OIL AND GAS FIELDS

OF

MICHIGAN

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

GEOLOGICAL SURVEY DIVISION
R. A. Smith, State Geologist

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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

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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 R. 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 has 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.

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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 preglacial 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 is 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

OIL AND GAS FIELDS OF MICHIGAN

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By Robert B. Newcombe

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

The 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 and C. Harold Riggs. O. F. Poindexter examined many of the well cuttings and F. R. 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 R. 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. McReavy 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.

[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).

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 seas which somewhat resembled our present Great Lakes. In the formation of these rocks, the waves worked on the shores of the land masses

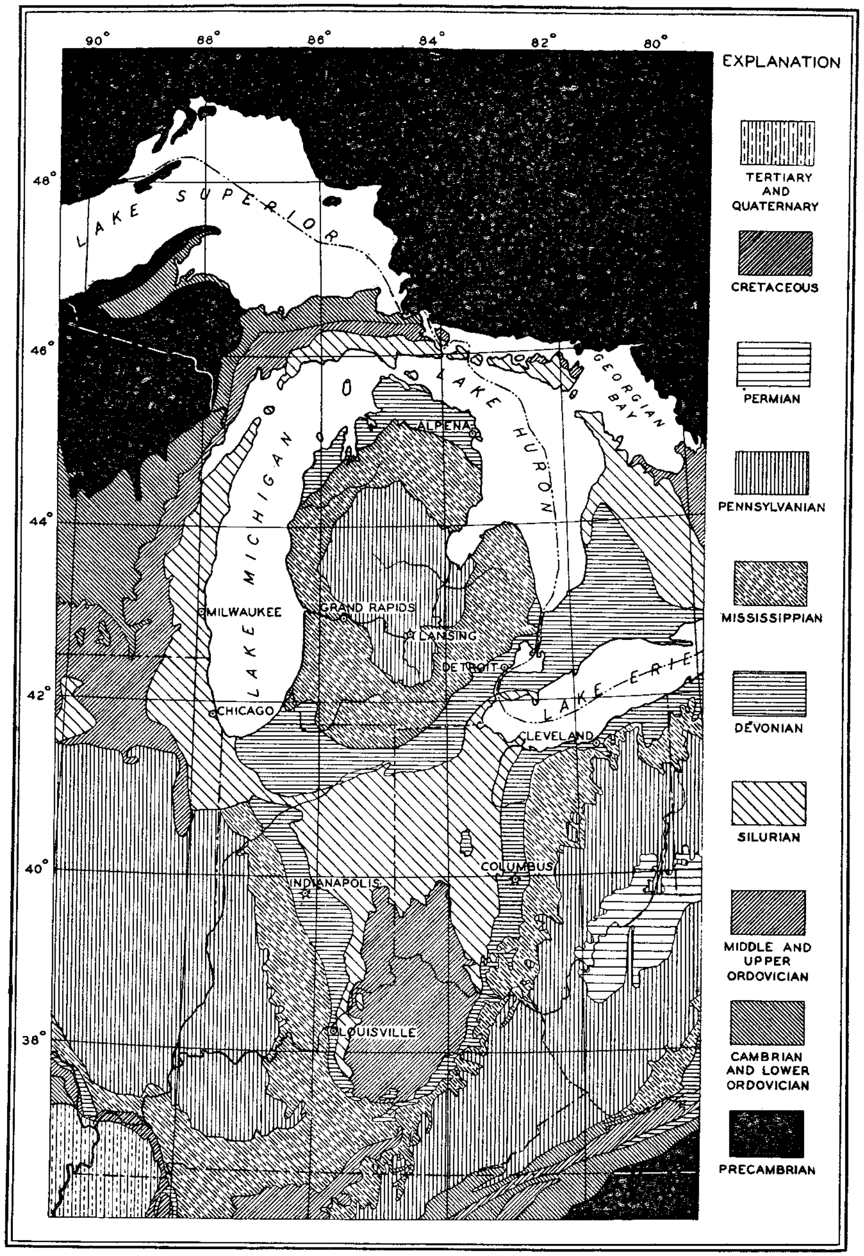
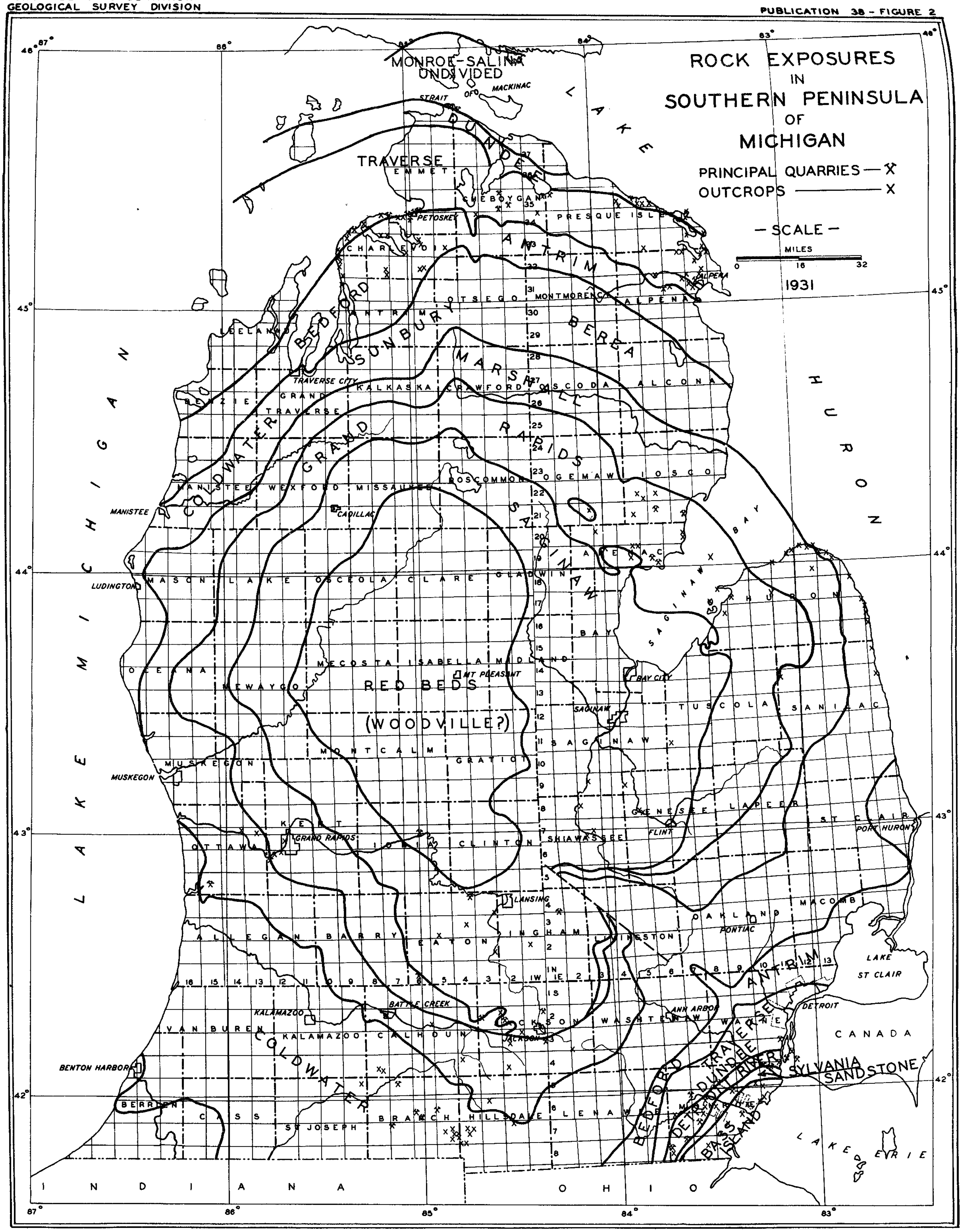


