. Fish remains are found in some of the smaller concretions and probably indirectly caused their formation.

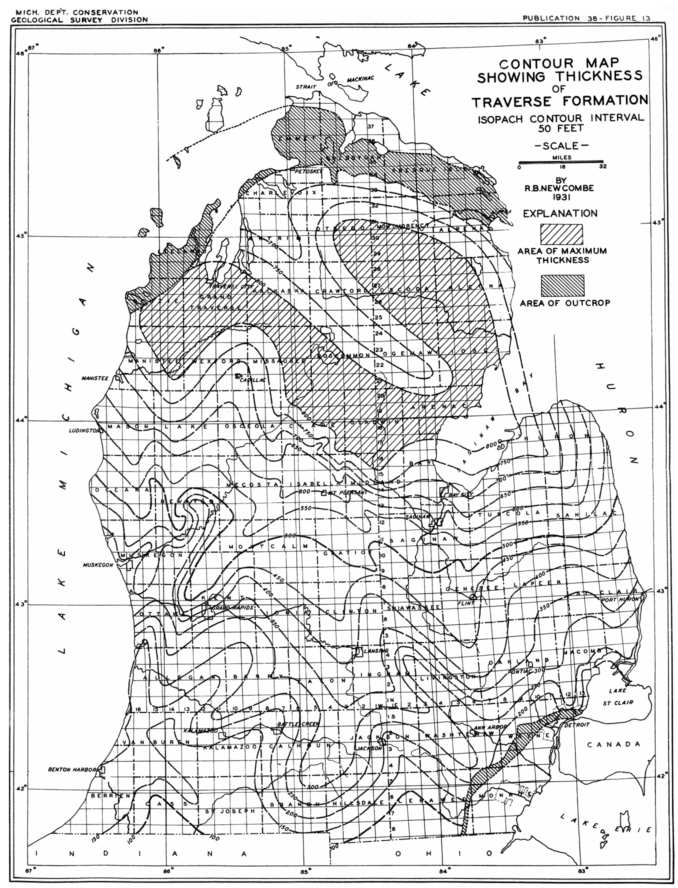


Figure 13. Contour map showing the thickness of the Traverse formation in the southern peninsula of Michigan.

After the Antrim sea had occupied the region for a period, a retreat must have taken place, because Mississippian fossils were found in the upper part of the formation. The beds laid down during the waning of Antrim time are much more irregular in color and other physical properties than the lower strata of the formation. Apparently, some oscillation of the sea took place, and possibly some of these beds represent the remotely distributed fine material from the delta deposits in the east.

The contour map (see fig. 14) showing the thickness of the beds deposited in Antrim time indicates that the deepest sinking and greatest sedimentation took place near the present geographical center of the southern peninsula. This basin, although irregular in shape, has a northwest-southeast elongation which is very narrow. The upwarped district in Saginaw and Midland counties divides it almost into two parts. A secondary deep basin, trending more nearly north-south, is located to the northeast. This relation suggests an avenue of sea migration from a northeasterly direction. The two basins are separated by an upwarp trending across a similar part of Crawford, Ogemaw, and Arenac counties that was crossed by the same type of structural feature in Traverse time. Two other shallower troughs extend to the southeast, and these may have been intermittent channels of sea invasion. The sharp Livingston County ridge separates these troughs. A gentle basin-ward slope indicates a land mass on the southwest side of the basin area, and the contours suggest several deep local basins in that region.

The western side of the southern peninsula was evidently an area of shallow waters during much of Antrim time. A northeast trending shallow trough seems to extend more or less continuously from the vicinity of Grand Rapids, across Kent, western Montcalm, and Mecosta counties. Minor east-west troughs occur throughout the western counties and evidently sedimentation took place in this part of the State in a very irregular manner. The apparently featureless area in Lake and northern Newaygo counties may possibly be explained by the scarcity of reliable data in that particular section.

MISSISSIPPIAN PERIOD

ELLSWORTH-BEDFORD-BEREA TIME

An increase in the relief of the land and quickening of the streams took place at the beginning of Berea time. This may have been accomplished either by uplift of the land or by a general drop in sea level from other causes. The former seems most plausible.

Conditions favorable to sandstone deposition were initiated with the depositing of the Bedford gray muds, differing markedly from the Antrim carbonaceous sediments. There is no evidence of great climatic change between the Bedford sandy shales and the Berea sandstone. The shoreline probably shifted from the east, possibly by a general westward progression of the Appalachian delta phase of Devonian times. Slow subsidence permitted the local deposition of a considerable thickness of sandstone, and the Berea is widespread from the Appalachian trough to the Michigan synclinal basin.

Students[15] of the Berea suggest that a rather important movement at the northern end of the Cincinnati anticline took place subsequent to early Mississippian, and this structural feature was not so pronounced as at present, or if so, it maintained an attitude quite different from that of the present time.

That the source of these sediments was to the east and north is indicated by the thick sandstone deposits in northwestern Ohio and eastern Michigan, the thinning of the Berea to the northwest, north, and south, and the low-lying character of the western limb of the Cincinnati anticline, which did not furnish any sediments with sandy phases farther to the westward in Indiana. The delta-like cross section of the deposits has been mentioned by Robinson[16], who points out the great thickening in eastern Michigan. The uniformity of ripple marks with northwest direction discovered by Hyde[17] may indicate sufficiently the direction of the shoreline to be an argument for the northwest elongation of the depositional basin. The local presence of shoal water caused by the immense thickness of sediments dumped in northwestern Ohio would explain the abundance of ripple marked sandstone.

The extent of Berea sedimentation is shown in Figure 5. The outlines on the map emphasize the fan shaped plan of the area over which the deposits were laid down. This fan-like spread of the deposit makes the delta conception seem even more logical.

In western Michigan, another set of depositional conditions prevailed during Berea-Bedford times. The isopachous map (see fig. 15) indicating the variations in thickness of the two formations together shows an entirely different picture. The deepest part of the basin is in the northwestern part of the State, instead of the southeast where the Berea sandstone attains its greatest thickness. A possible explanation would be that these fine sediments are the bottom-set beds of the delta originating to the southeast. This would seem logical if it were not for the fact that the texture, color, and composition of the thick shales of northwestern Michigan do not resemble either the Bedford shales or the shale partings in the Berea of the southeastern area.

It would seem, therefore, that the thick greenish gray shale in northwestern Michigan, approximately equivalent in stratigraphic succession to the Berea-Bedford of southeastern Michigan, is older and has a different depositional history. This shale series has been given the name Ellsworth formation. The history of Ellsworth time might be conceived as follows:

The shallow area extending northeast-southwest across Michigan was an axis of tilting throughout early Mississippian. At the close of Antrim time, an uplift took place along this axis, and the basin area was down-tilted to the northwest. A sea invaded the area and brought in clastic sediments of variable nature, chiefly clay but including limy and sandy muds. The products of weathering of the "Wisconsin island" were added to this material and the resulting deposits must have been originally somewhat red in color. However, climatic conditions might have been such that nearly all of the red ferric iron was reduced to the green ferrous state. Whether this took place before or after deposition has not been determined, but a thick series of green colored sediments was laid down.

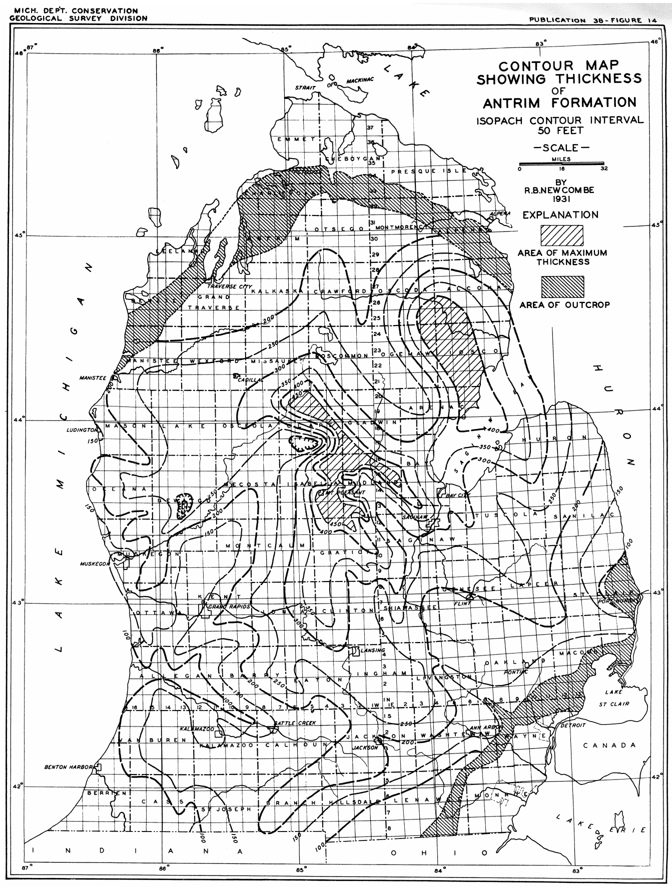


Figure 14. Contour map showing the thickness of the Antrim formation in the southern peninsula of Michigan.

The minor structural irregularities in this downwarped area probably resulted from slight folding along pre-existing lines of weakness. In the main, they all have either an east-west or northwest-southeast trend. The north-south ridge in the northern part of the State is suggestive of the shallow basin which had existed in this general area since Traverse time.

At the beginning of Bedford time, tilting occurred in a reverse direction along approximately the same axis and the sea came in from the southeast. This sea deposited the Berea and Bedford sediments which correlate with those of Ohio. A red shale, which probably resulted by alteration of local ferruginous weathered clastic material, was laid down locally and is possibly equivalent to the Ohio red Bedford. Minor depressions in which thicker sediments were deposited trend northwest-southeast on the southwest side of Livingston County and south of Jackson, Jackson County. Shallow areas extend across Genesee and Lapeer counties and also northeastward across the "Thumb" region. A small trough parallels the upwarping in the "Thumb" on the northwest.

The complexity of sedimentation during the period may be partly explained by evident changes in the direction of the forces causing earth movements in the "basin." Instead of a warping with dominant northwest-southeast trend, the direction was almost at right angles to the former prominent direction. This condition may have exercised some control over the unusual movements along the axis of the Cincinnati anticline which are so difficult to interpret.

