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MISSISSIPPIAN COLDWATER FORMATION
OF THE MICHIGAN BASIN

By

Pham Kim Chung

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ABSTRACT

MISSISSIPPIAN COLDWATER FORMATION
OF THE MICHIGAN BASIN

By

Pham Kim Chung

The stratigraphic study of the Coldwater Formation (Early Mississippian) of Michigan has been undertaken with the objective to interpret the nature of lateral changes in lithology; to gather information adding to a better understanding of the direction, as well as the nature, of the source; to present a better picture of Early Mississippian paleogeography; and to relate facies to the implied sedimentary environments and to Early Mississippian paleostructural development.

Detailed structure contour and isopach maps were constructed employing about 775 control wells. The construction of cross-sections and lithofacies maps resulted from a microscopic observation of about 180 well cutting sets.

The results show that the eastward thickening of the formation relates to the proximity of an eastern source and the subsidence of the major depositional center

in eastern Michigan. A secondary basin near the present center in central Southern Michigan is inferred to have effected the sedimentary conditions at time of the deposition. The Coldwater sediments are mostly marine. The eastern facies is sandy consisting of up to a maximum of 40 percent sandstone; the western facies consists of mostly shale and some impure carbonates. The X-ray diffraction method was used to determine the clay mineral composition of the Coldwater sediments. Kaolinite, illite and chlorite mainly form the clay mineral suite, with a markedly higher proportion of kaolinite in the coarser clastics. The sediments were derived largely from the Laurentian Highlands. They were formed by a delta in the area of the Findlay Arch, and the Coldwater shale in Michigan is considered a pro-delta. The nearshore sea in eastern Michigan was shallower and less saline than in the offshore area in the west. The sourco area is believed to have consisted of granitic and/or gneissic rocks weathering under a warm climate and high rainfall.

The Upper Devonian-Lower Mississippian sediments in Michigan represent a succession of two transgressive-regressive "cycles"--the Antrim-Bedford-Berea cycle and the Sunbury-Coldwater-Marshall cycle--each characterized by a lower black shale unit followed by a gray shale and a sandstone. Coldwater deposition starts the regressive phase in Michigan and is a prelude to active evolutionary changes in the Michigan Basin during the Marshall and up to at least Middle Mississippian (Meramecan) time.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

INTRODUCTION

Scope and Purpose

The Coldwater formation (Early Mississippian) is a thick sequence of shale in the Michigan Basin. Because of a lack of economic interest, this formation has not received much attention from investigators. Most studies of the Coldwater shale to date have been either general or based on fewer well samples than available today; or have been of restricted geographic scale.

This report presents the results of a stratigraphic study of this formation. The primary purposes for this study are to interpret more precisely the nature of lateral gradation within the Basin; to gather information adding to a better understanding of the likely nature and direction of the source; to contribute to the understanding of Early Mississippian paleogeography, and to relate facies to the implied sedimentary environments and to Early Mississippian paleostructural development.

Previous Work

Prior to the naming of the Coldwater Formation by Lane in 1893, rocks younger than Traverse and older than Marshall had been described and considered rock equivalents to at least the present formation designated Coldwater.

During the early times, geologists generally mentioned a somewhat argillaceous strata lying between coarse clastic rocks above and black shales below. Winchell (1861) assigned these argillaceous strata to the Huron group with a total thickness of 210 feet based on outcrop measurings. Four years later, Winchell reviewed the boring data and gave thickness of this group as 500-600 feet.

The Huron group was believed by Winchell (1869) to correlate with the Portage group of New York and to consist of three lithologic types, shown in descending order:

<u>Huron Group</u>	Feet
- Argillaceous shales and flagstones . . .	500
- Green arenaceous shale	25
- Black bituminous shales (Genesee shale) .	25

The bluish shale containing of "kidney iron ore" in Branch County was considered the upper part of that Huron Group. Lane (1893) named this shale the Coldwater Formation. He stated:

> This formation, which has numerous outcrops in Branch and Hillsdale Counties, and is well exposed by the Coldwater River, from which I have named it, . . . It consists of light colored greenish or bluish, sometimes darker, shales, growing dandier toward the top and gradually passing into the Marshall.

In following years, most of the literature dealing with the Coldwater Shale were very brief and cursory.

In 1900, in a report on Huron County, Lane discussed the geology of the Huron Group based on exposures and well data and also compiled valuable information on paleontology. Cooper (1900) in the same report correlated the Coldwater to the Cuyahoga and the lower part of Logan Formation in Ohio.

Newcombe (1933) described the general lithology and historical and economic geology of the Michigan Basin. This report included a thickness contour map of the Coldwater Shale showing the outline of the depositional basin with two separate troughs trending northeast (major) and northwest (minor).

Hale (1941) studied the lower Mississippian of western Michigan making special reference to the carbonate facies of that area.

Monnett (1948), in a study principally on the Marshall sandstone, recognized the Coldwater as occurring in an eastern and western facies based largely on the quartz content.

Cohee (1951) described the general geology of the upper Devonian and Carboniferous including the Coldwater and recognized the problem of the Coldwater-Marshall contact in eastern Michigan.

Wooten (1951) studied the Coldwater in the area of the type locality, and recognized the difficulty of the correlation of the surface exposures and the subsurface sections in Branch County.

McGregor (1954) made a Michigan regional study of the Upper Devonian and Lower Mississippian rocks which he divided into lithologic groups, the Coldwater Shale and Marshall Sandstone forming one group. Lithofacies and isopach maps were constructed for the combined units. Though a helpful background reference, the stratigraphy of the Coldwater is not singled out and is somewhat lost in his interpretation of the combined formations handled as a unit.

LeMone (1964) touched on the Coldwater shale in a study directed mostly at the Antrim and Ellsworth Formations but did show the Coldwater in a regional isopach map for Michigan, and structure and isopach maps for Bay County, Michigan.

Methods of Investigation

Except for a few outcrops found in Branch, Hillsdale, Calhoun, Huron and Sanilac Counties, the formation is unexposed within the Basin. Most of the information obtained in this study is from subsurface data. Examination of samples were made by binocular microscope from well cuttings of the Michigan State University Department of Geology, no well cores being available. This technique was considered appropriate for the semi-quantitative results sought regarding sand percentages and clastic ratios. Sand sizes were measured by a micrometer occular and grains above 1/16 mm. were placed in the sand grade size with silt placed with the clay-sized fraction. Where a mixed lithology, as sandy shale, was encountered, the percentages of sand and clay for the sample interval were estimated and placed with their respective grade size categories.

A few cross-sections were constructed for correlation purposes as well as to demonstrate the facies changes. Regional isopach and structure contour maps were constructed employing about 750 control wells.

Several composite samples chosen from several wells representing basinal spacing were X-rayed to determine the clay mineral suites as well as to check any significant vertical and lateral changes in clay minerals.

Finally, depositional environments of the Coldwater Shale were suggested by lithologic and paleontologic data. Fossils in well cuttings are of course largely fragmented. Pieces of brachiopods, bryozoans, crinoid stems and some well preserved ostracods were observed. Paleontologic data compiled in the literature also added information to the understanding of environment of the Coldwater formation.

TECTONIC FRAMEWORK OF THE MICHIGAN BASIN

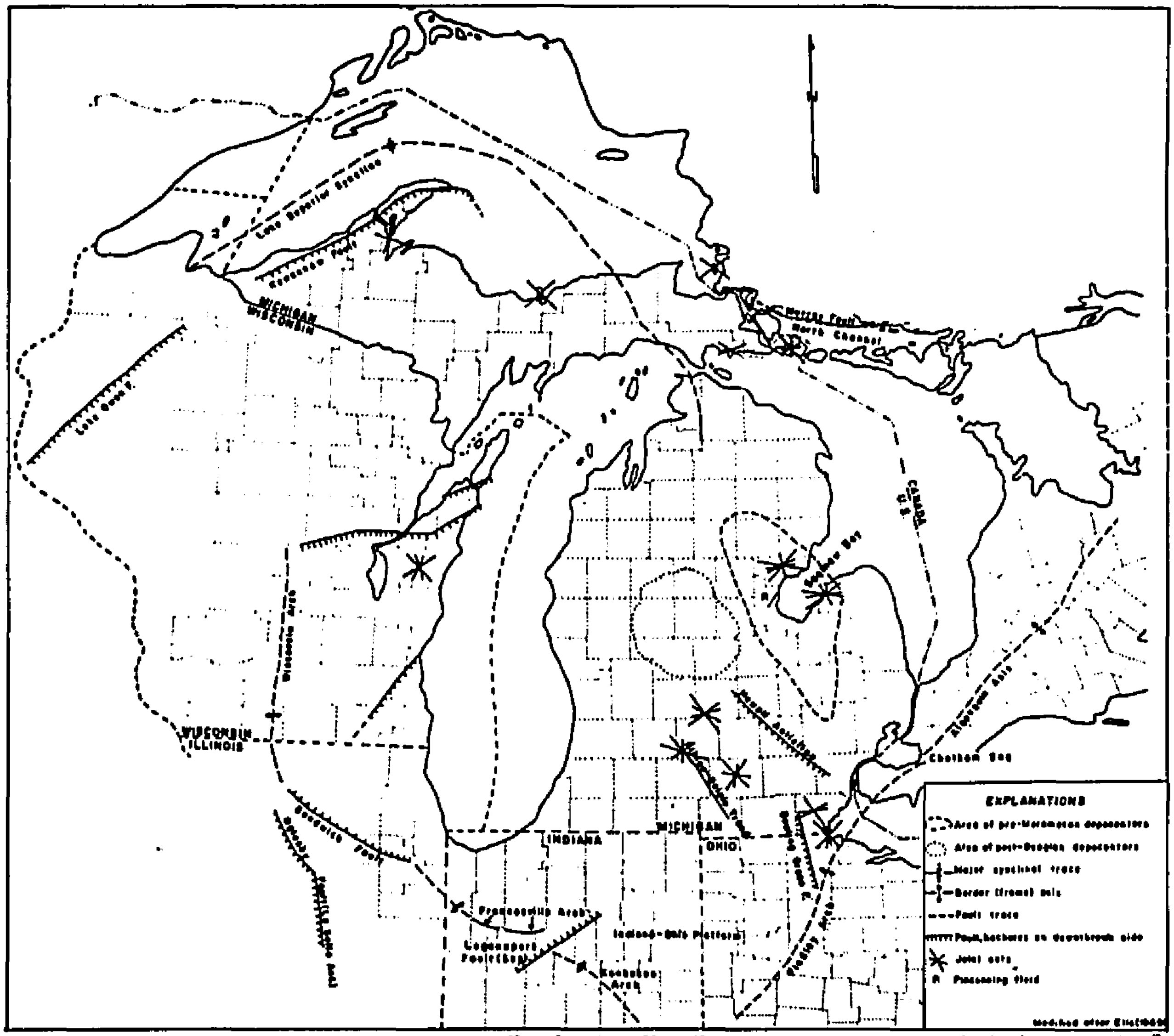
Regional Setting of the Michigan Basin

The Michigan Basin, a roughly circular structural depression, has been long referred to as the type example of an autogeosyncline (Kay, 1951) or as an intracratonic basin. Its center is located near the center of Southern Michigan and its flanks are outlined essentially by Lake Michigan, Lake Huron and Lake Superior.

The Canadian Shield which occupies almost the entire Lake Superior area and extends through northern Ontario, forms the northern boundary of the basin.

The Basin is surrounded by several arches; the Algonquin Arch to the east; the Findlay Arch to the east and southeast; the Wisconsin Arch to the west; and the Kankakee Arch to the southwest (Figure 1). To the south of Michigan the north-south trending Cincinnati Arch is another structural feature. The Kankakee Arch and Findlay Arch generally are considered the western and eastern bifurcations, respectively, of the Cincinnati Arch.

The Canadian Shield and the Wisconsin Highlands are Precambrian in age. The Kankakee, Findlay and Wisconsin Arches have been referred to as possible upper Cambrian age by various investigators (Cohee, 1945;



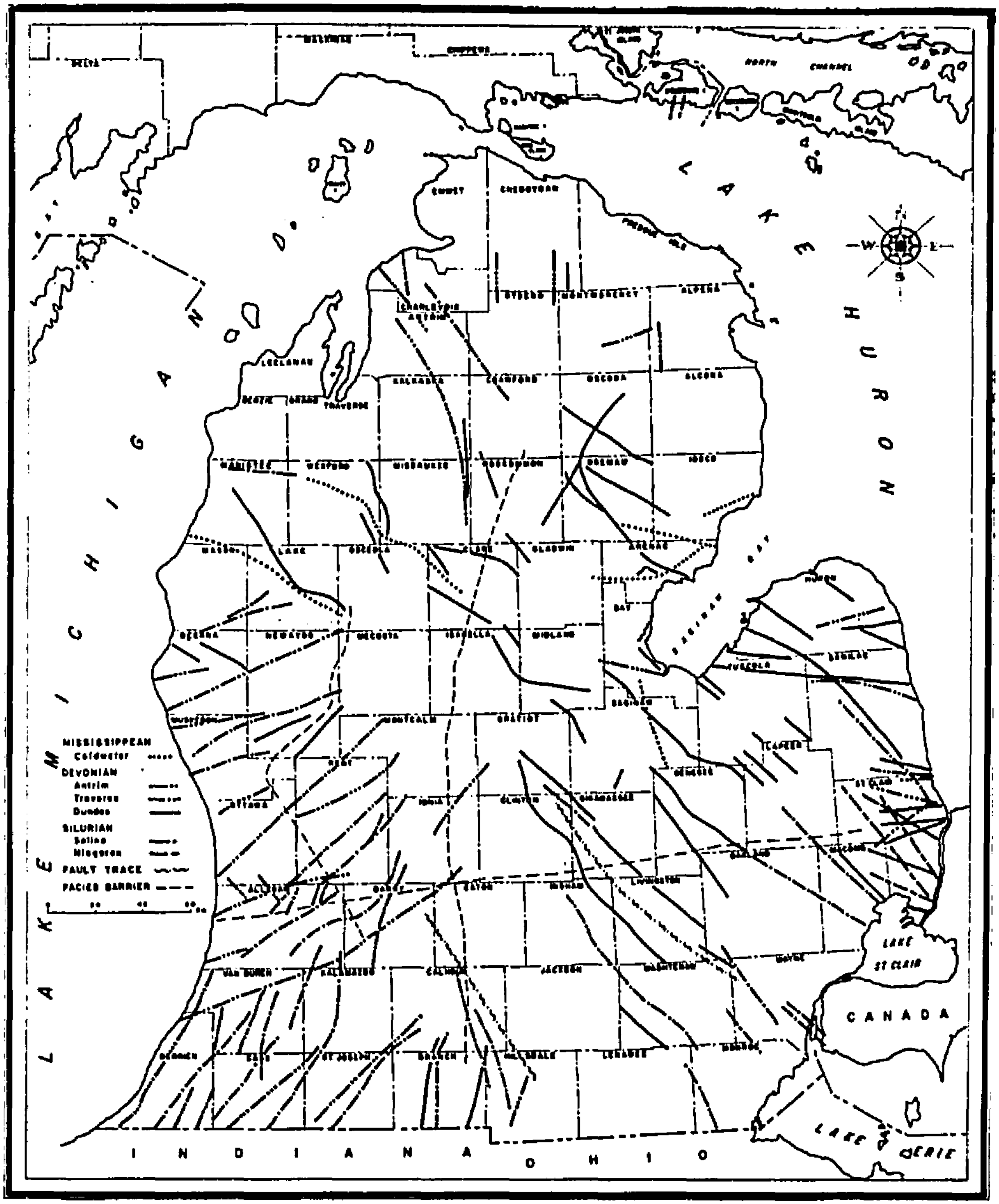
Basin structures after Prouty, 1971

MAJOR STRUCTURAL TRENDS—MICHIGAN BASIN AND ENVIRONS

Figure 1

Cline, et al., 1959). These structural features have been considered to be key factors in the formation of the Basin. The northwest elongation of the Basin and the dominant northwest and northeast directions of folds and faults (Figure 2) appear to be closely associated to these positive structures in one way or the other.

The origin of the Basin has been a subject of discussion for many years. Newcombe (1933) related the northwest elongation of the Basin, the northwest direction of the anticlinal trends and the downward sinking of the Basin to the compression from northeast along the Keweenaw fault. Pirtle (1932) is of the opinion that the Basin originated from simple sinking with the sediment load, and the fold trends in the Basin are related to the lines of weakness in the basement rocks. On the other hand, Locket (1947) believed that the dominant positive features were reactivated while the negative areas were being subsided with load of sediments during the Paleozoic Era. Recently, Hinze (1963) basing his studies on gravimetric and magnetic surveys in the Southern Peninsula of Michigan suggested that the Michigan Basin had its origin in the isostatic downward yielding to the added mass of the Keweenawan basic rocks in the basement complex. But there is little doubt that since the Basin was formed, it has undergone many changes from time to time, and based



Compiled by Prouty, 1971

Figure 2.--Major Fold Axes--Southern Michigan.

on various studies of isopach and structure maps its depocenters have shifted position slightly from time to time.

Intrabasinal Structures

Structure contour maps based on different horizons illustrate that the Basin has an oval shape with a slight northwest elongation and many structural features within the basin have two recognized major trends--northwest (dominant) and northeast. Most of the northwest folds are confined to eastern, southeastern and central Michigan; while the northeast folds occur mostly in the western and southwestern portion. Few minor east-west and north-south folds are also recognized within the Basin. Other "radial-like" structures were observed by Asseez (1967, 1969) on the Antrim shale structure contour map. In a discussion of the development of the Michigan Basin, Prouty (1971) has compiled the important anticlinal axes from the Silurian Niagarian Formation up through the Mississippian Coldwater Formation (Figure 2); some of these were considered as radial folds which are most prominent in the Salina rocks. Prouty (1971) relates these folds to the rapid basinal settling in Salina and the more sensitive response of the evaporites to deformation than other, more competent, rocks. Faults (Figure 2) and joints (Figure 1) are also recognized within the

Basin (Prouty, 1971), showing primary and secondary northwest and northeast trends.

Structure maps show the Michigan Basin to be a fairly symmetrical basin. Its present center, located in central Southern Michigan, is elongate somewhat north-northwest in the deepest part. The basin centers in pre-Mississippian Paleozoic systems are believed (Prouty, 1971) centered in eastern Michigan near Saginaw Bay, but shifted west to the present position because of stresses from the southeast, probably the Appalachians, during early phases of the Appalachian orogeny.

Some studies indicate north-south barriers in south-central and west-central Michigan at various times. Hale (1941) in a study of the Lower Mississippian in western Michigan found a marked difference in sedimentation from western to eastern Michigan. This study allowed her to postulate the existence of a north-south axis extending from Calhoun County north through Eaton, Clinton, Gratiot, Isabella and Clare Counties. Later, Jodry (1951) in a study of the Traverse Group farther west recognized a western (lagoonal) facies and eastern (open environment) facies separated by his West Michigan Barrier. LeMone (1964) recognized an axis ("B" axis) farther east and indicated that it influenced sedimentation of the Antrim black shale. Asseez (1967) preferred to consider the north-south axis close to LeMone's "B" axis as rather a facies barrier than a structural barrier (Figure 2).

Structure of the Michigan Basin During Coldwater Deposition

It has been demonstrated difficult, and sometimes impossible, to find criteria suitable to determine the contact of the Marshall Sandstone and the subjacent Coldwater Shale in eastern Michigan. The top of the latter, therefore, cannot be used to construct a contour map. The base of Coldwater, however, is considered a very good horizon for determining the structure of the Basin. The contact of the Coldwater and subjacent Sunbury formation is easy to determine on the basis of the blackness of the Sunbury shale; also the gamma-ray neutron logs show high deflections within the Sunbury shale. In the southwest part of the Basin, especially in Allegan, Barry, Van Buren and Kalamazoo Counties, the Sunbury is not recognized as a formational entity. However, another good marker bed, the lowest "red rock" in the Coldwater, serves as an adequate contact indicator with the Ellsworth shale below.

As shown in Figure 3, the regional structure contour map based on about 775 wells, is constructed on the base of the Coldwater formation. Two basin centers were recognized: one primary center located in the region of

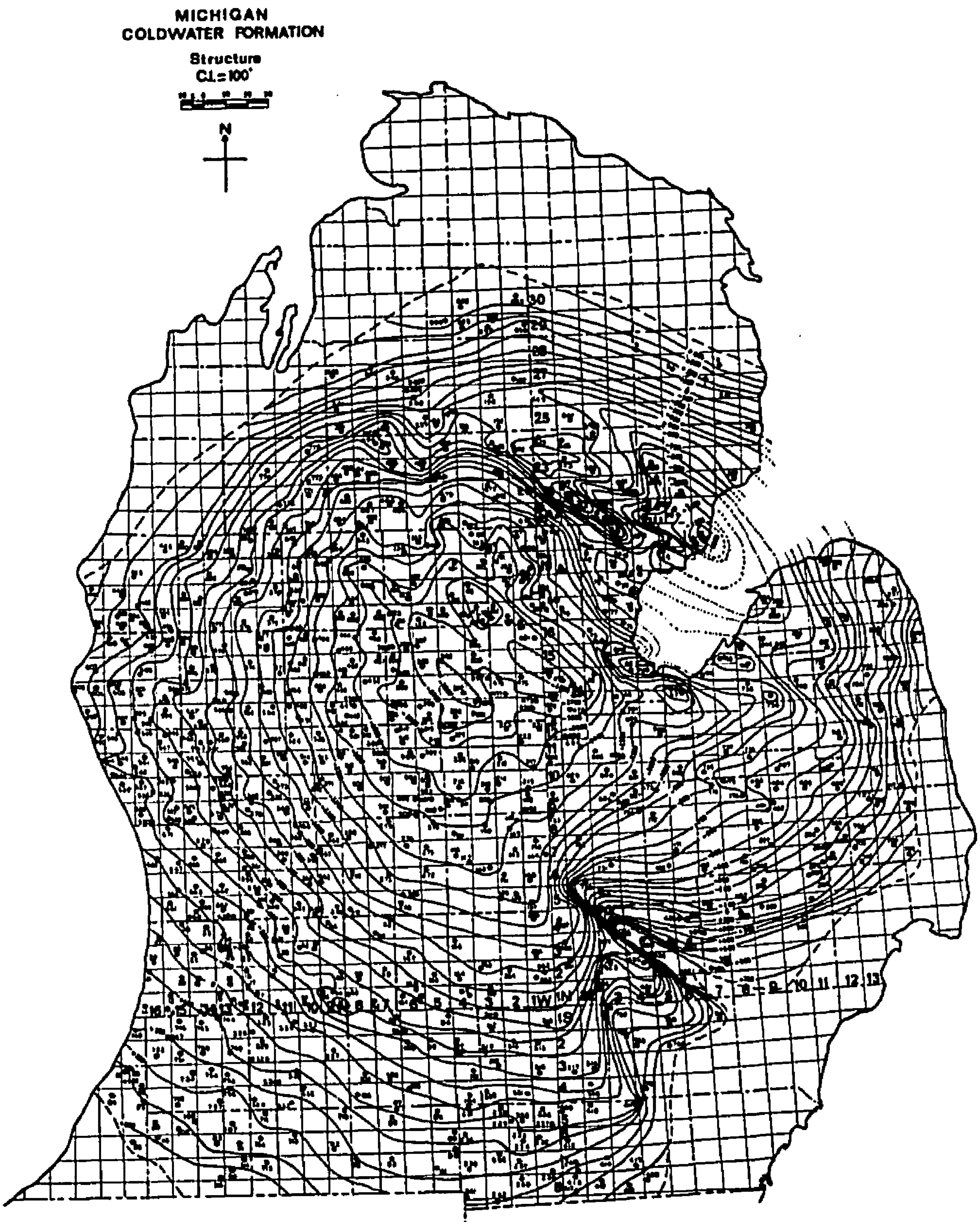


Figure 3.--Structure Contour Map at Base of Coldwater Formation.

Clare, Gladwin, Isabella and Midland Counties; and a smaller secondary center occurring in Iosco and Arenac Counties. This double-centered basinal feature was first noticed in the Traverse group structure contour map drawn by Cohee (1947) and later in the Dundee limestone (Bloomer, 1969). The secondary center is the area which accumulated the thickest Coldwater sediments and is considered as the principle depocenter of this time.

The Howell Anticline (Figure 1) is the predominant structure in the Basin, trending in a northwest direction through Monroe, Livingston and Clinton Counties in the southeastern part of the Basin. Structural displays suggest an asymmetrical anticline with faulting occurring along the western flank of the structure (Newcombe, 1933). Kilbourn (1947) in his study of the Howell Anticline, suggested that it formed at the beginning of Coldwater time because of faulting in the basement rocks, and demonstrated by thinning of the Coldwater formation towards the anticline. However, by means of geologic cross-section of the Howell anticline, Ells (1969) indicated that the Coldwater and Marshall thin and offlap the Howell structure, possibly because of erosion, suggesting that the folding could have occurred at least by Meramecian (Late Mississippian) time, or even possibly as late as Cretaceous time. It appears that most anticlinal axes manifest in the Coldwater occur in the east and northeast

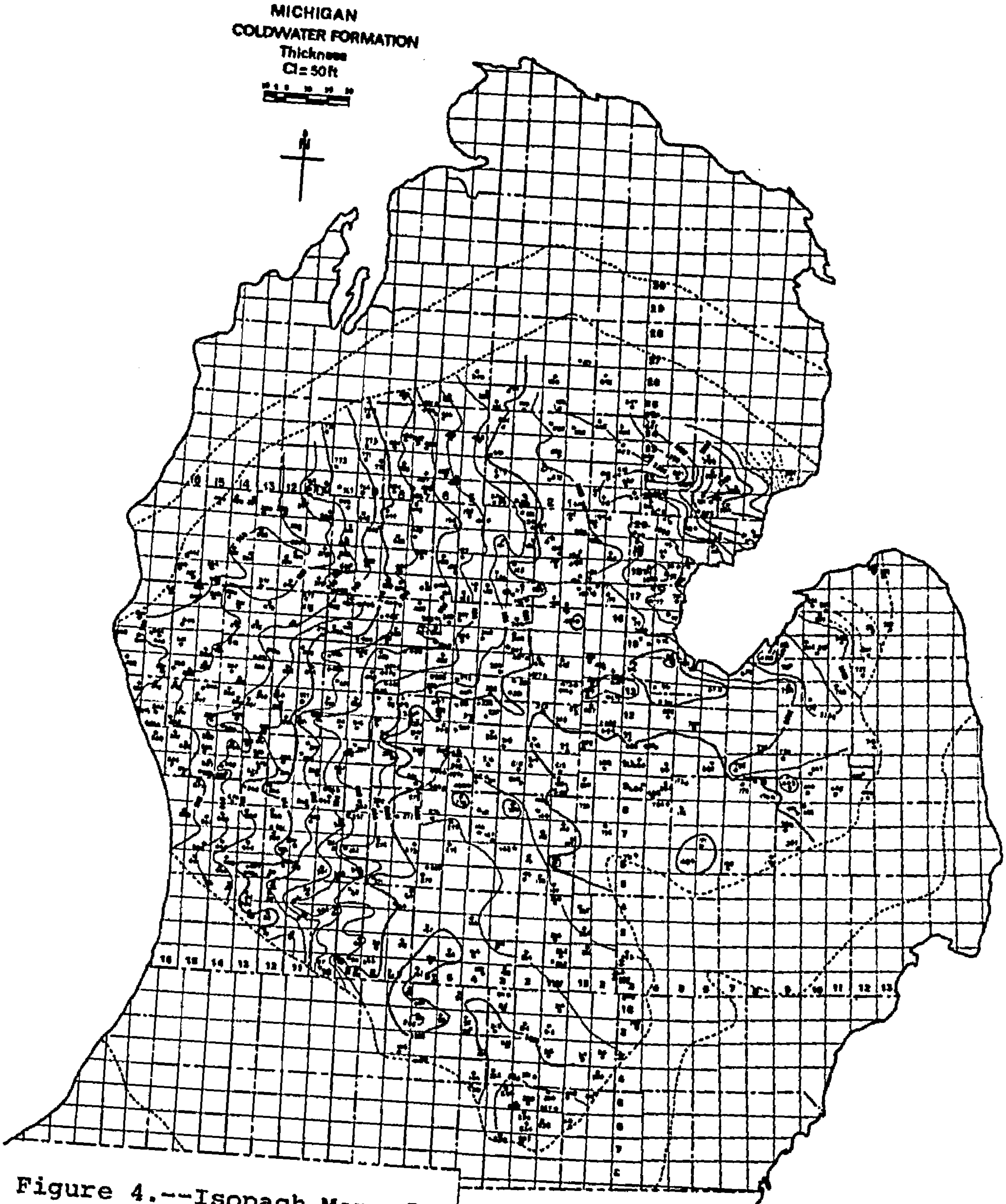


Figure 4.--Isopach Map of the Coldwater Formation.

parts of the Basin. Few somewhat northwest trending folds occur in Ogemaw, Iosco, Arenac and Bay Counties, also the region of the Coldwater depocenter. Two other structurally high areas trending northwest are found in the northwestern part of the Basin: one from Wexford to Clare; and another from Lake to Mecosta Counties. These folds are also observed by the closure in the isopach map (Figure 4).

Some structures without clear trends are distributed throughout the western and southwestern parts of the Basin. They probably occurred on top of older eroded axes developed in the Antrim and older formations. Thus it is inferred that folding occurred at different times within the Basin. Some folds recognized within a given formation may not be developed in overlying formations. Anticlinal axes clearly observed in the Antrim shale (Asseez, 1967) may be represented by some isolated "highs" in the Coldwater.