Figure 1. Geological map showing the area which comprises the Michigan Basin province. (After Bailey Willis with revisions for Michigan).

MICH. DEPT. CONSERVATION
GEOLOGICAL SURVEY DIVISION
PUBLICATION 38 – FIGURE 2


ROCK EXPOSURES
IN
SOUTHERN PENINSULA
OF
MICHIGAN
PRINCIPAL QUARRIES — X
OUTCROPS — X
— SCALE —
MILES
0
16
32
1931
MONROE-SALINA
UNDIVIDED
DUNDEE
TRAVERSE
ANTRIM
BEDFORD
SUNBURY
BEREA
MARSHALL
COLDWATER
GRAND RAPIDS
SAGINAW
RED BEDS
(WOODVILLE?)
SYLVANIA
SANDSTONE
DETROIT RIVER
BASS ISLAND
LAKE MICHIGAN
LAKE HURON
LAKE ERIE
LAKE ST CLAIR
STRAIT OF MACKINAC
SAGINAW BAY
CANADA
INDIANA
OHIO
MANISTEE
LUDINGTON
MUSKEGON
BENTON HARBOR
PETOSKEY
TRAVERSE CITY
CADILLAC
ALPENA
MT PLEASANT
BAY CITY
SAGINAW
FLINT
PORT HURON
GRAND RAPIDS
LANSING
PONTIAC
DETROIT
ANN ARBOR
JACKSON
BATTLE CREEK
KALAMAZOO
EMMET
CHEBOYGAN
PRESQUE ISLE
CHARLEVOIX
OTSEGO
MONTMORENCY
ALPENA
ANTRIM
LEELANAU
BENZIE
GRAND TRAVERSE
KALKASKA
CRAWFORD
OSCODA
ALCONA
MANISTEE
WEXFORD
MISSAUKEE
ROSCOMMON
OGEMAW
IOSCO
ARENAC
MASON
LAKE
OSCEOLA
CLARE
GLADWIN
HURON
OCEANA
NEWAYGO
MECOSTA
ISABELLA
MIDLAND
BAY
TUSCOLA
SANILAC
MUSKEGON
MONTCALM
GRATIOT
SAGINAW
GENESEE
LAPEER
ST CLAIR
OTTAWA
KENT
IONIA
CLINTON
SHIAWASSEE
OAKLAND
MACOMB
ALLEGAN
BARRY
EATON
INGHAM
LIVINGSTON
VAN BUREN
KALAMAZOO
CALHOUN
JACKSON
WASHTENAW
WAYNE
BERRIEN
CASS
ST JOSEPH
BRANCH
HILLSDALE
LENAWEE
MONROE
87°
86°
85°
84°
83°
46°
45°
44°
43°
42°

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 some 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

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

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."

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."

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. III) 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.

[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).

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.

[6] Rominger, Carl, Geology of the Lower Peninsula: Geol. Survey of Michigan, Vol. III, Pt. 1, pp. 21, 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.

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 deposi-

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[1] Fenneman, N. M., Physiographic Divisions of the United States: Annals of Assoc. of Am. Geog., Vol. VI, Pl. 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).

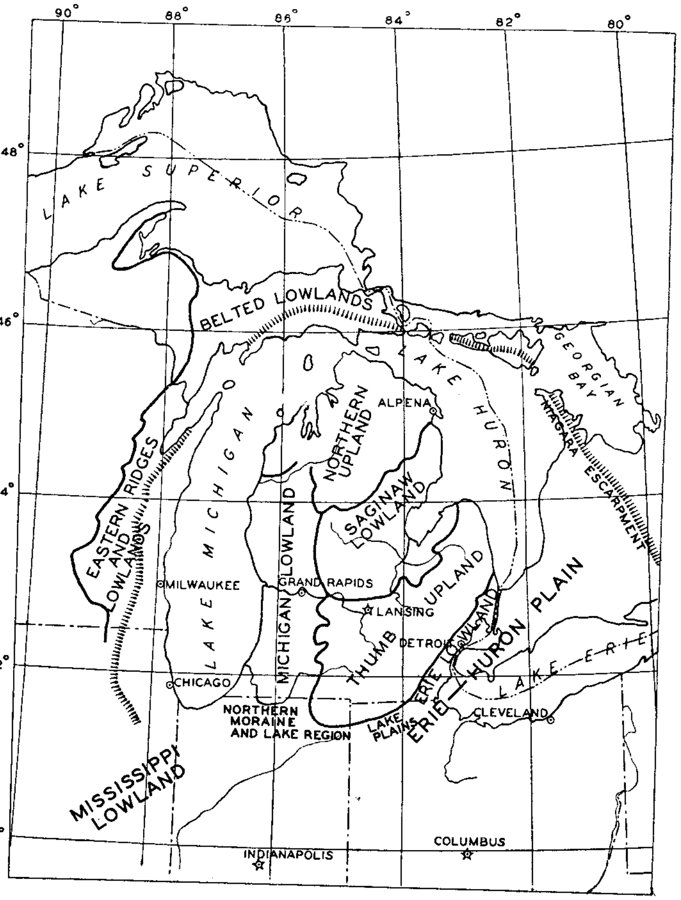

Figure 3. Physiographic divisions and subdivisions of the region included by the Michigan Basin.

tion. 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 1,300 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

[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.

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.

[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).

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

[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).

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.

[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

[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).

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

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[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).

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.

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[6] Copper Deposits of Michigan: Op. cit., p. 18.
[7] Houghton, Douglass, Michigan Senate Document No. 7, pp. 74-75 (1840).

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" (Tenn-essean)	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	"270-800"
			Manistique	Cordell		Limestone, dolomite, white, blue, gray, buff, cherty, shaly	
				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		
	Lower	Chazyan	Stones River (?)		Limestone, shaly	"0-30"
		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	"0-250"
		Ozarkian	Hermansville			
Cambrian		St. Croixan	Lake Superior	Munising	Sandstone, red, pink, white, variegated, cross bedded	"0-1500"
				Jacobsville		

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 Resser[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.