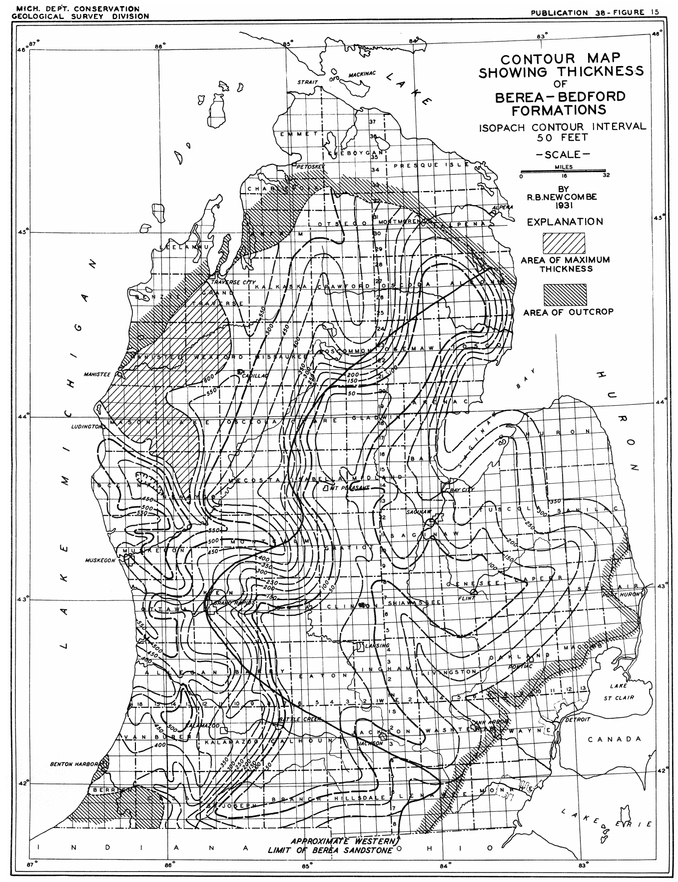


Figure 15. Contour map showing the thickness of the Berea-Bedford (and Ellsworth) formations in the southern peninsula of Michigan.

COLDWATER TIME

Coldwater time evidently began by a general downwarping of the central basin region where shallow water probably prevailed in the preceding period. A progessive tilting took place to the westward in which the waters gradually deepened in that direction. Various changes in the land relief and the depth of the sea resulted, but in the main, disintegration of the rocks furnishing waste material must have been rather complete. Climate favorable to the growth of vegetation, together with lowland conditions set in again at the beginning of Coldwater time, and black shale was laid down. This deposit was for the most part thin and widespread, but occasional sections of thick Sunbury shale suggest possible stream distributary channels depositing mud under broad, low, delta-like conditions. The location of the principal area of uplift to the east of the basin is shown by the coarser sandy phase of the beds in the "Thumb" part of the State. The proximity of the land is suggested by the quantity of undecomposed mica in some of the beds. Near the beginning and the close of the period, there were local conditions of sedimentation favorable to the preservation of red color. The source of this color was probably the ferruginous weathered product of basic igneous rocks which made up a part of the adjoining land mass. Likely, a humid climate with alternating long dry periods furnished the active agents for complete weathering to soils which were predominantly red in color. Throughout the greater part of the Coldwater time, there were low shore lines and the luxuriant vegetation decomposed to give products which helped reduce the reds and pinks to gray, blue, and light green, colors. The climate was probably colder when the lighter colored shales were being deposited.

At the time of the deposition of the Coldwater, western Michigan was affected by conditions of sedimentation differing from those in other parts of the State. Deeper waters and less wave action caused intermittent limestone deposition. Early in the period, the conditions which brought about red sandy shale in the eastern part of the State probably gave rise to a red shaly limestone on the western side of the State. The macerated fossiliferous material in this red member indicates that the limestone was produced from the disintegration of older limestone shores. That the red limestone is more or less equivalent to the red shales to the east has been found by tracing in wells the lateral gradation across the State.

In western Michigan, another series of calcareous sediments is found about 250 to 300 feet below the top of the Coldwater formation. These beds are somewhat fossiliferous but not typical of a limestone sea. They are locally sandy, and the granular, oolitic texture suggests that they were laid down on shallow flats which were receiving calcareous sediments from the weathering of a limestone land area.

The character of the Coldwater is, therefore, the result of conditions shifting from those of the shore to those of the open sea, and the period ended with a general shallowing. The outline of the depositional basin is shown in Figure 16. The major elongation in a northeast-southwest direction continued over from Berea time, but the area of greatest down-warping was transferred into the central region of the State, Cross-warping in the opposite direction gained additional importance and almost divided the basin into two separate troughs. Minor wrinkling along this northwest-southeast direction governed sedimentation to a marked degree, and there was evidently uneven compaction of the muds over the topographic ridges resulting from older structural features. The larger of these features is in southwestern Ingham, northeastern Eaton, Ionia, northeastern Kent, and Newaygo counties; Livingston, southwestern Shiawassee, Clinton, Montcalm, Mecosta, and southeastern Lake counties; Genesee, Saginaw, eastern Gratiot, southern Midland, northeastern Isabella, Clare, Missaukee, and Wexford counties; southwestern Arenac, southeastern Ogemaw, and southwestern Iosco counties. The deposits of Coldwater time very strongly reflect the control of minor structures on sedimentation.

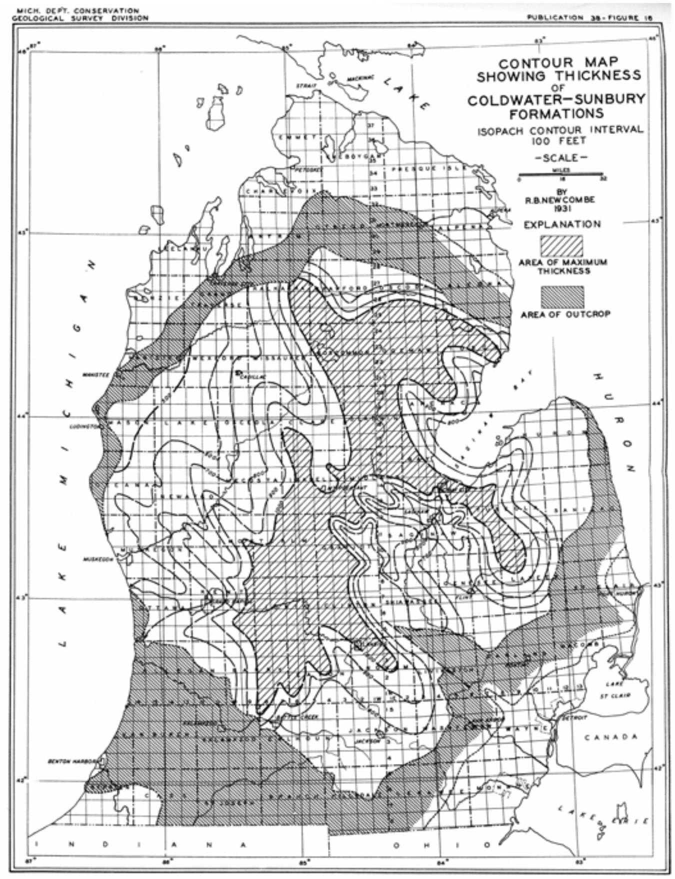


Figure 16. Contour map showing the thickness of the Coldwater-Sunbury formations in the southern peninsula of Michigan.

MARSHALL TIME

A widespread uplift of the land took place at the beginning of Marshall time, and streams were quickened, giving greater erosive power. The western part of the basin probably remained out of water longer than the eastern, although there was probably greater topographic relief on the east. The Lower Marshall began in the "Thumb" area with a thin bed of fine-grained, so-called "peanut" conglomerate. These basal deposits, typical of rugged shores, were laid down westward across the State with the sea invading in that direction. The conglomerate and other basal beds of the Lower Marshall grade to the west into a pink, medium grained sandstone. As the shoreward phase moved westward, the eastern part of the basin gradually deepened and micaceous shaly sandstones were deposited. This type of deposit is a probable result of rather rapid disintegration of the large areas of basic greenstones, hornblende schists, and other ferruginous metamorphic rocks in regions furnishing the sediments. Local red beds indicate complete oxidation at times when rock disintegration was more complete, and although vegetation was probably locally abundant, the climate must have been for the most part temperate. The prevalence of red color scattered through the whole formation is evidence that there was a large quantity of iron in the waters of the Lower Marshall sea throughout the period. The absence of the red color in areas where it is usually present is ascribed to later reduction due to leaching along structural "highs." Since these generally represent regions of shallow water, the wave action would probably rework the sand and remove much of the red colored cementing material.

With the close of Lower Marshall time, an uplift again occurred that may have been simply a general tilting to the east. The waters were at least temporarily withdrawn, permitting considerable weathering and erosion. The relief of the irregular surface at the top of the Lower Marshall is just beginning to be appreciated from a study[18] of the many core test wells which penetrate this formation in the "Thumb" part of the State.

The deposits of the Napoleon sea are practically free from mud, and the coarse clastic sediments suggest the approach of drier climate. The Napoleon sandstone beds also indicate more pronounced wave action for the exposures are often extensively cross-bedded. The greenish gray color which prevails is probably due to waste products derived from greensands and chloritic rocks. Fragments of coaly material in the Napoleon sandstone are proof that some vegetation grew during Marshall time. They are probably carbonized chunks of driftwood entombed in the beds.

The Napoleon sea transgressed westward resulting in overlap and ginning of beds in that direction (See fig. 17). An uplift at the close of the period also may have contributed to the westerly thinning of this sandstone member and general widespread withdrawal of the waters culminated Marshall time. The top of the Napoleon was eroded giving rise to considerable surface relief and locally the entire formation may have been removed in the western portion of the basin. Several products of this erosion period are found at the Upper Marshall contact. These products of weathering include gibbsite (Al OH_3), glauconite, chlorite, and other unidentified aluminous minerals.

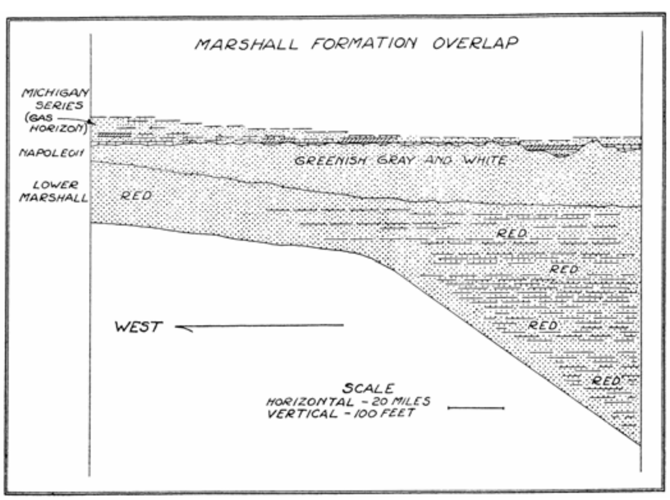


Figure 17. Diagrammatic sketch of the westward Marshall overlap.

The deep part of the basin in Marshall time again shifted to the eastern side of the State (see fig. 18) and a small local deep area was formed in the south central portion. A shallower region trending northeast-southwest through the center of the synclinal area corresponds closely to a similar shallow area of Berea time. This feature of the basin may have exercised some control upon the origin of coarse clastic sediments. Excepting the uplifted region in Livingston County, the warping in the southeastern part of the State has a trend almost north-south and more or less parallel to the deep sinking areas. Folding or warping in the southwestern part of the State has a general northeast-southwest direction, but the predominant direction in the central and northwestern portions of the synclinal basin is northwest-southeast as in previous periods. Many local troughs indicate that minor structures guided sedimentation to a large degree.