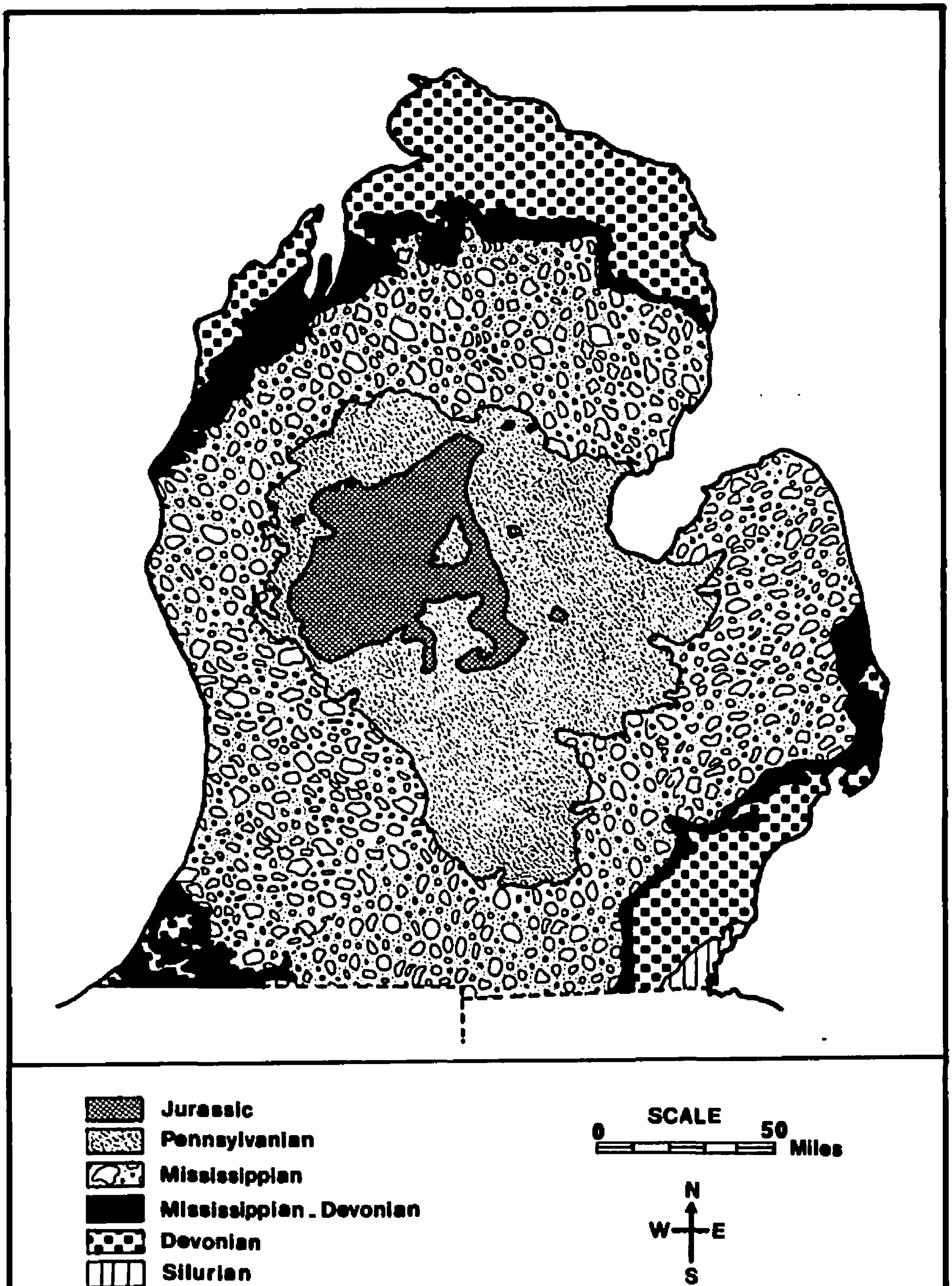
STRATIGRAPHY

Introduction

In the Southern Peninsula of Michigan a thick sequence of as much as 15,000 feet of sediments overlie Precambrian rocks. With the exception of the Pleistocene glacial drift and the late Jurassic "Red Beds," all the rocks lying above Precambrian belong to the Paleozoic. The rock layers occur as subcrops (beneath the glacial drift) in concentric bands (Figure 5) and dip towards central Michigan in true basinal form. All the Paleozoic systems are exposed at least locally in small exposures within the confines of the basin structure.

The Cambrian is characterized by an abundance of quartz sand and carbonates. The Ordovician, Silurian, and Devonian rocks in the Michigan Basin consist mostly of carbonates and evaporites and some clastic rocks.

The Mississippian time marked the return of clastic sediments in the Basin. The Devonian-Mississippian boundary has been a controversial problem. In Ohio, the Berea sandstone channels cut into the Bedford shale, and even the Ohio black shale. Pepper, et al. (1954) have placed the Bedford shale, if present, or the Berea in the absence of the Bedford in basal Mississippian. From



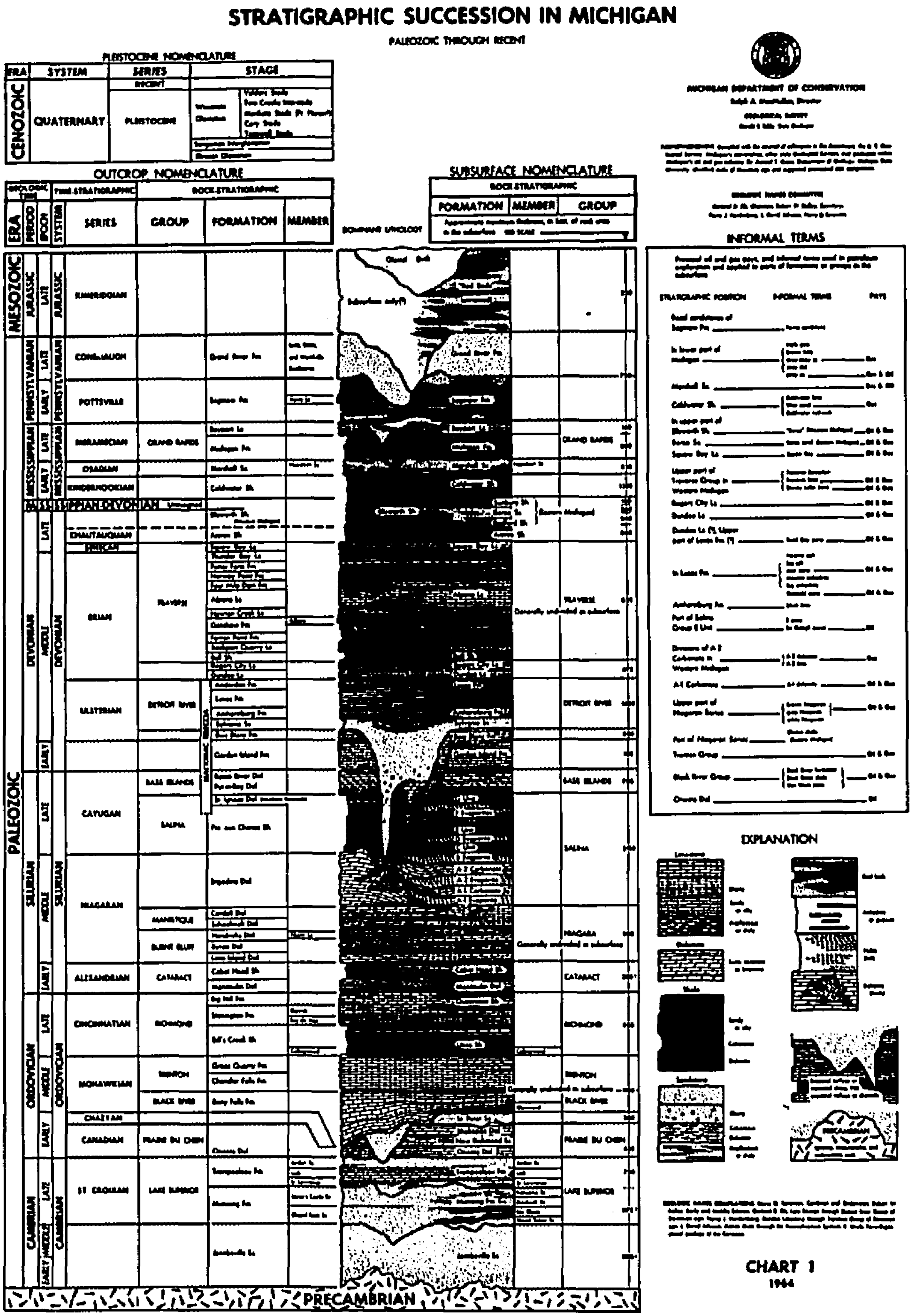
(Generalized after Michigan Geological Survey, 1968)

Figure 5.--Bedrocks of Southern Michigan.

eastern Michigan the Bedford-Berea sequence grades laterally toward the south, southwest and west into the black shale body.

Based on the stratigraphic chart published by the Michigan Geological Survey in 1964 (Figure 6), the rocks occupying the stratigraphic interval from the upper part of the Antrim shale to the base of the Coldwater was assigned to the undifferentiated Mississippian-Devonian. This sequence includes the Ellsworth and Sunbury shales in western Michigan, and the Bedford shale, Berea sandstone and the Sunbury shale in eastern Michigan. In general, the Mississippian-Devonian boundary probably occurs within the lower part of the Bedford shale and the upper part of the Ellsworth shale in the Michigan Basin.

The Antrim Shale was renamed by Lane (1901) for the St. Clair shale and its type locality is in Norwood in Antrim County, Michigan. The Antrim shale which is characterized by a dominately black carbonaceous shale and an abundance of Tasmanites spores is observed throughout the Michigan Basin. LeMone (1964), basing his study on gamma-ray neutron logs, subdivided this formation into an upper and a lower unit. The lower unit can be traced throughout the Basin and consists of three "subunits," the lowest and the highest sub-units being highly radioactive, while the middle is less radioactive than the other two. The upper Antrim unit according to LeMone is replaced by



STRATIGRAPHIC SUCCESSION IN MICHIGAN
PALEOZOIC THROUGH RECENT
PLEISTOCENE NOMENCLATURE
ERA
SYSTEM
SERIES
STAGE
RECENT
CENOZOIC
QUATERNARY
PLEISTOCENE
OUTCROP NOMENCLATURE
SUBSURFACE NOMENCLATURE
FORMATION
MEMBER
GROUP
MESOZOIC
JURASSIC
PALEOZOIC
PENNSYLVANIAN
MISSISSIPPIAN
DEVONIAN
SILURIAN
ORDOVICIAN
CAMBRIAN
LATE
MIDDLE
EARLY
CONEMAUGH
POTTSVILLE
MERAMECIAN
OSAGIAN
KINDERHOOKIAN
MISSISSIPPIAN-DEVONIAN
CHAUTAUQUAN
ERIAN
ULSTERIAN
CAYUGAN
NIAGARAN
ALEXANDRIAN
CINCINNATIAN
MOHAWKIAN
CHAZYAN
CANADIAN
ST CROIXAN
GRAND RAPIDS
TRAVERSE
DETROIT RIVER
BASS ISLANDS
SALINA
MANISTIQUE
BURNT BLUFF
CATARACT
RICHMOND
TRENTON
BLACK RIVER
PRAIRIE DU CHIEN
LAKE SUPERIOR
PRECAMBRIAN
INFORMAL TERMS
EXPLANATION
CHART 1
1964

Figure 6

and intertongues with the Ellsworth shale west of "B" axis (Figure 2), whereas on the east side of this axis, the upper unit tends to decrease in thickness away from the axis at the same time the Bedford-Berea sequence increases in thickness. Asseez (1967, 1969) did not observe this particular subdivision but did construct a lithofacies map based on the percentage of "grayness." The darker the gray, the higher is the organic content and consequently the more reducing and "sterile" is the environment, with less decay and greater preservation of organic matter. Asseez further correlated the darker color with deeper, more poorly circulated, stagnant areas of the sea floor with the converse relationship indicating shallower areas of better aerated waters and more complete decay of organic matter. By this relationship, Asseez's lithofacies map based on "grayness" could outline areas of contrasting sea-bottom relief including structural axes.

The Ellsworth shale entered the Basin from the west at about the same time the Bedford-Berea sequence was being deposited on the east side of the Basin, probably along a delta front which extended to about central. Michigan. It was named (Newcombe, 1933) for exposures near the town of Ellsworth in Antrim County, Michigan. The Ellsworth is characterized by the presence of greenish-gray shale which becomes darker eastward and probably interfingers with the upper part of the Antrim shale in the central part of the basin. Near the top of this formation, Hale (1941) described a dolomitic zone--the "Berea horizon"--which is composed of limestone, dolomite, some oolites and rounded quartz sanc grains. The north-south line which is either a structural barrier or facies barrier formed the western limit of the Bedford-Berea sequence and the eastern limit of the Ellsworth shale.

The Bedford shale and Berea snadstone form a clastic wedge lying between two black shale sequences, the Sunbury shale above and the Antrim shale below. The Bedford Shale was named by Newberry (1870) for exposures of soft blue shales at the town of Bedford, Cuyahoga County, Ohio. The Bedford is typically bluish gray shale and is restricted to the eastern half of the Basin. It grades into the overlying Berea sandstone. The latter was also named by Newberry (1870) for exposures in the town of Berea, also in Cuyahoga County, Ohio. The Bedford-Berea sediments are believed to have been derived from sources in the cratonic interior, chiefly the Canadian Highlands, and form a bird-foot delta in eastern Michigan. Pepper and Dewitt (1954) recognized a stream system subparallel to the Cincinnati Arch region leading into Ohio with distributaries into eastern Michigan. Asseez (1967) displayed the Bedford-Berea as mostly a prodelta in Michigan extending westward to about central Southern Michigan.

The Sunbury Shale marked the return to a reducing marine environment yielding black muds much like the Antrim shale, lithologically. It was named by Hicks (1878) for exposures of black shale on Rattlesnake Creek, near the town of Sunbury, Delaware County, Ohio. The formation was described as a black pyritiferous, carbonaceous shale and characterized by the presence of Lingula melia and Orbiculoidea newberryi. The Sunbury, widespread throughout the entire Basin, is generally 20 to 50 feet thick; but its extreme range is from a few feet in the southwest to more than 140 feet in the "thumb" area of eastern Michigan.

The Ellsworth Shale was believed (LeMone, 1964) to be the facies equivalent of the Upper Antrim-Bedford in the Michigan Basin; the "Berea Horizon" in the upper part of the Ellsworth was considered a probable correlative of the Berea sandstone.

The Sunbury black shale is followed by the Coldwater shale which is comprised of mostly clastic sediments derived from a northeastern source. It apparently marked the end of the Devonian-Mississippian black shale environment in the Michigan Basin.

The objective of the present study is concentrated on the Coldwater formation.

Vertical Relationship of the Coldwater Formation

The Coldwater rests everywhere on the Sunbury Shale, the contact being recognizable in most places, expecially the western half of Michigan, by a red bed near the base of the Coldwater. In the few counties where this key red bed is locally absent or located stratigraphically higher than the Coldwater base, the top of the Sunbury shale, recognized by its blackness, can be used to mark the contact without significant error. In central part of the Basin where the Bedford-Berea sequence and the Ellsworth wedge out, it is difficult to distinguish the Sunbury from the Antrim shale. Most investigators prefer to consider the Coldwater in contact with the Sunbury in this region instead of with the Antrim black shale. In southwest Michigan, where there exists little or no typical Sunbury the red bed at base of the Coldwater shale can be used to define the Ellsworth-Coldwater contact.

The Coldwater-Marshall contact, especially in eastern Michigan, is still an unresolved problem today. The Coldwater shale grades upward into the Marshall sandstone. Lane (1900) compiled data on all the outcrops along the Lake Huron shore in Huron County and well data available at that time placing the Coldwater-Marshall contact at the base of the "Grindstone" beds in section 30, T. 19N., R. 14E. Based on this, the Coldwater shale appears to be less than 1000 feet and the Marshall sandstone is measured up to 560 feet in northern Huron County. Monnett (1948), questioning these thicknesses as recorded by Lane, believed that the Coldwater should be thicker because of the eastward thickening of that unit towards the source area. He preferred considering the rocks cropping out along the lake shore in northern Huron County as a transition zone called the Coldwater-Lower Marshall strata.

Moser (1963), in a study principally on the Michigan Formation, defined the Marshall sandstone in southwestern Michigan as the "True Marshall" which is the time equivalent to the lower part of the Michigan Formation. The strata between the stray sand and the Coldwater shale in the northeast, the "Marshall," is older than his "True Marshall." Therefore, Moser suggested there is an hiatus between the Coldwater and the Michigan Formations in the southwestern part of the Basin, and also the sandstone strata above the Coldwater in the northeast should be redefined and renamed.

The relative age of the Marshall at the Coldwater contact across the Basin apparently poses a problem unto itself and is beyond the scope of this present study. However, the nature of the Coldwater-Marshall contact is significant. Whereas a transitional contact exists in the east, a relatively sharp contact exists in the west. The uniform westward thinning of the Coldwater across

Michigan hardly suggests a major hiatus (actually erosional disconformity) implied by Moser that would be called upon to cut out the eastern type Marshall in western Michigan and place the considerably younger Mississippian sandstones (his "True Marshall") superjacent to the Coldwater.

Problems of Nomenclature and Correlation

As previously cited, the Coldwater formation was named by Lane in 1893 for exposures along the Coldwater River in Branch County. Original description of the Coldwater shale (Lane, 1893) apparently included the Berea shale or the Sunbury black shale. However, owing to differences in lithology and color, the tendency since 1932 was to split these two shales into distinct formations.

In 1900, in a report on Huron County, Lane discussed the geology of this County and compiled a geological column in which the Coldwater section was suggested as below:

Coldwater Shale	Feet
- Blue and sandy shales	172
- Lighthouse point conglomerate	4
- Blue shale (*Chonetes scitulus* cf. *pulchella*)	720
- Black shale (Berea shale)	103
TOTAL	1,000±

In the same year, in a geological study of Sanilac County, Gordon divided the Coldwater Shale of this County into three parts, shown in the usual chronological order:

Coldwater Formation	Feet
- Forestville, blue shale	100-200
- Richmondville, sandstone	50-80
- Blue shale	200-250

Lane (1893) believed the Richmondville sandstone to be the Berea sandstone lying stratigraphically below the black bituminous shale at the base of the Coldwater shale. Gordon (1900) discussed that point and suggested the Richmondville sand should be occurring about 200 feet below the top of the Coldwater section in Sanilac County.

The Lower Mississippian rocks in eastern Michigan comprise (ascending) the Bedford shale, Berea sandstone, Sunbury black shale, the Coldwater and Marshall formations. The sequence of rocks in Michigan, Ohio, Pennsylvania, Indiana and Kentucky are somewhat similar but different nomenclature was applied for these regions.

In Ohio, the lower Mississippian rocks were referred to the Waverly "series" which included everything between the Ohio black shale and the Coal Measures strata. Prosser (1901) proposed the classification of the Waverly series as follows:

Waverly Series

Logan formation (Andrews)
Black Hand formation (Hicks)
Cuyahoga formation (Newberry)
Sunbury shale (Hicks)
Berea grit (Newberry)
Bedford shale (Newberry)

The U.S.G.S. invalidated the Waverly "series" in 1960.

The Cuyahoga formation was named by Newberry in 1870 for a rock sequence whose typical exposures were located in the region of Cuyahoga River in Cuyahoga and Summit Counties, Ohio. The Orangeville, Sharpsville, Strongsville and Meadville are members of the Cuyahoga formation, with the Sunbury being considered only a basal unit of the Orangeville shale in this region (Dewitt, et al., 1954). Toward central and southern Ohio, the Black Hand was believed (Hyde, 1915) to be a member of the Cuyahoga and that the upper contact was placed at the base of the Logan formation. Initially, the Cuyahoga was used as a "group" in northern Ohio and northwestern Pennsylvania (Cushing, 1931); but in central and southern Ohio it was regarded as a "formation." Gradually, divergent ideas on the stratigraphy of Ohio have developed. The most striking point was the introduction of the Buena Vista sandstone into the stratigraphic column. Originally, this sandstone was placed at the base of the Cuyahoga shale, but Hyde (1921) suggested that the Buena Vista should be correlated to the Berne sandstone which formed the lower member of the Logan formation. Holden (1942) basing his work on the ideas of Hyde (1915, 1921), Prosser (1912), divided the Cuyahoga formation into seven lithofacies, each facies in turn divided into varying members and submembers. In a recent work on the Cuyahoga formation in northern Ohio, Szmuc (1957) raised some submembers to member rank and proposed some new members with a classification comprised ot ascending order, the Orangeville, Sharpville, Strongsville (new), Meadville, Rittman, Armstrong, Wooster (new) and Black Hand (Table 1). He considers the lower part of the formation to be Kinderhookian; the Meadville to contain mixed late Kinderhood-early Osage assemblages; and the upper part to represent the Osagian. Clastic sediments of the Cuyahoga formation are mainly fine to very fine sand, silt and clay. Coarser sandstones are predominant in the Black Hand member. Szmuc also suggested that the Cuyahoga sediments are shelf sediments and deltaic or bar sediments which were derived from an eastern source.

Lower Mississippian rocks of Indiana and Kentucky are somewhat similar to those of Ohio and Michigan. Stockdale (1939) in his work on the Lower Mississippian of the east-central interior, concluded that the clastic Borden group of Indiana and Kentucky is equivalent to the Waverly series of Ohio, and to the combined Coldwater and Marshall formations in Michigan. According to Stockdale

TABLE 1.--Chart Showing Stratigraphic Names Applied to the Post-Berea Lower Mississippian Rocks.

EASTERN PENNSYLVANIA (Colton, 1970)		NORTH-CENTRAL PENNSYLVANIA (Colton, 1970)		NORTHWESTERN PENNSYLVANIA (Szmuc, 1957)	NORTHERN AND NORTH-CENTRAL OHIO (Szmuc, 1957)
				"Shenango" Formation	Logan Formation
				Hempfield Member	Vinton Member
			Burgoon ss.		
				Shenango Member	Allensville Member
	Mount Carbon Member				Byer Member
					Berne Member
			Patton Red Shale		
POCONO FORMATION		POCONO GROUP		Cuyahoga Formation	Cuyahoga Formation
					Black Hand Member
					Wooster Member
					Armstrong Member
					Rittman Member
	Beckville Member				
				Meadville Member	Meadville Member
				Sharpsville Member	Strongsville Member
				Orangeville Member	Sharpsville Member
					Orangeville Member
				Berea Formation	Berea Formation

(1939), the New Providence formation, a unit at the base of the Borden group, is equivalent to the Cuyahoga formation, therefore to the Coldwater formation of Michigan. The stratigraphic relation of northwestern Pennsylvania and Ohio also raise an important problem. I. C. White (1880, 1881) suggested that his Meadville group with three units, the Orangeville shale, Sharpsville sandstone and Meadville shale, is apparently equivalent with the Cuyahoga in northern Ohio. Overlying the Meadville group is the Shenango group with Shenango sandstone and Shenango shale (White, 1881). The Shenango sandstone was thought to correlate to the Logan formation in Ohio (Orton, 1882; and many others). However, in recent years, it has been regarded as the stratigraphic equivalent of the upper part of the Meadville member of Cuyahoga and Medina Counties, Ohio (Szmuc, 1957).

Farther east in Pennsylvania, the Pocono orthoquartzites have the stratigraphic position of the Lower Mississippian and because of the position superjacent to the upper Devonian Catskill red beds, the sediments are considered post-orogenic (Acadian) and therefore of Mississippian age. The relatively barren eastern Pocono apparently become "more marine" westward. Two faunal zones have been recognized and described by Bolger and Prouty (1953) from shales and sandstones considered "Pocono" on the bases of stratigraphic position and gross lithologic comparisons. However, the faunas are not diagnostic but have forms conspecific with some of the Upper Devonian Chemung and Lower Mississippian. The general lack of Productids and Syringothyrids adds to the uncertain nature of the fauna. The eastern Pocono has been referred to as fluviatile in origin (Pelletier, 1958) with a clastic and low rank metamorphic provenance farther east near the New Jersey coast. The western Pennsylvania sequence would be about intermediate lithologically between the coarser clastic eastern Pocono and the Michigan Basin Coldwater shaly terraine. Modifying effects of local structure on the Michigan Basin Lower Mississippian sediments is discussed under Paleogeographic Inferences.

Correlation has been attempted between the lower Mississippian strata in Michigan and the Waverly group of Ohio. The first of such works dated back to 1900 based on the work of Cooper. The Coldwater formation was apparently correlated to the rocks between the lower part of Logan formation, the Racoon shale, the Cuyahoga shale and the Buena Vista in Ohio. In the light of new information on Ohio stratigraphy, Cooper's correlation needs to be reviewed. In general, the Coldwater can be correlated to the lower part of the Pocono formation of Maryland and Pennsylvania; to at least the four lowest members of the Cuyahoga in Ohio (Orangeville, Sharpsville, Strongsville and Meadville); and also to the New Providence formation of Indiana and Kentucky. Regional correlation is generally based on the 1947 publication of the Mississippian Subcommittee of the Committee on Stratigraphy of the National Research Council (Table 2).

The exact age of the Coldwater has long been a controversial problem. It has been assigned at times to the Kinderhook and/or Osage and even to the Devonian Chemung. Weller and others (1948) assigned the Coldwater and Lower Marshall to the Kinderhookian, and the Napoleon sandstone to a lower Osagian age. In 1951, Cohee concluded that part of the Coldwater and the Marshall formations are of Osage. In a more recent study by Miller (1953, 1955) of the cephalopods of the Coldwater and Marshall, the upper Coldwater was considered of Kinderhook and early Osage age. In a study of Mississippian brachiopods in Michigan, Oden (1952) concluded that species found in the Coldwater and Marshall formations are of Early Mississippian age but regional correlation of these two formations based on brachiopods are restricted because of lack of duplication of certain species in geographically removed collections. Camarotoechia huronensis var. precipua (Winchell) and Syringothyris pharovicina (Win.) were observed by Oden only at Lighthouse Point, in the upper Coldwater. On the other hand, the time-equivalent of Syringothyris cf. textus which was found in the quarry of the Wolverine Cement Company at Coldwater, Branch

TABLE 2.—Regional Correlation Chart (after Weller, J. M., et al., 1947).

STANDARD STRATIGRAPHIC SECTION		Formation in Type Region	SOUTHEAST IOWA	ILLINOIS BASIN	WESTERN MICHIGAN	EASTERN MICHIGAN	SOUTH CENTRAL OHIO	CENTRAL KENTUCKY
OSAGE SERIES		Keokuk ls.		Osage Fm.	Michigan Fm.	Michigan Fm.		Muldraugh Fm. Lloyds Knob Fm. Broadhead Fm.
		Burlington ls.					Waverly Group: Logan Fm.	
		Fern Glen Fm.		Copper Sand	? Marshall Group: Napolean SS.	? Marshall Group: Napoleon SS.	? Cuyahoga Grit	New Providence Sh.
KINDERHOOK SERIES	Easley Group	Gilmore City ls.			Lower Marshall SS. ?	Lower Marsiall SS. ?		
		Sedalia ls.	Hampton Fm.		Coldwater Fm.	Coldwater Fm.		
		Chouteau ls.	English River ss.	Rockford ls.				
		Maple Mill sh.	Maple Mill sh.	New Albany sh.	Ellsworth sh.	Sunbury sh. Berea ss. Bedford sh.	Sunbury sh. Berea ss. Bedford sh.	Sunbury sh. Berea-Bedford Fm.
	Fabius Group (Dev. or Miss.)	Louisiana sh.	(Sweet Land Creek)	(Sweet Land Creek)	Antrim sh (upper part)	Antrim sh upper part)	Ohio sh. (upper part)	Ohio sh. (upper part)
		Saverton sh.						
		Grassy Creek sh.		"Hardin" ss.				
Underlying Formation			Cedar Valley ls. M. Dev.	Dev.	L. Antrim sh.	L. Antrim sh.	L. Ohio sh.	L. Ohio sh.

County also cannot be obtained exactly because of its recognized wide range in stratigraphic time (Oden, 1952).

Lane and Cooper (1900) divided the Coldwater in Huron County into three "paleontologic zones": The Rock Falls series with Chonetes scitulus; The Lighthouse Point series with Syringothyris pharovicina, Proetus missouriensis and numerous spiriferids and Schizodus; and the Huron City series with Rhynchonelloids and Productids. The faunas as recorded by Lane and Cooper are shown below for comparative purposes:

The Rock Falls series:

Chonetes scitulus
Conularia gracilis
Productus loevicosta
Productus blairi
Spirifer centronota
Spirifer Shumardianus
Productus newberryi var. annosus
Streblopteria media
Phaethonides spinosus
Syringothyris, lamellibranchs, crinoids

The Lighthouse series:

Spirifer subattenuatus
Spirifer medialis
Spirifer huronensis
Syringothyris pharovicina
Spirifera ? (cf. Athyris) insolita
Eumetria (?) polypleura
Merista houghtoni
Pleurotomaria huronensis
Camarotoechia huronensis (Rhynchonella)
Orthis vanuxemi
Derbya crassa (Orthis crenistria)
Orthis iowensis?

Other genera:

Productus, Syringothyris, Streptorhynchus,
Rhynchospira, Spiriferina, Terebratula,
Schizodus, Aviculopecten
Spirifer deltoideus
Aviculopecten areolatus, (Crenipecten?)
Edmondia cf. binumbonata
Sphenotus aeolus Hall
Schizodus triangularis
Schizodus binumbonata cf. aequimarginalis
Prothyris meeki
Proetus missouriensis
Orthoceras barquianum

The Huron City series:

Camarotoechia (Rhynchonella) camerifera
Small Productid, Scolithus, Schizodus triangularis,
Myalina, Sphenotus?, Crenipecten winchelli
Microdon reservatus

Description of the Coldwater Formation

General

As previously cited, the lower contact of the Coldwater is rather distinctive though based on different criteria in western and eastern Michigan. The upper contact of this formation, because of the lithologic similarity to the overlying Marshall sandstone, is not easily defined and appears to be gradational. The upper contact is placed somewhat arbitrarily and some unavoidable errors may have been introduced into the isopach map, especially in eastern Michigan.

As shown in Figure 4, the thickest part of the Coldwater (1200 feet) is concentrated toward the northeastern part of the Basin in Iosco and Arenac Counties in the Saginaw Bay area; however, the deepest part of the present Basin (see structure map, Figure 3) received only about 1000 feet of sediments. Thus the Coldwater depocenter and present structural center do not coincide. Assuming the area of maximum subsidence in Coldwater time received the thickest sediments (1200 feet) the basinal center as seen on the present structure map must have shifted its position in post-Coldwater time.

Thicknesses of about 1000 feet occur throughout the central portion of Michigan from Mecosta and Gladwin Counties to Ionia, Eaton and Jackson Counties. The formation thins gradually toward the west, where less than 550 feet in thickness extends from Lake County to the western margin of Oceana and Muskegon Counties.

It is apparent that the Coldwater formation thickens geometrically to the east where the coarse clastics are prevailing. The westward thinning of the Coldwater reflects either an overlapping on higher structure in western Michigan or because of thinning away from the eastern source. It appears clearly that the first possibility is unlikely as the stratigraphy indicates westward convergence as opposed to the loss of lower beds expected in an overlap situation. Also the north-south structure (Figure 2) in central Michigan mentioned earlier as effective in influencing the pre-Sunbury sedimentation, showed no influence on Sunbury and Coldwater sedimentation. The South Michigan shelf, suggested by LeMone (1964), during the post-Antrim pre-Sunbury interval was ineffective on Coldwater sedimentation.

In the western and northwestern part of Michigan the Coldwater is mainly shale with some impure carbonate rocks and is thinner than to the east, both factors favoring an eastward source.

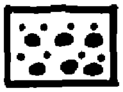
Reference to the structure and isopach map (Figures 3 and 4) show both the structural and depositional center of the Coldwater to be in the eastern part of the State, near Saginaw Bay. Prouty (1971) considers that the change in the structural center and depocenter to the present central location in Southern Michigan to have occurred before Grand River (Meramec) Mississippian time, and in response to extrabasinal orogenic stresses from the east, probably the Appalachians, and reflected in shear couples manifested as lateral faults and shear folds (Figure 1). Coldwater isopach lines infer that the Michigan Basin at this time was beginning to "fill up" with rapidly accumulating sediments reflecting at least partly the activity east of the Basin.

In general, the Coldwater Formation grades laterally from the east towards the west. The sandy shales and fine-grained sandstones which are prevalent in the east gradually change to silty shales and shales in the center of the Basin and then into calcareous shales in the west. Several beds of dolomite and limestone are observed along the western edge of Michigan. It is believed that the facies change is a continuous gradation and that the lateral rate of change is gradual. Despite the gradual change it appears difficult to trace lithologically any beds or units for appreciable distances across the Basin. Careful study of gamma-ray neutron logs show, however, that apparent unit-by-unit correlations can be obtained only between close control points (Figures 7, 8 and 9). The writer has studied some radioactivity logs available at the Geology Department, University of Michigan, and recognized that the "Coldwater red rocks" and the "Coldwater lime" may be traced laterally for long distances (Figure 10). The lower contact and also the upper contact, except in eastern Michigan, were also readily defined. The dolomite in the west and the sandstones in the east interfinger with the main shale body. However, some of the sandstones and dolomite units are considered lenses as opposed to offshoots or tongues of the principal bodies.

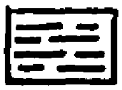
As the rocks of eastern Michigan consist almost entirely of terrigenous clastic materials, a regional sand percentage map (Figure 10) therefore was constructed to examine the sand distribution pattern. Units defined as either sand or shale in the sample study were assigned 100% sand or 100% shale values. Sandy shales or shaly sandstones were recorded by their relative percentages.