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.

[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).

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.

Many red erratic "marl" layers are found in the Eau Claire near Milwaukee where it represents the uppermost formation of Cambrian age.

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.

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,

[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).

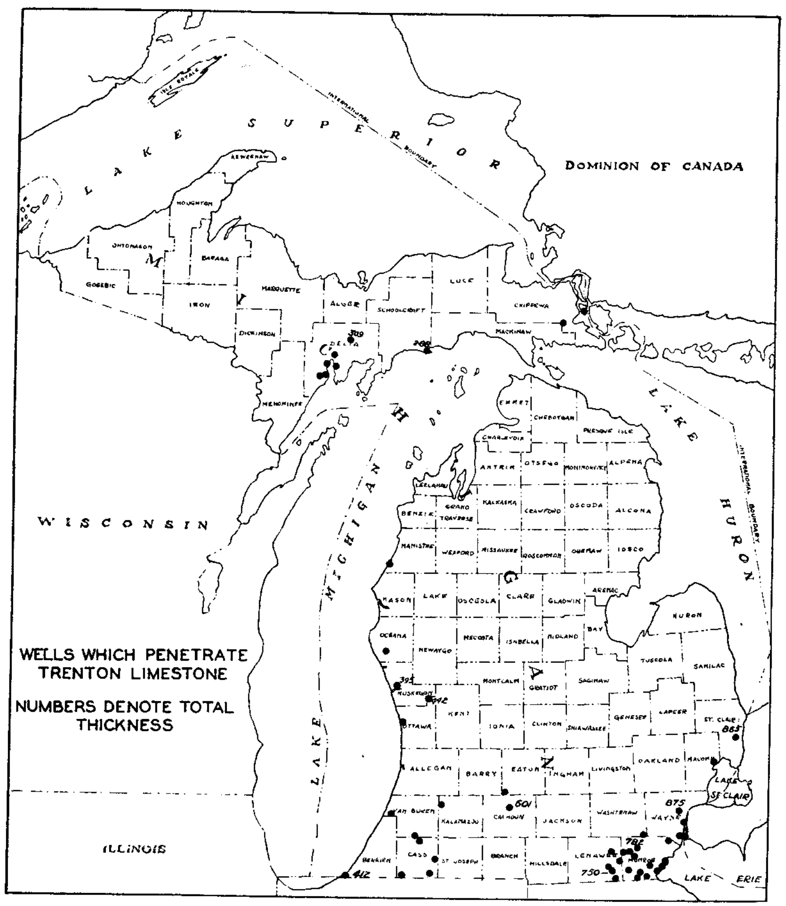

Figure 4. Wells which have penetrated Trenton limestone in Michigan. (Numbers indicate the thickness of the Trenton).

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

[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).

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"				
	Big Buffalo	St. Peter		St. Peter	St. Peter	St. Peter	St. Peter
(Lower)	(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
	(Ozarkian of E. O. Ulrich)	Hermansville			New Richmond	"New Richmond"	
					Oneota	Oneota	Oneota
							Madison Mendota, Devil's Lake

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.

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

[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).

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 interbedded 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 Rockwood (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

[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.

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.

[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).

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)	Engadine	Guelph	Cedarville Springfield	Huntington (Including New Corydon)	Port Byron	Guelph	Guelph (?)
		Lockport			Racine	Racine	Lockport
	Manistique Cordell Schoolcraft		Niagara	Liston Creek	Waukesha	Waukesha; Upper coral beds	
	Rochester (?)	Rochester		Mississinewa	Joliet	Lower coral beds	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

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."

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 Fiborn 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

[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.

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 Cumings[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

[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).

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

[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).

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. Newberry[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).

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[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).

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

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[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).

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.

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

[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).

TABLE V.—*Devonian*

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

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

[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).

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

[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.

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

[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).

(Footnote 79 continued on page 45.)

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 faunal 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

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.

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]

[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.

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 crystalliza-

[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.

tion 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 microfauna from well cuttings and a much larger number of accurate sections than are now available from present well records.

[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.

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."

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

[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).

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	Michigan		Mitchell	St. Louis	
				Salem	Spergen	
				Harrodsburg Upper, Lower	Warsaw	
Waverlian (Early)	Osagian	Marshall: Upper (Napoleon), Lower	Logan, Black Hand	Borden "Knobstone": 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)

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, Robinson[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

[101] Robinson, 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).

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).

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.

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 Ohio 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 Coldwater 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.

[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.