GRAND RAPIDS TIME

The uplift which preceded Grand Rapids time finally restricted the "basin" to the extent necessary for the temporary preservation of relict seas. For this reason, intermittent gypsum and anhydrite beds are characteristic of the Lower Grand Rapids or Michigan formation. The enclosure of the basin was affected by upward movement along both Cincinnati and Wabash arches, which temporarily cut off connections with the seas occupying the Appalachian trough and the Indiana-Illinois basin. This movement was probably related to the general emergence which brought about the formation of the thick Catskill beds in the East. Apparently, at the time of the first isolation, lime was present in the waters in sufficient concentration to be thrown down soon after evaporation set in. The streams entering the basin were flowing over Marshall rocks and a slight reelevation enabled them to cut down fast enough to bring considerable quantities of reworked Marshall sand into the sinking area. Local monadnock-like hills of sandstone also probably projected above the waters of the Michigan "series" sea for some length of time after the new period commenced. These conditions brought about the deposition of fine-grained sandstones near the base of the Lower Grand Rapids group with lithologic characteristics similar to the Upper Marshall. A gentle westward tilt seems to have taken place, for to the west and northwest (see fig. 17), these basal sandstone members occur successively higher in the series as if they were deposited by a sea retreating in that direction.

About the middle of the period, the sea was completely cut off and evaporation and concentration took place sufficiently to precipitate anhydrite, which later altered to gypsum. The influence of the chemical composition of streams which flowed southeastward over iron-bearing formations probably affected the color of the evaporite beds of Grand Rapids age formed in the area. That this exercised a coloring effect is suggested by the fact that gypsum of western Michigan is pink and red, while that of the eastern part of the State is white, gray, and cream colored. The gypsum deposits of Michigan are not distributed uniformly in all parts of the old sea basin, but are concentrated in comparatively small sized areas. Grimsley[19] attributed the cause of this concentration to "salt pan" conditions in lagoons similar to the Karaboghaz (Black Gulf) of the Caspian Sea. On the basis of present evidence, a structural explanation for the occurrence of anhydrite and gypsum is more likely than one strictly physiographic. As the basin area was down warped, local troughs probably formed roughly parallel to preexisting structural irregularities. Folding took place contemporaneously with the precipitation of anhydrite, and the thick gypsum beds that were formed largely by later hydration correspond to the minor downwarped regions. The gypsum beds thicken progressively into these smaller basins and are thin or even missing along the structural "highs." This relation has been found to hold for every extensively prospected area in the State and is, therefore, very significant.

The absence of salt beds might have been due to insufficient evaporation of the sea water, but this does not seem so likely as secondary removal of the salt by solution after burial. It is logical to assume that salt was formed locally somewhere within the basin because these dry periods probably were not interrupted for long duration and salines were probably constantly added from the erosion of exposed Salina beds surrounding the Michigan region. Much of the gypsum shows the effect of solution and both secondary crystalline gypsum and salt veins occur throughout the series. If salt beds were once present, they were probably not thick and the cover of superimposed sediments did not protect them from weathering agents and percolating ground water.

Conditions of sedimentation varied throughout Michigan "series" time. The muds washed into the basin were often from fine dust carried to the shores by the warm winds, and the mode of deposition was controlled by the flocculating effects of saline waters which were strongly concentrated and high in specific gravity. The resulting shales were fine grained, gray to black rocks with no particular structure or bedding. The toxic effect of high salinity on all forms of life brought about the concentration of carbonaceous material and many of the beds are thus black in color. The rocks derived from lime muds also show little or no structure and most of the limestones were precipitated from solution rather than through the agency of lime secreting life forms. The dolomitic character of the lime rocks is typical of saline basins. Red and green colors are more numerous in the thicker Michigan series section of the northwestern part of the State. These colors may be due to desert conditions, but more probably the streams from the proximate area of the crystalline rocks in the northern peninsula added iron in quantities sufficient for coloration. The streams bringing in sediments were not flowing over limestone beds to the same extent as in Salina time, and the dark colored mud rocks of the Michigan series indicate that much of the land waste was formed by extensive decomposition and disintegration. The dry climate probably did not prevail throughout the entire period.

The shape and configuration of the "basin" in Grand Rapids time is shown in Figure 19. This map demonstrates the shifting of the most rapidly sinking region to the approximate central area. The deep portion is divided into two small secondary basins which are not greatly elongated, although there is a northwest-southeast major axis in the northern one. A possible north-south connection between these basins would emphasize the meridional direction.

The contours indicate very sharp northwest-southeast minor basing and ridges. Some north-south features are present in southern and central Michigan in Clinton, Eaton, and Ionia counties. The sharpness of the troughs is probably partly due to contrasts in thickness that result from extensive post-Mississippian erosion which removed sediments from the upwarped areas. The outstanding characteristic feature of the map is the recurrence of a basin with the deep part approaching circular outline in about the same position as during Detroit River time when salt was deposited (Compare fig. 9). This comparison supports the conclusion that the reason for the frequent repetition of conditions of evaporation in Michigan was the structural position of the region, where recurrent upward earth movements of the surrounding positive structural areas caused periodic isolation of the basin. Future studies may show that similar structural conditions brought about the formation of many major saline basins.

New sea connections with the Illinois-Indiana basin opened in Bayport time, but rather warm dry conditions probably continued in Michigan for some period thereafter. Lane[20] suggested that the deposition of gypsum might have terminated in two ways,—either by an increase in the precipitation and supply of fresh water, or a downwarped connection with adjoining basins, permitting entrance of the sea. The Bayport deposits include alternating limestones and dolomites, limestones, sandy limestones, and white sandstones. The limerocks are crowded with life and comparatively free from shale. These sedimentary characteristics indicate that the climate was probably rather dry and gypsum deposition ceased because the waters of adjoining seas were added to those of the Michigan "basin." The water must have been relatively quiet to permit coral life in the sea, but the chert in the Bayport signifies that the streams were probably carrying silica in considerable quantities. The thickness of Bayport would indicate a short lived transgression, but the intense subsequent erosion may have removed large amounts of the soluble limestone beds. At the close of Bayport time, the entire basin area was raised above water and active streams eroded deeply into the rocks of the Grand Rapids group. At some places, as in Jackson and Shiawassee counties, they cut down through the Michigan series into the Napoleon sandstone. The flow of these streams was largely directed by preexisting structures, and in many places the absence of Bayport limestone is evidence that there has been some type of deformation in the district.

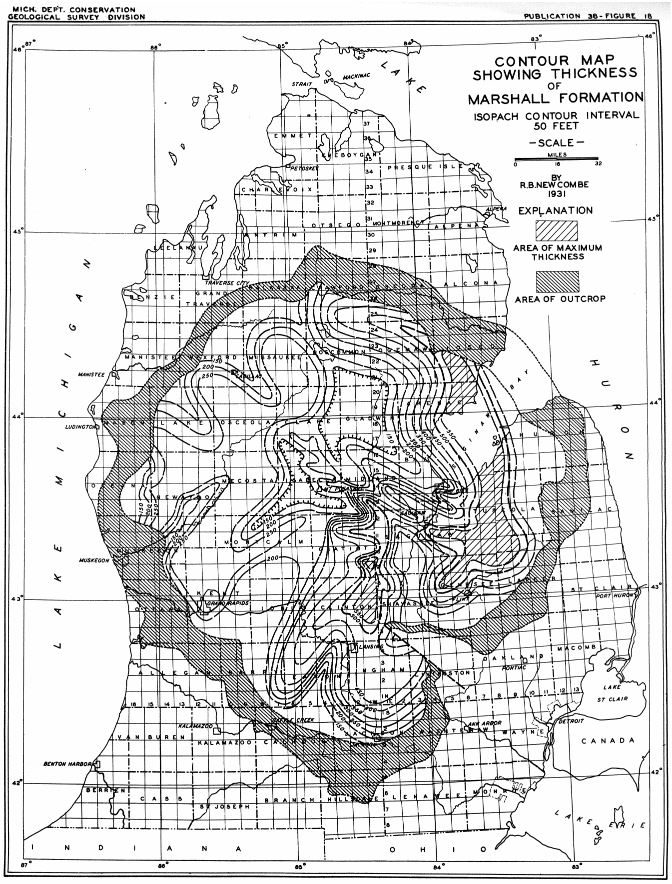


Figure 18. Contour map showing the thickness of the Marshall formation in the southern peninsula of Michigan.

PENNSYLVANIAN PERIOD

<u>PARMA TIME</u>

The uplift continued in the old positive land areas, but the Pennsylvanian age opened in Michigan with a shallow sea which formed rather continuous sandy shore deposits. The land must have been relatively close by and the parent rocks consisted of comparatively pure white quartz. Occasionally at the Parma-Bayport contact, later mineralization formed green and blue colors and chalcopyrite has been observed. Apparently, the colored rock contains hydrated carbonates of copper, but this has not been definitely proved. The basal beds are usually conglomeratic and have pebbles about the size and shape of a split pea. The sand was strewn widely and filled the hollows in the old pre-Pennsylvanian topography. Subsequently some of the Bayport limestone must have been periodically reworked because layers of limestone are often intercolated with typical Parma sandstone. Bayport intraformational breccias within the Parma indicate that wave action must have been decidedly violent on the shores of some of the limestone islands which remained above sea level during the early stages of Parma time.

<u>SAGINAW TIME</u>

Climatic conditions in Saginaw time showed only a few changes. The basin became a great shallow area supporting luxuriant vegetation in the swamps which occupied local basins. These swamps were seldom continuous with each other, and the resulting coal beds thin out laterally. The trend of the coal basins may parallel the predominant structural axes, but the relation between structure in the coal beds and deeper folding does not seem to be direct.

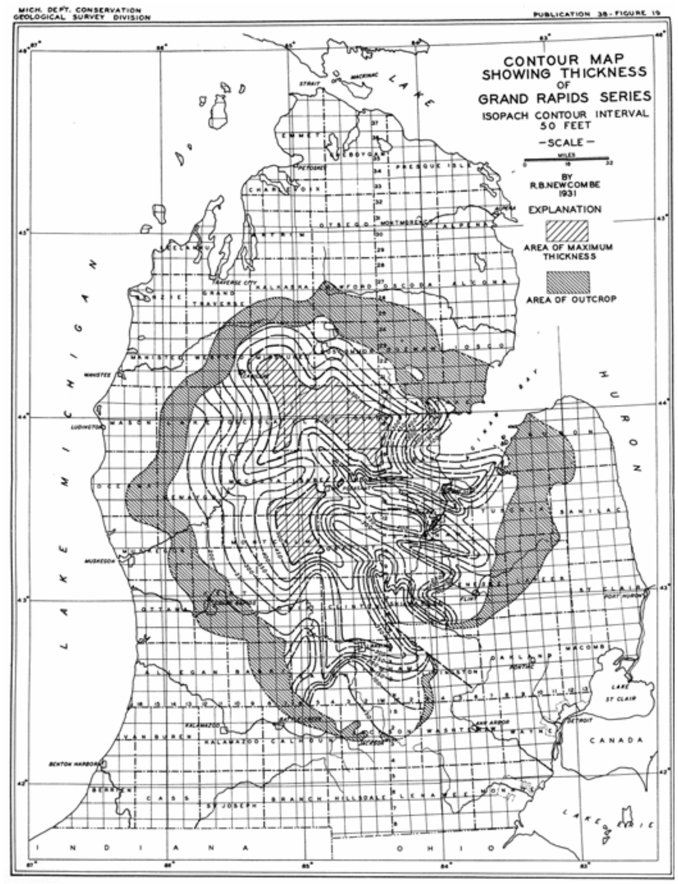


Figure 19. Contour map showing the thickness of the Grand Rapids series in the southern peninsula of Michigan.