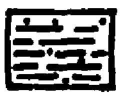
EXPLANATION FOR FIGURES 7, 8 & 9

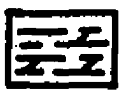
 Sandstone, micaceous

 Sandstone, conglomeratic

 Sandstone, shaly

 Shale

 Shale, sandy

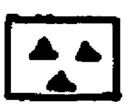
 Shale, dolomitic

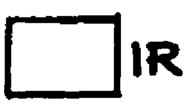
 Dolomite

 "Speckled" dolomite

 Dolomite, glauconitic

 Fossiligerous

 Chert



Red rock

 No sample

 Limestone, pyritic

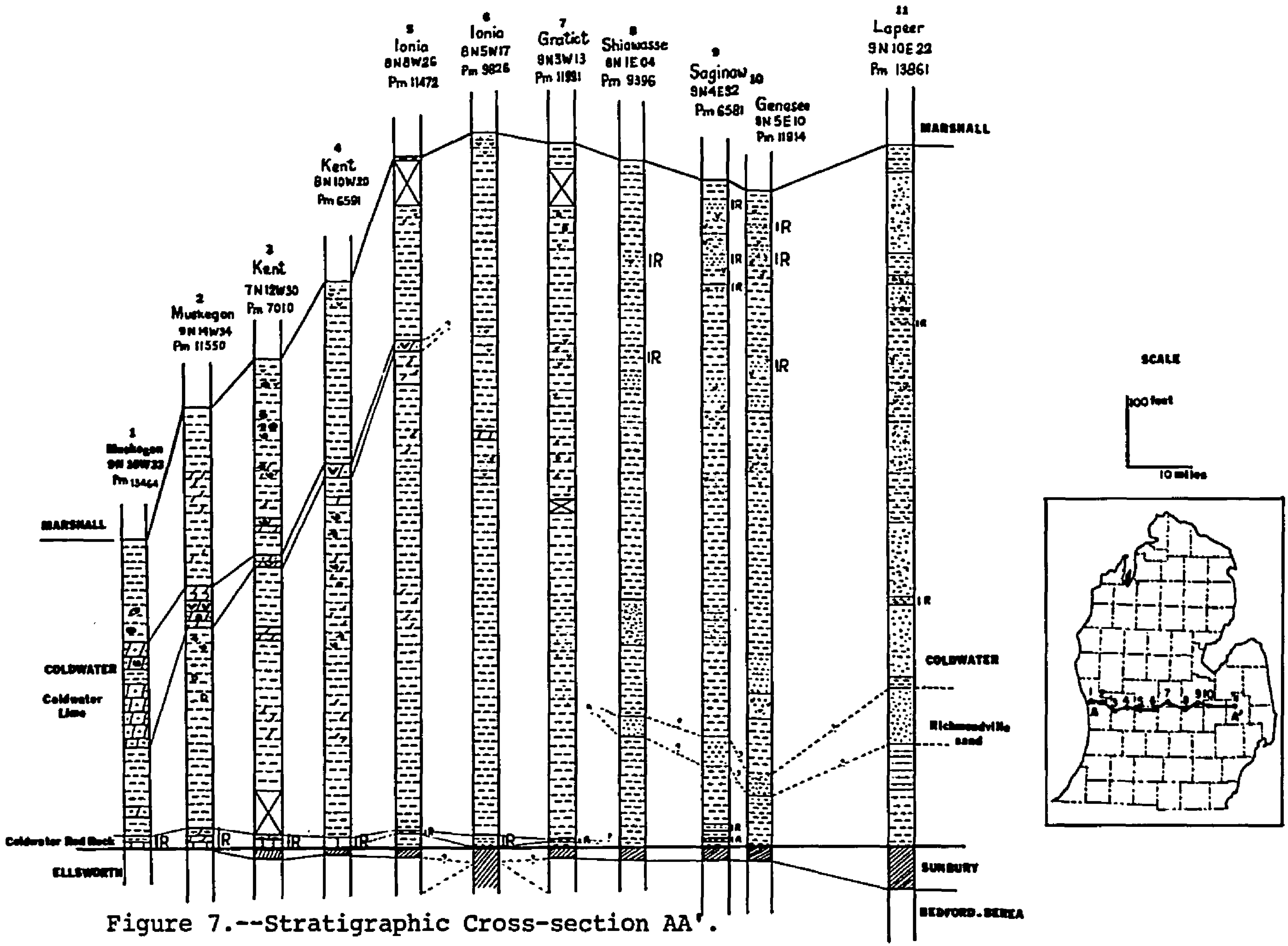


Figure 7.--Stratigraphic Cross-section AA'.

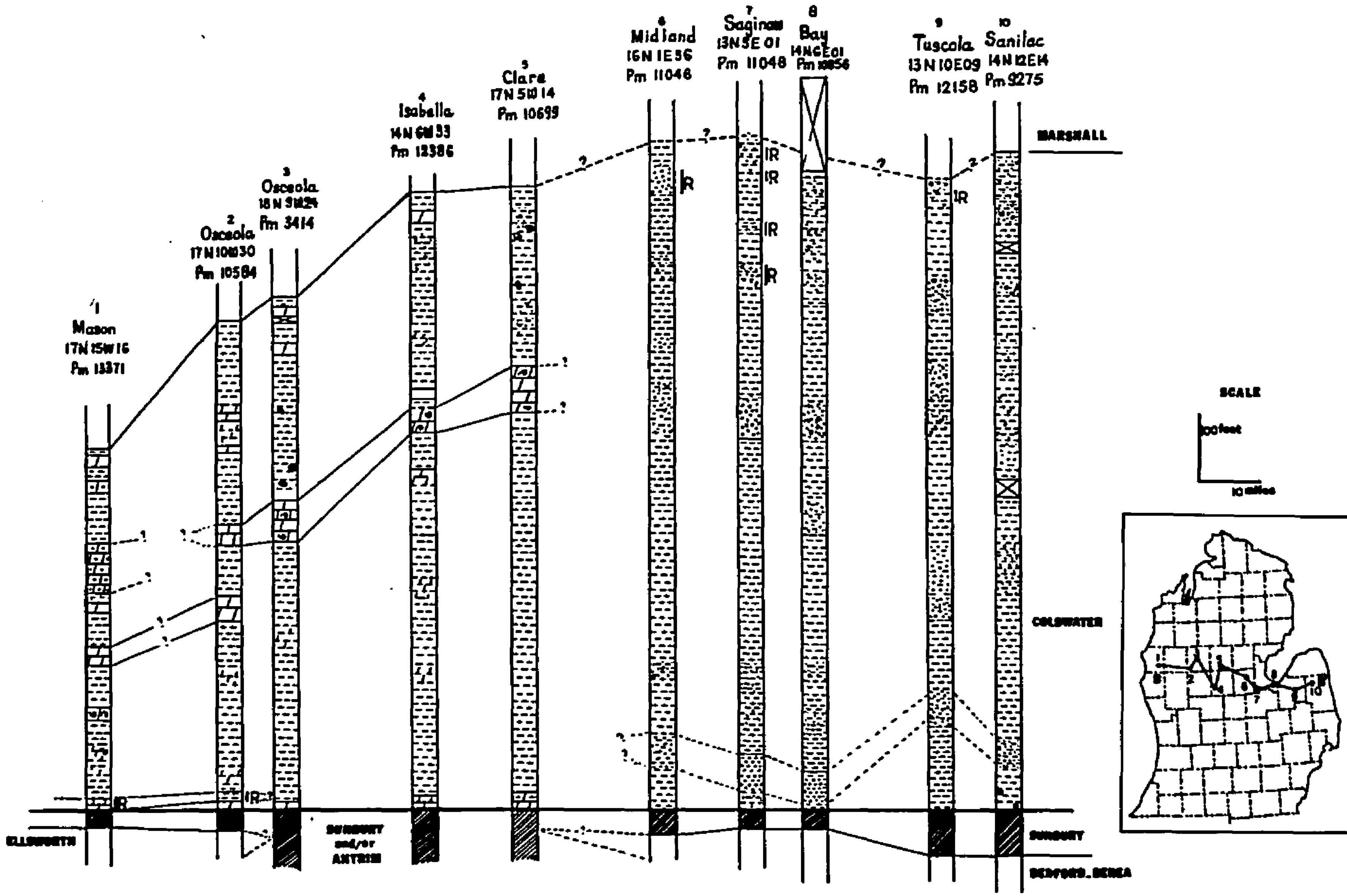


Figure 8.--Stratigraphic Cross-section BB'.

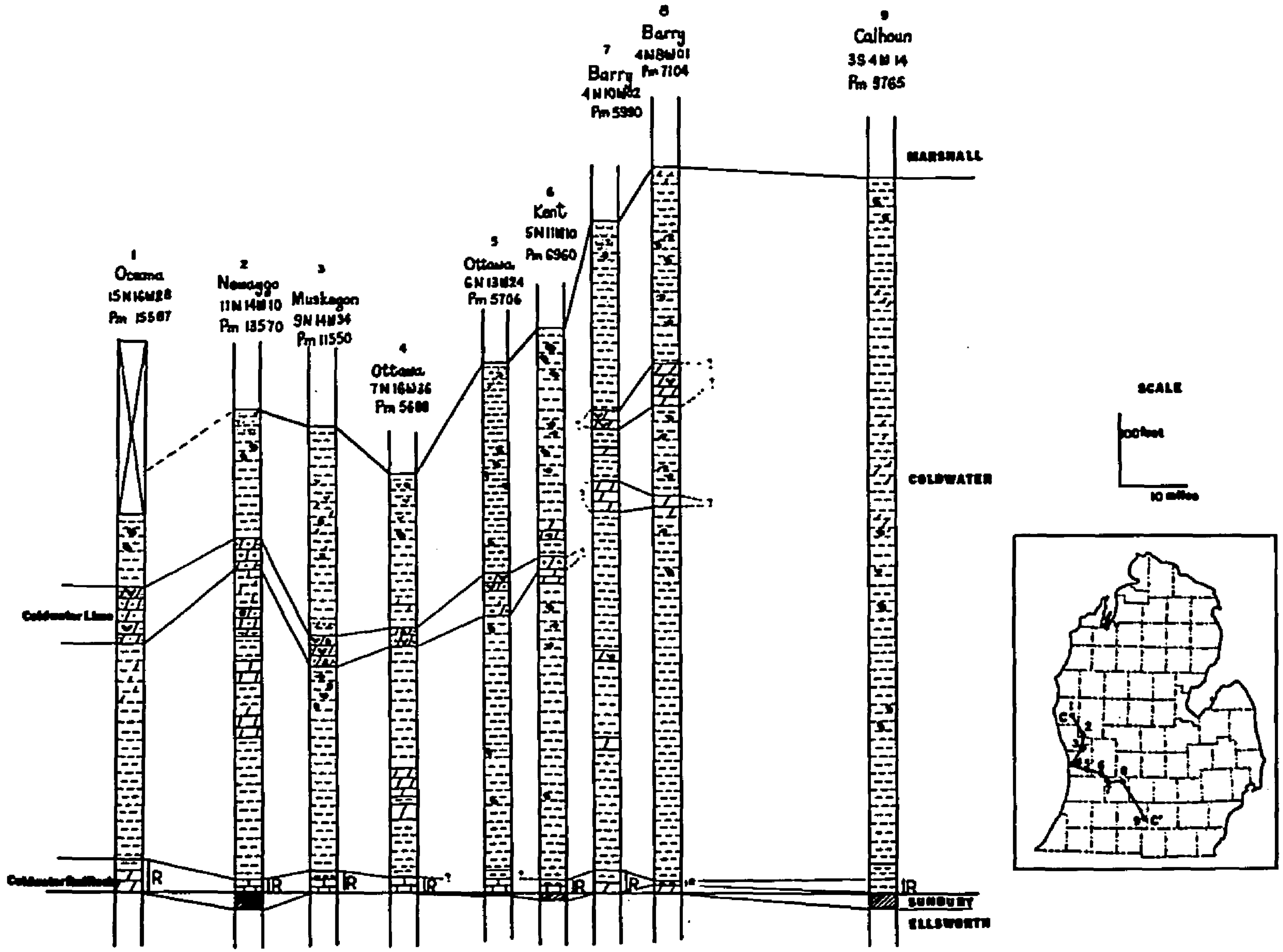


Figure 9.--Stratigraphic Cross-section CC'.

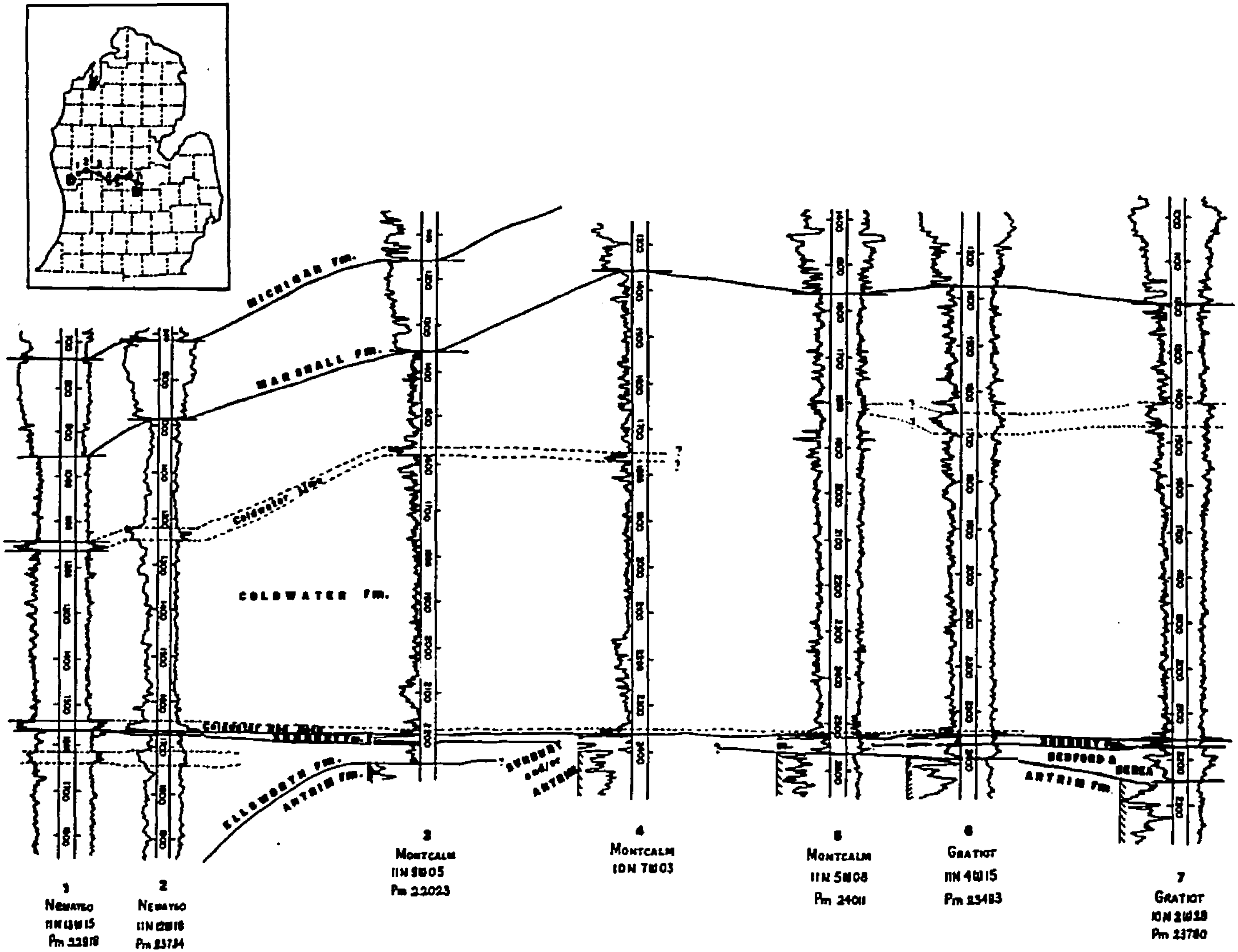


Figure 10.--Cross-section DD' (Gamma ray-neutron log control).

Silt grade size grains were placed with shale grade in this study. The sand percentages were then determined by the following procedure:

$$\text{sand percentage} = \frac{\text{total of sand thickness}}{\text{total thickness}}$$

Lithologic components other than just sandstones and shales are important to the lithologic composition of the Coldwater Formation. As carbonate rocks are important constituents of the western Coldwater sequence, clastic percentages were computed to demonstrate the variation of clastic and non-clastic materials and are displayed in Figure 11. Although, three lithologic components--sandstone, shale and carbonate rock--are present in the Coldwater one might consider a triangle facies display to indicate the component percentages. However, because the facies change is rather uniform, with sandstone confined mostly to the east and the carbonate rocks--dolomite and limestone--are prevalent only in the west, the writer preferred display by isopleths. The sand percentage decreases gradually westward, from a maximum of about 30% in the Coldwater depocenter area and also in Tuscola, Genessee and Lapeer Counties, to about 1-5% over most of the central part of the Basin (Figure 11). The western extent of sand forms the boundary of the eastern and western facies. It is significant to note

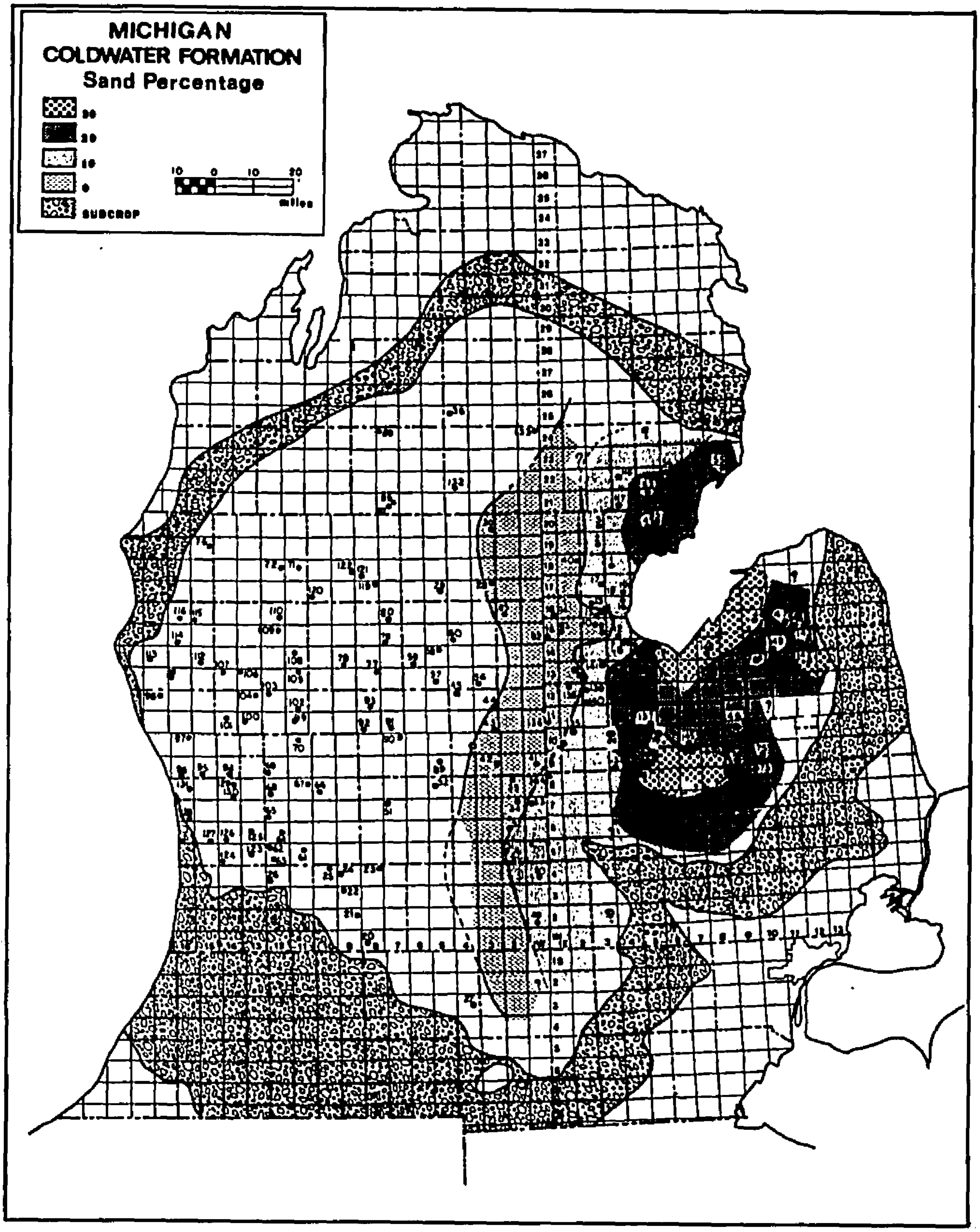

MICHIGAN
COLDWATER FORMATION
Sand Percentage
SUBCROP
miles

Figure 11

that the sand percentage is highest where the Coldwater is thickest and could be interpreted to mean that the distribution of coarse clastic sediments, in addition to the greater proximity to the inferred source, is related to the subsidence of the Coldwater depocenter. In this eastern part of the Basin the higher quartz sand content was likely close to the shore, and the water was likely shallower, with a high energy wave and current environment with higher potential conducive to the destruction of organic matter in the sediments, effecting the color of the sediment. Also, towards the east, the mica content increases, with large mica flakes also increasing at the same time with the quartz sand content. More concerning the clay minerals will be covered later.

Likewise, the clastic percentage also decreases westward (Figure 12). Total 100% clastic content is located in eastern and central Michigan. In western Michigan the clastic percentage decreases to about 60-70%. Moreover, the approximate parallelism of the facies gradient and the isopachous line in the west can be interpreted as indicating that the contribution of find muds is reduced in quantity because of distance from source area and that the lime and lime muds increase.

The color of the Coldwater sediments varies from dark gray to light gray and red. The distribution pattern of shale color is illustrated in the shale color map

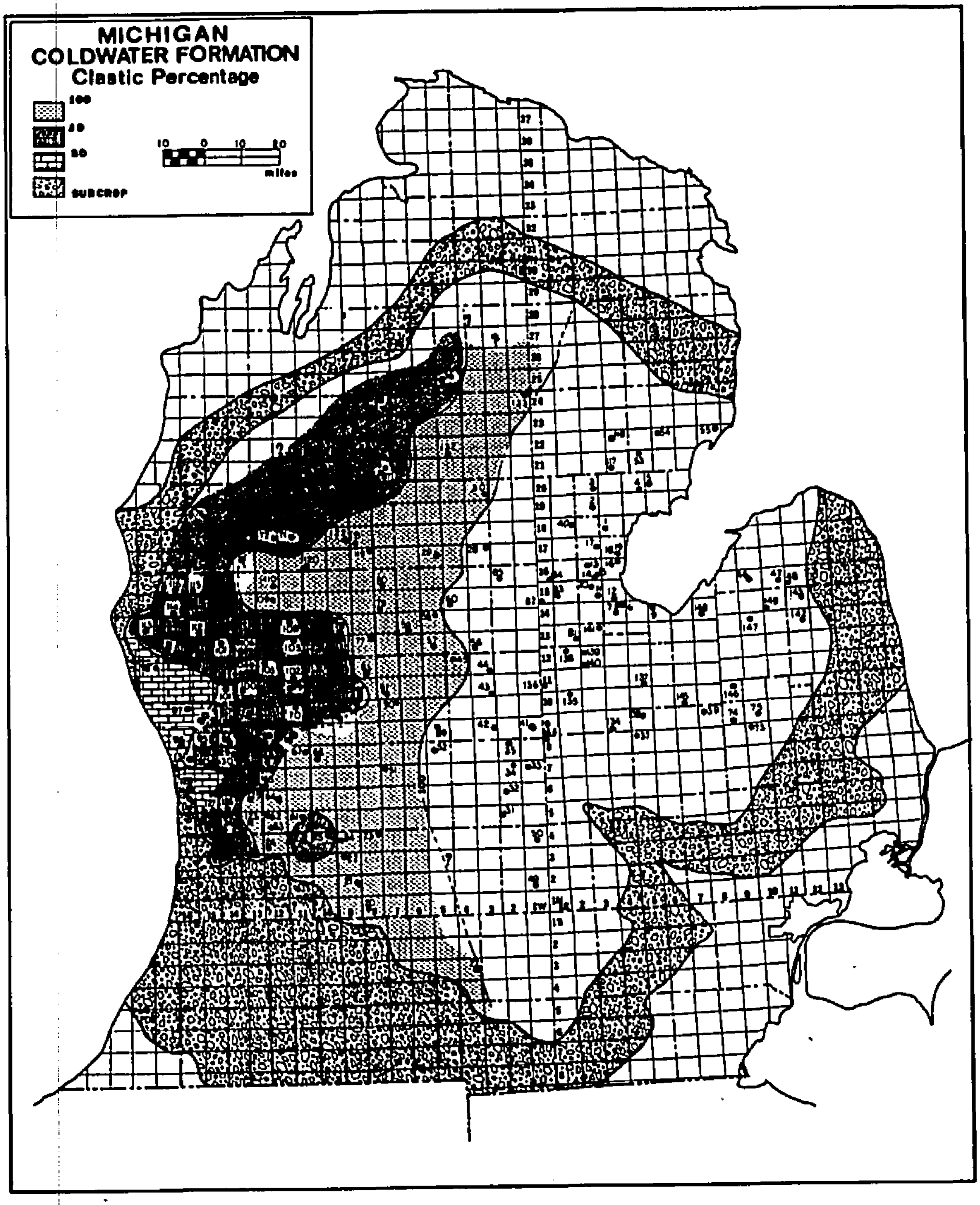

MICHIGAN
COLDWATER FORMATION
Clastic Percentage
miles
SUBCROP

Figure 12

(Figure 13). Dark gray shales, including dark shales, exceed the light gray shales in total thickness. They are located in the central part of northwestern Michigan, covering the area from Roscomon to Muskegon Counties. The darker color suggests reducing conditions of poorly aerated deeper waters. It is also possible to interpret that low permeability in the homogeneous fine-grained shales, which deposited far from source areas, account for the development of reducing environments. From this region, the shale color becomes lighter towards the west, southwest and the east, where light gray exceeds dark gray. It is difficult to state how much "grayness" defines "light" gray and "dark" gray. However, for the sake of some standardization, the writer used the Rock Color Chart (1948) and dark gray is apparently close to 5YR N2-N3 and the light gray close to 5YR N5-N6.

Northeastern Michigan contains a significant proportion of red rocks. These reds mostly are confined to the upper part of the Coldwater Shale, limited from 500 feet below the top to the top of the formation. The lowest zone of red siltstones and shales can be traced as the most persistent zone. Between this zone and the top, there exists three or four other red units of sandstones and shales. The areal distribution limit of these upper red zones in the Coldwater Formation is displayed in Figure 14. It is evident that a major influx of red

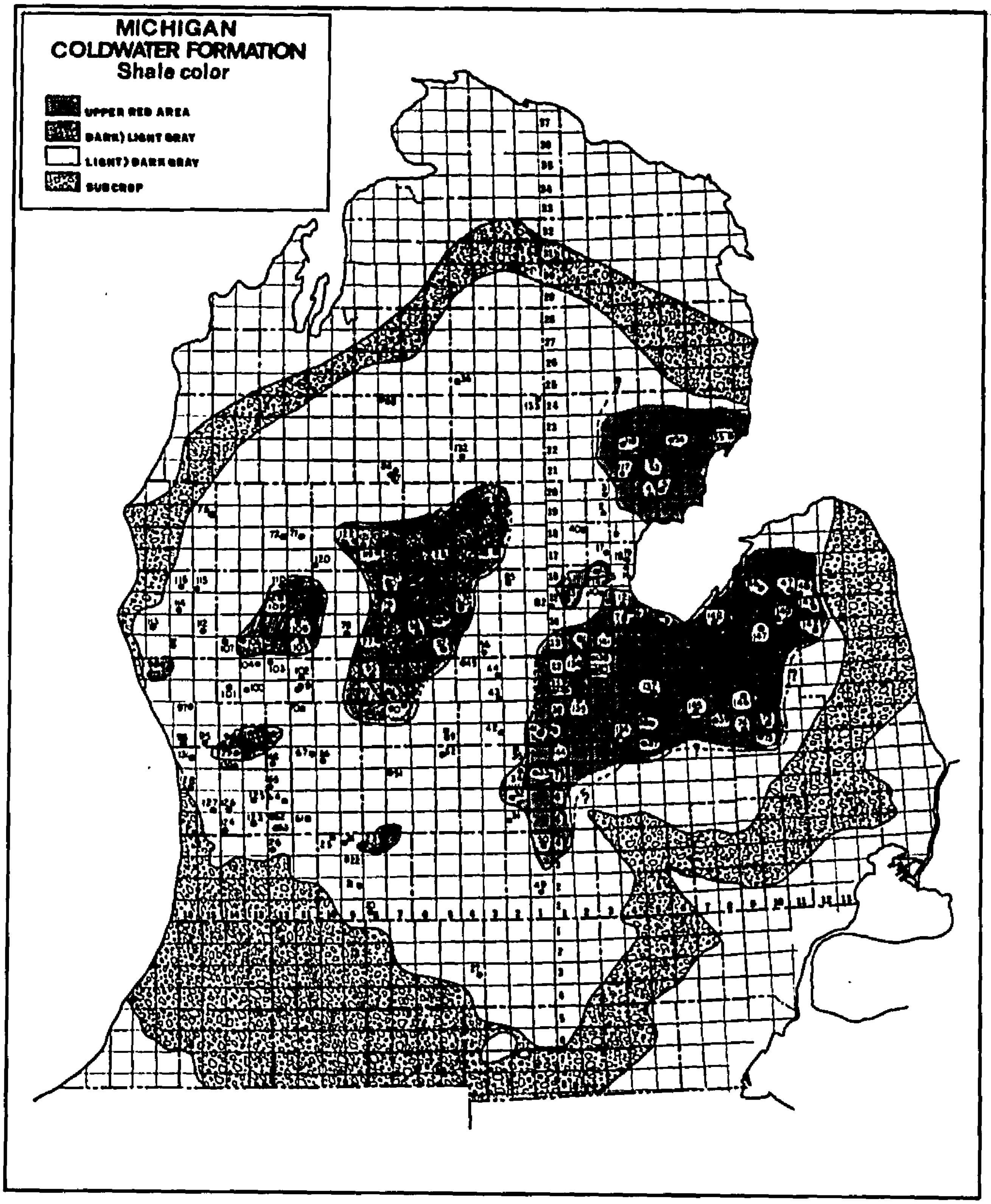

MICHIGAN
COLDWATER FORMATION
Shale color
UPPER RED AREA
DARK) LIGHT GRAY
LIGHT) DARK GRAY
SUBCROP

Figure 13

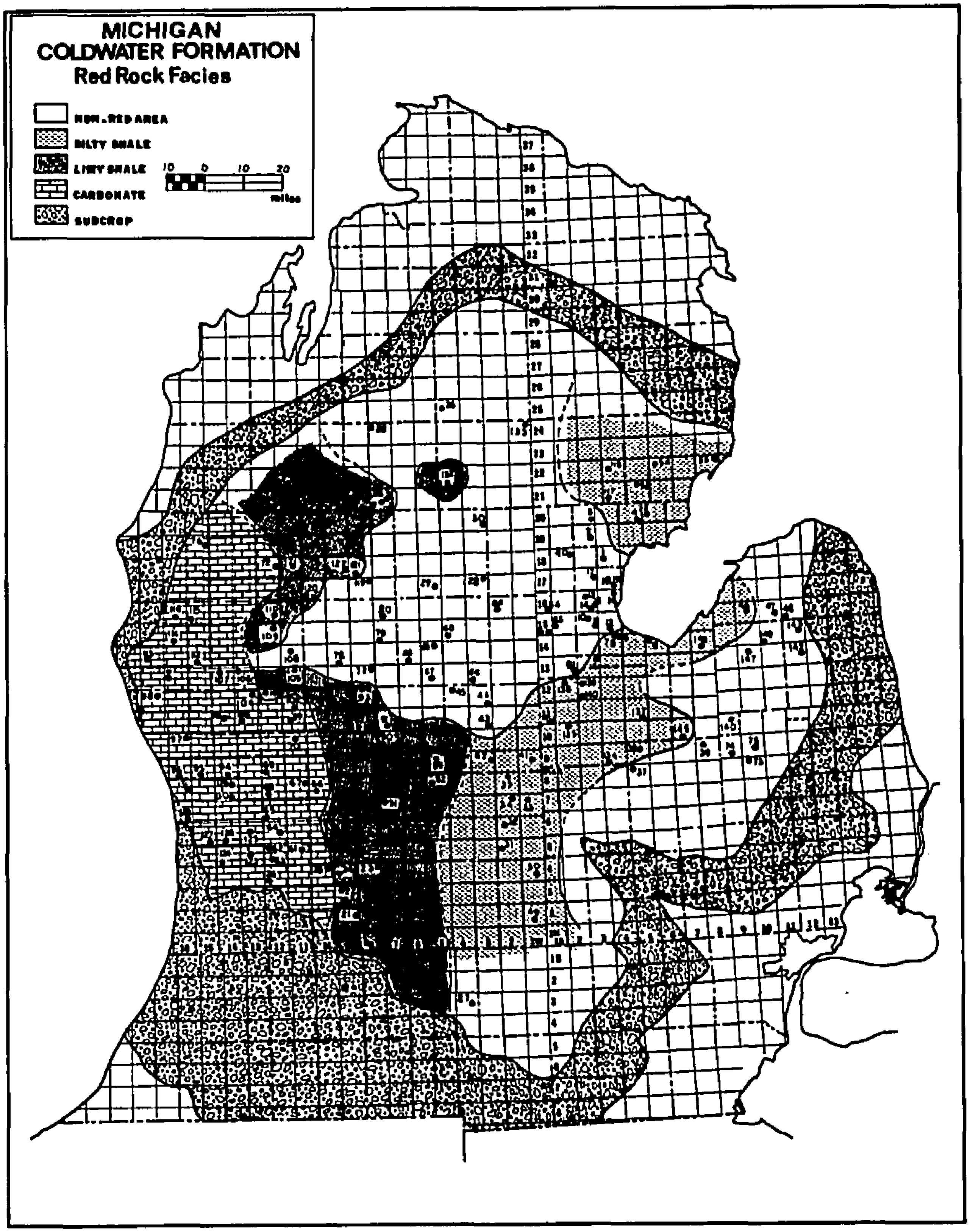

MICHIGAN
COLDWATER FORMATION
Red Rock Facies
NON-RED AREA
SILTY SHALE
LIMY SHALE
CARBONATE
SUBCROP
10 0 10 20
Miles

Figure 14

sediments entered the Basin from the east and/or the northeast. The red color suggests well-oxidized, perhaps highly-aerated, shallow-water environment, during the late Coldwater deposition in this region. It is possible to believe that the shoreline should be very close to the Saginaw Bay area at this time. A study of the environmental implication of fossils as reported in the literature from eastern outcrops and the meager information gleaned from fragmented fossils in subsurface samples play some part in the sedimentary environmental interpretations and will be discussed later. The above information leads to the conclusion that the Coldwater clastics were derived from a generally north-northeastern source, or sources. The clastics probably were derived from the Laurentian Highlands and transported to the Basin area by a river system perhaps not unlike that to which the Berea-Bedford deltaic system was attributed in Late Devonian-Early Mississippian time (Pepper, et al., 1954). Thus a prodelta model is conceived in the area east of Michigan and will be discussed more later.