The environmental control of deposition was featured by temperate climate and abundant rainfall. Torrential streams evidently brought in quantities of coarse clastic materials, and the land areas must have been rather completely disintegrated. The alternating character of the color and kind of sediments proves the oscillating nature of the surface on which they were laid down. The reducing properties of carbonaceous clay and silt probably played an important part in producing the drab colors which characterize the deposits. Occasional seas inundated the basin, depositing limestone beds which contain marine fossils. The principal connection seems to have been to the southwest with the Indiana-Illinois basin because the life forms in the Michigan beds are closely related to those of the Eastern Interior region.

"PERMO-CARBONIFEROUS" (?) PERIOD

<u>"RED BEDS" TIME</u>

At the close of Saginaw time, Michigan was again raised above water, and an unconformable unnamed series of deposits followed. The thickness of this series indicates that tilting must have taken place to deepen the basin to the north and west. The basal pink or russet colored sandstone has been called Woodville (Ionia) and may possibly be equivalent in age to the beds above which commonly have a red color. For the time being, the entire series is called "Red Beds" because it is similar in color, composition, and perhaps age to the "Red Beds" of the southwestern United States.

The origin and age of these beds is not known. Lane[21] has suggested that the coloring is caused by weathering or secondary oxidation, and that the beds may be Conemaugh, later Carboniferous, or early Permian. The general outline of the area of thick "Red Beds" has been determined, and the widespread presence of gypsum in the series indicates the manner of their origin.

An uplift to the south shut off additions of the sea and quickening stream activity brought in coarse sand. The approach of desert-like conditions caused sufficient oxidation to slightly color this basal sandstone. After the deposition of the basal Woodville, a warm alternating moist and dry climate set in. The exposed rocks on the land were rather completely disintegrated and red ferric oxides of iron were formed in the soils. Conditions of evaporation followed and, as a result, gypsum and gypsum residues were laid down in thin beds, alternating with red plastic shales, gray shales, and red shaly sandstones. The "Red Beds" are the latest consolidated rocks recorded in the sedimentary history of Michigan.

MESOZOIC AND CENOZOIC ERAS

TERTIARY PERIOD

The clues of erosional history of the Mesozoic and Cenozoic eras are masked by glacial drift, but recent erosion has not greatly affected the physiography of the pre-Pleistocene rock surface. Near the close of the Mesozoic, the region was considerably uplifted after the upturned edges of the strata had been leveled and the land surface had been reduced to a peneplain. The Tertiary period began with a slight uplift and a variety of residual weathering products resulted. Before the beginning of Pleistocene glaciation, a thick mantle of soil and fragmental rock had formed. Toward the close of the Cenozoic era, a second important uplift probably took place and the streams eroded deeply into the rocks. The present topographic features of the rock surface in Michigan were incised largely at this time, and the bedrock topography reflects the Cenozoic physiographic history. Several drainage patterns postulated by Spencer[22] and Grabau[23] have partly explained the nature of the major streams which flowed across the region previous to the Great Ice Age. These writers postulate that the principal drainage was across Michigan in a northeast-southwest direction with the stream channel occupying a wide valley which is now filled in part by the waters of Saginaw Bay. Spencer believed that the direction of flow was northeast and called the stream the Huronian River, a tributary of his great ancient Laurentian River system. On the other hand, Grabau contended that the Ancient Saginaw River flowed southwestward in this same valley. Present data would favor Grabau's conceptions with certain minor modifications.

The origin of the deep basins now occupied by the lower Great Lakes is still a mooted question. Probably, all of the important weathering agents aided in the bringing about of these great troughs, but the respective roles of water, wind, and ice are still disputed subjects.

The fracturing of the Devonian limestones and the formation of large sinks along their strike in Alpena County, the unusual breccias in the St. Ignace region, and the major features of the Salina salt basin of Michigan revealed by a large number of recent wells records throw some new light on this problem of the origin of the Great Lakes basins. It is significant that there is a close correspondence between the outcrop of Salina rocks and several of these lake basins. The only known exposures of rocks in Michigan that might be Salina in age are near St. Ignace and Mackinac Island and these consist of a jumbled, brecciated mass, the origin of which has never been satisfactorily determined. Erosion remnants of this type are similar to talus slopes along bluffs formed of beds containing or directly overlying salt bearing rocks. These breccias are almost positive proof of slumping, no matter what may have been the cause of the undermining action that brought it about. Following around the strike of the Salina rocks into the lake basins, the depths of Lake Michigan and Lake Huron seem to be closely related to the variations in the thickness of the salt deposits in the central part of Michigan. Furthermore, the total known maximum thickness of salt in the Salina does not differ* greatly from the maximum lake depths. The deepest part of Lake Michigan compares very closely with the strike of the maximum downwarped area of the synclinal basin during Salina time. That is, the major axis of the Michigan Basin trends toward the deepest part of Lake Michigan. Since the Salina comes up under the lake, this would naturally be the locality of thickest salt beds along its outcrop. These relationships, though not conclusive, are strong arguments that the solution of salt brought about the initiation of the deep lake basins. The controlling effect of hard and soft rocks in the cutting of deep erosion channels now occupied by the four lower Great Lakes has been previously cited in several papers[24], but the close relation of the thickness of Salina salt to the depth of the lake basins suggests a plausible explanation of this important physiographic problem.

*This relation was first pointed out to the writer by Evan Just.

PHYSIOGRAPHIC HISTORY OF LOWER MICHIGAN

The physiographic history of lower Michigan can be traced best from a contour map showing the configuration of the base of the Pleistocene. (See pl. I). The bedrock surface beneath the glacial drift has considerable relief. The original pre-Pleistocene topography has been somewhat modified by ice action which removed old soils and much loose rock and probably gouged and deepened some of the valleys. In spite of these changes, the major pre-glacial physiographic features seem to be largely preserved.

The deep channel reaching below sea level apparently parallels the Lake Michigan shore as far south as Muskegon, and the direction of this channel is indicated by the elongated lakes and bays of the Grand Traverse region. The depths of the Lake Michigan basin seem to show that pre-glacial drainage took place northward along the depression which the lake now occupies.

A shallower channel can be traced across the State from Saginaw Bay to central Ottawa County, between Grand Haven and Holland. (See pl. I). Topographic ridges resulting from structural irregularities caused changes in the course of this channel, but the main valley is well defined. The river forming this valley was probably a consequent stream which resulted from a westward tilt of the land in Mesozoic or Cenozoic time or both. The channel does not appear to have sufficient fall northeastward to permit the stream to flow in that direction, although there may be a small sharp valley not revealed in the borings around Saginaw and Bay City. The fall to the southwestward is more definite.

A significant feature is the depression along this channel in the central part of the State. Possible errors may have crept into calculation of the depths to rock because the soft "Red Beds" might have been correlated in some wells as drift. The size of the topographic basin would seem to discount this source of error.

The depression must have been caused by differential erosion of the various hard and soft rocks. The pre-Pleistocene drainage basin in the approximate center of the area underlain by the "Red Beds" and their ease of erosion may possibly explain the origin of this topographic depression. The large stream flowing across central Michigan probably spread out like a braided river over these flats which were possibly saline, and the moving water eroded widely because of the soft and soluble character of the gypsum and of the weakness of other associated rocks.

Subsequent streams formed tributaries to the main river and the valleys of these streams closely follow the general structural "grain" of the region. One of these streams headed in southeastern Calhoun County and flowed northwestward to the larger valley on the west side of Kent County near Grand Rapids. Another headed in central Jackson County and flowed into the main stream at about the same place in northwestern Kent County. Numerous other valleys formed by subsidiary streams of this type can be observed on the map. (See pl. I).

The principal divides of this drainage system are in the south central and the northeastern parts of the State. The main ridges forming these divides trend northeast-southwest and more or less parallel to the drainage course of the largest river. The ridges are dissected by the valleys of the smaller subsequent streams. The highest known preserved pre-glacial topography is over 1,100 feet above sea level and is located on the southern divide. The region in Northern Michigan which is mapped as a broad plateau stands at above 800 feet, but the maximum relief of the rock surface is unknown because of the lack of exploration. The surface topography would permit elevations of the rock of more than 1,100 feet, but no drilling has penetrated deep enough to reveal the depth to rock throughout the area.

An unusually high district rising above 700 feet and extending nearly north and south across western Kent County is difficult to explain. The rocks of this region are mapped as the Grand Rapids group and should respond readily to erosion. The most plausible explanation for this prominent bedrock physiographic feature seems to be a structural disturbance in the region, and the thickness and regional structure maps seem to support this conclusion.

QUATERNARY ERA

PLEISTOCENE PERIOD

The Pleistocene Ice Age which practically completed the geological history of Michigan rocks is complex in detail. The temperature gradually decreased until the accumulation of winter snows in northern ice centers was in excess of summer thaws, and a great mantle of snow and ice covered the State. The dispersion of these glacial masses was from northern centers in Labrador, the Keewatin center west of Hudson Bay, and possibly from an area between these two near Patricia, Ontario. The ice moved southward and occupied the larger depressions left by Tertiary erosion.

Two stages of glaciation have been recognized in Michigan, but there were also probably two preceding ones. After the Illinoian drift was deposited, the return of warmer climate caused a retreat or removal of ice from the region, and a period of weathering followed. With another general lowering of temperature, the ice again formed over the State, and the Wisconsin drift was laid down. Due to minor changes in climate there were retreats and readvances of the ice front, and as the weather gradually became more temperate these gave rise to a series of ice dammed glacial lakes.

The glacier front receded from the State in great ice lobes which were principally confined to the major topographic depressions. These lobes usually presented a convexly curved front which governed the form and alinement of resulting deposits. The glacial lobes, known as the Lake Michigan, Saginaw and Huron-Erie lobes, occupied the basins now filled by the Great Lakes. The directions of movement taken by the various lobes were largely controlled by climate, by distribution of ice load, and by the shape of the depressions which held and confined the ice. These directions are locally shown by the orientation of scratches and grooves which have been preserved on the surface of the bedrock. At the end of the Ice Age, the temperature finally moderated enough so that the ice sheet disappeared and the features of the glacial deposits were left much the same as they are now.

[1]Hussey, R. C., Personal communication.

[2]Ulrich, E. O., Notes on New Names in the Table of Formations and on Physical Evidence of Breaks between Paleozoic Systems in Wisconsin: Trans. Wisconsin Acad. Sci., Arts & Letters, Vol. 21, p. 106 (1924).