Special Sedimentary Features

The most striking characteristic of the Coldwater shale is its lateral gradation from the east towards the west. However some special sedimentary features such as the clay ironstones, the red rocks, glauconite are also so important that they could add some information to a better understanding of the Coldwater shale.

Concretions.--During the early stage of this study, the writer visited the type locality and some other exposures of the Coldwater in Branch and adjacent counties. At the time of the visit, these exposures including two old abandoned quarries--the Peerless and the Wolverine Portland--were in such poor shape that the writer could not recognize the section as described by Wooten in 1951, much less the type description by Lane (1893).

Generally, bluish-gray shales and few clay-ironstone concretions were observed in most places.

The Peerless cement quarry (NE¼ sec. 16, T. 5S., R. 7W.) presents a few feet of somewhat thick-bedded, arenaceous, greenish-gray shale. The clay-ironstone concretions, which G. M. Ehlers (1916) called "intra-formational conglomerates," occur in zones along the bedding. The individual concretions range from ¼ of an inch to as much as 4 inches in diameter. They are often nearly spherical, though some are elongate or of crescent-shaped form. Hematite is often in the center surrounded by concentric gray silty claystone. There also includes some "pebbles," being angular or rounded, composed of light gray calcareous claystone and embedded in the greenish gray ferrunginous shale.

In the abandoned Wolverine Portland Cement Company quarry (NW¼, sec. 32, T. 6S., R. 6W) the cobble-sized clay-ironstone concretions are concentrated near the top of a 19 foot-section in gray silty shale. The gray claystone in the center is surrounded by concentric limonitic shale layers. In this quarry Wooten (1951) described several horizons of concretions which varied through a range of sizes. The "canon ball" horizon refers to concretions measuring about 6 inches in diameter, which often contain fossils as nuclei; whereas, the "pillow" horizon, stratigraphically below the previous horizon, indicates those larger in size (18" x 12" x 3") often show septarian structures and no fossil nuclei.

Although no fossiliferous beds were observed in place a number of float blocks were observed by the writer to contain chonetid brachiopods (probably *Chonetes scitulus* Hall) and some limonitized crinoid stems. It is evident that some of these concretions are secondary, because the bedding can be seen passing through these concretions.

As all materials are broken to small chips during the drilling process it is impossible to recognize the size and shape of the concretions in the well-cuttings as well as to locate a special stratigraphic zone of clay-ironstones. However, the hard brown iron "shale" found in well cuttings, as suggested by Hale (1941), apparently are drilled-up concretions. During the course of lithologic study, the writer found these hard brown shales mixed with the gray shale in many of the wells studied. However, these materials are apparently abundant in the southwestern part of the Basin, especially in Branch, Kalamazoo, Barry and Ottawa Counties (Cross-section CC'). In some wells, these hard brown shaly materials may comprise about 70 to 80 percent of the 100-foot thickness of shale, apparently indicating a rich concretion zone. Some fragmented fossils, mostly brachiopods, not unlike some at the type locality (Chonetes scitulus cf. pulchella) are usually found within these zones.

It is apparent that the concretion zones are concentrated in the upper part of the Coldwater formation, and to that extent are of some limited stratigraphic significance.

Coldwater red rock.--Coincident with the base of the Coldwater formation is a distinctive key red bed which is traceable in the subsurface over a large area within the Basin. The informal term for this bed is the "Coldwater red rock." Typically, this unit is pink, yellowish-red and deep red.

The Coldwater red rock varies irregularly in thickness from a few inches to as much as 50 feet. The thickest part of this bed generally occurs in the western part of the Basin, where there exists lithologically two different units of red. The red shale locally lies above the red dolomite and/or red limestone (Figure 7, cross-section AA', wells 1, 2 and 3). The limestone is aphanitic with some secondary crystals of clacite; the dolomite is aphanitic to finely crystalline. There is no evidence of an areal distribution pattern for the limestone or dolomite.

The important fact is that this key bed grades laterally across the State. As shown in the cross-section CC' (Figure 9) from well 1 to well 6 there are red limestone and dolomite beds; wells 7 and 8 have calcareous shale; and well 9, red shale. This gradational character is also observed in cross-section AA' (Figure 7) and BB' (Figure 8).

The facies distribution of the basal Coldwater red rock is illustrated in Figure 14, which is based on the well samples studied by the writer and also on the data from published wells. Red dolomite and limestone facies occur in the counties on the western margin of the state; the calcareous shale facies in the north central and south central parts of the Basin; and to the east, red shale and silty shale. A non-red area is located in about central Michigan (Figure 14). As illustrated in the cross-section BB', wells 4 and 5, about 15 feet of non-red dolomite have been observed directly above the Sunbury shale, and is the same unit as the red dolomite farther west. Based on this observation, the writer believes that the red sediments likely may have deposited in this area but transformed to gray because of some environmental factor as a change to reducing conditions. It is perhaps more than coincidental that this general area is also the same where darkest shale occurs (Figure 13) lending additional support that reducing environment prevailed in this area. Similarly, in some localities the red shale occurs as much as 40 feet or more above the Sunbury shale. It is possible that the gray sediments between the Sunbury and red bed once were red.

On the basis of X-ray diffractograms of red samples, Assez (1967) concluded that hematite is the main pigment of the red unit.

Hale (1941) has suggested that the source of red pigment is from the landmasses on the north and west, where the Precambrian iron deposits are abundant. The writer believes if there is any red pigment from these directions, it is not the major source. Based on the lateral gradation of this bed, the writer suggests the source of this hematite is more likely from the east and/or northeast. Moreover, near the top of the formation another series of red sandstones and siltstones occur only in the northeast part of the Basin. These apparently grade to gray siltstone and shale to the west, again suggesting the source of red pigment in Coldwater time is from the east and northeast.

It is possible that the red color may have originated at the site of deposition due to shallow-oxidizing conditions as has been envisioned for other red-bed units (Walker, 1967). However, either being primary in origin or being formed in place, the red color proves at least the well oxidizing environment at the beginning of the Coldwater deposition as opposed to the reducing environment during the Sunbury deposition.

The distribution of the red rock or greenish-gray facies appears related to an oxidizing environment (ferric) or reducing environment (ferrous) respectively, existing in various parts of the basin at various times. Just what were the factors in controlling the oxidizing or reducing environments is not altogether clear. From the isopach and/or structural maps in studies of earlier rocks as the Upper Cambrian (Prouty, 1970) and late Devonian (Asseez, 1967) reducing environments appear tied in with deeper, isolated "pockets" in the sea floor and can be related to thicker areas revealed in the isopach maps. Some suggestions for shallow water oxidizing environment are noticed in the western part of the Basin where the carbonate, both limestone and dolomite, are also hematitic and form the red rock. This shallow area also may have been a factor in the concentration of Mg^{++} to bring about dolomitization in the carbonate environment.

Glauconite.--A remarkable feature is the presence of glauconite which is closely associated with the dolomite in the western part of the Basin. Hale (1941) described the glauconite as abundant in the "speckled dolomite" (facies) and the crystalline dolomite (facies). The writer observed glauconite grains also in the greenish-gray shale immediately above and below the "Coldwater lime" horizon. The glauconite grains are often nearly spherical with their diameters from .2 mm to 1 mm; although some are elongate or long and thin, prolate forms with a length ranging from .5 mm to as much as 2 mm. There is no evidence of an areal distribution pattern for the size and shape of the glauconite. Variable sizes and shapes are observed in the same piece of the well cuttings. This fact is likely to require one to reject the idea that these glauconite grains are reworked materials. Also, no specific distribution (abundant or rare) of the glauconite is indicated.

Many investigators have long believed that glauconite is formed during marine sediment diagenesis; and that it is derived from clays, micas and feldspars. According to Cloud (1955) glauconitization is favored by these physical conditions: in marine water with normal salinity; in a slightly reducing condition in the presence of decaying organic materials; in an area of slow deposition; and in cool water.

These physical conditions may not totally satisfy the formation of glauconite in the "Coldwater lime," but the proposed conditions above may be suggestive of the environmental conditions at the time of "Coldwater lime" deposition.

Chert.--A few pieces of chert were observed in the "speckled domomite," mixing with the glauconite grains and dolomite grains. The chert is aphanitic and light gray in color. In well cuttings, the chert content is not so high that one would assume it to represent chert nodules or chert layers. The writer calls attention to this occurrence of chert in the "speckled dolomite," but it is not a quantitatively important feature.

"Speckled Dolomite".--"Speckled dolomite" was used by Hale (1941) referring to an impure carbonate which consists of light gray dolomite matrix with embedded grains of light brown dolomite. The dolomite grains yielding a somewhat pelletoid or pseudo-oölitic texture and ranging from 0.2 to .05 mm in diameter float in a dolomitic matrix which is argillaceous and sometimes silty. This "speckled dolomite" is a part of the "Coldwater lime" which forms a marker zone in the western part of the Basin. Glauconite and chert are observed in this calcarenite.

As previously cited, the Coldwater Formation is divided into a western and an eastern facies (Monnett, 1948) based mostly on the quartz sand content. The writer agrees with Monnett's idea and prefers to use his facies terms.

Western Facies

The western facies consists almost entirely of gray shales with a minor amount of carbonate rock. Two marker zones are defined in this facies: the "Coldwater red rock" at the base; and the "Coldwater lime" located about 200 feet below the top.

Several exposures of the Coldwater western facies are observed in Branch and Hillsdale Counties, including the type locality along the Coldwater River in section 10 of Union Township. In a study of the Coldwater shale in the type locality, Wooten (1951) compiled a list of exposure localities and also briefly described these localities. The location of the exposures of the Marshall and Coldwater formations in Hillsdale County can be found in the report of Hillsdale County written by Helen M. Martin (1957). The writer had an opportunity to visit some of these exposures where mostly gray silty shales and shales with abundant clay-ironstones were observed. These shales were quarried for cement and brick materials. High silica content is a remarkable characteristic of the Coldwater shale in the type area. A chemical analysis of a shale sample quarried by Peerless Portland Cement Co.

(NW¼ section 15, T. 5 S., R. 7 W.) was reported as follows (Brown, 1924):

Silica (SiO_2)	64.56%
Alumina (Al_2O_3) . . .	22.00
Iron Oxide (Fe_2O_3) . .	2.96
Lime ($CaCO_3$)	.60
Magnesium ($MgCO_3$) . . .	none
Sulphur (SO_3)	trace
Organic	9.88

The basal part of the Coldwater western facies is composed mainly of shales. The thickness of shale in between the key red bed and the Coldwater lime marker bed increases from the west towards the center of the Basin showing the convergence westward (Figure 7). Referring to the isopach map (Figure 4), the thickness of the formation also increases from about 550 feet in the western margin counties to about 1050 feet in the center of the Basin.

The "Coldwater lime" marker zone is a specific feature of the Coldwater facies. Hale (1941) described four types of dolomite belonging to this zone: (1) speckled dolomite without glauconite; (2) speckled dolomite with glauconite; (3) crystalline dolomite with glauconite; and (4) crystalline dolomite without glauconite.

Based on the fact that the western outer rim of this horizon is much thicker, Hale (1941) concluded that a "trough trending northwest and southeast received the deposition of the speckled dolomite sea." The "Coldwater lime" is located about 250-350 feet beneath the formation top. Its thickness ranges about 50 to 80 feet in western margin counties and thins gradually towards central Michigan where it grades laterally into gray shales. A few "lenses" of the crystalline dolomite were observed in west-central Michigan, especially in the northwest where they are associated with pyrite and darker gray shales.

The upper part of the Coldwater western facies is somewhat similar to the lower shale. Reddish brown hard shale observed in the upper part of shale body probably came from a drilled clay-ironstone concentration zone. This upper part shale is siltier than the lower part with more mica flakes. It apparently proves that in upper Coldwater time more clastic materials spread toward the west and that there was regression and a prograding shoreline westward.

Eastern Facies

Eastern Michigan Coldwater consists chiefly of sandy shales and fine-grained sandstones. Several exposures crop out along the lake short of Huron and Sanilac Counties. Napoleon Sandstone and Lower Marshall

Sandstone are exposed in the western shore and the northern part of Huron County notably at Little Oak point, Hat Point, and Point Aux Barques. Toward the south, shale and sandstone of the Coldwater Formation crop out at Port Hope, Harbor Beach, White Rock in Huron County and at Forestville and Richmondville in Sanilac County. Land (1900) and Gordon (1900) described those exposures and also compiled the geological column for Huron County and Sanilac County, respectively.

The writer intends to review these geological sections and then correlate them into the subsurface stratigraphy.

East of the Burnt Cabin Point, about 25 feet of fine-grained sandstone are exposed, the Grindstone Beds, which grade downward into a blue shale. Lane (1900) placed the Marshall-Coldwater contact on top of this blue shale. This shale is about 30 feet thick becoming increasingly sandy below.

A series of alternating beds of sandstone and blue shale are exposed along Willow River, Huron City and at the Lighthouse. These sections were described and measured by Lane (1900).

Section of Coldwater Strata exposed at Willow River, Huron City and the Lighthouse (after Lane, 1900):

	Feet	Inches
From 89 feet below the top of Coldwater Shale.		
Dirt		6
Sandstone, red (*Rhynchonella*, *Productus*, *Pleurotomaria*, etc.)		3
Barren		3
Shale, sandy		6
Shale, blue, sparingly fossiliferous	3	
Shale, blue, without fossils	2	
Shale, arenaceous	-	-
From 156 feet below the top.		
Shale, blue	11	3
Sandstone, calcareous		3
Shale, blue, sandy	3	
From 170 feet below the top.		
Sandstone (Schizodus)		4
Shale, blue	1	3
Sandstone, conglomeratic, pyritic	3	8
Shale, blue (Productid, *Spirifer*, Trilobite larvae (?) corresponding forms observed in *Romingerina julia* zone	12	

The conglomeratic sandstone at about 170 feet below the top of Coldwater Shale is called Point Aux Barques Lighthouse Conglomerate. This nomenclature is easy to confuse with the Point Aux Barques Sandstone or Lower Marshall sandstone which occurs considerably above the Lighthouse Conglomerate. The Point Aux Barques sandstone is massive, cross-bedded and fine to coarse-grained.

About 283 feet below the top is a blue sandy shale which is exposed along the shore south of Port Hope and at the mouth of Diamond Creek.

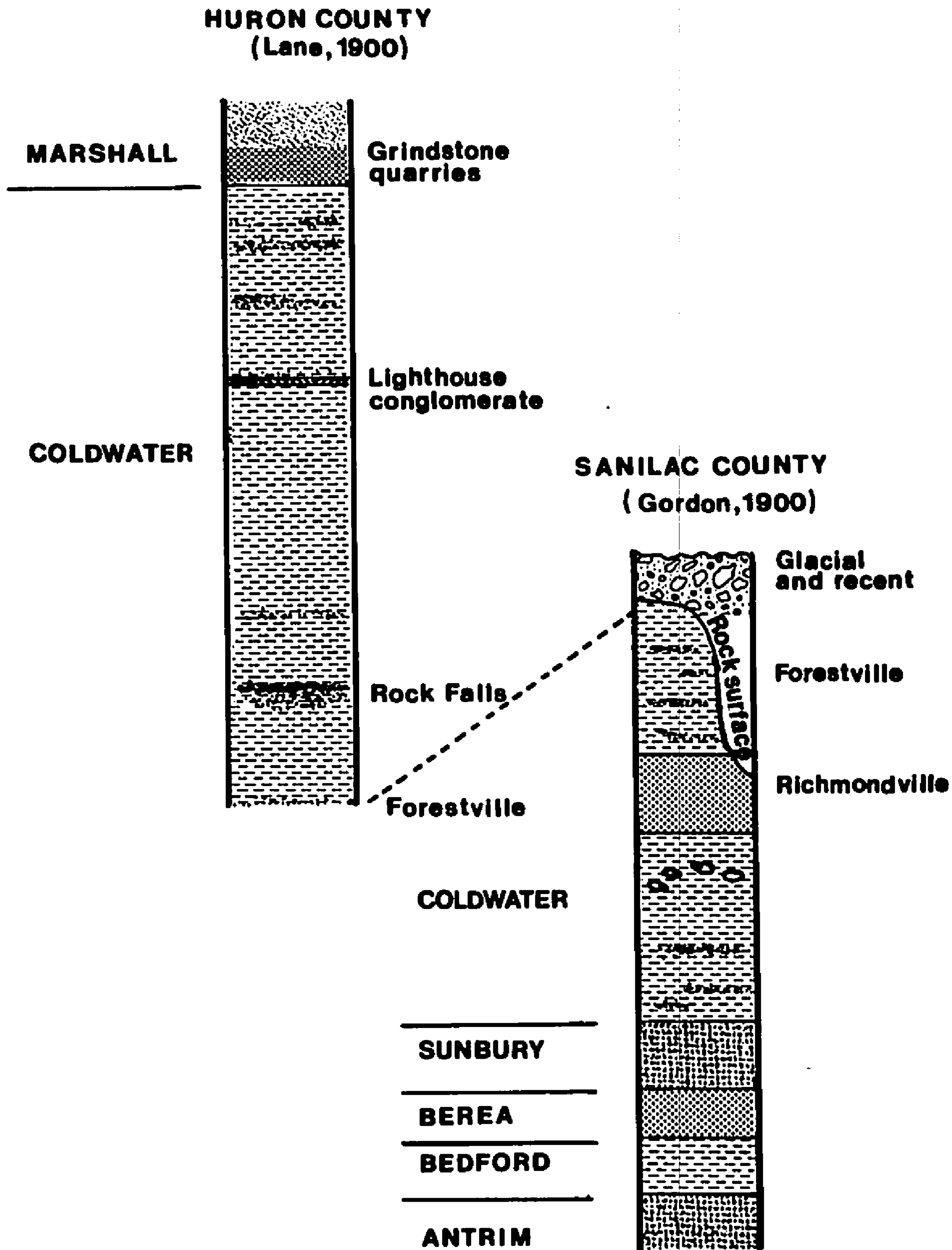
Toward the south, shales and arenaceous shales with carbonate of iron are exposed near Harbor Beach where Lane (1900) described Chonetes scitulus cf. pulchella, Productus loevicosta, and Conularia gracilis.

Blue shale and sandy shales with Chonetes also are exposed at Rock Falls and White Rock. They are about 450-500 feet below the top of the Coldwater Shale.

In Sanilac County, shale and sandstone are exposed at Forestville and Richmondville. The Forestville shale is thinly laminated and interbedded with fine-grained micaceous sandstones. The Richmondville sandstone refers to an outcrop of sandstone exposed near Richmondville, Sanilac County. Gordon (1900) described it as 50-80 feet thick of sandstone and placed it within 100-200 feet below the top of the section (the Forestville blue shale).

Based on the geological column of Gordon (Figure 15) the maximum thickness of the Coldwater Formation is about 500 feet in Sanilac County. This thickness is too thin for the full Coldwater section (see Coldwater isopach map, Figure 4), and the glacial drift probably rests on the truncated upper part of the formation.

Comparing two geological columns of Lane and Gordon (Figure 15), the writer believes that the Forestville shale at the bottom of Lane's column is equivalent to the



(Pham Chung, 1973)

Figure 15.--"Standard Section" of Eastern Coldwater. (after Lane, 1900; Gordon, 1900)

Coldwater at the top of the section (the Forestville shale) of Gordon's column. The Forestville blue shale is 500 feet above the Sunbury black shale and 550 feet below the top of the Coldwater. It is apparent from the isopach map (Figure 4) that the thickness of this formation should be about 1000-1050 feet thick in Huron and Sanilac Counties. The Richmondville sandstone, in terms of stratigraphic sequence (subsurface), should be close to the base of the formation, or about 200 feet above the Sunbury black shale. The combine of these two columns tied in according to Figure 15, can be considered a "standard section" for the Coldwater formation in east Michigan. Near the top, the Coldwater is sandy with some coarse clastics (the Lighthouse conglomerate) then followed downward by interbedded sandstones and shales (Harbor Beach, White Rock). The Formation is somewhat shaly at Forestville, becoming sandstone (Richmondville) and blue shale towards the base. However, the writer recognizes the difficulty in correlating the "standard section" into the subsurface section. As previously stated, the Coldwater formation grades laterally across the State. No lithologic criteria could be used with confidence to subdivide the formation into specific members; and no one unit can be traced all the way across the state. However, as indicated later, the east and west extremes can be roughly tied together by use of several geographically overlapping data planes.

As shown in Gordon's geological column in Sanilac County, fine-grained sandstone exposed at Richmondville is about 200 feet above the black shale. The basal part of the eastern facies consists mostly of gray shales and fine-grained sandstones. The writer suggests that these sandstones in the subsurface may represent the westward extension of the sandstones exposed at Richmondville, Sanilac County. Newcombe (1933) stated:

> 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 source.

The areal distribution of the sandstone of the Coldwater basal part is shown in Figure 16. It is very fine-grained, micaceous, white to light-gray sandstone. The grain size is about 1/8-1/32 mm in diameter in Huron and Genessee Counties and grades into silt size in Clinton, Saginaw and Midland Counties.

The medial part of the Coldwater eastern facies composes chiefly of gray shales and silty shales. The thickness of this medial shale ranges up to 400-500 feet thick in most parts of eastern Michigan. These gray shales are probably equivalent to the shales exposed at Forestville, Sanilac County.

The upper part of the Coldwater eastern facies is very characteristic. It consists mostly of the interbedded sandstones and shales. This part has a higher quartz sand

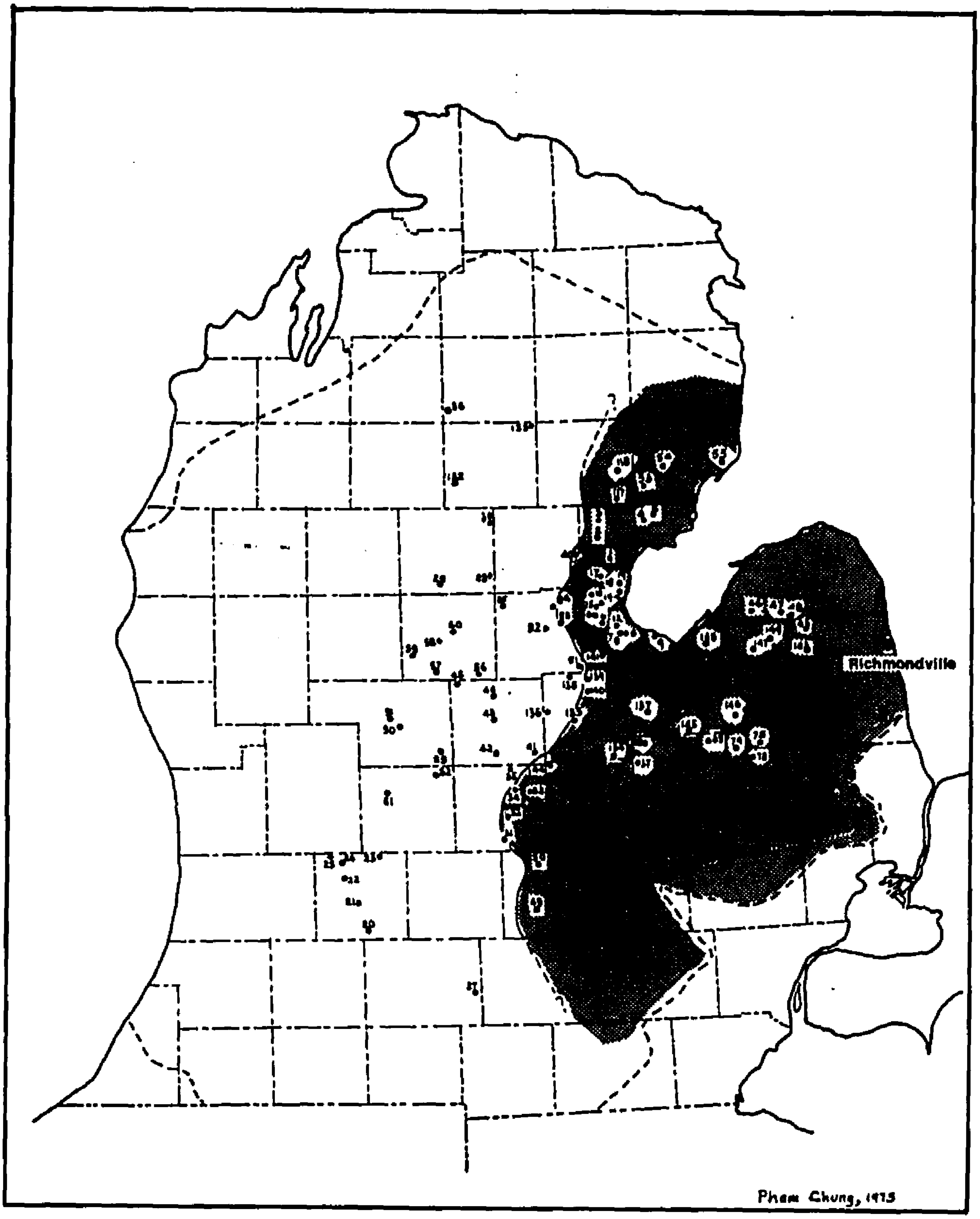


Figure 16.--Aeral Distribution of the "Richmondville" Sand.

content than the lower part of the formation. As many as three or four red zones of sandstones and shales are observed. However, it appears difficult to trace these zones for long distances and they probably grade laterally into gray sandstones and shales. One or two conglomeratic sandstone beds at about 700-800 feet above the Sunbury are observed in Huron, Sanilac Counties but the writer cannot trace their extent because of lack of well samples in this area. It is also noted that these strata are very micaceous with large flakes observed in the sandstones.

In general, the Coldwater eastern facies cannot be divided into viable members but three gross lithologic types exist. The subsurface data is somewhat similar to the outcrop data compiled by Hale (1900) and Gordon (1900) in Huron and Sanilac Counties, respectively.

Clay Mineral Analyses

Review on structure of clay minerals*.--One-third of the mineral composition of the average shales is clay minerals. Clay minerals are referred to as a group of minerals with a particular chemical composition and crystallographic structure. These minerals are described as hydrous aluminum silicates with some adding and replacement of the aluminum by iron and magnesium. Structurally,

---

*After Grim, 1968.

all crystalline clay minerals belong to the phyllosilicate group which has sheet structure with a hexagonal pattern somewhat like that of the micas.

Two structural units are involved in the clay structure: one is silica tetrahedral layer (SiO_4) and the other, octahedral layer (gibbsite and brucite). The thickness of the octahedral layer and the silica tetrahedral layer is 5.05Å and 2.1Å, respectively. With the exception of the allophane clay minerals which are amorphous to X-ray diffraction, the classification of clays is based on the possible combination of the tetrahedral and the octahedral units.

The kaolinite group is classified as a two-layer (1:1) type which is formed by the link of an octahedral sheet to a silica tetrahedral sheet. The first order spacing (001) of the kaolinite is 7.15-7.20Å.

The illite group is structurally represented by an octahedral sheet intercalated between two silica octahedral sheets (2:1). Some of the silicon in its structure are replaced by aluminum, then potassium will be added to balance its charge. Illite is a "non-expanding lattice" clay, and its first order spacing is about 10Å.

Montmorillonite is also a three-layer (2:1) type, like the illite group. It is referred to as an "expanding lattice" clay, because the water and other molecules can be adsorbed, causing swelling in the c-direction. Its swelling character is useful in identifying montmorillonite with X-ray diffraction. Table 5 shows that its first order spacing is 13-15Å, 18Å and 10Å corresponding to untreated, Mg-Glycerol treated and heated sample, respectively.

The chlorite is a regular mixed-layer type which consists of three-layer with an interlayer brucite sheet. Its first order spacing is 14Å.

Clay mineral analysis of the Coldwater was undertaken to determine if the various clay minerals could be correlated with lithologic types and the general facies relationships.

<u>Sample treatment and analytical methods</u>.--There were no available cores so well cuttings were used. Eleven wells (Table 3), with representative basinal spacing were selected for clay mineral analyses. Samples representing 5 or 10 feet intervals were contained in vials. About one quarter of a gram was taken from each vial to represent nearly one-third of the total depth of each well. Thus, three composite samples were obtained from each well studied even though no attempt was made to divide the Coldwater shale into a three-fold formation.

After initial fracture in an iron mortar, samples were further dissaggregated mechanically and ultrasonically and transferred to a 1000 ml graduated cylinder. Then, it was filled with distilled water until the volume was exactly 1000 ml and agitated vigorously with

TABLE 3.--List of Well Samples Used for X-ray Experiments.

Permit	Location	Sample
11333	SW-15 T.24N.R3E	1A: 700-1000' 2A: 1050-1400' 3A: 1450-1850'
7462	SE-13 T19N.R3E	2A: 550- 810' 2B: 820-1110' 2C: 1120-1510'
9275	NW-14 T14N.R12E	3A: 335- 600' 3B: 625- 900' 3C: 925-1300'
12612	NE-33 T10N.R7E	4A: 450- 800' 4B: 805-1140' 4C: 1150-1495'
9215	SE-25 T20N.R3W	5A: 1530-1900' 5B: 1940-2270' 5C: 2290-2500'
12130	NW-15 T9N.R1W	6A: 1045-1280' 6B: 1300-1700' 6C: 1720-1920'
9987	SW-22 T4N.R1W	7A: 950-1280' 7B: 1300-1600' 7C: 1620'1950'
9765	SW-14 T3S.R4W	8A: 300- 550' 8B: 570- 900' 8C: 920-1250'
7381	SE-24 T21N.R9W	9A: 1750-2000' 9B: 2050-2250' 9C: 2300-2450'
8998	SW-20 T16N.R11W	10A: 1600-1730' 10B: 1750-1950' 10C: 2000-2200'
10596	SW-12 T8N.R11W	11A: 800-1100' 11B: 1150-1350' 11C: 1400-1650'

a stirring rod. The <2μ fraction was siphoned off after 24 hours settling at the 10 cm depth. The cylinder then was refilled with distilled water and the same procedure was repeated.

A few cubic centimeters of clay suspension were allowed to settle on a ceramic plate so that most of the flakes were oriented parallel with the plate. The liquid portion was drawn through the plate by means of a vacuum procedure. The oriented sample was leached with 3 increments of 0.1N $MgCl_2$, then rinsed with several increments of water, 10% glycerol by volume.

Samples, after successively drying in air and in a dessicator over $CaCl_2$, were ready for X-ray as a magnesium saturated, glycerol solvated, oriented aggregate (following the method of Dr. Max Mortland, Department of Crop and Soil Science, Michigan State University).

After the first X-ray taken, samples were continued to be treated following the flow-sheet procedure shown in Table 4 for total clay mineral composition. The cation saturation was varied by passing three increments of 0.1N KCl solution through the plate, then rinsed with distilled water. After heating the plate to 100°C for two hours, the sample was X-rayed as a potassium saturated aggregate. A third and a fourth X-ray were run after the sample was heated for two hours at 300°C and 550°C, respectively.

TABLE 4.--Flow-sheet of X-ray Procedure.

SAMPLE

Dispersion

Settle (24 hrs.)

Decant

SUSPENSION	RESIDUE	
Deposit on ceramic film	Dispersion	
Leach (3 incrememts 1N Mg-Gly)	Settle (24 hrs.)	
Rinse (Dist. H_2O-10% Gly)	Decant	
Dry (room T^0-dessicator)	Suspension	Residue

<u>X-RAY (1st)</u>

Leach (3 increments 1N KCl)

Rinse (Dist. Water)

Heat (2 hrs. +110°C)

<u>X-RAY (2nd)</u>

Heat (2 hrs. +300°C)

<u>X-RAY (3rd)</u>

Heat (2 hrs. +550°C)

<u>X-RAY (4th)</u>

The X-ray diffraction was carried out with a Norelco diffractometer equipped with a copper target, scanning speed of 2°2θ per minute, the scale factor setting at 8. Scanning occurred over the range either from 2° to 35°2θ for clay mineral composition or from 2° to 15°2θ for statistical analysis.

After the samples were run, each diffractogram was examined, every peak was measured and a record of its d-spacing and intensity was compiled. For mineral identification, d-spacing could be checked in the common mineral d-spacing lists such as Grim (1963) or Griffin (1970). In order to determine the relative proportion of the end-member clay minerals, the semi-quantitative analysis by peak-height ratios was used. The peak height is a function not only of clay amount but also of size, crystallinity and other factors. According to Griffin and Ingram (1955):

> It is realized that the use of intensities of (00ℓ) lines as a measure of absolute clay mineral abundances is open to many uncertainties; but as all the samples were handled in the same manner and as only ratios of intensities of (00ℓ) lines in the same pattern were used, the results . . . are considered to be significant.

The method to measure the peak-height ratio was explained in detail by Griffin (1970). Thus, to make the estimation of clay proportions contained in the Coldwater shale, the 10Å/7Å and 14Å/7Å peak height ratios were used. These peaks represent the (001) peak of chlorite (14Å), illite (10Å) and chlorite and kaolinite(7Å).

TABLE 5.--X-ray Diffraction Data for Clay Minerals (Different Treatments).*

Clay Minerals	Natural	Mg-Glyc.	K sat. Heat 100°C	K sat. Heat 555°C
Illite, mica	10.0Å	10.0A	10.0A	10.0A
Kaolinite	7.15A	7.15A	7.15A	--
Chlorite	14.5A	14.5A	14.5A	13.8A
Vermiculite	14.5A	14.5A	10.0A	10.0A
Montmorillonite	13-15A	18A	10.0A	10.0A

*Data after Dr. Max Mortland, Department of Crop and Soil Science, Michigan State University.

TABLE 6.--X-ray Diffraction for Clay Minerals and Quartz.*

Quartz		Illite		Kaolinite		Chlorite		Montmorillonite	
d(A)	hkl	d(A)	hkl	d(A)	hkl	d(A)	hkl	d(A)	hkl
4.26	100	10.0	001	7.15	001	14.2	001	18.0	001
3.34	101	5.0	002	3.56	002	7.1	002	9.0	002
2.46	110	3.33	003	2.38	003	4.71	003	6.0	003
2.28	102	2.5	004	1.78	004	3.56	004	4.5	004

Analytical results.--Some X-ray diffractograms are shown in Figures 17, 18 and 19. They generally display relatively symmetrical and sharp 10Å peaks suggesting fine-grained and well-crystallized illite. Kaolinite may be confused with chlorite in the X-ray diffractogram, because both of them have 7.0Å reflection. However, chlorite is clearly identified by (003) reflection at 4.7Å and also by the (001) reflection 14Å which shifted to 13.7Å after heating the sample to 550°C. At 550°C, the 7Å peak disappears; thus, the presence of kaolinite is verified.

Clay mineral composition of the Coldwater shale.--The Coldwater shale analysed in this study was composed almost entirely of the minerals illite, kaolinite and chlorite, and colloidal-sized quartz, but in widely different proportions. A minor proportion of vermiculite was found in the samples. However, it was diluted by illite and could be detected only by the additional CEC analysis. Montmorillonite and mixed-layer minerals were not detected in the X-ray diffraction studies. In a study of Lower Mississippian sediments, Asseez (1967) also recognized that kaolinite, illite and chlorite are the only clay minerals in his samples. The absence of montmorillonite and mixed-layer clays could be interpreted as meaning that either no such clays were derived from the source areas, or were present but transformed to other minerals during burial.

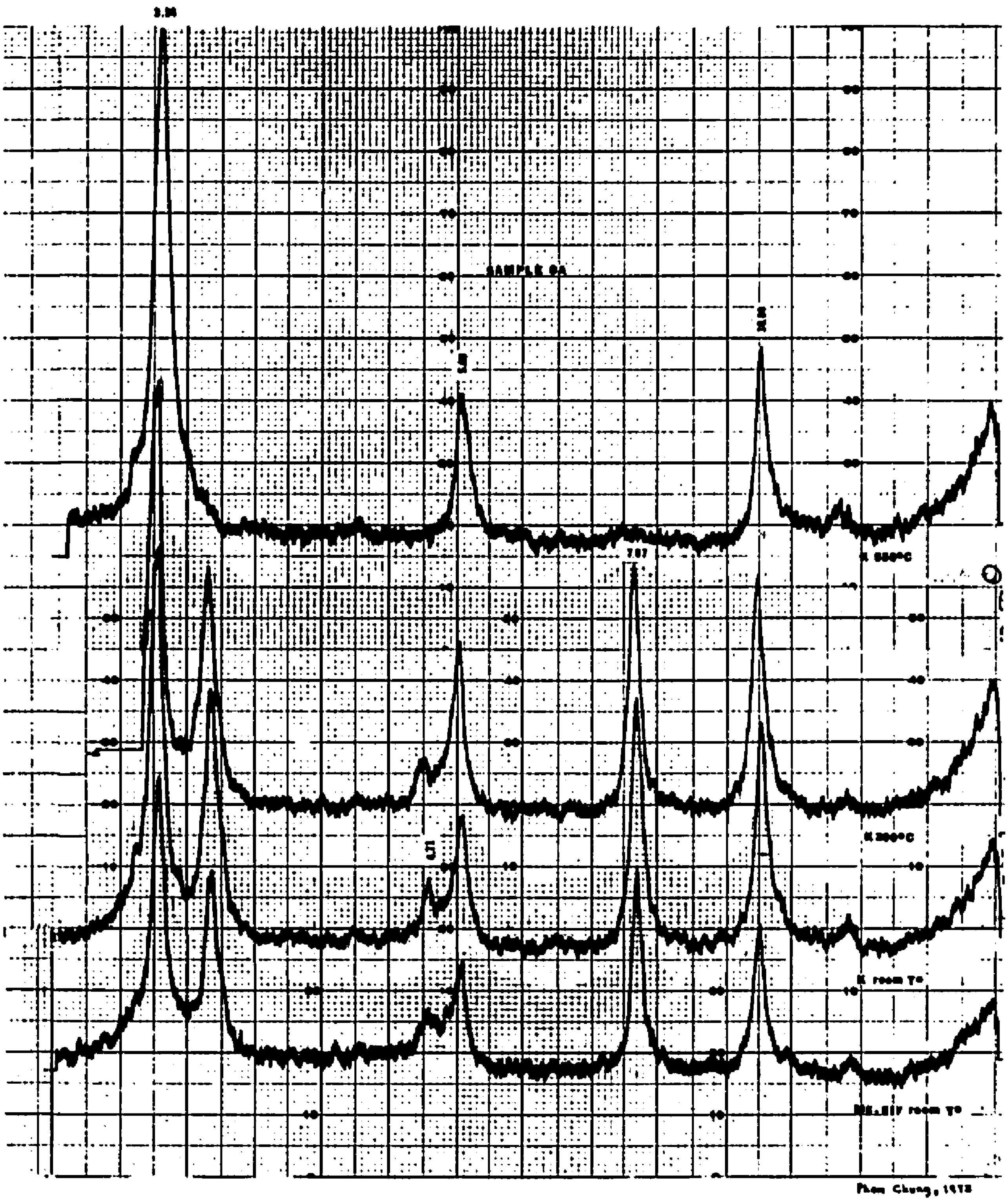


Figure 17.--X-ray Diffractogram--Sample 8A.

Figure 18.--X-ray Diffractogram--Sample 4B.

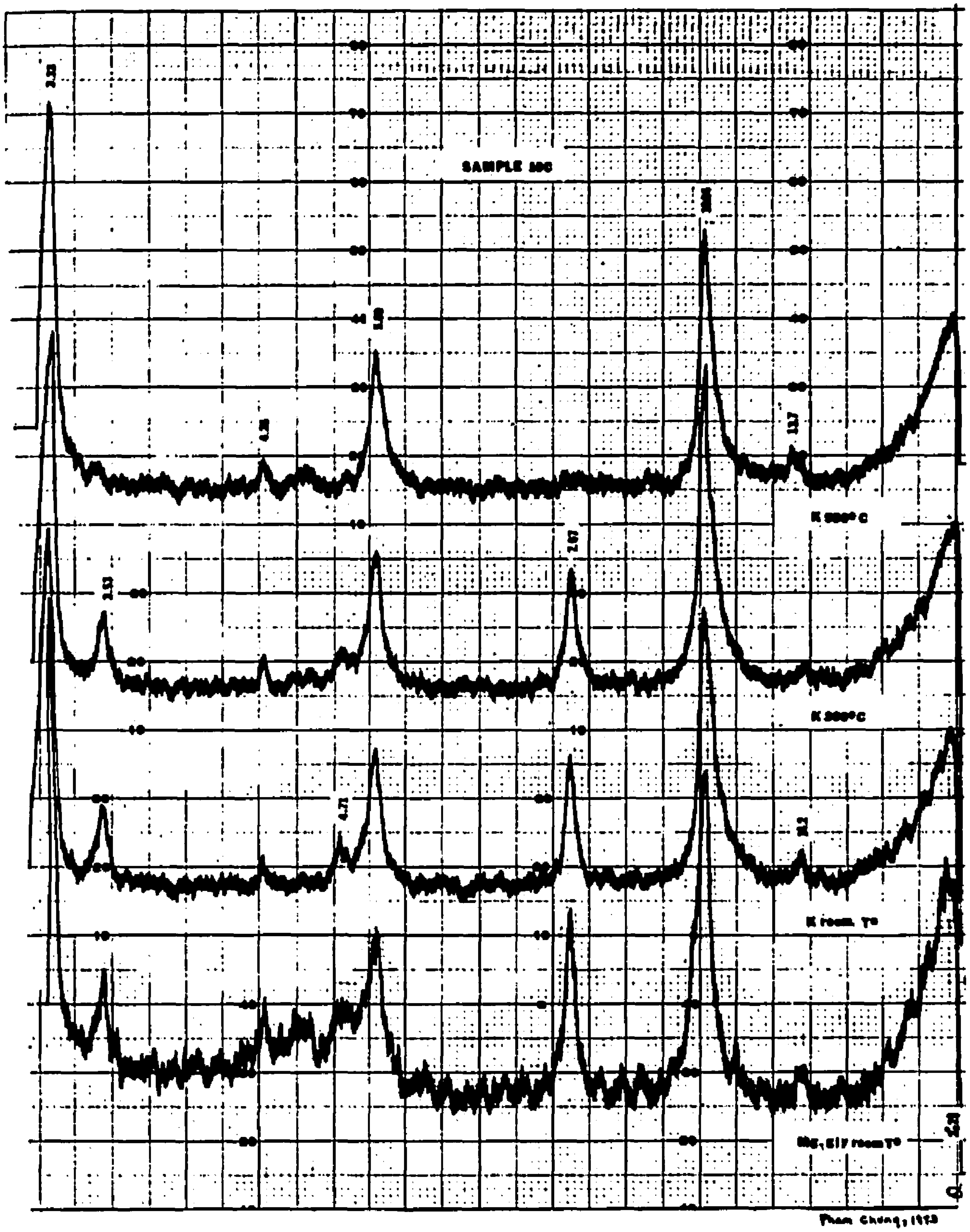


Figure 19.--X-ray Diffractogram--Sample 10C.

Based on the study of the clay mineral composition of the Lower Paleozoic shales of Illinois, Grim and associates (1957) found that illite is a prominent component, chlorite and kaolinite are present in lesser amounts, and montmorillonite is usually absent. They suggested that the montmorillonite and kaolinite may have been transformed into illite by the diagnostic process. In the old sediments such as the Coldwater shales, the same process may take place. However, the kaolinite content is relatively high in the Coldwater mineral composition. The conditions to form kaolinite are much different than those to form montmorillonite (Grim, 1958; Keller, 1970; and many others). Therefore, based on the fact that the kaolinite is abundant and the montmorillonite is absent, the writer believes that in the source areas the conditions of climate and topology apparently favored the formation of kaolinite instead of the montmorillonite. If it is true, the Coldwater sediments should come from a region with the abundance of granites and gneisses, the climate should be warm, with high rainfall and good drainage.

<u>Lateral change in clays and lateral gradation in lithology</u>.--An attempt was made to determine any significance of vertical and lateral changes within the clay mineral assemblages. As shown in Figure 18 the sample 4B (eastern facies) has the 7.07Å peak more intense than the 10.04Å peak, suggesting that the kaolinite content is relatively

abundant compared with the illite. On the other hand, sample 10C (Figure 19) of the western facies, has the 7.07Å peak less intense than the 10Å peak. The 10A/7A ratio is shown in Table 7 illustrating the variation of the illite content with respect to the kaolinite within the Basin. Chlorite gave a relatively weak (001) reflection, therefore some 14/7Å cannot be recorded as shown in Table 7. The chlorite content is so low (about 2-4% total clays) that it could be considered insignificant.

As shown in Figures 20, 21 and 22, the 10Å/7Å ratio increases from east Michigan toward the west, therefore indicating significant change in the proportion of clays from east to west. The statistical analysis (Appendix 1) shows that there is lateral change in clays within the Basin.

The lateral change in the clay mineral assemblage appears to relate to the lateral gradation in lithology within the Basin. A high proportion of kaolinite appears to prevail in the eastern facies (high quartz sand content). There is a progressive decrease in kaolinite and a corresponding increase in illite and probably chlorite toward the west. Lithofacies shows coarse sand prevailing to the east and fine mud and carbonate lenses occurring in the west. The relation of facies demonstrates the nearshore-offshore relationship. Many investigators, such as Millot

TABLE 7.-- $\frac{\text{Illite}}{\text{Kaolinite + Chlorite}}$ and $\frac{\text{Chlorite}}{\text{Kaolinite + Chlorite}}$ Ratios.

Sample	10A/7A	14A/7A
1A	.61	.09
1B	.53	.10
1C	.86	.10
2A	.57	.10
2B	.50	.08
2C	.87	.13
3A	.60	.09
3B	.58	.12
3C	.86	--
4A	.35	.05
4B	.44	.09
4C	.82	--
5A	1.93	.25
5B	2.30	--
5C	1.16	.09
6A	.82	.08
6B	1.23	.14
6C	1.19	.11
7A	.87	.10
7B	.66	--
7C	.56	--
8A	.72	.09
8B	1.13	.13
8C	1.30	.15
9A	1.17	.25
9B	1.49	.27
9C	1.20	.20
10A	1.55	--
10B	1.64	.23
10C	1.78	.18
11A	1.08	.12
11B	1.59	.17
11C	1.76	.10

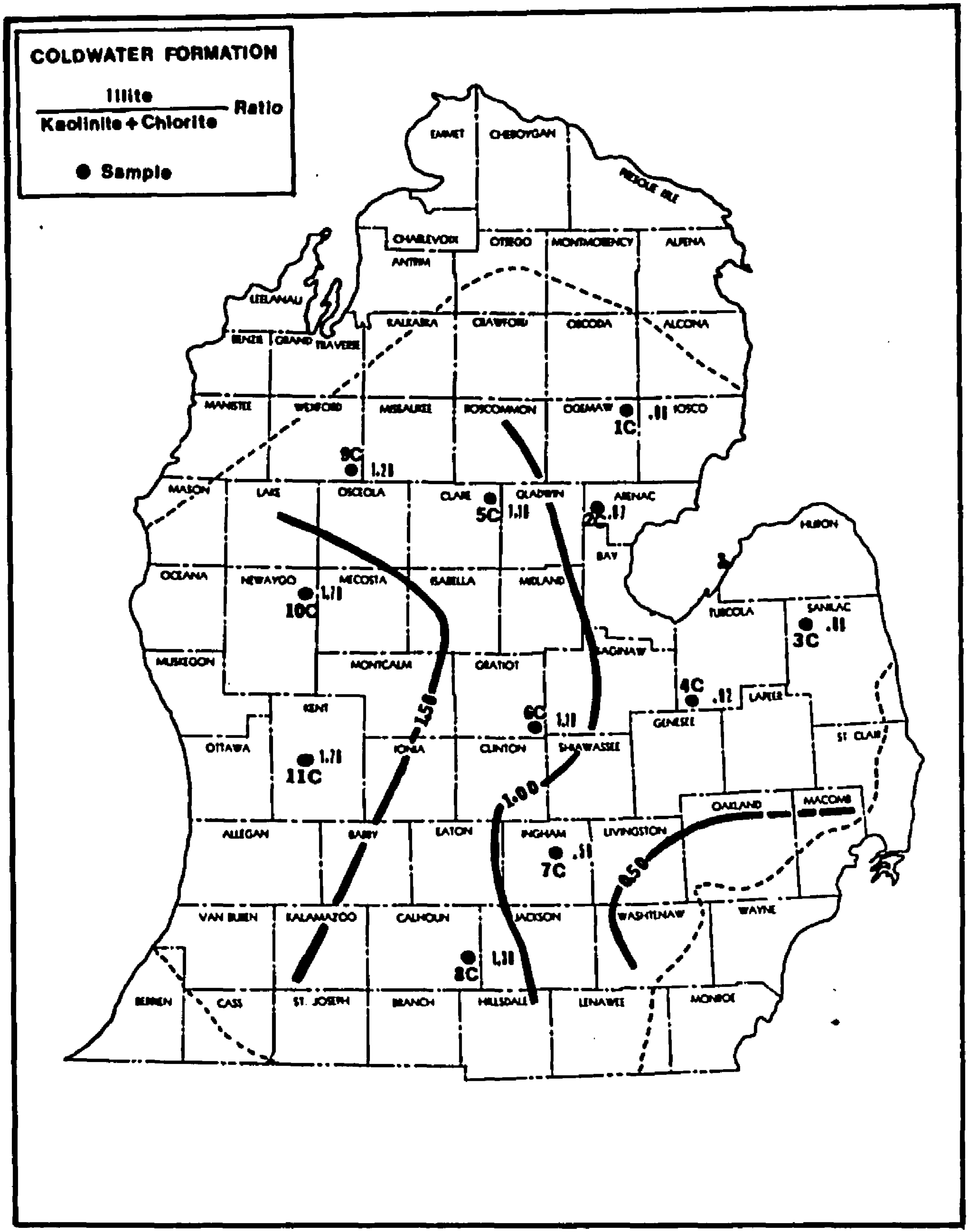


Figure 20.--Lower Third of Formation.

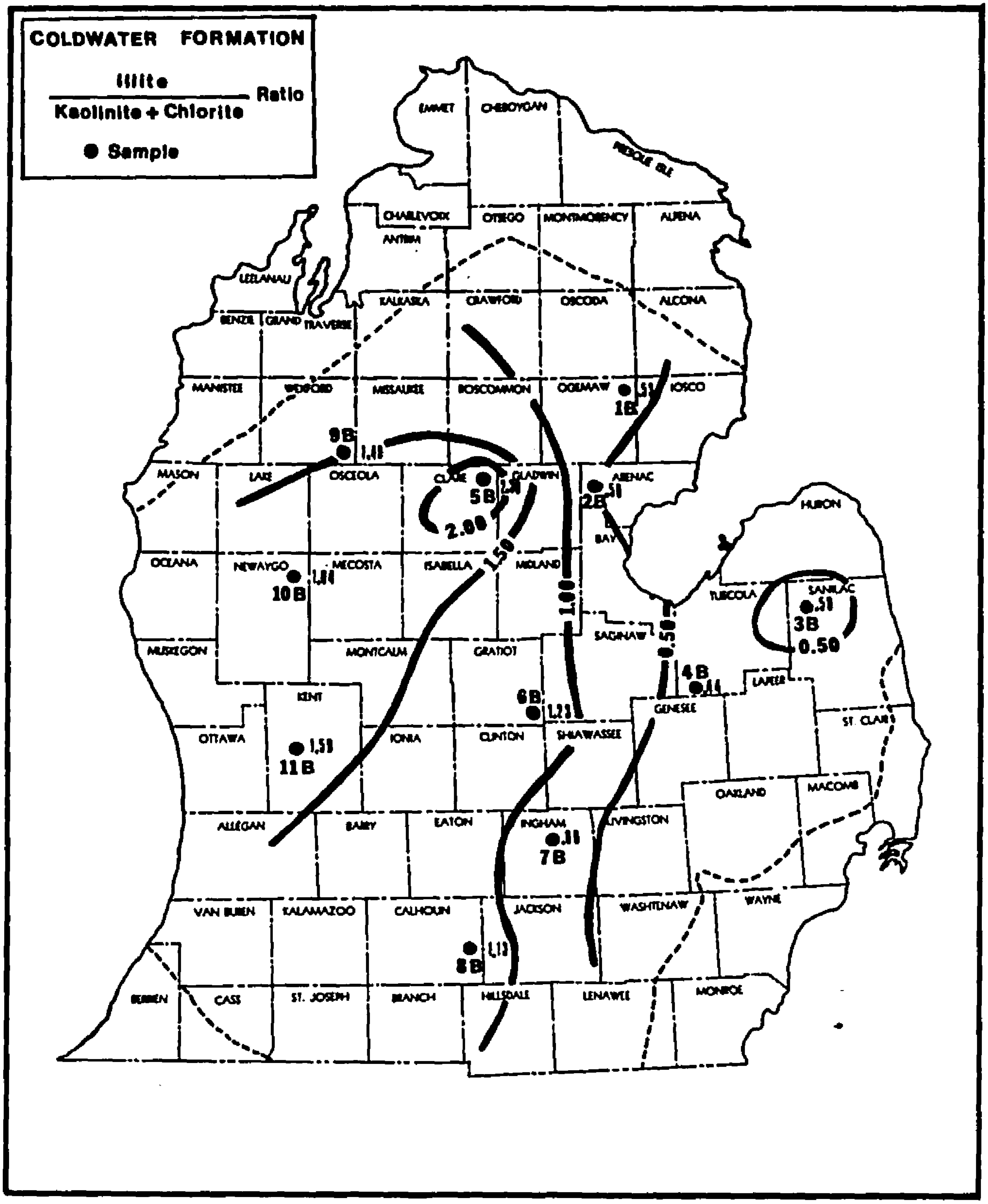


Figure 21.--Middle Third of Formation.

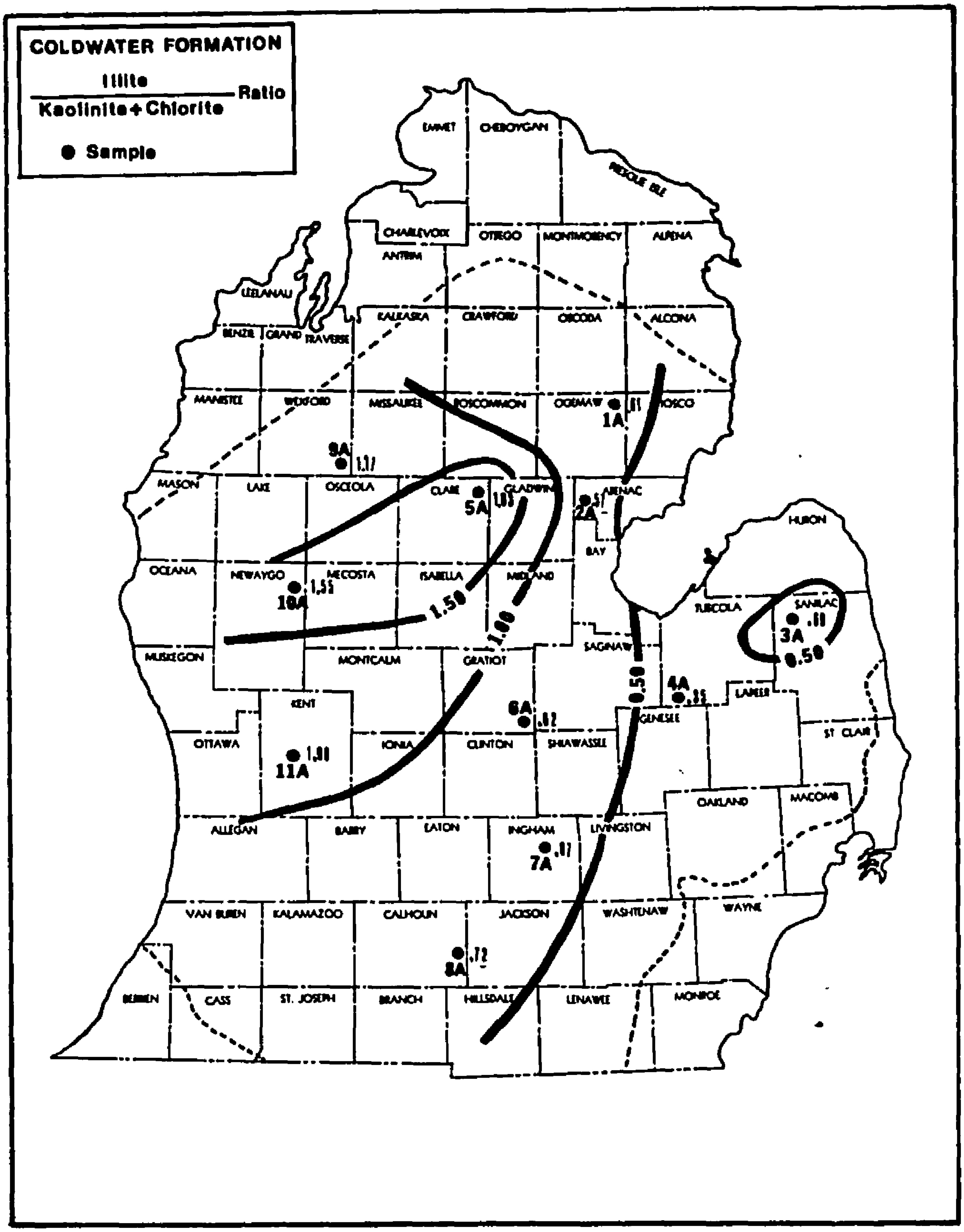


Figure 22.--Upper Third of Formation.

(1940, Grim (1953), Weaver (1961) and many others, have suggested that kaolinite generally is rich in continental and nearshore environments and decreases in abundance relative to illite and chlorite in the marine environment. Griffin and Ingram (1955), basing their work on the clay minerals of the Neuse River estuary along the Atlantic Coast of the United States, found that kaolinite is prevalent in the source material and decreases in abundance relative to chlorite and illite in saline waters and concluded that the illite and chlorite are high on content at the lower end of the estuary. It is possible to state that the western waters were "more marine" than eastern waters and that the sandier eastern facies therefore was nearer the source.

Likely, the upper third samples having higher kaolinite content than those of the lower third in eastern Michigan suggests probably the shoreline prograded closer to Michigan in upper Coldwater time. As previously cited, the Coldwater shale consists of more quartz sand in the upper part in the eastern facies. It suggests that there is a correspondence between an increase in kaolinite content and in the quartz sand content, both in turn likely related to the proximity of source.

The lateral variation in clay suites seaward may be explained by the differential settling velocities of clays. In mixtures of illite and kaolinite, the settling velocity of illite is faster than that of kaolinite in the case of increased salinity (Whitehouse and Jeffrey, 1953). Probably the slow rate of decomposition in sea water gives time for kaolinite to decompose, as kaolinite is generally unstable in the alkaline environment. Keller (1970) suggested that the kaolinite once transported from fresh water to marine probably starts to dissolve. Moreover, the increase in the proportion of illite westward may be because of the cation exchange of potassium and magnesium into the clay supplied from source areas. It is believed (Grim et al., 1949) that the "degraded" illite and chlorite could reconstruct their structure by absorbing potassium and magnesium from sea water.

The writer has no intention in this clay mineral study to attempt to clear up the controversial question of "environment of formation versus environment of deposition." The principle objective in this study was to demonstrate the nature of the lateral clay mineral variations.