[3]Ehlers, G. M., Unpublished manuscript.

[4]Williams, M. Y., The Silurian Geology and Faunas of the Ontario Peninsula and Manitoulin and adjacent Islands: Canada Geol. Survey, Mem, 111, p. 70 (1919).

Chadwick, G. H., Stratigraphy of the New York Clinton: Bull., Geol. Soc. Am., Vol. 29, pp. 355-359 (1918).

[5]Ehlers, G. M., Unpublished manuscript.

[6]Cumings, E. R., Silurian Studies. Two Fort Wayne Wells in the Silurian and their bearing on the Niagaran of the Michigan Basin: Proc. Ind. Acad. Sci., Vol. 39, p. 195 (1929).

[7]Grabau, A. W., Geology and Paleontology of Niagara Falls and Vicinity: Bull., New York State Mus., No. 45, pp. 127-128 (1901).

[8]Grabau, A. W., and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, p. 85 (1910).

[9]Newcombe, R. B., Interpretation of Recent Discoveries in the Salt-Bearing Rocks of Michigan: Papers, Michigan Acad. Sci., Arts & Letters, Vol. 12, p. 248 (1929).

[10]Grabau, A. W., and Sherzer, W. H., Op. cit., p. 57.

[11]Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. Am., Vol. 41, pp. 734, 735 (1930).

[12]Pohl, E. R., The Middle Devonian Traverse Group of Rocks in Michigan: A Summary of Existing Knowledge: Proc. U. S. Nat. Mus., No. 2811, Vol. 76, Art. 14, p. 20 (1930).

[13]Pohl, E. R., Op. cit., p. 33.

Ehlers, G. M., Personal communication.

[14]Pobl, E. R., Idem, p. 23.

[15]Hyde, Jesse E., The Ripples of the Bedford and Berea formations of Central and Southern Ohio, with notes on Paleontology of that epoch: Jour. Geol., Vol. 19, p. 269 (1911).

Robinson, W. I., Unpublished manuscript.

[16]Robinson, W, I., Unpublished manuscript.

[17]Op. cit, pp. 260, 261.

[18]Kirkham, Virgil R. D., Verbal communication.

[19]Grimsley, G. P., Origin of Gypsum with special reference to the origin of Michigan Deposits: Trans. Kansas Acad. Sci., Vol. 19, p. 114. (1905).

[20]Lane, A. C., Geological Report on Huron County, Michigan: Geol. Survey of Michigan, Vol. VII, Pt. II, pp. 103, 104 (1900).

[21]Lane, A. C., and Seaman, A. E., Notes on the Geological Section of Michigan: 10th Ann. Rept., State Geologist, Michigan Geol. Survey, p. 89 (1909).

[22]Spencer, J. W., Origin of the Basins of the Great Lakes of America: Am. Geologist, Vol. VII, p. 7 (1891).

[23]Grabau, A. W., Guide to the Geology and Paleontology of Niagara Falls and Vicinity: New York State Mus., Bull. 45, p. 44 (1901).

[24]Hall, James, In Foster, J. W., and Whitney, J. D., Report on the Geology of the Lake Superior Land District: U. S. Sen. Doc., Spec. sess. March 1851, Exec. No. 4, pp. 176-177 (1851).

_____, Organic Remains of the Lower Helderberg Group and the Oriskany Sandstone: Nat. Hist. Survey of New York, Pt. IV, Vol. 3, p. 31 (1859).

Leverett, Frank, The Illinois Glacial Lobe: U. S. Geol. Survey, Mon. 38, pp. 13, 14 (1899).

Grabau, A. W., Guide to Geology and Paleontology of Niagara Falls and Vicinity: Bull. New York State Mus., Vol. 45, p. 54 (1901).

Spencer, J. W., Relationship of the Great Lake Basins to the Niagara Limestone: Bull. Geol. Soc. Am., Vol. 24, pp. 229-232 (1913).

Ruedemann, Rudolf, Fundamental Lines of North American Geologic Structure: Bull. New York State Mus., Vol. 260, pp. 79, 80 (1924).

Chapter V. STRUCTURAL GEOLOGY

DISTRIBUTION OF SURFACE ROCKS

The distribution of surface rocks in Michigan is very difficult to map because of the scarcity of exposures. Except in the northern and southeastern parts of the southern peninsula, outcrops are very rare, and the only clues to formation boundaries over wide areas are those in well records. The local effects of topography on formation boundaries cannot be determined because the hills and valleys of the present earth surface may differ greatly in local districts from those of the bedrock surface. Oftentimes, the data from well logs are somewhat unreliable where the bed rock is encountered. The rock directly beneath the glacial drift is soft when weathered, and the driller often drives his pipe several feet into the bedrock before commencing to save samples of the material penetrated. The result of this oversight is that the boundaries of rock formations are incorrectly mapped, and the thickness of the glacial drift as determined is locally in error. The latter error may greatly distort the picture of pre-glacial topography which is partly shown by the present bedrock surface. Another source of error difficult to avoid is the possible misinterpretation of the age of formations in shallow wells which do not penetrate easily identifiable beds.

The map of the areal geology of the hard rock in Lower Michigan is shown in Plate II, and the tentative nature of this map is indicated by the dashed and dotted lines used for contacts. The regions which are mapped in greatest detail because of rock exposures are in Monroe, Jackson, Huron, Alpena, Presque Isle, Cheboygan, Emmet, and Charlevoix counties. Recent test well drilling in Huron, Tuscola, Sanilac, Livingston, Oakland, Wayne, Allegan, Ottawa, Kent, Roscommon, Kalkaska, and Presque Isle counties has aided in more accurately mapping many of the contacts in these counties. The extensive deep well exploration for oil and gas in western and central Michigan has necessitated many radical changes in the formational boundaries, especially in Lake and Wexford counties. Previous test borings for coal in Saginaw, Bay, Midland, Tuscola, Genesee, Shiawassee, Ingham and Jackson counties have greatly aided in the determinations of the formations from new wells. The results of test well projects completed and under way in Arenac, Ogemaw, Iosco, and several other counties have not been released, and the corrections which will necessarily follow any discoveries that may take place because of these operations must be omitted from the prsent map.

The following are some of the more important changes made on this map: The concentric arrangement of the outcropping rocks is still preserved, but the width of the outcrop and the sinuosity of the contact lines in many cases are very different than on previous maps. The changes in the areal geology which were described in a paper by Thomas[1] have been largely adopted. Other contacts that are radically different from previous maps are those in the vicinity of the Howell structure in Livingston and bordering counties; the new boundaries of the Saginaw formation in the northwestern part of the State in Wexford and Lake counties; and those of the Traverse-Dundee, Dundee-Monroe boundaries in Cheboygan and Presque Isle counties. Minor alterations have been made to the Bedford-Antrim contacts in north central Michigan, in Leelanau and Cheboygan counties, and in southeastern Michigan in St. Clair, Wayne, Washtenaw, and Oakland counties. Changes have also been made in the Saginaw formation, Grand Rapids series, Marshall formation, and Coldwater-Sunbury-Berea contacts in the western counties of the State. The Saginaw-Grand Rapids contact has been altered in Arenac County, and the Grand Rapids-Marshall contact has been revised in Huron, Tuscola, Ogemaw, Arenac, and Sanilac counties. The Coldwater formation also appears at the surface beneath the drift on the West Branch structure, Ogemaw County.

The "Red Beds" have been added to the formation units, and the region underlain by these beds is mapped in the central part of the State. The complete continuity of these deposits is only postulated, but the characteristic red strata have been found so regularly throughout the region that the area mapped as "Red Beds" seems approximately correct. As new information is gained from drilling operations the outer boundaries now drawn will be found to have irregularities and there will also be separate erosion remnants beyond. Accurate mapping will always be difficult because the soft clay-like layers are easily mistaken for drift material. Close observations in all new wells for the first appearance of red colors should aid in further corrections of the boundaries of the Michigan "Red Beds."

The occurrence of outliers is illustrated by the remnant of the Grand Rapids group in northeastern Allegan County (see pl. II) and this suggests that numerous other unmapped remnants probably exist. The outliers of Marshall formation in Calhoun and Kalamazoo counties and in Hillsdale County seem to represent erosional remnants of sandstone, which may be partly due to structural control of pre-glacial drainage. The inliers or "windows" of the Grand Rapids group in Jackson County result from the uneven erosion surface at the top of the Mississippian and similar Bayport hills should protrude through the Saginaw formation in other localities. The inlier in southern Ogemaw County is indicated by the outcrop of Marshall sandstone in the valley of the Rifle River. This exposure is due to a large anticlinal structure in the region (West Branch anticline), and the size and shape of the mapped district is determined by a comparison with other better known anticlinal structures in the State. The outlines of the formation contacts in this area will probably be greatly modified when more exact data become available. The peculiar shaped outcrop of the Saginaw formation in central Arenac County may be evidence of the southwest parallel syncline in the same structural trend as the Ogemaw County anticline. (West Branch anticline).

The information from wells which outline the large Howell structure in Livingston County necessitates several radical changes in formation boundaries in this region, but the interpretation of both the boundaries and the structure is by no means final. It is quite certain, however, that all of the wells in the portions of northern Livingston County and southern Shiawassee County where Coldwater is mapped, really found the Coldwater formation directly beneath the drift. The presence of Marshall formation on both the northeast and southwest flanks of the structure is also fairly certain from scattered deep wells. Many shallow water wells penetrate the bedrock in western Livingston County and eastern Ingham County, and these wells if properly interpreted are an aid to accurate mapping. The faulted zone on the southwest flank is postulated on subsurface evidence and the proofs of the Howell structure are presented in Part II, Chapter IV. The type of faulting is not well understood but it must have been complex and covered a zone of some width. The disturbance may not continue to the surface along its entire mapped trend as there is local evidence of the disconformable overlap of the younger beds. The narrowing of the Marshall formation outcrop on the flanks of the structure is probably due to both the steep dip and formation overlap originating at the time of deposition. The feathering out of the Grand Rapids outcrop to the north of the structure must be due to overlap almost entirely and the reentrant in the "Red Beds" contact in southeastern Gratiot County may have some bearing on the northwestern extension of the Livingston County structure.

CROSS SECTIONS

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

(See figs. 10 and 11). The section A-A' is intended to indicate conditions parallel to the long axis of the synclinal basin; the section B-B' is drawn to represent conditions transverse to the long axis.

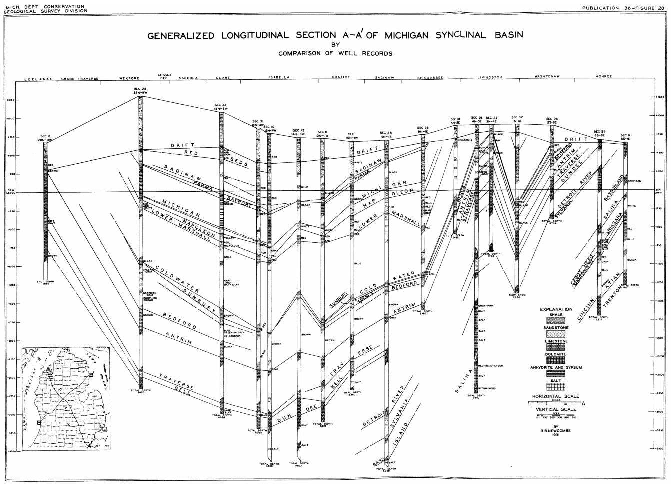


Figure 20. Generalized longitudinal cross section (A-A') of the Michigan synclinal basin.