ENVIRONMENTAL INTERPRETATION

The lithologic characteristic and the distribution of the Coldwater Formation may suggest some conclusions regarding the depositional basin and its environment. Within the basinal environment, some factors such as structure and sea floor topology also control the conditions of sedimentation.

The distribution of sediments reflects the basinal shape of the depositional environment of the Coldwater. In the Saginaw Bay area, the subsidence was faster than the surrounding area which allowed rapid deposition and burial favoring the preservation of red color in the upper part and also the relatively organic-free gray shales. Though sinking was rapid in the major depocenter area, it is believed sedimentation rates essentially kept pace with subsidence.

An interesting observation by Monnett (1948) was that the red zones in the upper part of the Coldwater and lower part of the Marshall strata, were missing over the crest of an anticlinal fold in Arenac and Ogemaw Counties. Monnett in indicating the distribution of the redbeds in the Marshall formation recognized that ". . . the red colors are absent near the outcrops of the formation in southern and eastern Michigan and in the areas adjacent to the large anticlines in Shiawassee, Bay and Arenac Counties." He related the disappearance of red color to reducing and leaching conditions and concluded that the areal distribution of red sediments results from the processes after the formation of anticlinal structures. The writer was restricted in his attempts to verify adequately Monnett's hypothesis because of the lack of sufficient well data in strategic locations relative to the arches. However, comparing the data of the cross-section of Monnett against the composite structural axes map (Prouty, 1971, Figure 2) the writer recognizes that the reds are generally absent over the fold axes. The writer suggests an alternate theory that the "highs" (anticlinal folds) apparently were areas of high energy and may have precluded ferric iron-bearing clay deposition. This would place a penicontemporaneous timing on the red bed origin and suggest the anticlinal axes were there at the time of red-bed sedimentation.

The writer observed that western Michigan samples were generally somewhat lighter gray on anticlinal areas developed, for example, in the older Antrim or Traverse formations; and darker gray in "pockets" suggested by local "thicks" on the isopach map. It is obvious that there exists an oxidizing condition in the "high" areas precluding the preservation of organic matter, and the sediments are lighter shades (of gray, usually) than those deposited in the "low" areas. However, the well samples were scattered such that no precise pattern of distribution of "darker" and "lighter" Coldwater according to "highs" and "lows" was displayed in this study as Asseez (1967, 1969) considered possible in his studies of the Antrim shale color distribution.

The common area in central Michigan where there is no red Coldwater (Figure 14) and the shale is generally darker in color (Figure 13), the crystalline dolomitic zones are highly pyritiferous, further suggesting a local reducing environment. This is probably caused by local deeper water in a lower energy area of relatively restricted circulation. It is of interest to note that the above area is also the approximate position of the Coldwater secondary depocenter, the present structural basin and post-Osagian depocenter. Though the Coldwater and earlier depositional and major structural centers were farther east (Prouty, 1971), this study would indicate that the structural shift was well in effect by Coldwater time and that at least there existed a secondary basin, at the present center.

A useful environmental indicator in this study was the illite/kaolinite + chlorite ratio. This ratio suggests a quantitative estimate of the relative "marine-ness" of a particular locality. As previously cited, kaolinite is prevalent in fluviatile and near-shore sediments, but it is unstable in open marine environment. In general, the lateral variation in kaolinite abundance may relate to a trend from non-marine to open ocean depositional environment. The highest ratio could indicate that, relatively, illite is more abundant than kaolinite; therefore farther from the shoreline, or "more marine." Samples in the eastern half of Michigan are somewhat low in ratio therefore they are regarded as having been deposited in a very near-shore environment, or "less marine."

Lithologic and paleontologic data support the use of illite/kaolinite + chlorite ratio as an indicator of relative "marine-ness" of samples.

A study of the environmental implication of fossils was made. Unfortunately, there are few exposures of the Coldwater shale and few fossils available for study. Most fossils collected from well cuttings were fragmented.

Miller and Garner (1953, 1955) reported the following cephalopods from the Coldwater exposures in Branch County Michigan: Chouteouoceras ? sp., Vestinautilus altidorsalis, Gattendorfia ? sp., Munsteroceras pergibbosum, Cycloceras ehlersi, and Mooreoceras.

In the well-cuttings from the western part of the Basin, fragments of bryozoans, crinoid stems, brachiopods and few well preserved ostracods were observed, but only the bryozoan fragments were abundant. Schopf (1969) and many others emphasized the relationship of the zoarial growth forms of the bryozoans to the environmental conditions. The thin branching zoaria of the Coldwater may suggest relative deep and quiet water in western Michigan. However, precise sedimentary environmental interpretations are of restricted value.

In the eastern half of Michigan, Lane (1900) reported some genera from several Coldwater exposures along the eastern lake shore of Huron County, Michigan: Spirifer, Pleurotomaria, Orthis, Myalina, Crenipectan, Aviculopecten and Edmondia. Therefore, it is assumed that two communities of pelecypods and spiriferid brachiopods were predominant in the east.

All of information may suggest a deltaic origin for the Coldwater shale with the Michigan Coldwater mostly prodeltaic. As a result of recent studies of modern deltas, criteria for the recognition of the deltaic deposits are well understood. Fisk and associates (1954) basing their study on the Mississippi delta proposed that the subaerial delta plain with its marshes, bays, distributaries and the subaqueous delta front and prodelta zones are the principal depositional environments of a delta. One most notable feature of most modern deltas is the vertical change from massive silty clay of the prodelta zone into interbedded silt, clay and cross-laminated sand in the delta front zone

(Shepard, 1960; Allen, 1965). The Coldwater shale grades upward into the Marshall sandstone and their contact is considered gradational in eastern Michigan. The latter formation is widespread within Michigan and it forms geometrically a continuous sheet sand. Evidences of cross-bedding were reported from Marshall exposures in Huron and Sanilac Counties (Lane, 1900; Monnett, 1948). The relationship of the Coldwater shale and the Marshall sandstone could be regarded as the vertical gradation of a prodelta into the delta front. The thick mass of silty shale and shale with more than 20% of sand of the Coldwater formation in the east could be assigned as the prodelta silty clay, and the shale with less than 20% of sand is the prodelta clay; both show the general picture of a prodelta environment (Figure 23). It is believed that a delta was formed to the east of Michigan, in the general region of the Findlay Arch. Silts and clays were swept westward into the Michigan Basin and deposited in the prodelta zone (Coldwater shale) to build up a platform necessary for the delta advance. The delta growth continued and sand deposited forming a continuous body of sand around the growing delta front (Marshall sandstone). However, despite the progradation of the delta toward Michigan, evidence of its deltaic plain and channel fills is yet to be observed within the state of Michigan. They most likely did not manifest this far west and would not, of course, survive

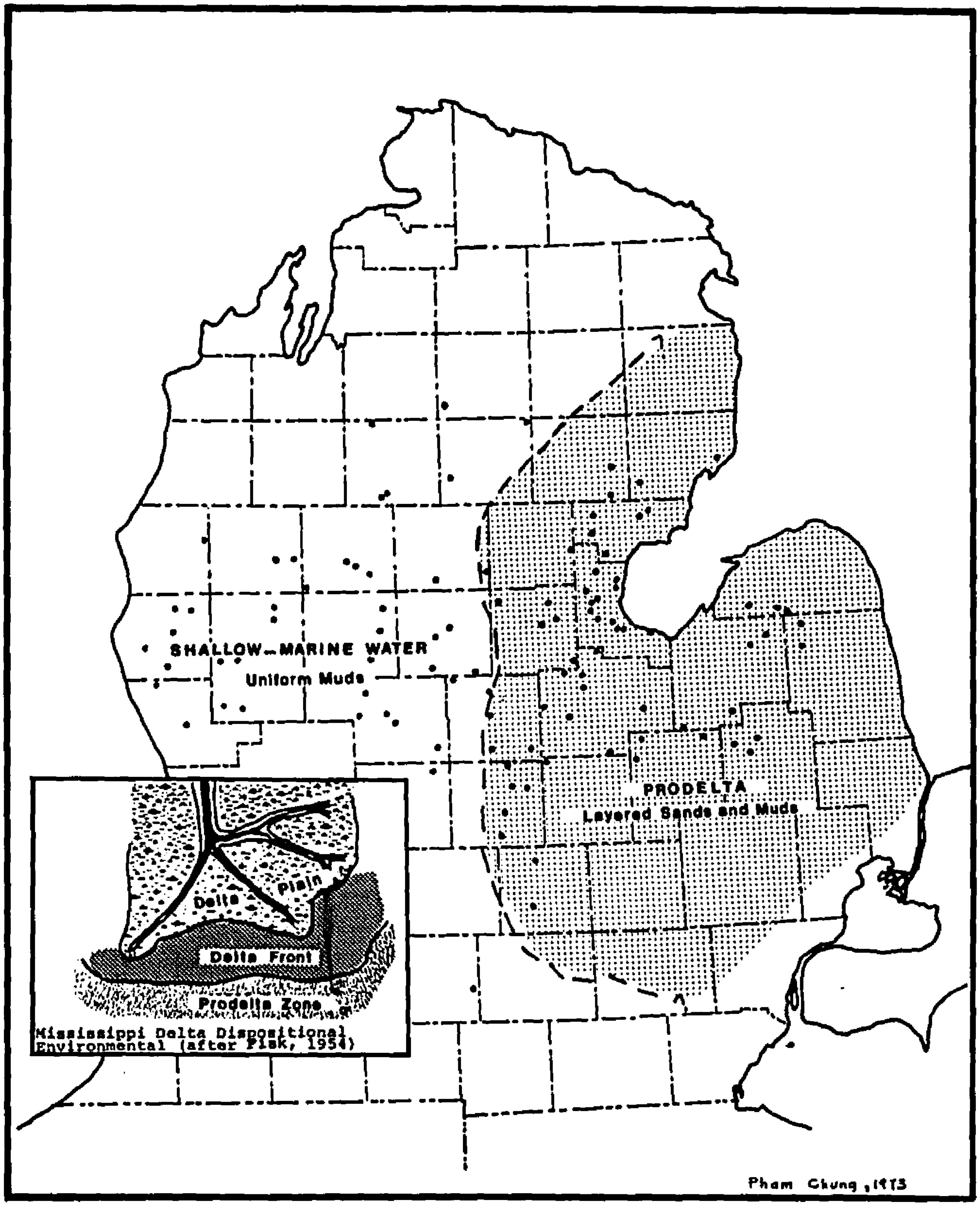


Figure 23.--Depositional Environment of the Coldwater Formation.

the post-Mississippian erosion that has exposed older Paleozoic in the present day area of the Findlay Arch and old Cincinnatia.

PALEOGEOGRAPHY

The purpose of this section is to interpret the origin of the Coldwater formation in Michigan and to test the extent to which this interpretation is harmonic with the adjoining areas in terms of the sedimentary and tectonic frameworks.

General Setting

During the Late Devonian-Early Mississippian, the Michigan, Appalachian and Illinois Basins were major areas of subsidence; the Laurentian Highlands, Wisconsin Highlands were apparently low and stable. The Cincinnati Arch separating the Michigan Basin and Appalachian Basin stood as a low peninsula at its maximum extent, perhaps reduced to small swampy islands. The mountainous northern Appalachians which were formed at the close of the Devonian by the Acadian disturbance were eroded intensively supplying clastic terrigenous sediments into the subsidence areas. The epeiric shallow sea covered a large part of the central United States, especially in the Mississippi Valley region.

The history of Late Devonian to Early Mississippian involves uplift movement of lands in the mobile belts as well as portions of the craton, and oscillation of sea-level. In general, the sedimentary framework consists of predominantly coarse to fine clastics in the areas east of the Cincinnati Arch, and medium to fine clastics and non-clastics west of this arch.

Paleogeography During Deposition of the Antrim, Bedford and Berea Formations

The paleogeography in Michigan, Ohio and adjacent states during Antrim and Bedford-Berea depositions has been discussed by a number of investigators (Pepper et al., 1954; Pelletier, 1958; Asseez, 1967, 1969).

During the deposition of Antrim shale, land masses were low and provided muds to the epeiric sea. The known land masses were the Ozark Dome (Ozarkia), Wisconsin Highlands, Lexington Dome (a portion of the Cincinnati Arch), New Brunswickia and Siouxia. The epeiric sea was widespread over the largest part of east central United States. The black shale can be observed in the Hudson Bay region (Long Rapids Formation), in Michigan Basin (Antrim shale), in Ohio and Pennsylvania (Ohio shale) and Indiana and Illinois (New Albany shale). The sea was somewhat shallow, probably less than 100 feet (LeMone, 1964). Thick mats of floating alga may have caused a reduction in wave and tidal action and contributed organic matter to bring about a strong reducing environment.

The Bedford-Berea deposition marked a dominance of clastic sediments which were carried by rivers into the Appalachian, Michigan and Illinois Basins. The Wisconsin Highlands and Canadian Shield were low but the orogenically developing Appalachia underwent activity and erosion.

Thick fluviatile sediments of Pocono in Pennsylvania and Maryland region suggested a vast coastal plain in this area (Pelletier, 1958). More fine sands and muds from eastern elevated land masses were carried by swift running streams flowing westward across the Pocono coastal plain into the shallow Ohio Bay. Among them, one river across Pennsylvania formed the Cussewago delta in northeastern Ohio. Another river formed the Virginia-Carolina delta in southeast Ohio. These deltas reached a maximum development in Middle Bedford time (Pepper, et al., 1954).

The Bedford delta was built of sediments derived from the Northern Appalachians and carried southward by the Ontario River into the Ohio Bay (Figure 24). This delta reached its maximum extent in Middle Bedford time. The Cincinnati Arch formed a long peninsula, Cincinnatia, which separated the Michigan and Appalachian Basins (Pepper, et al., 1954). The Ohio Bay was landlocked and likely showed restricted wave and tidal action.

In the Michigan Basin, influx of clastics entered from northwestern and northeastern sources. The former possibly built a delta with streams flowing eastward from

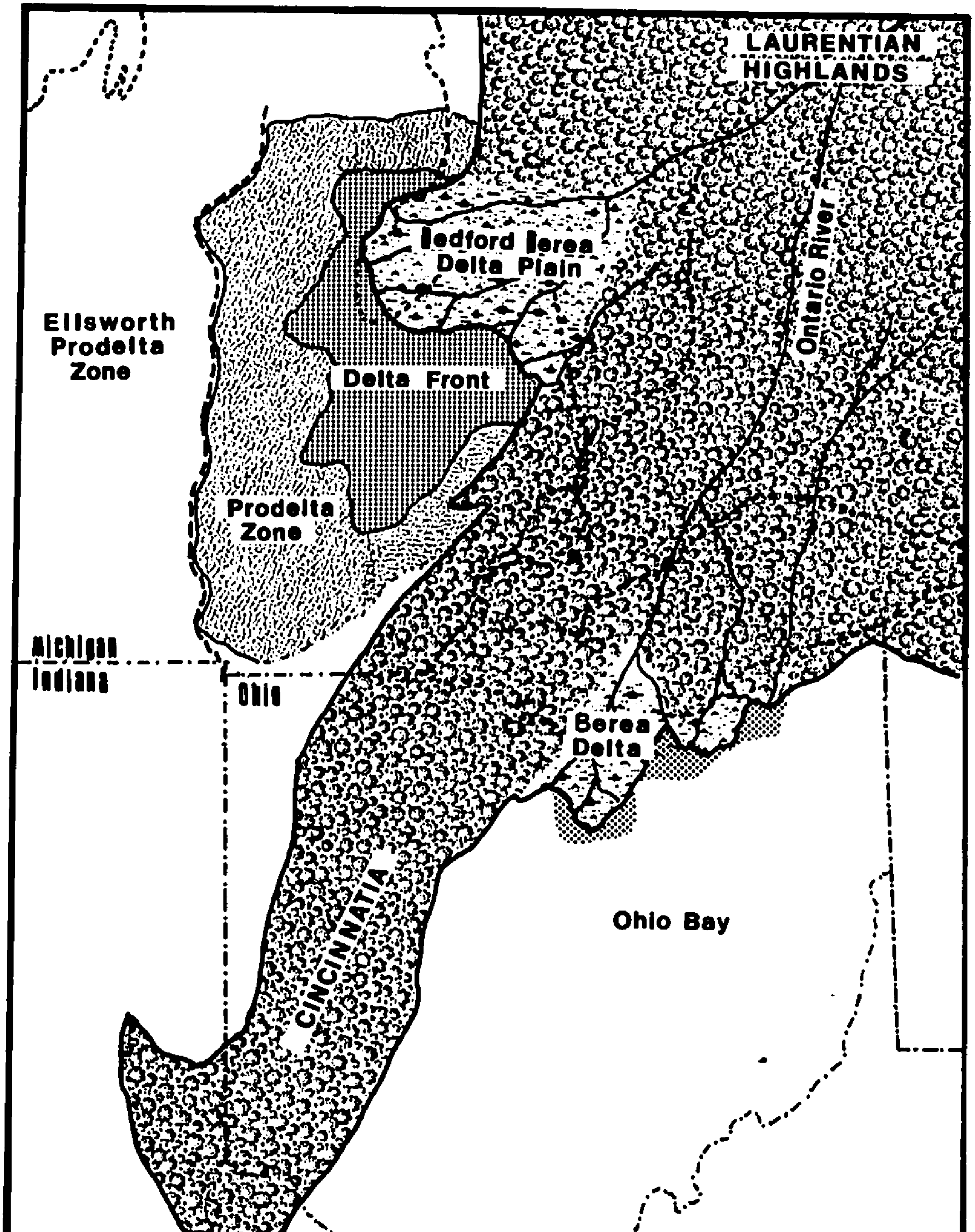


Figure 24.--Paleogeography during Bedford Berea Delta Disposition (after Pepper, et al., 1954 and Assqez, 1967).

the Wisconsin Highlands. This mass of green shale (Ellsworth) in the western half of the Basin may represent a prodelta relating to a delta farther west (Asseez, 1967, 1969). At the same time Ellsworth sediments reached the Basin, in the east the Ontario River built a birdfoot delta of which the Bedford formed the prodelta and the Berea, the deltafront. The shoreline prograded toward Bay and Huron Counties, and a delta plain was in the Lake Huron area. Distributaries advanced toward Michigan Bay and marshes developed.

The Sunbury marked the return of a quiet and widespread sea over a large area of Michigan, Ohio, Kentucky, West Virginia and Pennsylvania. The rate of sedimentation by streams into Michigan Bay and Ohio Bay decreased, and the slow deposition of black muds prevailed. Swampy shores were formed where the deltas were inundated. Quiet water and restricted circulation must have prevailed in the epeiric sea.

Paleogeography During Deposition of the Coldwater Formation

By the early Coldwater deposition, influx of clastic sediments entered the areas of subsidence. Uplift movement occurred in the source areas and streams rejuvenated. More fine clastics passed over the Pocono coastal plains by streams flowing westward, reaching Ohio Bay and Michigan Bay and also over the Cincinnati Arch into the Illinois

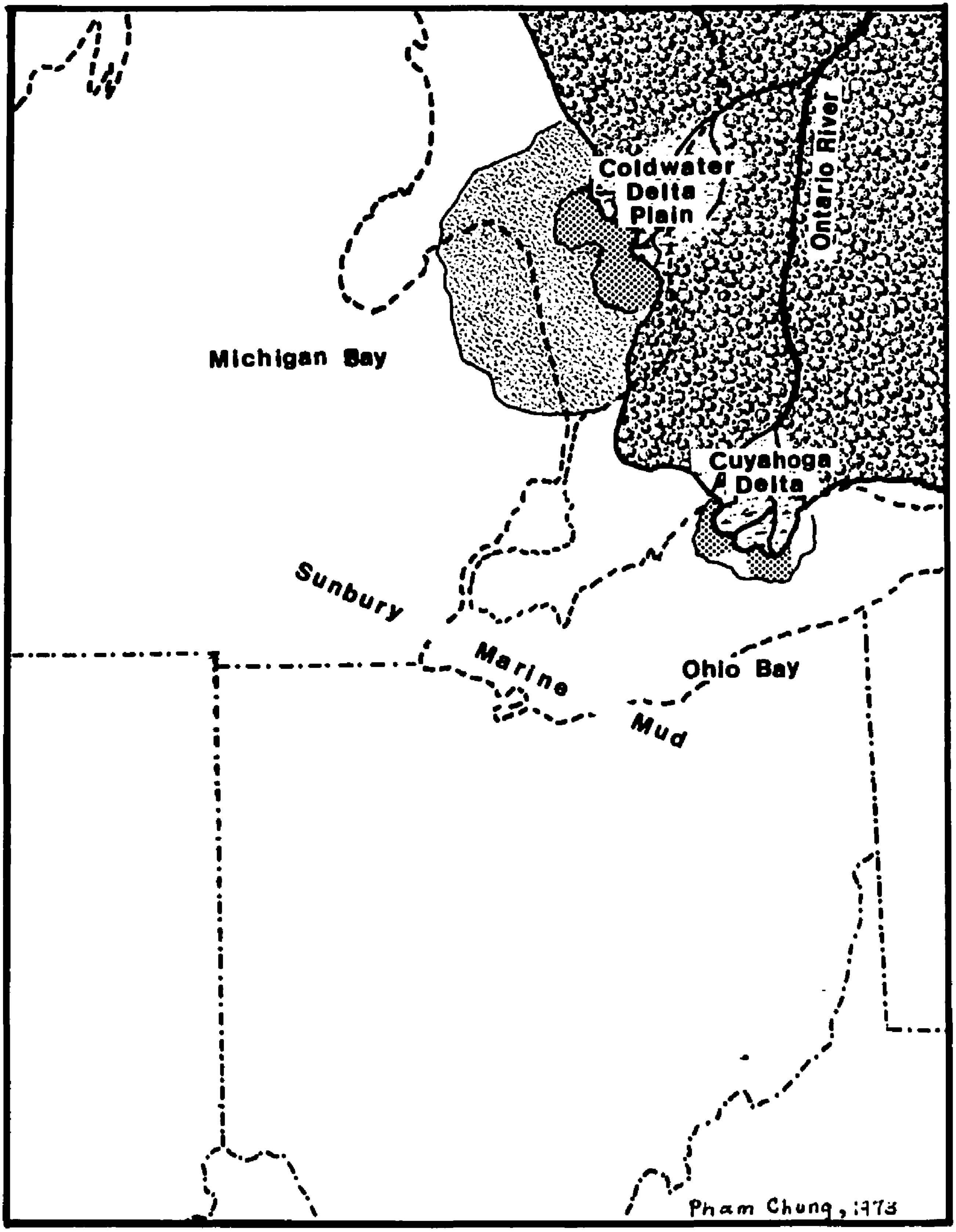


Figure 25.--Paleoglography during the early stages of the Coldwater Delta.

Basin. The Ontario River brought sediments into Michigan and Ohio (Figure 25). Fine silts and muds deposited throughout the epeiric sea--the Coldwater shale in Michigan, the Cuyahoga in Ohio and Pennsylvania, and the New Providence in Illinois and Indiana. The Wisconsin "Highlands" was stable at this time supplying little or no sediments into Michigan.

In a study of the dispersal centers of some of the Paleozoic systems, Potter, et al. (1961) concluded that the Osage and Kinderhook subgraywackes of the Illinois and Michigan Basins were derived from the northern Appalachian area. Another dispersal center to the east, the orogenically elevated Appalachia, provided vast quantities of clastic sediments to the epeiric shallow sea. The Pocono sediments were apparently fluviatile and were derived from the source located in the vicinity of Atlantic City, New Jersey (Pelletier, 1958). Lithologically, Pocono sediments composed of thick-bedded conglomerates and quartzitic sandstones. Pelletier (1958) recognized that toward the west the Pocono underwent diminution in numbers of the pebbles and the sand/shale ratio greater than two in eastern Pennsylvania and Maryland decreased to less than one in northwestern Pennsylvania and Ohio. It is clear that most sands from Appalachia deposited in the east and fine silts and clays winnowed and carried westward into the Ohio Bay. Cincinnatia stood as a low peninsula precluding sediments of the Appalachian Basin from entering the Michigan Basin in the earlier Bedford-Berea time. It reduced in size and elevation by the beginning of Coldwater deposition. The writer believes that if any sediments reached the Michigan area from Appalachia, it consisted only of fine silts and muds. Sands and silts found in the upper part of the Coldwater and Marshall formations were carried from the Laurentian Highlands by a river system flowing southwestward and emptying its loads into the Michigan Bay.

As previously discussed, in Michigan the Coldwater forms a prodelta (Figure 23). The delta front and the alluvial plain were in the general area of the Findlay Arch (Old Cincinnatia).

Near the end of the Coldwater deposition, the uplift movement was stronger in the Laurentian Highlands. Fine sands and silts were carried into the Michigan, Appalachian and Illinois Basins. The shoreline prograded westward and southward away from the Ontario region. Cincinnatia began to raise and formed a low peninsula (Figure 26), but it was probably smaller in extent than it was during the Bedford deposition.

The Borden sediments carried southwestward from the Canadian Shield and also formed a delta in Illinois and Indiana but the water was somewhat deeper than in the Michigan and Ohio Bays (Lineback, 1966).

In the Mississippi Valley region, shallow and clear water was prevalent. Thick carbonates deposited in this area.

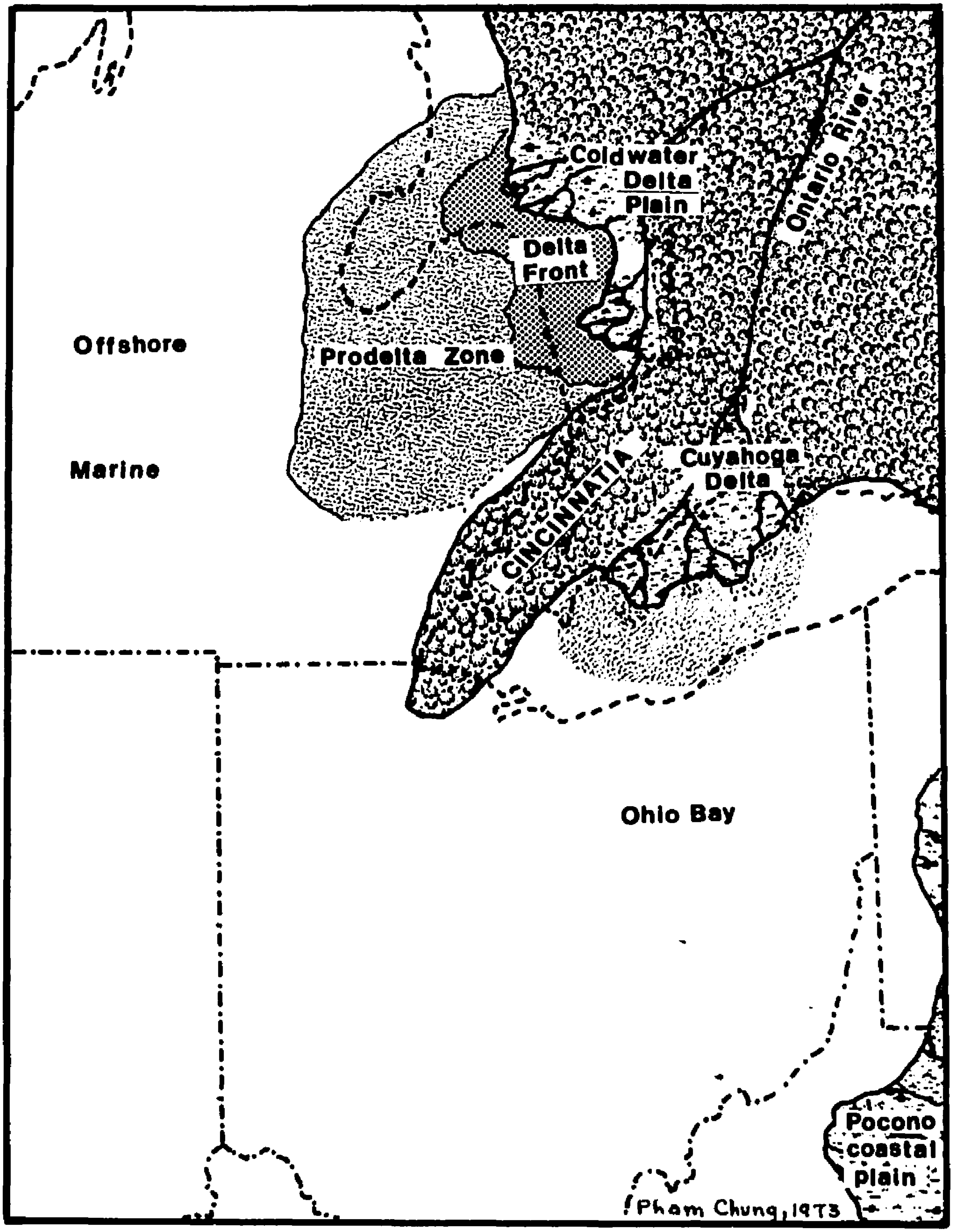


Figure 26.--Paleogeography during the late stages of the Coldwater Delta and earliest stage of the Marshall unit.

CYCLIC SEDIMENTATION OF UPPER DEVONIAN AND LOWER MISSISSIPPIAN ROCKS IN MICHIGAN

It is apparent that the Upper Devonian-Lower Mississippian rocks in Michigan demonstrate cyclic sedimentation. This is indicated by two repetitions of lower black shale units followed by gray shales and sandstones.

The interpretation of the black shale deposition of the Antrim (first cycle) and Sunbury (second cycle) were trangressive phases in widespread shallow seas covering almost the entire Basin, while the adjoining land masses reduced. The gray shale and upper sandstone units, such as the Bedford-Berea (first cycle) and Coldwater-Marshall (second cycle) represent regressive phases, resulting when the rivers prograded their deltas filling and reducing the size of the shallow sea. Figure 27 may be helpful in visualizing these relationships. Most of the contacts between formations are gradational.