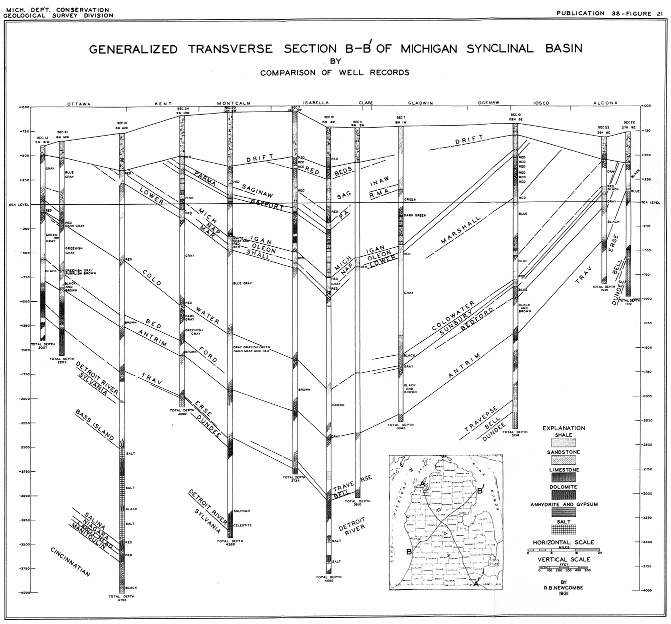


Figure 21. Generalized transverse cross section (B-B') of the Michigan synclinal basin.

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

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

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

REGIONAL STRUCTURE

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

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

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

PERIODS OF FOLDING

The structure of the Trenton (Ordovician) limestone does not conform to Devonian folding, and this can probably be explained by the intervening movements which took place during late Ordovician time. Slight deformation may also have taken place in pre-Sylvania time or at the close of Silurian because the Sylvania is extremely irregular in thickness. Evidently, it was deposited on a very uneven surface, because anomalous water conditions show the presence of individual catchment basins. That there was post-Monroe folding is shown in Monroe County where several gentle folds[4] with dips of 50 to 60 feet per mile do not persist upward into the Dundee strata. These folds seem to trend about north 60° east. Further evidence of the persistence of the lower Devonian movement is the abnormally rapid thickening of the Detroit River beds into the center of the State. Grabau[5] believed that this folding "was incidental to the larger deformation which produced the Michigan basin and the Cincinnati anticline." Post-Dundee warping is suggested by the extensive Middle Devonian[6] unconformity in southwestern Michigan and the apparent relation between buried Dundee land surface relief and lines of structural deformation. In oil field areas where extensive drilling has been carried on, the Dundee is usually thicker on the "highs" than on the "lows." This condition would indicate that folding was in progress at the time that post-Dundee erosion took place and either climatic conditions or later shifting of the axes made the present anticlines correspond more closely to the post-Dundee ridges than the valleys. A small amount of movement probably also occurred at the close of Traverse time, but this seems to have been simply in the nature of northward tilting. The tilting of the basin which took place during early Mississippian time (p. 45) was another important movement of this type. Numerous other gentle Devonian and Mississippian warpings have been shown by means of the thickness maps (See figs. 7, 8; 12-16, 18, 19). The irregularities of the Napoleon land surface and the variations in the lower part of the Michigan series suggest that some rather extensive deformation must have occurred at the end of Marshall time. The deformation seems to have taken place along the general trend of Devonian folding, because the structure of the Napoleon sandstone persists downward through the Devonian rocks. Post-Mississippian folding was much the same, for the Parma sandstone is deposited in the topographic valleys which conform more or less to the structural "highs." Most of the structural features in the Michigan area were probably sharpened, and the earlier movements were revived and accelerated during the Appalachian Revolution when the great eastern mountain chain was built. Since that time there is little evidence of deformation, but some normal faulting might have taken place from the eastern Triassic disturbance which affected a few of the Atlantic coast states. The "Red Beds" of central Michigan may be Triassic instead of Pennsylvanian or Permian as postulated, but this is doubtful. Although the rocks in the eastern part of the United States show scarcely any Tertiary deformation, a final post-Pleistocene uplift on the northeast side of the Michigan Basin is registered by the differential elevation of glacial lake beaches some distance inland from the shores of the present Great Lakes. This differentia] tilting of lake beaches is apparently an index of deformation that is still active.

DISCONFORMITIES

The reservoir conditions of oil producing formations and the local structural features of several oil fields in the Michigan Basin have been greatly influenced by disconformities. A disconformity, unconformity, or sedimentary break is a contact between beds giving evidence of a lapse in deposition. This evidence may indicate simply non-deposition, non-deposition and erosion, or erosion followed by tilting and folding before other beds were laid down. Disconformities have aided in the development of porosity by solution and secondary cementation by infiltration. Known structural conditions have been found changed at depth because of them. The structure developed in the shallow rocks in one field (pp. 142-144) has been shifted or almost entirely eliminated beneath a disconformable sequence of beds. The important sedimentary breaks which have been observed in Michigan are the NIAGARA-SALINA BREAK; the BASS ISLAND-SYLVANIA BREAK; the DETROIT RIVER-DUNDEE BREAK; the DUNDEE-TRAVERSE BREAK; the TRAVERSE-ANTRIM BREAK; the BEREA-COLDWATER BREAK; the MARSHALL-GRAND RAPIDS BREAK; and the GRAND RAPIDS-PARMA BREAK. Other minor interruptions in sedimentary history have not been so well worked out.

NIAGARA-SALINA BREAK

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

BASS ISLAND-SYLVANIA BREAK

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

DETROIT RIVER-DUNDEE BREAK

The Detroit River-Dundee break has also been discussed by Grabau and Sherzer[8] for Monroe and Wayne counties where these beds are widely exposed. This disconformable contact is marked by the zone of the "black water" of the drillers, which is commonly found in wells penetrating the horizon. The water usually possesses a characteristic dark blue or black color and a very strong hydrogen sulflde (H_2S) odor. In most wells, this water horizon is from 80 to 50 feet below the contact of the two formations. The Detroit River series changes in thickness basinward from less than 100 to over 1,060 feet, and the Dundee rests successively on different members of this series.

DUNDEE-TRAVERSE BREAK

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

TRAVERSE-ANTRIM BREAK

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

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

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

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

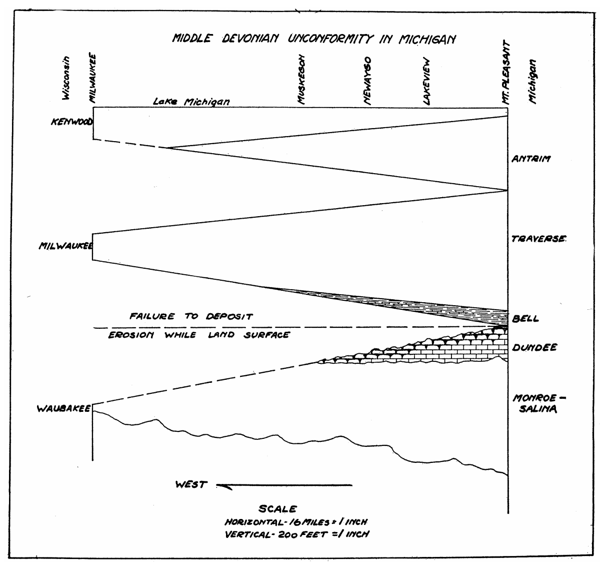


Figure 22. Diagrammatic sketch of the Middle Devonian Unconformity in Western Michigan.

BEREA-COLDWATER BREAK

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

MARSHALL-GRAND RAPIDS BREAK

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

GRAND RAPIDS-PARMA BREAK

The Grand Rapids-Parma break is at the Mississippian-Pennsylvanian contact, which is a zone of considerable erosional relief throughout much of the eastern United States. That a large amount of erosion took place is shown by the fact that locally the Parma sandstone rests directly on the Upper Marshall (Napoleon) sandstone. In these cases, the two are not easily separated in well sections without the aid of samples of the cuttings. The structural significance of this break is that average sized anticlines in the Pennsylvanian rocks do not persist with like characteristics to any depth in the underlying beds. The local deposition of the Parma sandstone in channels has resulted in pockets of gas being trapped, but these occurrences of gas seem very limited in extent. Some of this gas might be in the upper part of the Grand Rapids formation. The only recorded commercial pool of this kind is near Ashley in southeastern Gratiot County. There seems to be no direct relation between this small gas pool and local structure, although it is situated along a general regional "high." The Mississippian-Pennsylvanian disconformity seems to remove almost all direct correspondence between the shallow surface structures and the more deep seated deformation.

However, the Bayport limestone is usually thin or absent on producing structures.

[1]Thomas, W. A., A Study of the Marshall Formation in Michigan: Papers, Michigan Acad. Sci., Arts and Letters, Vol. XIV, pp. 487-498 (1930).

[2]Hall, James, Organic Remains of the Lower Helderberg Group and the Oriskany Sandstone: Nat. Hist. Survey of New York, Pt. IV, Vol. 3, p. 73 (1859).

[3]Blackwelder, Eliot, A Summary of the Orogenic Epochs in the Geologic History of North America: Jour. Geol., Vol. 22, pp. 633-643 (1914).

[4]Grabau, A. W., and Sherzer, W. H., The Monroe Formation of Southern Michigan and Adjoining Regions: Michigan Geol. & Biol. Survey, Pub. 2, Geol. Ser. 1, p. 57 (1910).

[5]Grabau, A. W., Op. cit., p. 58.

[6]Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. America, Vol. 41, pp. 725-738 (1930).

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

[8]Op. cit., pp. 54, 55.

[9]Newcombe, R. B., Middle Devonian Unconformity in Michigan: Bull., Geol. Soc. America, Vol. 41, pp. 734-735 (1930).

[10]Thomas, W. A., Oral communication.

[11]Kirkham, Virgil R. D., Unconformity at the top of the Traverse Formation in Michigan: (Abstract) Bull., Geol. Soc. America, Vol. 43, pp. 136-137 (1931).

[12]Thomas, W. A., A Study of the Marshall Formation in Michigan; Papers, Michigan Acad. Sci., Vol. XIV, pp. 487-498 (1930).

[13]Kirkham, Virgil R. D., Unconformity at the top of the Marshall Formation in Michigan: (Abstract) Bull., Geol. Soc. America, Vol. 43, pp. 137-138 (1931).

[14]Grabau, A. W., Principles of Stratigraphy: A. G. Seller & Company, p. 738 (1913).

Chapter VI. THEORY OF ORIGIN AND GROWTH OF THE MICHIGAN BASIN

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

GENERAL STRUCTURAL FEATURES

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

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

Structurally, the Michigan Basin is not a geosyncline in the true sense of the term, although some characteristics are strikingly similar. It probably was more typically a geosyncline during some of the earlier periods of its formation. Coarse clastic deposits, like conglomerates and thick sandstones, are comparatively scarce, unless they are present in the deeply buried Cambrian or pre-Cambrian sedimentary series. Assuming a normal thickening of these deeper rocks into the center of the State, the maximum thickness of all Paleozoic deposits would amount to between 12,000 and 15,000 feet.

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

ORIGIN OF THE SYNCLINAL BASIN

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

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

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

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

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

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

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

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

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

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

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

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

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

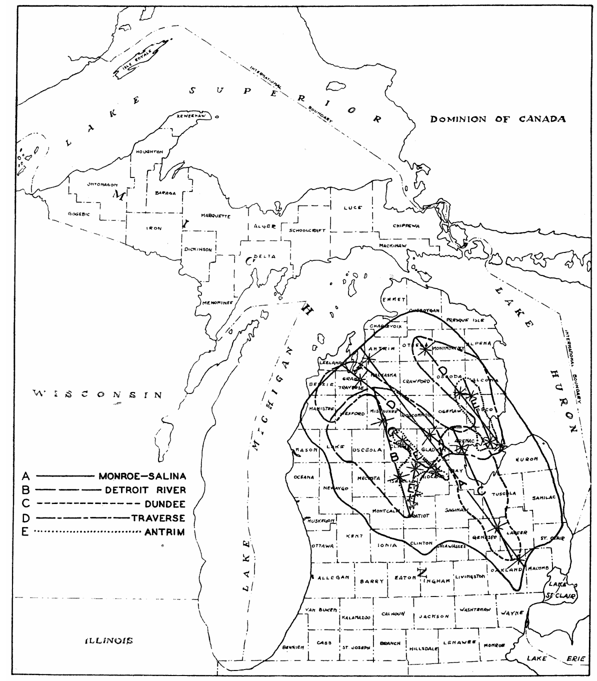
This relation can be carried still farther in comparing the minor cross effects of the Keweenawan and Appalachian movements. The trend of folding in the Michigan Basin seems to change in direction from northwest-southeast to more nearly north-south in the northern part of the southern peninsula. The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

The adoption of the isopachous or equal thickness maps, used previously in the discussion of the evolution of the synclinal basin to show the depositional as well as the structural history of the province, is patterned somewhat after the comprehensive study made by Cheney[21] on the history of Carboniferous sediments of the Mid-Continent oil fields. Structurally, the Michigan synclinal basin is a much more limited area and includes one structural province rather than several connected structural provinces. The isopach contour interval used for Michigan has been either 50 or 100 feet of thickness and, whenever possible, the figures have been compiled accurately for an individual formation. The results and the important deductions are similar to those of Cheney in the entirely remote Mid-Continent area, although no attempt is made to explain the causes for shifting of the basin by the transfer[22] of the subcrustal plastic material as did Cheney. An effort has been made, however, to indicate the origin of stresses causing the movement and consequent shifting of the location and elongated direction of individual troughs in the sinking sedimentary basin. It seems preferable in the Michigan region to explain the differential subsidence or downwarping of the basin by the change in predominant directions from which tangential stresses were applied through different periods, rather than simply by the shifting of subcrustal material. The transmission of tangential stresses by strong or competent beds may not have been of the order that is commonly understood to cause folding in connection with mountain building. The conception is rather that built up stresses were transmitted horizontally through the deeper seated rocks (not in the zone of plastic flow) and that the resulting strains were resolved into components and released by movements along preexisting lines or zones of weakness, which had been caused during earlier times of grand deformation. It would seem that the transfer of plastic material is actually an effect rather than a cause, and that the real cause for the shifting of downwarped areas in an individual sedimentary basin are the strains which exist within the crust of the earth. The source of these strains would be the accumulating pressures which later give rise to the major mountain making disturbances in the areas of greatest sinking.

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

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

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



DEVONIAN

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

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

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

Michigan. A marked shifting of the direction of the components of down-warping in the Michigan basin and the accentuation of the Logansport "sag" in northern Indiana took place at this time.

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

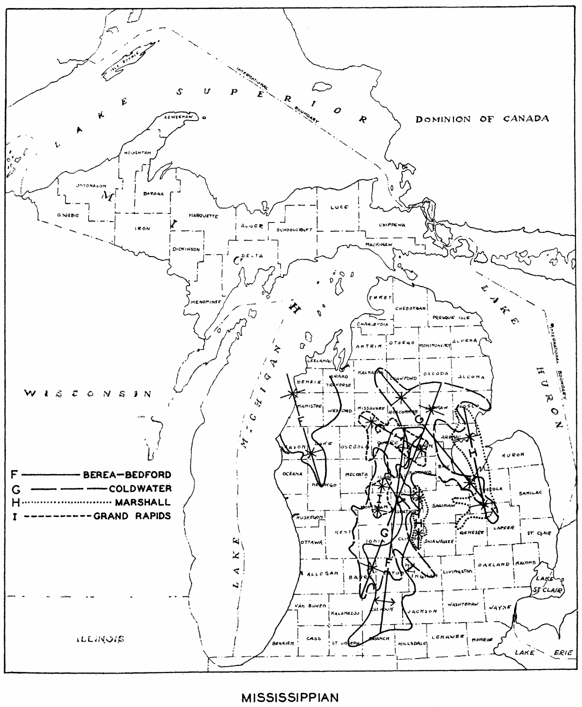


Figure 24. Map showing the axes and areal extent of the regions of tilting and greatest downwarping in Michigan in Mississippian time.

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

The similarity of folding in the southern peninsula with well known structural features like the LaSalle anticline in Illinois is particularly striking. The Howell structure (see plate III) is similar in size, trend, and basinward steep dip to the LaSalle anticline and, although the two are far removed, some sort of genetic connection is suggested by this comparison. The lines of weakness originating in Keweenawan in the Michigan synclinal basin may have been affected by the Devonian movement which developed numerous faults on the northeast side of the Ozark dome. According to Keith[30], the same movement formed gentle anticlines and synclines in northern Illinois, Wisconsin, and Iowa, which are slightly unconformable with the overlying Mississippian beds. Similar movements probably took place in the contiguous Michigan Basin. If this is true, then the principal folding which determined the structures in the middle Devonian rocks of the State must have occurred during the later part of the Devonian epoch, and subsequent deformation simply modified or accentuated the results of this movement.

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

FOLDING IN THE SYNCLINAL BASIN

CONTROLLING FEATURES OF THE FOLDING

The recognition of folding in the Michigan synclinal basin dates back to the time of the earliest geologists who made observations in the region. In 1865, Alexander

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

The idea that the principal forces causing the folding of the sedimentary rocks of southern Michigan had been those forces which acted vertically[33] prevailed for some time. The early structures discovered in Michigan seemed to pitch toward the central part of the State, and the prevailing notion that the "basin" was almost circular afforded evidence for this theory. The results of the intensive drilling from 1925 to the present time have revealed conditions indicating that this view of the importance of vertical structural causes will have to be somewhat revised. It seems that Hedberg[34] has concluded, "while low ill-defined folds of gentle dip may frequently be due to settling, it must be rarely and only under special conditions that large, well-defined, surface structures may be attributed solely to compaction over topographic features separated from them by thousands of feet of rock." The causey of folding in Michigan are now thought to have been complex and varied with many controlling elements effective in different parts of the sedimentary basin.

SECONDARY CAUSES OF FOLDING

The original causes of folding in Michigan have been outlined previously in discussing the development of the structure of the synclinal basin (p. 59). In addition to the great regional stresses, a number of other causes of deformation must be considered. Rotational shear due to faulting in the pre-Cambrian basement rocks, vertical compaction over buried hills, and the strains set up in overlying beds by the solution of underlying weaker, more soluble rocks are other possible sources of folding stresses. Probably, these forces were active either together or separately at different times.

DEEP SEATED FAULTING

The presence of a somewhat deeply buried regular fault system in the pre-Cambrian rocks beneath the area is practically certain. Thwaites[35] has recently mapped the major subsurface faults of eastern Wisconsin and described these faults in some detail. Faulting is known to be present in the Paleozoic of the western part of the Ontario[36] peninsula adjoining Michigan, and Carman[37] has definitely proved the faulted nature of the west flank of the Cincinnati anticline in northwestern Ohio. The Howell structure in Livingston County, Michigan, is faulted on the steep southwest flank, although the details of this zone of faulting have not been well worked out. The uniform, sharp, west dip of nearly all structures in the central part of the State strongly suggests deep seated faulting as a cause for the location of these structures. The en echelon or staggered arrangement of local domes in Midland and Isabella counties indicates (see pls. IV and V) the effects of shearing due to movements along deeply buried faults in the basement complex, as previously demonstrated by Chamberlin[38] and Thorn[39] for central Montana and Fath[40] for certain localities in northeastern Oklahoma and southeastern Kansas. The more likely method by which shearing took place was through differential movement along the two sides of a fault plane or zone, giving rise to torsional warping in the surficial rocks. This type of deformation was first illustrated by Mead[41] with a thick piece of rubber which was coated with paraffin and then twisted to show the effects of torsional movement. The same results may be obtained by simply twisting an ordinary hard rubber eraser. Sherrill[42] favored this type of movement, supplemented by a broad uplift, to explain the origin of the en echelon faults in north central Oklahoma, formerly studied by Fath[43] and Foley[44]. Aldrich[45] used this same explanation in accounting for the regular, systematic cross faults in the Gogebic Iron Range of Wisconsin and Michigan. Link[46] has recently suggested in supporting a former paper by McCoy[47] that faults of this type can be commenced by feeble tensile stresses which arise when sediments settle irregularly over a low arch or ridge. The incipient en echelon fissures thus formed develop into normal faults by later adjustment. A theory similar to that propounded by Sherrill for Oklahoma and Aldrich for Wisconsin and stated more generally by Cheney[48] for the entire Mid-Continent region, seems to explain the en echelon folding in central Michigan. Cheney states that "en echelon folding and faulting may be the natural result of the local features along an older line of weakness being accentuated by potent forces coming from a new direction." The idea thus expressed is in line with the statement of Bailey Willis[49] that "the orientation of shear planes in any but a homogeneous body is governed by lines of weakness." The interior of the "basin" was very likely subject to unequal subsidence, and the recurrent tilting movements caused by pressures from various directions completed the shearing effects along deep seated faults which resulted in the en echelon arrangement of the folds. The faults in the crystalline basement rocks were probably not the direct cause of deformation, but the "rudders" which determined the localization of nearly all movements throughout geologic time in lower Michigan. Abnormal initial dips and unequal sedimentation which Willis[50] considers so important in the commencement of folding would normally be concentrated along these zones by previous deep seated displacements. The perfection of pattern shown by Hobbs[51] to be the usual condition for nearly all earth features is clearly illustrated by the directions of folding in Michigan and the regular interval between parallel zones of folding. (See pl. III). These relations constitute further evidence of the control of pre-Cambrian basement faults upon the directions of folding in the Michigan Basin.