Antrim-Bedford-Berea Sequence

The Antrim-Bedford-Berea relationship was discussed by LeMone (1964) and Asseez (1967, 1969). The Antrim was divided into two distinct units and the lower

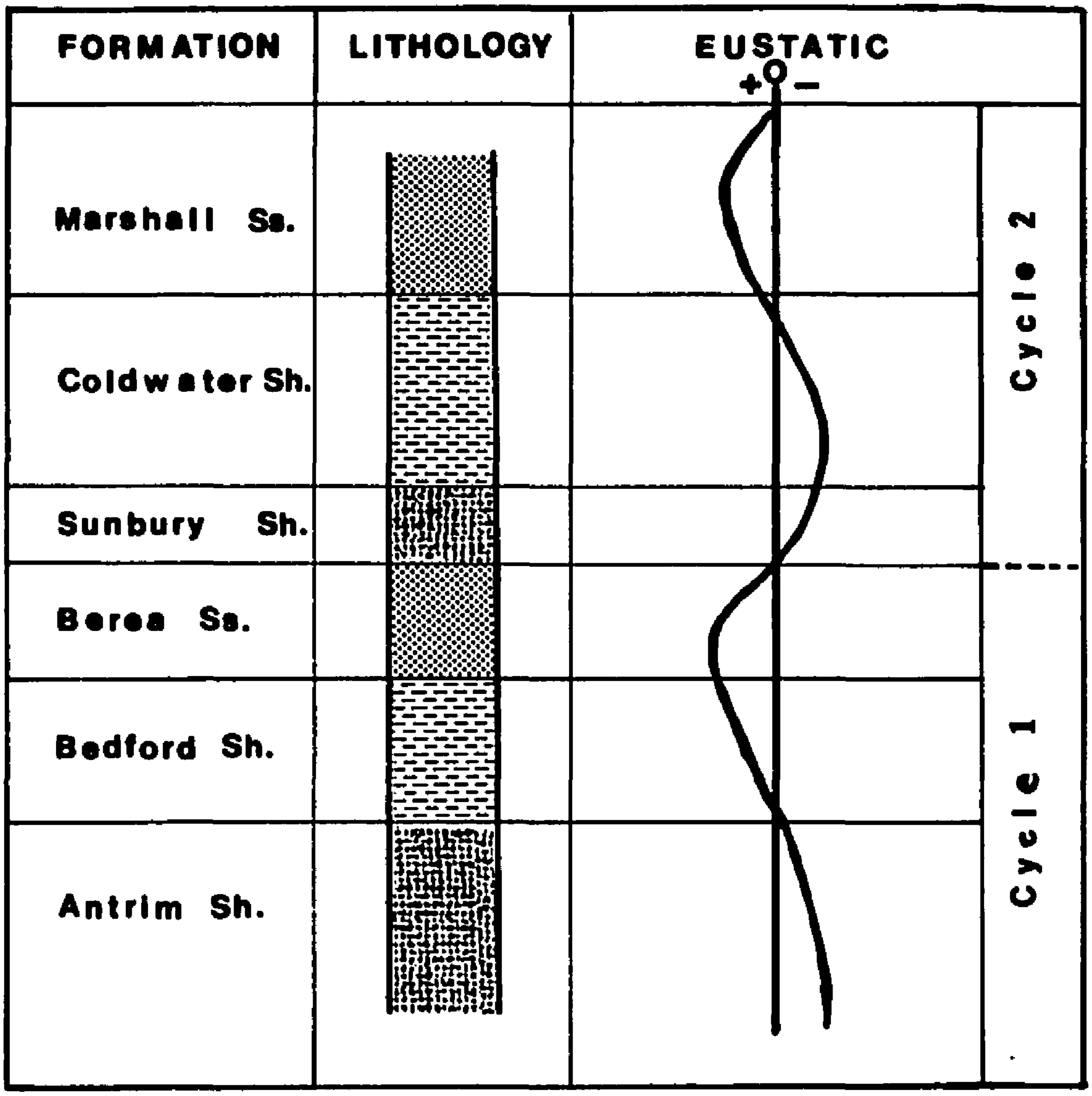


Figure 27.--Trangressive-Regressive "Cycles" of the Late Devonian and Early Mississippian in Michigan.

unit can be correlated throughout the Basin. The green shale lithosome, Ellsworth, in the west, is gradational and interfingering with the upper Antrim unit. The Antrim-Bedford-Berea sequence represents a suite of lithotopes ranging shoreward from shallow marine (Antrim black shale) to the prodelta (Bedford shale) and the delta front (Berea sandstone) (Asseez, 1967, 1969). The sequence forms the regressive overlap (offlap). The trangressive Antrim developed when the rate of subsidence exceeded that of deposition and marine black shale spread almost entirely over the Basin and adjacent states. During the regressive Bedford-Berea period, the rate of deposition exceeded the rate of subsidence and westward progradation of the shoreline resulted.

Figures 28 and 29 show restored sections of cycles 1 and 2. Time lines are believed to cut the isoliths in a theoretical manner such that the prodelta and delta front beds become younger eastward. The extent of the time transcension is not discernable in any quantitative manner and is displayed in a diagrammatic manner only.

Sunbury-Coldwater-Marshall Sequence

The Sunbury-Coldwater-Marshall interval also represents a trangressive cycle, in the early Mississippian in Michigan. The Coldwater formation marked clastic deposition replacing the reducing marine conditions during

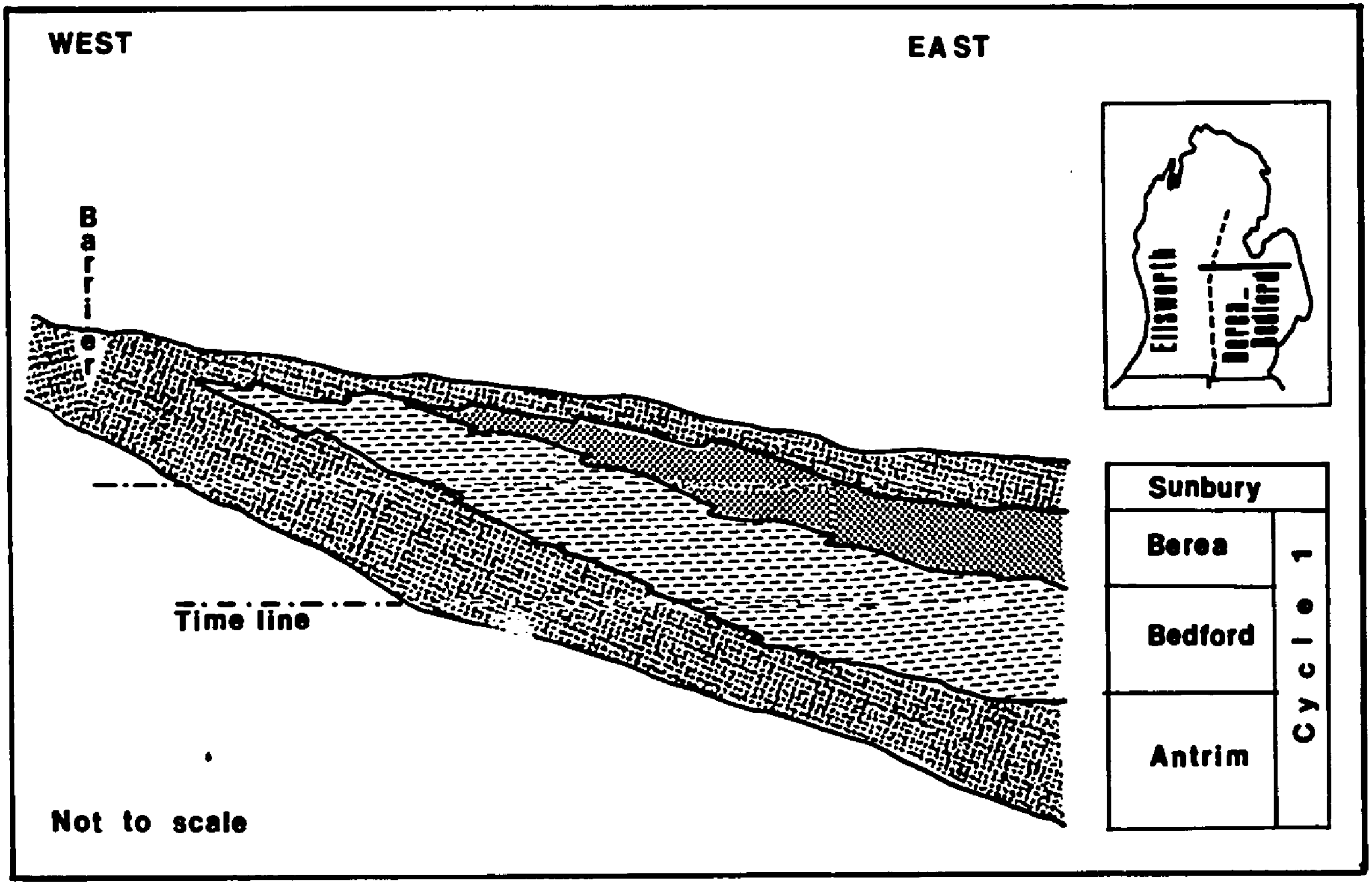


Figure 28.--Antrim-Bedford-Berea-Cycle 1 (modified from Asseez, 1967).

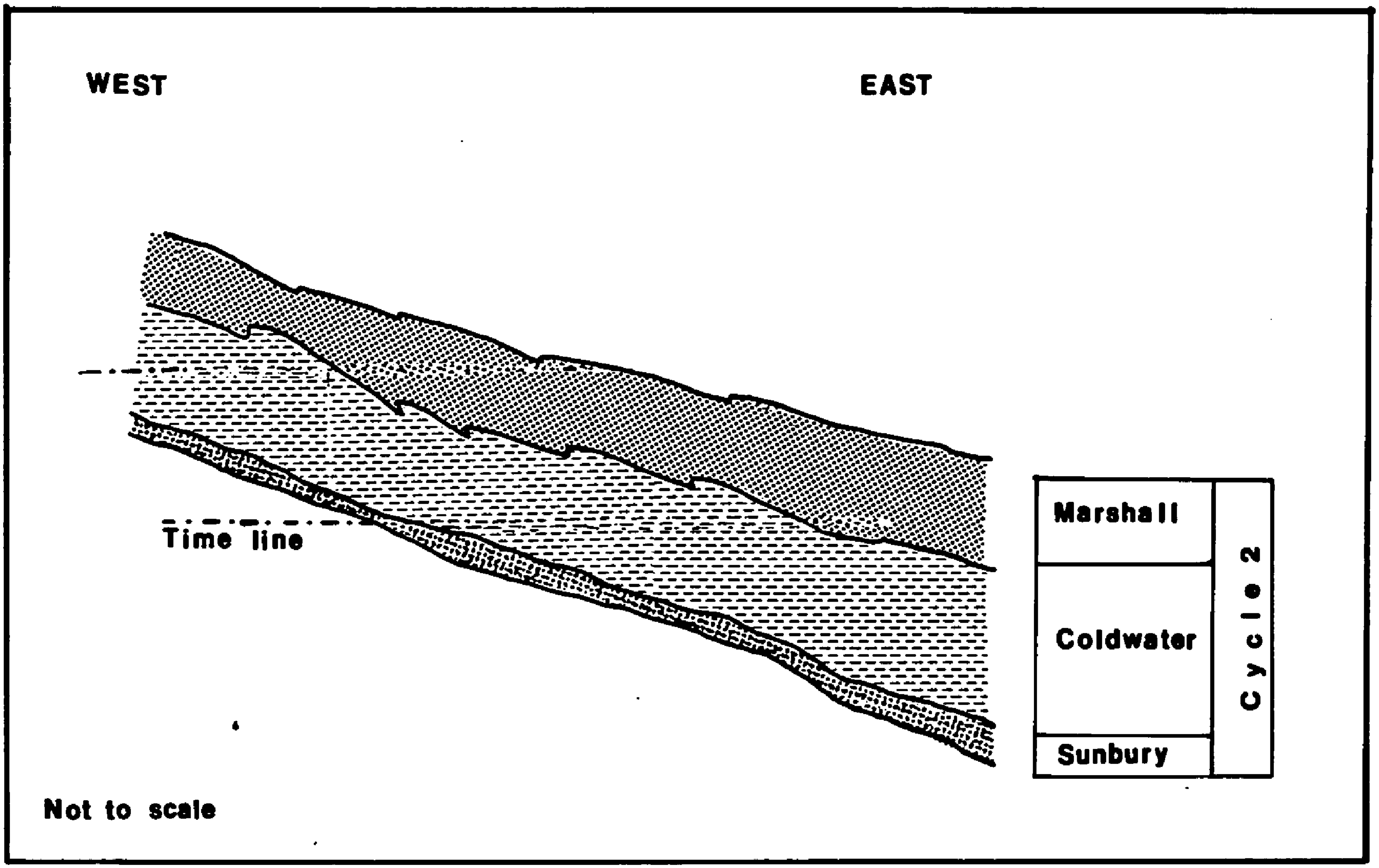


Figure 29.--Sunbury-Coldwater-Marshall-Cycle 2.

Sunbury deposition. The Coldwater shale is referred to a pro-delta sub-environment of a complex deltaic system which has been eroded away directly east of Michigan in the general area of the Findlay Arch (Old Cincinnatia). The Marshall formation is a sand sheet and it is questionable that it would be described accurately in the geomorphic sense as in the Berea sandstone. However, the Sunbury-Coldwater-Marshall sequence in Michigan proper is largely marine, as opposed to the Bedford and Berea of the earlier sequence, and apparently represent a neritic phase tied in likely with faster basinal settling at that time. A favorable analogy of this sequence appears favorable in the Catskill alluvial plane which spread westward across New York and Pennsylvania during Middle to Late Devonian deposition. Considering the Portage-Chemung-Montrose (Catskill) lithotopes (which might fit loosely into the "parvafacies" concept of Caster, 1934) the Sunbury and western Coldwater facies of Michigan might find a counterpart in the Portage dark to gray muds; and the eastern Coldwater facies and the regionally distributed and the regionally distributed Marshall to the marine Chemung. The delta plain portion of the Coldwater and Marshall, conceived as occurring generally east of Michigan in the area of the Findlay Arch and Cincinnatia source prior to post-Mississippian erosion, would represent the non-marine Montrose (Catskill) portion.

In a deltaic progradation situation, the sequence is progressively younger in the basinward direction. It is suggested here that a part of the lower Coldwater is equivalent to a part of the Sunbury black shale. Also, at the time the Marshall sediments deposited in the far east, some of upper Coldwater muds still were being deposited basinward.

The Bedford and Berea of the older cycle are restricted to the eastern half of the Basin because of the presence of a north-south "barrier" of some kind in central southern Michigan. On the contrary, the Sunbury-Coldwater-Marshall cycle is distributed throughout the Basin because the barrier is no longer present.

In a study of late Mississippian rythmic sedimentation of the Mississippi Valley, Swann (1964) observed many alternations of limestone and sandstone units of the Chesterian series, which were deposited in alternating marine environments and deltas of the so-called "Michigan River" flowing from the northeast into a sea in southern Illinois. Swann considered that neither sea level fluctuations nor the pulses of tectonism in the source areas caused the cyclic sedimentation. He concluded that variations in rainfall controlled the rythmic sedimentation and that each major rainy period marked a major delta. In the case of trangressive-regressive cycles of early Mississippian in the Michigan Basin, the writer believes that episodes of epeirogenic warping alternating with the subsidence of the Basin appear more logical as an explanation. At time of quiescence, a slow transgression of the shallow sea over the Basin including a prevalent reducing environment would result in widespread deposition of black muds in the Basin. At time of uplift activity in the source areas, great volumes of terrigenous sediments would be accumulated in the Basin reducing the size of the shallow sea. The progradation of the Bedford-Berea birdfoot delta may be tied synorogenically to the Acadian Orogeny. The regressive phase at the beginning of the Coldwater time ended the black shale sequence in Michigan. The study of the Coldwater isopach and structure maps (Figures 3 and 4) reveal that the Michigan Basin was starting to accumulate sediments at that time. The irregular isopach of the Marshall formation (LeMone, 1964) and the shift of pre-Meramecan depocenters from Saginaw Bay area toward the present center (Prouty, 1971) infer the tectonic effects of the Appalachian Orogeny.

Throughout the Late Devonian-Early Mississipean the Laurentian and the Wisconsin Highlands were unstable. The uplift movement apparently occurred synorogenically with the Acadian orogeny and the Appalachian disturbance. The Michigan Basin started to fill with sediments at the beginning of the Coldwater deposition, then underwent further changes during the deposition of the Marshall sandstone up to at least Middle Mississippian (Meramecan) time.

The delta building in early Mississippian in the Basin apparently was a prelude to the alternating alluvial plain marine conditions in the Michigan Basin in Pennsylvanian time.

Time-Stratigraphic Correlations

As pointed out earlier, the time lines in Figures 28 and 29 are hypothetical. Time-stratigraphic correlation of Early Mississippian in Michigan is not well understood.

Oden (1952) in his study on the occurrence of Mississippian brachiopods in Michigan concluded that time-stratigraphy cannot be determined by using brachiopods of the Coldwater and Marshall formations. Moreover, scattered outcrops in Michigan also add more difficulties to the time-stratigraphic problems.

It is possible that a palynological study of the Coldwater formation and potential equivalent formations in the bordering states may shed additional light regarding synchronous correlations. One such study by Leonard Eames (Michigan State University) on the Cuyahoga formation in Ohio is nearing completion.

CONCLUSIONS

Some significant conclusions derived from this study are as follows:

1. The regional structural contour map constructed on the base of the Coldwater Formation shows that the Michigan Basin has two structural centers. The Coldwater depositional and major structural centers located in the Saginaw Bay area do not coincide to the present deepest part of the Basin. This fact appears to be in keeping with the opinion (Prouty, 1971) that the Pre-Meramecan depocenters centering in eastern Michigan near Saginaw Bay area shifted west to the present position in central southern Michigan. This study reveals that the structural shift is well in effect by Coldwater time and a secondary basin exists at the present center.

2. The eastward thickening of the Coldwater Formation infers the proximity of the eastern source.

3. Lithologically, the Coldwater formation shows that the clastics are coarsest in the eastern area and become progressively finer to the west. Two facies are recognized and the facies change in continuous.

4. About a maximum of 40 percent of quartz sand is determined from sandy units in the east. The sand

percentage decreases westward and the limit of sand deposition is located in the central part of the Basin.

5. The highest proportion of carbonate deposits are in the western counties of Michigan.

6. In general, the lithofacies isoliths are parallel to the isopach lines.

7. The western facies is characterized by an abundance of clay-ironstone concretions. Concretion zones are concentrated in the upper part of the Coldwater Formation in the west.

8. The Coldwater sediments are mostly marine. Although no data are available on the regional distribution of grain sizes, this study reveals a strong relationship between the coarser clastics and the kaolinite content, with markedly higher proportion of kaolinite relative to illite in coarser sediments.

9. Lightly oxidizing conditions persist throughout the Coldwater environment partially based on the light gray sediments with the exception of an area in central Michigan where a light reducing condition existed. Dark gray and highly pyritiferous sediments are observed in this area indicating a possible deep, or at least partially restricted, environment.

10. Although no precise interpretation of depth can be made, the sea in the nearshore, eastern Michigan

area was shallower and less saline than in the offshore western Michigan region.

11. The clay mineral suite of Coldwater shale consists of kaolinite, illite and chlorite. No montmorillonite was recorded.

12. An abundance of kaolinite proportion in the Coldwater shale may reasonably indicate that the Coldwater sediments came from a granitic and/or gneissic source area where high rainfall and warm climate were indicated. Published data on Pocono sediments (considered pre-Chesterian Mississippian) in western Pennsylvania, indicate a shaley facies of the eastern Pennsylvania sandstones. This fact strengthens the conclusion that the quartz sandy Coldwater of eastern Michigan is more closely related to a nearby source (Cincinnatia).

13. A paleogeographic map constructed for the period during Coldwater deposition depicts a low peninsula, Cincinnatia, in the Findlay Arch area.

14. This study suggests a deltaic system developed east of Michigan. Coldwater shale is considered a prodelta shale whose delta front and alluvial plain probably are located in the general area of the Findlay Arch.

15. Two trangressive-regressive "cycles" of Late Devonian and Early Mississippian age in Michigan are recognized by the repetitions of black shale units.

(trangressive phase) followed by coarser clastic units (regressive phase). The Sunbury-Coldwater-Marshall cycle is distributed throughout most of southern Michigan whereas the upper part (Bedford-Berea) of the older Antrim-Bedford-Berea cycle cuts out along a north-south "barrier" of some kind in central Michigan.

16. The deposition of the Coldwater shale is a prelude to active evolutionary changes in the Michigan Basin during the Marshall and up to at least Middle Mississippian (Meramecan) time.

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APPENDICES

APPENDIX I

APPENDIX I

STATISTICAL ANALYSIS

The following data is the illite/kaolinite + chlorite ratio of eastern and western clay suite.

East: .61, .53, .86, .57, .50, .87, .60, .58, .86, .35, .44, .82, .87, .66, .56.

West: 1.93, 2.30, 1.16, .82, 1.23, 1.19, .72, 1.13, 1.30, 1.17, 1.49, 1.20, 1.55, 1.64, 1.78, 1.08, 1.59, 1.76.

Null Hypothesis:

Two samples are random samples from the same population.

$n_1 = 15$ $\quad\quad$ $n_2 = 18$

$\bar{y}_1 = .645$ $\quad\quad$ $\bar{y}_2 = 1.39$

$$\sum_{i=1}^{n_1} (y_i - \bar{y}_1)^2 = .415 \qquad \sum_{i=1}^{n_2} (y_i - \bar{y}_2)^2 = 2.75$$

$$s^2 = \frac{\sum_{i=1}^{n_1} (y_i - \bar{y}_1)^2 + \sum_{i=2}^{n_2} (y_i - \bar{y}_2)^2}{n_1 + n_2 - 2} = .102$$

$$t = \frac{(\bar{y}_2 - \bar{y}_1)}{\sqrt{s^2} \cdot \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} = 6.69$$

Referring to the critical value of t for $\alpha = .05$ and $(n_1 + n_2 - 2) = 31$ degrees of freedom, $t = 1.645$. The calculated t falls in the rejection region, therefore we reject the null hypothesis.

APPENDIX II

APPENDIX II

LIST OF WELL SAMPLES USED FOR LITHOFACIES MAPS

Map Number	Permit	Location	Sand Percentage	Clastic Percentage
ARENAC				
1	13242	20 T18N R4E	12.51	
2	7462	23 T19N R3E	15.32	
3	10676	25 T20N R3E	17.29	
4	12543	35 T20N R5E	22.14	
5	12100	19 T20N R6E	21.78	
BAY				
6	4080	1 T14N R4E	7.86	
7	5441	2 T14N R4E	7.55	
8	7900	2 T14N R4E	11.71	
9	10856	7 T14N R6E	31.40	
10	5288	10 T15N R3E	8.50	
11	12364	24 T15N R3E	7.75	
12	8452	33 T15N R4E	16.0	
13	12476	9 T16N R3E	13.35	
14	12476	19 T16N R3E	8.50	
15	3247	35 T16N R3E	8.58	
16	11966	2 T16N R4E	14.11	
17	12963	13 T17N R3E	17.10	
18	12860	35 T17N R4E	17.29	
BARRY				
20	7304	20 T1N R8W		93
21	7125	12 T2N R9W		95.18
22	6705	5 T3N R9W		92.35
23	7104	1 T4N R8W		91.36
24	6350	18 T4N R9W		92.19
25	5990	2 T4N R10W		87.74
26	4903	30 T4N R12W		94.54
CALHOUN				
27	9765	14 T3S R4W		98.18

Map Number	Permit	Location	Sand Percentage	Clastic Percentage
CLARE				
28	10046	1 T17N R3W	3.00	
29	10699	14 T17N R5W		96.73
30	9215	25 T20N R3W	4.00	
CLINTON				
31	6433	18 T5N R2W	10.42	
32	10484	17 T6N R2W	10.0	
33	10589	8 T7N R1W	11.90	
34	11803	2 T7N R2W	5.57	
35	10335	3 T8N R2W	7.72	
CRAWFORD				
36	12998	17 T25N R4W		86.47
GENESSEE				
37	12380	6 T8N R5E	30.52	
38	11914	10 T9N R5E	24.70	
39	8992	8 T9N R8E	32.15	
GLADWIN				
40	4894	12 T18N R2E	9.59	
GRATIOT				
41	12130	15 T9N R1W	6.33	
42	11991	13 T9N R3W	2.95	
43	10536	36 T11N R3W	3.22	
44	13308	36 T12N R3W	2.00	
45	10193	5 T12N R4W		97.20
HURON				
46	12508	T15N R10E	37.5	
47	8407	23 T15N R11E	24.36	
48	16488	31 T15N R12E	24.90	
INGHAM				
49	4837	28 T2N R1W	11.92	
50	9987	22 T4N R1W	12.72	
IONIA				
51	11027	6 T7N R7W		97.0
52	9826	17 T8N R5W		
IOSCO				
53	12531	4 T21N R5E	27.66	
54	3927	8 T22N R6E	20.0	
55	12163	1 T22N R8E	34.0	

Map Number	Permit	Location	Sand Percentage	Clastic Percentage
ISABELLA				
56	11254	29 T13N R3W		
57	7450	21 T13N R5W		94.50
58	11199	3 T14N R5W		94.14
59	12386	3 T14N R5W		95.70
60	12168	29 T15N R4W		
KENT				
61	6960	10 T5N R11W		91.65
62	6340	6 T5N R12W		92.45
63	4675	29 T5N R12W		93.00
64	6684	14 T6N R12W		92.85
65	9166	30 T7N R12W		90.0
66	6591	20 T8N R10W		93.25
67	10596	12 T8N R11W		91.70
68	6198	29 T8N R12W		87.20
69	7010	30 T9N R12W		88.84
70	16710	9 T10N R11W		87.60
LAKE				
71	8894	15 T18N R11W		87.41
72	13403	13 T18N R12W		84.29
LAPEER				
73	10117	5 T8N R10E	26.37	
74	5091	27 T9N R9E	29.53	
75	13861	22 T9N R10E	25.43	
MASON				
76	8159	13 T19N R15W		88.0
MECOSTA				
77	11723	1 T13N R8W		93.5
78	11460	34 T14N R9W		88.75
79	1175	32 T15N R7W	95.0	
80		28 T16N R7W	93.50	
MIDLAND				
81	11711	24 T13N R2E	7.74	
82	11732	28 T15N R1E	5.30	
83	10309	19 T15N R2E	5.73	
84	11046	36 T16N R1E	6.68	
85	13558	20 T16N R2W	3.90	
MISSAUKEE				
86	9442	14 T21N R7W		85.41
87	7357	22 T21N R7W		84.22
88	11822	6 T24N R7W		88.4

Map Number	Permit	Location	Sand Percentage	Clastic Percentage
MONTCALM				
89	11939	9 T9N R5W		
90	9469	2 T10N R7W		94.70
91	12343	28 T11N R7W		96.08
92	7299	29 T11N R8W		88.62
93	11888	27 T12N R8W		94.14
MUSKEGON				
94	11550	34 T9N R14W		85.17
95	7468	28 T9N R15W		83.70
96	13464	33 T9N R16W		76.68
97	15765	1 T10N R16W		
98	29538	11 T12N R17W		78.85
NEWAYGO				
99	10674	16 T11N R11W		88.47
100	13650	17 T11N R13W		85.83
101	13570	10 T11N R14W		81.22
102	13684	34 T12N R11W		88.58
103	13047	5 T12N R12W		86.6
104	19874	11 T12N R13W		85.47
105	9443	3 T13N R11W		87.52
106	20096	6 T13N R14W		88.20
107	16737	4 T13N R14W		86.41
108	10320	8 T14N R11W		89.76
109	16801	11 T15N R12W		93.72
110	15977	23 T16N R12W		96.84
OCEANA				
111	16824	18 T16N R16W		85.0
112	11294	28 T14N R15W		87.25
113	15273	20 T14N R17W		88.25
114	15587	28 T15N R16W		89.00
115	12030	31 T16N R15W		88.35
116	6880	27 T16N R16W		87.73
OGEMAW				
117	13272	29 T21N R4E	16.65	
118	10836	17 T22N R4E	18.90	
OSCEOLA				
119	11017	1 T16N R8W		95.51
120	10584	30 T17N R10W		93.60
121	10336	29 T18N R8W		93.20
122	3414	24 T18N R9W		92.12

Map Number	Permit	Location	Sand Percentage	Clastic Percentage
OTTAWA				
123	2481	36 T5N R13W		93.00
124	4648	29 T5N R14W		87.80
125	2482	16 T6N R13W		--
126	7444	28 T6N R14W		--
127	3678	35 T6N R15W		86.50
128	5689	36 T7N R16W		72.50
129	6749	11 T8N R14W		85.40
130	6592	35 T8N R14W		81.29
131	5750	13 T8N R16W		82.83
ROSCOMON				
132	5941	28 T22N R4W		93.0
133	13463	2 T24N R1W		--
SAGINAW				
134	3581	32 T9N R4E	17.11	
135	11700	3 T10N R2E	11.96	
136	11181	22 T11N R5E	28.79	
137	4503	35 T11N R5E	8.18	
139	11503	7 T12N R3E	11.0	
140	5472	31 T12N R3E	11.30	
141	11048	1 T13N R3E	19.22	
SANILAC				
142	10386	14 T13N R12E	32.50	
143	9275	14 T14N R12E	24.00	
SHIAWASSEE				
144	9396	4 T8N R1E	14.21	
TUSCOLA				
145	3449	10 T9N R9E	--	
146	12612	33 T10N R7E	25.55	
147	12158	9 T13N R10E	21.75	
148	9036	28 T14N R8E	33.50	
149	12217	31 T14N R11E	23.25	

APPENDIX III

APPENDIX III

LIST OF WELLS USED FOR ISOPACH AND STRUCTURE CONTOUR MAPS

Map Number	Permit Number	Location	Thickness	Structure
ALGONA				
1	24102	N26 E07 02		+214
2	11519	N26 E08 34		+ 68
3	23265	N27 E06 27		+139
4	24359	N27 E08 20		+434
5	27060	N28 E05 30		+200
ALLEGAN				
6	7997	N01 W11 28		-100
7	11491	N01 W12 03		-115
8	9906	N01 W12 30		- 49
9	15719	N01 W13 06		+ 48
10	19744	N01 W13 15		- 20
11	16507	N01 W14 33		+100
12	15797	N01 W15 05		+141
13	15003	N01 W15 30		+129
14	12468	N01 W16 20		+159
15	15556	N02 W11 18	740	-200
16	15221	N02 W12 06		-184
17	18529	N02 W13 27		-100
18	23533	N02 W13 27		- 5
19	14791	N02 W14 16		0
20	17313	N02 W16 14		+ 43
21	7303	N02 W16 04		+100
22	16028	N03 W11 21	805	-400
23	10977	N03 W12 17	725	
24	18798	N03 W13 05	757	-274
25	12072	N03 W13 15	769	-160
26	12784	N03 W14 10		-100
27	21849	N03 W14 17		- 59
28	25869	N03 W15 15		- 20
29	7361	N03 W16 27		+ 30
30	17884	N04 W11 23	897	-475
31	18245	N04 W11 23	903	-400
32	15752	N04 W12 04	808	-300
33	11626	N04 W12 21	783	-224

Map Number	Permit Number	Location	Thickness	Structure
34	17214	N04 W13 21	751	-200
35	17232	N04 W14 11		-177
36	20690	N04 W15 02		-120
37	16439	N04 W16 25		+10
38	16342	N18 E04 01	1029	-888
39	10421	N18 W04 16	963	-735
40	13579	N18 E04 36	1060	-795
41	9733	N18 E05 05	1052	-836
42	10797	N19 E03 05	1052	-842
43	11952	N19 E04 14	1050	-863
44	14772	N19 E04 29	1038	-720
45	13469	N19 E06 06	1090	-1050
46	10431	N20 E03 30	1040	-843
47	3811	N20 E04 09		-320
48	13468	N20 E05 16	1175	-700
49	11515	N20 E06 21		-815
50	22635	N20 E07 14		-1320
51	25751	N20 E07 33		-1286
BARRY				
52	16868	N01 W07 19	1045	-450
53	17496	N01 W08 07	926	-426
54	12279	N01 W09 03	969	-425
55	13890	N01 W09 06	1010	-440
56	6557	N01 W09 23	1015	-515
57	14782	N01 W10 21	909	-235
58	6828	N02 W07 10		-636
59	6231	N02 W08 22		-523
60	7125	N02 W09 12	920	-500
61	12122	N03 W10 01	870	-516
62	11826	N03 W10 08	942	-530
63	7104	N04 W07 01	1040	-900
64	17268	N04 W07 29	992	-833
65	15541	N04 W09 09	991	-710
BAY COUNTY				
66	10275	N13 E04 07	980	-1423
67	8746	N13 E06 03	960	-1469
68	10868	N14 E03 09	995	-1624
69	7900	N14 E04 02	940	-906
70	19460	N14 E05 04	1097	-942
71	10728	N15 E03 13	1038	-1100
72	19093	N15 E04 08	1026	-1174
73	18814	N16 E03 17	1032	-1369
74	3247	N16 E03 35	1064	-1233
75	17769	N16 E04 03	1013	-956
76	12053	N17 E03 07	1065	-880