VERTICAL COMPACTION

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

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

SOLUTION

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

ALINEMENT OF FOLDS

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

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

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

MODIFYING STRUCTURAL FACTORS

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

FAULTING

Faults with large displacements have not been observed in the surface rocks of the southern peninsula of Michigan, although the results of small movements have been found in several localities[70]. The presence of larger faults is indicated by the distribution of the rocks in Presque Isle County and, according to Hindshaw[71] these fault zones can be traced for some distance. Faulting has been recognized in several coal mines and displacements of from 50 to 100 feet have been reported.

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

SOLUTION

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

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

EXPANSION

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

REEFS

Coral reefs are strongly developed in the Silurian and Devonian rocks of the State and bring about local structural irregularities because of unequal deposition of sediment on their uneven surfaces. Beds when consolidating naturally conform to the irregularities caused by the more compact masses of fossils such as *Stromatopora*, *Prismatophyllum* (more commonly called *Acervularia*) and other types of reef-forming organisms. The size of the individual areas involved in this kind of deformation is relatively small, although some of the Traverse reefs of northern Michigan and the Niagaran reef mounds which are exposed around the margin of the synclinal basin have remarkably steep dips over a short distance. The coral reef structures are very seldom reflected upward to any degree and no oil fields that can be ascribed to them alone have been found in Michigan. The principal effect of these structural features is the influence which they have on local porosity in an oil producing area. This kind of porosity may be original in part but is mostly developed by the unequal solution and possibly some dolomitization of the reefs. The local original and secondary porosity of reefs explains erratic oil production in the fields of Michigan where much of the oil is obtained from the Traverse formation. This same condition of local structure and porosity accounts for the frequent, unusual occurrence of noteworthy oil shows in regions that are structurally "low" or synclinal. Many unsuccessful drilling operations in Michigan have been prompted by these "shows" of oil and gas from locally porous zones of coral reefs in the upper part of the Traverse formation.

PERSISTENCE OF STRUCTURAL TREND LINES

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

ANGULARITY OF SHORE FEATURES

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

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

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

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

ELONGATION OF LAKES FRINGING LAKE MICHIGAN SHORE

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

DRAINAGE NETWORK PATTERN

The drainage network and small physiographic features in a glaciated area are usually very haphazard[80] in pattern. Locally, this condition holds true in Michigan, but the diagonal pattern of physiographic features in the State was long ago recognized by Winchell[81]. This diagonal arrangement is illustrated remarkably well in maps showing the areas of the various drainage systems by means of different colors. The principal divide takes a zig-zag course north and south through the southern peninsula with changes in direction which closely correspond to some of the known structures in the underlying rocks. The Grand River-Saginaw River systems divide through the central part of the State along a line strikingly parallel to the northwest prolongation of the Howell structure although this parallelism is imperfect in detail.

GLACIAL FEATURES

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

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

PHYSIOGRAPHICAL FEATURES OF THE BEDROCK SURFACE

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

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

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

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

MINING DISTRICTS OF NORTHERN MICHIGAN

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

HINGE LINES OF POST-GLACIAL UPLIFT

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

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

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

SUMMARY AND CONCLUSIONS

The features of deposition and structure of the Michigan Basin, as worked out from comparison of drill records, tend to place it in a new category. Although embodying many characteristics of a typical sedimentary basin, the region has acted structurally like a geosynclinal area throughout many periods of geological history. The basin has been progressively downwarped. The beds thicken markedly into the central area, the outline of the course of the outcropping rocks is roughly oval, and the minor structures are mostly parallel to the longer diameter of the downwarp. These are features of geosynclines. On the other hand, the basin has been isolated and subjected to periods of evaporation at various times. The absence of thick series of coarse clastic sediments is conspicuous in the post-Cambrian rock column of Michigan. These conditions are more characteristic of a major structural basin.

The origin of the lower Michigan synclinal basin is probably related to the Keweenawan disturbance which formed the Lake Superior geosyncline and caused the Keweenaw fault. The structural relationships of the province suggest that the principal source of the movement which originally warped the lower Michigan synclinal basin came from the northeast. These earth forces acting against the Wisconsin land mass and its southeast extension in the region of the present Wabash arch caused and developed the great downwarp in

Michigan, which is comparable in many respects to the Appalachian geosyncline of a much later mountain making disturbance. The uplift of the positive element known as the "Wisconsin island" probably was going on at the same time as this downward movement.

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

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

Oil and gas accumulation in the local domes has been somewhat controlled by the important disconformities. The principal oil producing strata in Michigan are limestones or dolomites and the porosity in these reservoir beds is largely the result of solution and leaching, both before and after the burial of' the rocks. The porous zones are, therefore, concentrated near places in the stratigraphic section where breaks in deposition have occurred. The disconformities have also aided in modifying deformation and trapping pools of oil and gas. Unequal settling over hills or ridges beneath a disconformable contact has both changed the location and amount of folding. Thickening of the beds toward the central area of the "basin" has caused the alteration of structure at depth. Oil and gas have been locally trapped because overlapping and lenticular sediments prevented lateral migration. Porosity beneath old buried erosion surfaces often varies laterally because deep valleys have cut out the beds most susceptible to solution. These factors have had a very effective control on the accumulation of petroleum in Michigan.

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

---

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

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

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

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

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

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

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

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

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

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

[10]Butler, B. S., and Burbank, W. S., and Others, Copper Deposits of Michigan: U. S. Geol. Survey, Prof. Paper No. 144, pp. XI and XII (1929).

[11]Butler, B. S., and Burbank, W. S., and others, Op. cit., p. 51.

[12]Collins, W. H., North Shore of Lake Huron: Canada Dept. Mines, Canada Geol. Survey, Mem. 143, p. 106 (1925).

[13]Op. cit., pp. 50, 51, 52, 53.

[14]Lane, A. C., Keweenaw Fault: Bull. Geol. Soc. America, Vol. 27, p. 93 (1916).

[15]Aldrich, H. R., Op. cit., p. 123.

[16]Op. cit., page 623.

[17]Mead, M. J., The Mechanics of Geologic Structures: Jour. Geol., Vol. 28, pp. 505-523 (1925).

[18]Price, Paul, The Appalachian Structural Front: Jour. Geol., Vol. 39, No 1, p. 40 (1931)

[19]Keith, Arthur, Outlines of Appalachian Structure: Bull. Geol. Soc. America, Vol. 34, pp. 313, 326 (1923).

[20]Chamberlin, T. C., Geology of Wisconsin: Wisconsin Geol. Survey, Vol. 4, PI. 8 (1882).

Thwaites, F. T., The Buried pre-Cambrian of Wisconsin: Bull. Geol. Soc. America, Vol.

[21]Cheney, M. G., History of the Carboniferous Sediments of the Mid-Continent Oil Fields: Bull. Am. Assoc. Petroleum Geologists, Vol. 13, No. 6, pp. 557-594 (1929)

[22]Cheney, M. G., Op. cit., pp. 569, 588-594.

[23]Cheney, M. G., Op. cit., p. 588.

[24]Keith, Arthur, Structural Symmetry in North America: Bull,, Geol. Soc, America, Vol. 39, p. 330 (1928).

[25]Cheney, M. G., Op. cit., p. 586.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

_____, The Occurrence of Oil and Gas in Michigan: Michigan Geol. & Biol. Survey, Pub. 14, Geol. Ser. 11, pp. 50-246 (1912).

_____, Oil Development in Michigan and the Anticline at Seul Choix Point: Michigan Acad. Sci., Papers, Vol. 1, pp. 269-272 (1921). Published in 1923.

_____, Natural Gas Possibilities in Michigan: Address delivered at 39th Ann. Meeting and published by Michigan Gas Association—Mackinac Island (July 1, 1931).

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

_____, Geological Factors affecting the search for Oil and Gas in Michigan with results of drilling: Nat. Pet. News, pp. 71-76 (Sept. 6, 1922).

_____, Folds Resulting from Vertically Acting Forces: Jour. Geology, Vol. 31, pp. 336-343 (1923).

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[64]Thwaites, F. T., Buried Pre-Cambrian of Wisconsin: Geol. Soc. America, Bull., Vol. 42, pp. 739, 740 (1931).

[65]Collins, W. H., North Shore of Lake Huron: Canada Dept. of Mines, Canada Geol Survey, Mem. 143, pp. 9, 10 (1925).

[66]Ehlers, G. M., An Ordovician Reef on Sulphur Island, Lake Huron: Papers, Michigan Acad. Sci., Arts and Letters, Vol. 4, pp. 425-429 (1925)

[67]Robinson, W. I., Op. cit., p. 340.

[68]Hobbs, W. H., Repeating Patterns in the Relief and in the Structure of the Land: Bull., Geol. Soc. America, Vol. 22, pp. 148-176 (1911).

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

[70]Sherzer, W. H., The Detroit Folio No. 205: U. S. Geol. Survey Atlas, Field Addition,

Pohl, E. R., The Middle Devonian Traverse Group of Rocks in Michigan: A Summary of Existing Knowledge: U. S. Nat. Mus., Proc., Vol. 76, Art. 14, pp. 18, 19 (1929).

Personal observation in Sanilac and Wayne counties.

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

[72]Schneider, P. F., A Geologic Fault at Jamesville near Syracuse, New York: Am Jour. Sci., Vol. 3, pp. 458-459 (1897).

_____, The Marcellus Fault: Onondaga Historical Assoc. Sci., Ser. No. 2, pp. 1-7 (1899).

_____, Preliminary Note on some Overthrust Faults in Central New York: Am. Jour. Sci., Vol. 20, pp. 308-312 (1905).

Gwynne, Chas. S., A Study of the Structural Features south of the Helderberg Escarpment in the Vicinity of Syracuse, New York: Master of Science Thesis, Syracuse Univ. Library, Syracuse, New York.

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

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

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

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

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

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

[79]Cook, C. W., The Influence of Joints in the Formation of the Islands at the Western End of Lake Erie: Papers, Michigan Acad. Sci., Arts and Letters, Vol. 5, pp. 243-251 (1925).

[80]Hobbs, W. H., Earth Features and Their Meaning: The MacMillan Company, p. 309 (1912).

[81]Winchell, Alexander, The Diagonal System in the Physical Features of Michigan: Am Jour. Sci., 3d Ser., Vol. 6, pp. 36-40 (1873).

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

[83]Op. cit, p. 255.

[84]Idem, pp. 255-261.

[85]Leverett, Frank and Taylor F. B., The Pleistocene of Indiana and Michigan and the History of the Great Lakes: U. S. Geol. Survey, Mon. 53, pp. 502-518, Map, p. 503 (1915).

[86]Hobbs, W. H., The Late Glacial and post-Glacial Uplift of the Michigan Basin: Michigan Geol. & Biol. Survey, Pub. 5, Geol. Ser. 3, pp. 11-68, Map, p. 35 (1910).

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