Map Number	Permit Number	Location	Thickness	Structure
77	18756	N17 E03 24	1013	-947
78	17476	N17 E04 24	1025	-887
79	2670	N18 E03 11	1005	-800
BERRIEN				
80	6588	S03 W17 04		+336
81	7410	S03 W17 07		+432
82	5636	S03 W17 35		+331
83	10140	S04 W17 24		+400
84	6128	S04 W18 10		+420
85	7199	S06 W17 09		+510
BRANCH				
86	27650	S05 W05 08		-48
87	20355	S05 W09 02		-20
88	27853	S05 W07 15		+22
89	19967	S06 W05 01		+65
90	26432	S06 W05 01		+110
91	25240	S07 W05 30		+184
92	18528	S07 W07 10		+171
93	21599	S07 W08 07		+200
CALHOUN				
94	23255	S01 W05 12	1010	-587
95	22927	S01 W06 30	967	-370
96	22706	S01 W07 12	1002	-504
97	27259	S02 W04 07	1005	-422
98	26997	S02 W04 28	1017	-400
99	9839	S02 W05 07	990	-400
100	9382	S02 W06 08	950	-300
101	21333	S03 W04 23	1000	-280
102	12329	S03 W07 34		-120
103	20241	S03 W08 22		-100
104	23551	S04 W04 22		-176
105	26877	S04 W06 08		-110
106	7749	S04 W08 17		-20
CASS				
107	5985	S05 W13 20		+329
108	19104	S05 W15 13		_386
109	23876	S05 W15 29		+414
110	7794	S05 W16 17		+437
111	18554	S05 W13 15		+363
112	23698	S06 W14 14		+388
113	6955	S06 W16 04		+484
114	94365	S07 W13 02		+421
115	6221	S07 W13 20		+512
116	19009	S07 W14 36		+540

Map Number	Permit Number	Location	Thickness	Structure
CLARE				
117	8352	N17 W03 03	992	-1818
118	1681	N17 W03 19	980	-1729
119	4732	N17 W03 26	1007	-1915
120	9904	N17 W04 08	941	-1648
121	10699	N17 W05 14	906	-1684
122	10222	N17 W05 20	875	-1760
123	11833	N17 W06 18	825	-1540
124	16139	N17 W06 33	813	-1610
125	8029	N18 W03 08	1015	-1860
126	14537	N18 W04 22	985	-1725
127	19040	N18 W05 06	873	-1440
128	16487	N18 W06 04	855	-500
129	8475	N18 W06 25	872	-1545
130	3666	N19 W03 12	989	-1579
131	7306	N19 W04 11	967	-1645
132	9863	N20 W03 09	970	-1480
133	19209	N20 W03 25	979	-1500
134	8775	N20 W04 19	912	-1400
135	8378	N20 W05 16	885	-1275
136	8438	N20 W06 36	846	-1366
CLINTON				
137	9737	N05 W01 20	1030	-1214
138	3495	N05 W02 11	1094	-1251
139	6433	N05 W02 18	1062	-1200
140	13619	N06 W01 29	938	-1244
141	10484	N06 W02 17	1095	-1284
142	12925	No6 W03 02	1086	-1320
143	11278	N07 W01 03	1020	-1246
144	3586	N07 W01 25	1003	-1130
145	3395	N07 W02 14	1024	-1265
146	9033	N07 W04 21	1082	-1329
147	13175	N07 W04 36	1095	-1340
148	15762	N08 W02 12	1000	-1300
149	2732	N08 W02 22	1020	-1300
150	14458	N08 W03 15	1124	-1400
151	12514	N08 W04 28	1081	-1367
CRAWFORD				
152	15507	N25 W02 26	1108	-488
153	4278	N25 W03 33	1046	-589
154	19302	N25 W04 02	992	-416
155	15329	N25 W04 20	994	-365
156	11774	N26 W02 16		-440
157	21027	N27 W01 28		-339

Map Number	Permit Number	Location	Thickness	Structure
EATON				
158	27766	N01 W03 03	1032	-805
159	18459	N01 W04 14	1037	-765
160	22947	N01 W06 02	970	-640
161	22939	N01 W06 17	975	-567
162	27461	N01 W06 24	1015	-602
163	12604	N02 W03 08	1054	-926
164	95384	N02 W04 28	1021	-826
165	21952	N02 W05 21	487	-781
166	1806	N03 W04 05		-940
167	22945	N03 W06 22		-789
GENESSEE				
168	7275	N06 E05 13	1007	-571
169	23948	N06 E07 29		-430
170	24028	N06 E08 12		-400
171	1943	N07 E06 31	1023	-643
172	20140	N07 E05 09		-831
173	11914	N09 E05 10	953	-1000
174	9669	N09 E07 11		-800
175	10916	N09 E08 06	960	-640
176	10482	N09 E08 25		-727
GLADWIN				
177	15084	N17 E01 02	1030	-1400
178	3912	N17 E01 09	1040	-1465
179	4762	N17 E02 20	1045	-1320
180	4101	N17 W01 10	1030	-1480
181	4985	N17 W01 32	1017	-1773
182	15451	N17 W02 06	990	-1822
183	4143	N17 W02 23	1015	-1781
184	3565	N18 E01 33	1053	-1434
185	4957	N18 W01 09	1020	-1522
186	4885	N18 W01 23	1025	-1400
187	7986	N18 W02 11	1010	-1630
188	4665	N19 E01 11	1050	-1300
189	5352	N19 E03 29	1030	-1212
190	5740	N19 W01 23	1035	-1520
191	4812	N19 W02 09	1010	-1618
192	3898	N19 W02 25	1040	-1680
193	4237	N20 E01 22	1076	-1330
194	7234	N20 E02 07	1067	-1200
195	14500	N20 W01 08	1041	-1490
196	14665	N20 W01 34	1015	-1400
197	16558	N20 W02 31	1006	-1512

Map Number	Permit Number	Location	Thickness	Structure
GRATIOT				
198	11562	N09 W01 05	963	-1395
199	12110	N09 W01 31	983	-1320
200	11991	N09 W03 13	1035	-1400
211	2661	N09 W04 10	1030	-1500
212	21296	N09 W04 18	1055	-1459
213	1774	N10 W01 32	975	-1400
214	2920	N10 W02 19	1015	-1437
215	4707	N10 W03 26	1015	-1482
216	12041	N10 W04 22	1041	-1530
217	9625	N11 W01 34	995	-1500
218	2971	N11 W02 17	988	-1470
219	12845	N11 W03 31	1020	-1520
220	18673	N11 W04 11	1007	-1570
221	2693	N12 W01 13	1010	-1580
222	2693	N12 W01 13	1010	-1580
222	16664	N12 W01 31	1000	-1560
223	2576	N12 W02 10	1000	-1666
224	16022	N12 W04 06	1034	-1750
225	12664	N12 W04 21	1040	-1660
HILLDALE				
226	17936	S05 W01 09	938	-80
227	22749	S05 W01 35	935	-5
228	25271	S05 W02 27		-9
229	26715	S05 W02 30	945	+25
230	21216	S05 W03 02	940	-67
231	23894	S05 W04 04		-107
232	21109	S06 W01 18		+31
233	24250	S06 W02 04		0
234	23590	S06 W02 22	932	+59
235	26578	S06 W04 08		+60
236	23058	S07 W01 35		+246
237	18056	S07 W02 16		+114
238	18519	S07 W03 03		+150
239	23670	S07 W04 28		+163
240	22298	S08 W02 04		+215
241	27045	S08 W04 32		+280
242	14088	S09 W03 04		+300
HURON				
243	15420	N15 W09 20	1102	-870
244	12508	N15 W10 07		-724
245	16222	N15 W10 27		-700
246	4593	N15 W11 15	1067	-736
247	24002	N15 E12 35		-612
248	9224	N15 E14 14		0

Map Number	Permit Number	Location	Thickness	Structure
249	11738	N15 E16 31		+423
250	12907	N15 E10 02		-830
251	24789	N16 E12 36	918	-531
252	5519	N16 E13 27		-376
253	5045	N16 E15 10		0
254	2180	N17 E10 28		-935
255	24040	N17 E10 36		-831
256	4509	N17 E14 01		0
257	11834	N17 E15 22		+94
258	18019	N18 E12 12		-377
259	8107	N18 E13 17		-264
INGHAM				
260	22607	N01 E02 13	1057	-220
261	9477	N02 E01 01	1060	-900
262	4918	N02 W01 23	1071	-900
263	4837	N02 W01 28	1060	-875
264	24518	N02 W02 16		-880
265	10011	N03 E01 14	1040	-1000
266	22676	N03 W01 33	1070	-973
267	8132	N04 E01 15		-1068
268	3352	N04 W01 09	1052	-1130
IONIA				
269	10865	N05 W06 04	1035	-1100
270	25688	N05 W06 17	1007	-1027
271	15063	N05 W08 29	1018	-860
272	5993	N06 W05 05	1042	-1222
273	3154	N06 W07 12		-1200
274	25025	N06 W08 04		-1040
275	27397	N07 W05 08	1043	-1351
276	20289	N07 W06 03	1098	-1317
277	11027	N07 W07 06	1035	-1200
278	15607	N08 W05 10	1010	-1400
279	11588	N08 W07 01	1087	-1345
280	3135	N08 W08 29	965	-1120
IOSCO COUNTY				
281	12531	N20 E05 04		-856
282	23084	N21 E05 11	1283	-907
283	23060	N21 E05 27	1250	-1029
284	10420	N21 E06 16	1222	-1012
285	17812	N22 E05 02	1300	-930
286	15686	N22 E06 23	1270	-1015
287	12163	N22 E08 01	962	-558
288	8557	N23 E05 15	1259	-979
289	17142	N24 E09 10		-177

Map Number	Permit Number	Location	Thickness	Structure
ISABELLA				
290	18344	N13 W03 04	1013	-1845
291	8751	N13 W03 20	1016	-1770
292	10963	N13 W04 27	1000	-1750
293	5576	N13 W05 08	944	-1653
294	7865	N13 W05 22	985	-1654
295	18999	N13 W06 05	923	-1615
296	14147	N13 W06 30	988	-1547
297	1804	N14 W03 01	995	-1684
298	4540	N14 W04 25	998	-1848
299	16745	N14 W06 10	860	-1643
300	8835	N15 W03 04	995	-1750
301	3451	N15 W03 30	974	-1739
302	15009	N15 W04 18	946	-1800
303	11145	N15 W05 21	934	-1736
304	12374	N15 W06 05	847	-1580
305	11858	N15 W06 29	843	-5173
306	7287	N16 W04 20	975	-1700
307	18645	N16 W04 30	896	-1750
308	11216	N16 W06 29	846	-1530
309	19265	N16 W06 35	873	-1623
JACKSON				
310	7149	S01 W01 26	1032	-600
311	21842	S01 W03 11	1021	-632
312	9781	S01 W03 34	1020	-541
313	26981	S02 W01 17	1020	-500
314	26548	S02 W02 16	1010	-500
315	21161	S02 W03 29	979	-400
316	21898	S03 E01 26		-307
317	18265	S03 E02 22	937	-326
318	22422	S03 W01 28		-332
319	22107	S03 W03 14	975	-310
320	22017	S04 E02 09		-244
321	18202	S04 W02 24	960	-160
322	22013	S04 W03 17	960	-170
KALAMAZOO				
323	20572	S01 W10 27		-100
324	7313	S01 W11 13		-187
325	8433	S01 W12 02		-40
326	20072	S01 W12 30		+35
327	7180	S02 W09 21		-73
328	8766	S02 W12 03		+45
329	13483	S02 W12 30		+80
330	95259	S03 W11 13		+100

Map Number	Permit Number	Location	Thickness	Structure
331	6899	S03 W11 31		+180
332	7186	S04 W10 06		+134
333	25006	S04 W11 27		+230
334	17004	S04 W12 19		+294
KALKASKA				
335	13895	N25 W05 12	992	-343
336	18664	N25 W06 16	903	-614
337	31650	N25 W07 35	872	-700
338	14659	N25 W08 27	785	-435
339	15638	N26 W05 06		-146
340	871	N26 W05 16	960	-200
341	17328	N26 W08 33	800	-275
342	20110	N27 W05 26	715	-170
343	20133	N27 W06 10		-13
344	16632	N27 W07 02		+100
345	27287	N27 W08 17		+41
KENT				
346	7103	N05 W09 23	885	-755
347	15568	N05 W10 17	826	-535
348	733	N05 W10 36	910	-630
349	11805	N05 W11 08	783	-480
350	4989	N05 W12 14		-400
351	13046	N05 W12 32	782	-300
352	11969	N06 W09 19	965	-833
353	9786	N06 W10 23	877	-716
354	154	N06 W11 19	780	-576
355	6375	N06 W12 04	740	-486
356	16685	N06 W12 35	782	-447
357	6768	N07 W09 06	900	-910
358	18083	N07 W10 13	850	-895
359	13926	N07 W11 23	814	-728
360	18874	N07 W12 05	719	-577
361	6070	No7 W12 32	743	-476
362	11422	N08 W09 22	885	-1028
363	13104	N08 W10 05	848	-900
364	12301	N08 W10 16	847	-900
365	14731	N08 W11 34	782	-790
366	18454	N08 W12 06	770	-630
367	9776	N09 W10 14	910	-1055
368	18113	N09 W11 24	820	-840
369	17388	N09 W12 03	740	-800
370	17096	N09 W12 16	700	-740
371	15618	N10 W09 05	860	-1224

Map Number	Permit Number	Location	Thickness	Structure
372	15918	N10 W09 18	901	-1183
373	16710	N10 W11 09	777	-900
374	16835	N10 W11 29	774	-874
LAKE				
375	16610	N17 W11 15	641	-1086
376	13941	N17 W12 22	596	-951
377	2883	N17 W13 33	597	-748
378	12885	N18 W11 02	582	-957
379	13403	N18 W12 13	534	-838
380	17893	N18 W12 20	590	-844
381	25972	N18 W14 17	581	-478
382	10798	N18 W14 24	565	-568
383	25983	N19 W12 14	571	-676
384	13587	N19 W12 36	548	-748
385	27806	N19 W13 20	570	-520
386	22693	N20 W11 24	635	-929
387	20224	N20 W12 12	600	-676
388	20234	N20 W12 30	558	-541
389	26832	N20 W13 32	533	-481
390	17677	N20 W14 07	519	-156
391	15419	N20 W14 12	528	-215
LAPEER				
392	3307	N06 E09 30		-221
393	12933	N06 E11 25		-32
394	24048	N06 E12 06		-109
395	24010	N06 E12 17		-42
396	18530	N07 E09 04	997	-533
397	2402	N07 E09 36		-400
398	24075	N07 E11 14		-240
399	23947	N07 E12 15		-159
400	26696	N07 E12 25		-81
401	11286	N08 E09 08	1035	-619
402	2562	N08 E09 13	1027	-600
403	19736	N09 E09 15	1056	-590
404	11777	N09 E10 20	1018	-583
405	24142	N09 E11 21		-485
406	5069	N09 E12 26		-317
407	24233	N10 E10 28	1027	-577
408	10466	N10 E12 27		-460
LENAWEE				
409	27785	S05 E01 18		-50
410	18835	S05 E02 05		-73
411	18914	S05 E03 01		-70

Map Number	Permit Number	Location	Thickness	Structure
412	23838	S06 E01 20		+124
413	23723	S07 E01 34		+329
414	26853	S07 E02 13		+300
415	23087	S07 E03 25		+422
416	23276	S08 E01 03		+344
417	21916	S08 E01 27		+400
418	24595	S08 E02 15		+421
419	23618	S08 E03 27		+523
420	16693	S08 E04 18		+557
LIVINGSTON				
421	23073	N01 E04 23		-279
422	15875	N01 E06 06		+738
423	10038	N02 E03 09	-259	
424	13518	N02 E04 01		+705
425	25868	N02 E04 14		-464
426	23374	N03 E03 02		+600
427	10990	N03 E03 11	1000	-420
428	12481	N03 E04 14		+700
429	27030	N03 E05 25		+416
430	24029	N03 E06 22		+323
431	15263	N04 E03 06		+100
432	22995	N04 E06 20		+185
433	23426	N04 E06 22		+35
MASON				
434	8263	N17 W15 09	510	-340
435	13646	N17 W15 22	565	-375
436	24262	N17 W16 18		-145
437	26172	N17 W16 26		-180
438	19204	N17 W16 36		-213
439	20908	N17 W17 10		-125
440	21278	N17 W17 26		-146
441	15417	N17 W18 26		-72
442	27310	N18 W16 33	527	-200
443	24188	N18 W17 14		-98
444	16753	N18 W18 03		+42
445	24454	N19 W16 20		-105
446	9511	N20 W15 22		-134
MECOSTA				
447	19603	N13 W08 02	888	-1478
448	19628	N13 W08 21	931	-1441
449	20240	N13 W09 01	861	-1422
450	26503	N13 W10 06	759	-1164
451	2613	N13 W10 22	824	-1200

Map Number	Permit Number	Location	Thickness	Structure
452	19610	N14 W07 06	850	-1554
453	11756	N14 W08 07	854	-1418
454	24275	N14 W08 36	890	-1500
455	11832	N14 #09 16	824	-1371
456	17912	N14 W10 19	820	-1200
457	9608	N15 W07 02	869	-1576
458	17892	N15 W08 11	809	-1466
459	12915	N15 W08 33	840	-1460
460	19965	N15 W09 29	759	-1300
461	16651	N15 W10 01	731	-1268
462	7483	N15 W10 08	730	-1200
463	16329	N16 W07 03	845	-1541
464	10903	N16 W08 12	833	-1500
465	16406	N16 W08 31	774	-1454
466	10612	N16 W09 08	685	-1300
467	11724	N16 W10 01	706	-1245
468	16764	N16 W10 08	650	-1141
MIDLAND				
469	1738	N13 E01 11	1014	-1700
470	2267	N13 E01 28	1070	-1664
471	95135	N13 E02 03	1075	-1732
472	95128	N13 E02 28	1030	-1689
473	7524	N13 W01 02	1030	-1685
474	1694	N13 W01 15	1042	-1606
474	1360	N14 W01 06	1005	-1720
476	1142	N14 W02 05	1005	-1700
477	1435	N14 W02 34	1008	-1634
478	10969	N14 E01 15	1033	-1822
479	5430	N14 E02 19	1042	-1844
480	3664	N14 E02 27	1040	-1800
481	18085	N16 W01 23	995	-1755
482	23861	N21 W07 19	800	-1270
483	7357	N21 W07 22	820	-1270
484	7726	N21 W08 21	774	-1194
485	8870	N22 W06 33	885	-1272
486	27768	N22 W06 36	908	-1261
487	11584	N22 W07 34	837	-1269
488	7767	N22 W08 14	808	-1132
489	9960	N23 W05 11	957	-606
490	17806	N23 W06 10	903	-751
491	11675	N23 W07 19	810	-951
492	10095	N23 W07 27	811	-975
493	10847	N23 W08 14	812	-961
494	12388	N23 W08 28	792	-916
495	16271	N24 W06. 18	857	-666
496	16347	N24 W07 12	860	-685

Map Number	Permit Number	Location	Thickness	Structure
MONTCALM				
497	20931	N09 W05 10	1090	-1462
498	19429	N09 W05 25	1096	-1470
499	23585	N09 W06 01	1091	-1448
500	13981	N09 W06 36	1075	-1356
501	16481	N09 W07 26	984	-1319
502	19380	N10 W05 04	1040	-1481
503	8123	N10 W05 21	1059	-1475
504	13864	N10 W06 13	1050	-1465
505	10451	N10 W07 13	1013	-1423
506	3112	N10 W08 23	942	-1345
507	11409	N11 W05 08	1012	-1553
508	11565	N11 W06 02	1054	-1589
509	13288	N11 W07 01	1015	-1500
510	16820	N11 W07 26	1012	-1454
511	16273	N11 W08 07	910	-1331
512	7560	N11 W08 33	1000	-1359
513	20521	N11 W09 16	871	-1278
514	21158	N11 W11 14	875	-1167
515	27505	N12 W05 08	1002	-1610
516	11835	N12 W05 36	996	-1610
517	20683	N12 W06 09	977	-1562
518	18555	N12 W06 27	988	-1560
519	3310	N12 W07 06	996	-1476
520	15690	N12 W07 26	1017	-1500
521	11919	N12 W08 03	934	-1431
522	13959	N12 W08 06	928	-1407
523	20004	N12 W09 08	839	-1246
524	17732	N12 W10 07	808	-1160
MUSKEGON				
525	22722	N09 W14 17	658	-475
526	19486	N09 W14 28	645	-458
527	24158	N09 W15 11	622	-438
528	7468	N09 W15 28	625	-425
529	3605	N09 W16 20	580	-260
530	7636	N09 W16 35	590	-300
531	20151	N10 W13 03	672	-685
532	14740	N10 W13 18	640	-583
533	15296	N10 W13 33	657	-615
534	16316	N10 W14 15	658	-500
535	18553	N10 W15 03	638	-410
536	8860	N10 W15 34	605	-400
537	15374	N10 W16 05	587	-241
538	11999	N10 W16 23	580	-300
539	27497	N10 W17 10	570	-276

Map Number	Permit Number	Location	Thickness	Structure
540	15820	N11 W15 23	655	-472
541	14620	N11 W16 03	612	-371
542	15364	N11 W16 19	580	-358
543	25472	N11 W17 15	567	-340
544	26783	N11 W17 32	554	-262
545	18227	N11 W18 13	585	-300
546	15995	N12 W15 09	615	-485
547	15789	N12 W15 19	640	-447
548	8193	N12 W16 05	596	-415
549	14982	N12 W17 03	550	-300
550	20084	N12 W18 12	540	-210
NEWAYGO				
551	19331	N11 W11 07	804	-966
552	10778	N11 W11 12	860	-1040
553	23149	N11 W12 10	710	-900
554	12128	N11 W13 35	704	-741
555	6045	N11 W14 14	654	-587
556	14415	N11 W14 29	634	-488
557	17331	N12 W11 20	729	-946
558	434	N12 W12 05	700	-850
559	12815	N12 W12 21	706	-885
560	12961	N12 W13 10	676	-724
561	16042	N12 W13 19	652	-677
562	19028	N12 W14 04	630	-567
563	18604	N12 W14 23	617	-659
564	9443	N13 W11 03	750	-1050
565	25189	N13 W12 03	685	-960
566	411	N13 W13 12	650	-830
567	20406	N13 W14 16	622	-646
568	22866	N13 W14 26	625	-663
569	10683	N14 W11 07	735	-1000
570	24988	N14 W12 19	685	-800
571	17183	N14 W13 32	642	-700
572	20002	N14 W14 05	600	-500
573	26487	N15 W11 25	750	-1160
574	16801	N15 W12 11	641	-973
575	26666	N15 W13 17	634	-663
576	27173	N15 W14 16	584	-559
577	95192	N16 W11 07	636	-1035
578	27850	N16 W11 28	643	-1062
579	15997	N16 W13 23	609	-800
580	15649	N16 W14 18	623	-440
581	16239	N16 W14 33	614	-531
OAKLAND				
582	18766	N02 E07 25		+600
583	9719	N02 E07 32		+688

Map Number	Permit Number	Location	Thickness	Structure
584	9262	N03 E07 18		+252
585	23407	N03 E11 01		+500
586	22665	N04 E07 09		-112
587	9751	N04 E08 02		-100
588	13072	N04 E08 22		+62
589	12454	N04 E09 16		+46
590	23655	N04 E11 08		+100
591	7798	N05 E09 15		-147
592	26658	N05 E11 08		-35
593	26436	N05 E11 14		0
OCEANA				
594	19099	N13 W15 09	595	-526
595	20027	N13 W16 19	568	-410
596	8331	N13 W16 23	600	-500
597	17201	N13 W17 26	539	-325
598	14328	N13 W18 09		-147
599	18340	N14 W15 24	610	-600
600	11294	N14 W15 28	590	-570
601	22494	N14 W16 21	560	-442
602	20238	N14 W17 06	561	-300
603	23128	N14 W17 10	570	-329
604	20684	N14 W18 11	533	-241
605	17758	N14 W19 13		-144
606	24241	N15 W16 28	579	-430
607	15681	N15 W18 23		-200
608	19688	N16 W15 22	570	-351
609	20881	N16 W16 25	550	-300
610	15059	N16 W17 05		-100
611	23765	N16 W17 13		-187
OGEMAW				
612	12267	N21 E01 08	1082	-1044
613	16723	N21 E01 15	1111	-993
614	4830	N21 E02 02		-283
615	14832	N21 E03 03	1156	-700
616	19978	N21 E03 16	1074	-427
617	18508	N21 E03 36		-322
618	1770	N22 E01 23	1100	-421
619	19167	N22 E02 18		-310
620	4753	N22 E02 33		-261
621	1143	N22 E04 16	1109	-563
622	14474	N22 E04 25		-682
623	5264	N23 E02 05		-293
624	3825	N23 E03 29		-387
625	8213	N24 E01 08		-400
626	17239	N24 E02 18		-304
627	23711	N24 E03 04	1224	-431

Map Number	Permit Number	Location	Thickness	Structure
OSCEOLA				
628	15489	N17 W07 11	818	-1541
629	18068	N17 W08 08	743	-1412
630	18778	N17 W08 14	777	-1481
631	6838	N17 W10 08	662	-1057
632	27578	N17 W10 31	644	-1100
633	5572	N18 W07 10	804	-1600
634	20395	N18 W08 35	802	-1420
635	9918	N18 W09 28	685	-1255
636	15915	N18 W10 17	614	-1000
637	23121	N18 W10 26	634	-1132
638	25862	N19 W07 17	806	-1548
639	16379	N19 W08 15	772	-1500
640	10159	N19 W09 01	750	-1300
641	9434	N19 W10 02	662	-1100
642	26157	N19 W10 27	655	-1047
643	26254	N20 W07 05	800	-1342
644	18698	N20 W08 18	761	-1200
645	14405	N20 W09 26	690	-1100
646	18709	N20 W10 15	654	-1000
OSCODA				
647	12242	N25 E02 22		-446
648	18586	N25 E03 34		-500
649	25175	N26 E01 09		-500
OTSEGO				
650	17787	N29 W01 13		60
651	17455	N29 W02 10		200
652	16183	N29 W02 16		148
653	26216	N29 W03 16		269
654	25873	N29 W04 02		386
655	18467	N30 W01 10		378
656	20543	N30 W03 21		241
OTTAWA				
657	9738	N05 W13 21	768	-247
658	7833	N05 W13 35	765	-235
659	5162	N05 W04 10	715	-229
660	19398	N05 W14 21	682	-155
661	9589	N05 W15 09	650	-124
662	14697	N06 W13 21	729	-355
663	20414	N06 W14 21	683	-227
664	26332	N06 W15 26	647	-200
665	8141	N07 W13 08	728	-472
666	5557	N07 W14 16	651	-336
667	5629	N07 W15 23	620	-256

Map Number	Permit Number	Location	Thickness	Structure
668	5888	N07 W16 13	582	-200
669	7099	N08 W13 07	703	-500
670	6592	N08 W14 35	658	-442
671	19373	N08 W15 04	592	-370
672	15837	N09 W13 15	676	-635
673	19745	N09 W13 28	684	-575
ROSCOMON				
674	4270	N21 W01 36	1050	-1337
675	16985	N21 W03 29	960	-1443
676	9616	N21 W04 32	914	-1523
677	5221	N22 W02 06	1050	-1169
678	18973	N22 W02 28	1007	-1200
679	5941	N22 W04 28	955	-1233
680	4603	N23 W02 26	1075	-996
681	8625	N23 W04 31	1009	-1079
682	15756	N24 W01 20	1085	-400
683	10241	N24 W02 16	1052	-428
684	26722	N24 W04 22	1015	-610
SAGINAW				
685	9273	N09 E01 10	968	-1321
686	95235	N09 E03 13		-1128
687	10355	N09 E04 11		-1074
688	3581	N09 E04 32		-1000
689	95145	N10 E02 28	991	-1328
690	3148	N10 E03 11	950	-1284
691	95236	N10 E04 14		-1158
692	20583	N10 E06 10		-968
693	4099	N11 E01 33	995	-1465
694	6535	N11 E02 11	975	-1400
695	19538	N11 E03 17	1011	-1368
696	15019	N11 E04 28	981	-1300
697	19363	N12 E01 02	1028	-1580
698	2683	N12 E02 31	1025	-1481
699	95642	N12 E04 14		-1200
700	11347	N12 E05 35	1030	-1174
701	12262	N13 E04 33	980	-1300
ST. CLAIR				
702	22468	N06 E13 08		+67
703	22409	N06 E13 33		+145
704	26903	N06 E14 11		+270
705	27872	N06 E15 29		+370
706	25593	N07 E13 22		0
707	25841	N08 E13 12		-114
708	25859	N08 E14 19		-70
709	24274	N08 E15 33		+190

Map Number	Permit Number	Location	Thickness	Structure
ST. JOSEPH				
710	18405	S05 W09 02		+110
711	17184	S05 W12 03		+276
712	24183	S06 W09 29		+262
713	1244	S06 W11 02		+320
714	14283	S06 W12 09		+324
715	7045	S07 W12 10		+463
SANILAC				
716	24220	N09 E14 08		-188
717	24346	N09 E15 31		+70
718	22856	N11 E12 25		-555
719	22857	N11 E14 07		-215
720	18725	N11 E15 05		+185
721	10921	N12 E13 02		-140
722	23769	N12 E14 27		-32
723	10386	N13 E12 14		-330
724	23500	N13 E13 20		-205
725	23616	N13 E14 06		-170
726	24139	N13 E15 34		+260
727	23583	N14 E12 28		-541
728	24047	N14 E15 21		0
SHIWASSEE				
729	7013	N05 E03 08		-300
730	8214	N06 E02 35		-400
731	1570	N06 E03 11		-566
732	14349	N07 E02 03		-1000
733	9396	N08 E01 04		-1300
734	21026	N08 E04 01		-900
TUSCOLA				
735	13821	N10 E07 28	1085	-755
736	20209	N10 E09 05	1074	-730
737	4943	N11 E08 32	1050	-856
738	12808	N13 E09 04	1030	-869
739	19757	N13 E10 29		-1042
740	15817	N13 E11 05	1167	-574
741	21169	N14 E07 15	1084	-830
742	18882	N14 E09 10	1147	-930
743	20159	N15 E08 29	1165	-970
VAN BUREN				
744	8533	S01 W14 01		+100
745	59580	S01 W14 08		+137
746	5697	S01 W15 09		+135

Map Number	Permit Number	Location	Thickness	Structure
747	10866	S01 W16 36		+200
748	15601	S01 W17 22		+200
749	5363	S02 W13 21		+100
750	10752	S02 W14 20		+168
751	19370	S02 W15 21		+203
752	7999	S02 W16 21		+245
753	25991	S03 W13 19		+258
754	24819	S03 W14 10		+232
755	6533	S03 W15 13		+245
756	8442	S04 W13 05		+300
757	19190	S04 W14 24		+322
758	25679	S04 W15 29		+396
WHASTEMAW				
759	21477	S01 E03 06		+52
760	19371	S01 E05 33		+132
761	10792	S01 E07 33		+460
762	19751	S02 E03 14		+200
763	18945	S02 E04 30		+222
764	19202	S02 E05 28		+480
765	18886	S04 E04 21		+365
WEXFORD				
766	23837	N21 W09 28	693	-1000
767	11755	N21 W10 21	661	-900
768	16018	N21 W11 23	645	-857
769	10181	N21 W11 29	668	-771
770	25348	N22 W09 13	719	-1000
771	4584	N22 W09 17	706	-856
772	10245	N22 W10 30		-778
773	12415	N23 W09 32	718	-840
774	10303	N23 W11 11	658	-479
775	26022	N24 W09 20		-544